code V

DESIGNER'S MANUAL

Optical Research Associates

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CODE V™

DESIGNER'S MANUAL

SYSTEM OF OPTICAL DESIGN PROGRAMS
Second Edition

THIS MANUAL DESCRIBES THE FEATURES AND USAGE OF CODE V , A PROPRIETARY PRODUCT OF OPTICAL RESEARCH ASSOCIATES, PASADENA, CALIFORNIA.

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PREFACE

CODE V provides the capability of analysis, image evaluation, and automatic design. It reflects research and experience in automatic design techniques dating back to 1954. ORA has used automatic design techniques as its basic design approach since 1963 and CODE V (Computerized Optical Design and Evaluation, Version V) embodies the results of operating experience on hundreds of complex lens designs. It and its predecessors have been in daily use by ORA and other active design groups.

The key premises on which this system has been developed are the following:

1. It must be easy to use, requiring only the input data naturally associated with the optical problem.

2. It should be flexible, with added data, to give the optical designer sufficient command of the program to handle special optical problems.

CODE V incorporates features which have resulted from real needs. It is frequently expanded to include new capabilities. From time to time, partially complete concepts are included to provide a limited new capability. Depending upon response to these features and experience with them, ORA will develop the capability in a complete form.

History of ORA's Program Developments

The current program is the outgrowth of research by the principals of ORA and reflects the combined interaction of extensive lens design experience with mathematical and programming skills.

The early phases* of this research seem rudimentary by today's standards but provided valuable background on both the possibilities and limitations of automatic optical design. The first work was done on the Burroughs E101, the first machine low enough in cost to be dedicated to optical design. The "automatic design program" consisted of a 3 x 3 matrix solution for the changes needed to produce a desired set of third order spherical aberration, coma, and astigmatism coefficients when given a change table of these aberrations for three variables. It took 45 seconds to trace a skew ray through one optical

*This was done while the principals were with Bell & Howell Company, with that company's encouragement and support.

surface, a speed which precluded doing much else in "automatic design."

In 1955, work was transferred to an LGP-30. With the aid of a hardware alteration and highly optimized machine language coding, a ray tracing and third order package was developed which provided skew ray tracing at 1.4 seconds per ray-surface -- twice as fast as the package developed for the optical industry a year later and distributed with the machine.

Work by others (D. Feder, J. Meiron) using larger machines not devoted exclusively to optics had progressed by 1957 to the point that it appeared feasible to apply gradient techniques to optimization on the LGP-30. After six months of spare time study and mathematical analysis, the project won company endorsement and programming started; it must be remembered that Fortran was not available and all programming had to be done in machine language without benefit of assemblers.

The program employed a scheme of pseudo-raytracing[1] to develop the merit function; this produced the third and fifth order contributions to the ray aberrations for the selected rays to be minimized.

Investigations in the optical industry prior to 1955 can be roughly categorized as the time when a number of relatively unrelated processes were tried (Baker, Black, Hopkins and McCarthy); the process of least squares of underconstrained equations (Hopkins and McCarthy) enjoyed the widest success. 1955 to 1960 can be categorized as the period of the "gradient process." As experience built up it became evident that gradient processes surpass matrix processes only when the merit function can be so quickly calculated that the calculation time of a matrix process is dominated by the matrix solution itself; for optics, the use of gradient processes cannot surpass matrix processes for much more complex a merit function than one composed of the third order aberrations. The disenchantment with gradient processes led to the rediscovery of the damped least squares method (by Wynne and Girard) just before 1960, and to the orthonormalized aberration method (by Grey) in the early 1960's. Both of these processes recognize the fact that gradient processes throw away a great deal of information which can only be recovered by a sophisticated acceleration technique (method of conjugate gradients); the method of orthonormalized aberrations employs a transformation of the variables which makes it easy to apply a variable-by-variable reduction method proposed much earlier by Black (and without which Black's method is impractical). These two methods now are the dominant processes in use; each has been extensively enhanced by a number of acceleration techniques developed since their introduction.

The LGP-30 program for third and fifth order ray aberrations was effective for correcting systems dominated by these two orders,

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[1]See "A System of Optical Design," Arthur Cox, Focal Press, p. 175-178.

but was overly ambitious for a gradient process on such a slow machine. After cutting it back to a third order correction program it served as the vehicle for experimenting with a wide variety of acceleration techniques culminating in a special conjugate direction method[2] combining the method of conjugate gradients with the parabolic approximation method of J. Meiron.

In 1961 the need for a more sophisticated optimization program using damped least squares became evident. Two basic difficulties arose. The first of these was that no literature references could be found which gave methods of employing the damped least squares technique subject to side constraints, except by including them in the merit function. It was, and is, our belief that the merit function should represent only the quality of the solution and should not include deviations from physical requirements (effective focal length, back focal length, edge or center thicknesses, clear apertures, etc.); the "cleaner" the merit function is, the simpler and more constant the weighting of it becomes. After considerable mathematical analysis and experimentation a process was evolved wherein the damped least squares process could be solved subject to side constraints within the same size matrix as the damped least squares alone could be solved.

The second basic difficulty was that the optimization program had to be adaptable to an IBM 7070 with 5000 words of memory for program, data and operating system. The solution of this problem was aided by the realization that the processes in the damped least squares method are separable. This produces the rather paradoxical result that a program can allow an unlimited number of aberration defects but fit into less space than any other approach.

Early in 1963, ORA was formed and development continued. Introduced at that time was the monitor concept wherein any sequence of operations (scaling, automatic design, analysis, MTF, etc.) can be executed in a chain, operating on the current system in memory. This is the heart of an efficient production optical design operation and eliminates the need for data conversion from program to program with intermediate punched decks, and keeps the data entries independent of any preceding operation so that they may be performed in any order.

In 1964, the program was converted into what is believed to be the first zoom automatic design program. In 1965, ORA acquired its first computer, with a memory capacity of effectively 12,000

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[2] "Conjugate Direction Methods in Automatic Optical Design," Thomas I. Harris. Presented at Optical Society of America meeting in Pittsburgh, Pa., March 3, 1961.

words and converted the program so that the entire optimization process could be contained in memory at once without program overlays or peripheral data storage. At the same time, a major revision was made in order to permit an increase in the allowed number of variables to 45.

Part of this revision included the conversion from the previous method to the Lagrangian multiplier method of handling the side constraints. The prime advantage of the latter is that it permits the programming of a precise, reliable method of including or dropping inequality constraints.

Since 1965, many extensions and improvements of the program have been made. In that year, ORA developed one of the first polychromatic diffraction MTF programs and added it to the package. Accelerations have been introduced which accomplish an optimization in 1% of the time needed by the program in 1964. Transfer to ORA's larger, faster machines has permitted an increase in the number of variables (not normally required except for complex zoom lenses) as well as allowing additional basic operations under the monitor concept. In recent years, particular attention has been devoted to developing comprehensive lens tolerancing techniques.

Acknowledgements

The technology underlying CODE V is derived from many sources, including literature references. But more important have been many direct discussions with optical scientists. To them, collectively, we express our gratitude.

As essential as the technology is, it is equally important that it be cast into a useful form. Our users, staff and customers are responsible for many features of the present program which have arisen from their suggestions and comments. We welcome these as the foundation for future improvements in CODE V.

In particular, we appreciate the vigorous representation of the user within our own group by Robert Hilbert and his staff and the many technical developments generated by Matthew Rimmer in recent years.

We would also like to acknowledge the valuable contribution of Patricia Wilson, who has shared the programming load with us for several years, and both Mary Jo Poague and Leigh King who have supervised the generation and printing of this manual.

Darryl E. Gustafson
Thomas I. Harris

September 1, 1978

CODE V - CONTENTS

CODE V

Introduction

CODE V is an optical programming system - a language of optical design. Its aim is to permit the designer to communicate with the program in as easy, natural and simple a manner as possible.

CODE V permits the specification of simple or complex lens systems, both rotationally symmetric and decentered. It is a powerful tool in the development of zoom (or multi-configuration) systems as well as non-zoom systems. Features facilitate the design of anamorphic and wide angle lenses, afocal systems, multi-spectral lenses and systems employing diffraction gratings. Surfaces can be:

- Spherical
- Aspheric (spline or standard polynomial)
- Aspheric toroidal
- Cylindrical
- Fresnel
- Diffraction gratings
- Radial index gradient
- Decentered and tilted

A lens can be input to the computer, either according to the designer's data or by retrieval from the lens library. Glass information is supplied from disc stored optical glass catalogs to complete the data. The lens system remains in memory, to be operated upon or analysed by the computer acting under the designer's directions, until it is replaced by another lens.

Once defined, the lens can be altered by scaling, by optimization or test plate fitting, by change of environment, by a given perturbation under a tolerance budget, or by specific request of the designer. It can be saved in a lens library for later retrieval or conditionally replace the former version if it is better.

At any time, the lens can be analysed with a wide variety of geometrical and diffraction based techniques, have its structure drawn on a plotter for checking its mechanical suitability, and have its physical properties evaluated.

The data can be tabulated in a form suitable for the mechanical designer and released with an optical layout; tolerance budgets can be established with sensitivity analysis and checked with a Monte Carlo simulation of fabrication. The finished design can be automatically fitted to test plates; report-ready plots of final performance data can be generated as required.

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code V

Optical Research Associates
550 NORTH ROSEMEAD BOULEVARD
PASADENA, CALIFORNIA 91107

DATE____________
BY____________

TITLE: DATA

SURFACE DATA

	CURVATURE (1)	CCY (16)	THICKNESS (21)	THC (36)	GLASS (41)	GLC (56)	GLASS CHARACTERISTICS (61)	SPEC (76)	TYPE (79 80)
OBJ								[redacted]	
1	1.7301		.088		SSK4				
2	.5274		.003						
3	2.849		.125		SK1				
4	0.0		.038		F15				
5	4.6296		.152						
6	0.0		.130						
7	-3.6765		.038		F15				
8	0.0		.109		SK16				
9	-2.8409		.003						
10	.1694		.069		SK16				
11	-1.5748								
12(FP)									

Figure

CODE V is thus intended to be a powerful tool supporting the designer in all of the computational tasks from concept to finished hardware.

Organization of Design Task

Just as an optical design task may be broken down into sub-tasks, CODE V is organized into distinct operations. These are called options; there are more than forty of them. The designer might outline his basic tasks as:

I. Define system data
II. Optimize
III. Save result
IV. Compute third order and ray trace analysis
V. Draw sketch of lens
VI. Compute diffraction MTF

In CODE V, these would be done by calling for the options (each represented by a card):

DATA
AUTOMATIC DESIGN
LIBRARY
ANALYSIS
LAYOUT
DIFFRACTION MTF

Following each of these option cards would be data which would define any special instructions to the computer applying to that specific operation. Most options will operate without supplying any additional data, by using standard assumptions or default settings; the additional data is supplied only if these standard assumptions are to be modified. Any such group of additional data cards following an option card is usually order independent. Thus it is easy to get useful results without lengthy data preparation and with little experience with the program

Entry of Lens Data

The initial entry of lens data is done through the DATA option. There are two essential types of data required by every system. First, the construction of the system (curvature, thicknesses and separations, and materials) must be defined; second, the usage of the system (nature of the light bundles) must be specified. In addition to these, it is desirable to have a label attached to the data; this is used for titling printed and plotted output. Some systems require data also to define mechanical apertures, special refractive materials, or to generate constructional data based on use (solves).

For convenience, the surface data is entered in a special format that requires one card per surface for normal surfaces. The three items

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PASADENA, CALIFORNIA 91107

DATE ____________
BY ____________

DATA

TITLE DOUBLE GAUSS EXAMPLE U.S. PAT. 2,532,751

SURFACE DATA

	CURVATURE	CCY	THICKNESS	THC	GLASS	GLC	GLASS CHARACTERISTICS	STOP		TYPE
OBJ										
1	1.7301		.088		SSK4					
2	.5274		.003							
3	2.849		.125		SK1					
4	0.0		.038		F15					
5	4.6296		.152							
6	0.0		.130					F		
7	-3.6765		.038		F15					
8	0.0		.109		SK16					
9	-2.8409		.003							
10	.1694		.069		SK16					
11	-1.5748									
12(FP)										

SPECIFICATION DATA

F/N	2.0		
WL	650.	550.	450.
YAN		10.72858	15.0
VUY		.2828	.4
VLY		.2828	.4
SOLVES			
RED	0.0		
PIM			

Figure

required for each surface are surface shape, distance to the next surface and the material following the surface. The surface shape is normally defined by the curvature, the distance to the next surface by the physical distance along the mechanical axis[1], whether in glass or air, and the material by a suitable code which will permit the computer to provide all necessary indices of refraction. The codes used by this program are the manufacturer's glass type code or the equivalent 6 digit code[2]; nine catalogs are included on the CODE V disc.

The surface data can be put on a form such as that shown in Figure I, where the data for a double Gauss lens has been entered. Normal sign conventions are used; i.e., any surface whose center of curvature lies to the right of the surface has a positive curvature; any surface for which the following surface lies to the right has a positive thickness. All materials are represented by their codes; air is represented by a blank or the code AIR. Reflection would be indicated by REFL and the computer will assure that indices have the proper sign.

Thus on the form, the curvature, distance and glass code have been entered for each surface of the double Gauss. Note that a blank space has been left for the object surface at the beginning and for the image surface at the end; data for a curved object or image would be entered there. Note also that surface 6 has been flagged as the aperture stop (column 76). The remaining items of SURFACE DATA shown on the form are optional and will be discussed in detail later; the data given is all that is necessary for many of the operations needed.

The second type of data that is always required for any optical problem is the usage of the system (definition of light bundles). That is, some indication must be provided of the aperture, magnification, and field requirements of the lens system and the wavelength region over which it is to operate. This data and almost all other data is entered one item per card with a mnemonic code, as an identifier, followed by the value. See Figure II.

The aperture is indicated by entering the f/number of the cone of light in the image space; thus, since the lens is an f/2 lens with an object at infinity, the first card after SPECIFICATION DATA is

```
     F/N       2.0
```

---

[1] It should be noted that, for centered systems, the optical axis and mechanical axis coincide. For decentered systems, the two coincide only if the designer sets it up that way.

[2] The codes for all nine catalogs, together with ten indices of refraction calculated from the stored coefficients, can be obtained by using the GLIST request of the CATALOG option. For example, the Schott designation for 517-642 glass is BK7; no spaces or hyphens are used. The same glass would be obtained with 517642.

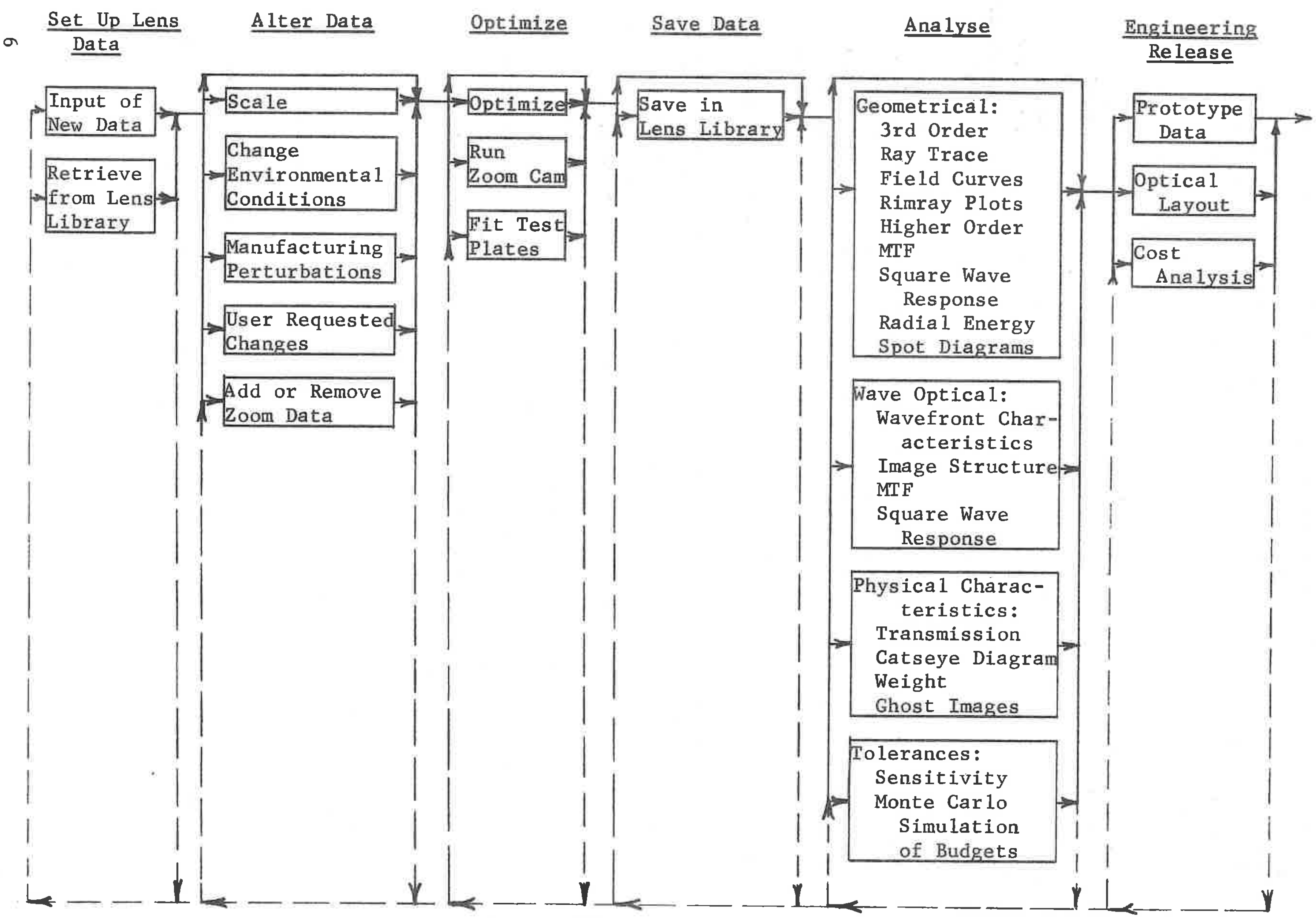

Figure III: Design Functions

Next, the wavelength band is specified by entering

```
WL        650.0     550.0     450.0
```

From one to seven wavelengths may be specified. Unless otherwise specified, the middle one of these will be used as the reference wavelength for first order and other calculations.

The field specification is given in terms of the desired input angles as

```
YAN                 10.72858  15.0
```

This requests three field angles at 0.0^{o}, 10.72858^{o}, and 15^{o}; up to 5 may be included. For this design some vignetting is permissable, so the amount of fractional bundle reduction on the upper and lower parts of the entrance pupil is entered as

```
VUY                  .2828    .4
VLY                  .2828    .4
```

This clips both upper and lower halves of the pupil by 28.28% at the second field angle and by 40% at the outer field angle.

The object distance may be entered on the object surface card or, as in this example, inserted by the program as a result of a SOLVE request for zero reduction ratio. The reduction ratio SOLVE is most useful for finite conjugate systems; if the lens were to work at 2:1 reduction, this would have been entered as

```
RED       .5
```

In addition, if evaluation of all system variants is needed with reference to the paraxial image distance, the PIM SOLVE requests that this distance be inserted by the computer as the thickness of surface 11.

This, plus the single title card (following DATA itself) complete the normal input data shown in Figure II. When this is entered, the computer supplies the object and image distance and all refractive indices and ckecks the data for completeness. At this point the designer may perform any of the other functions which the options represent. These are shown schematically in Figure III; there is no restriction implied on the order of options - they may be executed in any sequence. A brief description of all of the options is given in the Functional Contents.

If the designer chooses to perform an AUTOMATIC DESIGN operation, some additional data should be supplied on the input form. Even though it may have local significance only in the optimization options, for convenience of association with their variables we can supply control codes in DATA. These control codes tell the program which variables (curvatures or thicknesses in the current example) are to be varied or coupled to each other. For example, in the double Gauss, the designer may wish to freeze the curvature of the focal surface at zero, the

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PASADENA, CALIFORNIA 91107

DATE ____________
BY ____________

DATA

TITLE DOUBLE GAUSS EXAMPLE U.S. PAT. 2,532,751

SURFACE DATA

	CURVATURE	CCY	THICKNESS	THC	GLASS	GLC	GLASS CHARACTERISTICS	Slope		Type
OBJ										
1	1.7301		.088		SSK4					
2	.5274		.003	100						
3	2.849		.125		SK1					
4	0.0		.038	100	F15					
5	4.6296		.152							
6	0.0		.130					F		
7	-3.6765		.038	100	F15					
8	0.0		.109		SK16					
9	-2.8409		.003	100						
10	.1694		.069		SK16					
11	-1.5748									
12(FP)		100								

SPECIFICATION DATA

F/N	2.0		
WL	650.	550.	450.
YAN		10.72858	15.0
VUY		.2828	.4
VLY		.2828	.4
SOLVES			
RED	0.0		
PIM			

Figure IV

thicknesses of the negative lenses and separations between the doublets and singlets at their starting values. This could be done by calling the CHANGE option with:

```
CHANGE
CCY 12      100
THC  2      100
THC  4      100
THC  7      100
THC  9      100
```

where the 100 designates a freeze. Or these entries could be made as part of the input data as shown in Figure IV.

To complete the operation laid out earlier in the example would require the data of Figure IV plus the cards:

```
AUTOMATIC DESIGN
EFL        1.0           Maintains 1" EFL
MXT        .2            All ct's less than .2"
MNT        .038          All ct's greater than .038"
MNE        .038          All et's greater than .038"
MNA        .003          All airspaces greater than .003"
WTW        121           Color weights for 650, 550, 450, resp.
LIBRARY
SAVE       USERNAME      Saves optimized system under USERNAME
ANALYSIS                 (defaults:  3rd Order and Raytrace fans)
LAYOUT
DIFFRACTION MTF          (one focus position with default assignments)
END
```

The designer can obtain useful results, therefore, with relatively simple input. The choices may be expanded and refined at will as experience dictates.

Manual Organization

The remainder of this manual covers the detailed option descriptions and notes for data preparation. The options are grouped by chapters which follow, approximately, the design functions outlined in Figure III. In addition to these, Chapter XI is a collection of programs that are of value in optical systems analysis and that are usually used independently of the other options.

The new user should review the appendix on DATA PREPARATION PROCEDURES at the back of the manual to become acquainted with punching or entering data for CODE V including features such as comma input and comment cards. The early pages of the DATA option provide some of the philosophy for the way in which parts of CODE V data interact. The appendix to the DATA option describes the coordinate system used; this is of most concern to the designer of decentered systems.

Immediately following is an overview of all of the CODE V options. A second appendix at the back of the manual is an index of the options that can be used to find the chapter in which any option resides.

Updates will be provided from time to time to this manual. Stripes at the top of each page indicate all new sections; stripes at the outside edge indicate new program features; stripes at the inside edge indicate manual changes only.

Functional Contents - CODE V Options

Chapter I: Data Entry

These options allow the generation of the starting optical system:

A. DATA - Input for first configuration (the first zoom position) consisting of:
 Title Card - Designer's label for output.
 SURFACE DATA
  Defines the mechanical structure of the optical system with surface shapes, separations, and materials.
 SPECIFICATION DATA
  Defines the optical usage of the system - the wavelength, aperture, field and vignetting of the light bundles entering the system.
 APERTURE DATA - optional
  Defines special aperture shapes and sizes to be used, if needed, in evaluating the system.
 SOLVES - optional
  Defines special conditions to be imposed on the system which will be maintained by altering one or more structural items.
 PRIVATE CATALOG - optional
  Defines special materials referenced by the SURFACE DATA.

B. ZOOM DATA - Input for parameters changed in generating the additional configurations of a multi-configuration (zoomed) system.

C. DEZOOM - Removal of selected parameters from zoom list, or extraction of a chosen configuration.

D. SET DATA - Allows computer to generate some of the special input data rather than requiring it of the designer.

Chapter II: Data Alteration

These options allow the designer to change individual items of DATA, the scale of the system or to generate the dimensional changes associated with changes in the environment around and within the lens:

A. CHANGE - Allows the alteration of any zoomed or non-zoomed item of DATA, by mnemonic code references.

B. SCALE - Allows the alteration of the total system data to conform to a given EFL, Total Track, or scale factor, or to convert all of the dimensions to a different set of units (inches, centimeters, or millimeters).

C. ENVIRONMENTAL CHANGE - Allows the alteration of the total system data due to specified changes in:
   1. Temperature
   2. Pressure (or altitude)
   3. Radial Thermal Gradients
   4. Pressure Gradients or Gases

Chapter III: Lens and Procedure Libraries

These options allow the storage of lenses or procedure sequences for later retrieval:

A. LIBRARY - Provides for saving, replacing or retrieval of lens, data and for the conditional replacement of improved lenses after optimization.

B. SEQUENCE - Provides for saving any sequence of option and data cards and for its later execution. Useful for repeating groups of operations.

Chapter IV: Data Display

This option allows the listing of the system data, and display of selected data:

A. PRINT

Chapter V: Optimization

These options alter the lens system data in accordance with specified measures of lens quality to produce an optimum for each function:

A. AUTOMATIC DESIGN - Arrives at optimum values of all variables according to a defined merit function and subject to specified constraints.

B. TEST PLATE - Chooses best test plates for all possible surfaces while retaining optimum performance.

C. CAM - Chooses the optimized value for each cam increment for mechanically compensated zoom lenses.

Chapter VI: Evaluation - Geometrical Performance

These options provide varied approaches to establishing performance, ignoring the effects of diffraction:

A. ANALYSIS - Performs third order and ray trace evaluations in all wavelengths.

B. FIELD ABERRATIONS - Plots and/or prints distortion and Coddington-type field curves.

C. RIMRAY - Plots ray trace aberration curves (aberration vs. pupil point) for all wavelengths.

D. HIGHER ORDER ANALYSIS - Using the Aldis Theorem, calculates the surface-by-surface contributions to higher order ray aberrations.

E. GEOMETRICAL FREQUENCY RESPONSE - Plots and/or prints polychromatic geometrical MTF as a function of focus and frequency for each field angle. Square wave response, line spread function, edge gradient and detector responses are available special computations.

F. RADIAL ENERGY DISTRIBUTION - Prints polychromatic geometrical radial energy distribution as a function of focus and percentage for each field angle. Scanning is done to ensure correct minimum radii.

G. SPOT DIAGRAM - Plots polychromatic spot diagrams for all field angles at each requested focus position.

Chapter VII: Evaluation - Wave Optical Performance

These options provide varied approaches to establishing performance, including as part of the model, the effects of diffraction:

A. WAVEFRONT CHARACTERISTICS - Prints RMS wavefront errors and the resulting Strehl definition.

B. POINT SPREAD FUNCTION - Plots and/or prints a representation of the polychromatic intensity structure of the image. Scaling may be relative, Strehl, or db. Special computation provides the phase structure of the image. Plotting can be contour or oblique projection.

C. DIFFRACTION FREQUENCY RESPONSE - Plots and/or prints polychromatic diffraction MTF as a function of focus and frequency for each field angle. Special computations are spatial phase shift, polychromatic diffraction square wave response, and ray theoretic (geometrical) approximation. Orientations normally are 0° and 90°; optionally they may be 45° and 135°.

D. BEAM PROPAGATION - Computes Gaussian beam waist dimensions and positions as a function of anamorphic waist widths in the object.

Chapter VIII: Evaluation - Physical Performance

These options provide analysis of the physical properties of the system:

A. TRANSMISSION - Computes the integrated system transmission at each wavelength, assuming MgF_2 coatings, and for each field angle. Print-out gives the transmission factors and the system totals at each wavelength.

B. CATSEYE DIAGRAM - Plots the edges of designated clear apertures as projected on the entrance pupil plane, for each field angle. Since real rays are used, contours involve all aberrations and accurately represent the composite clear aperture shape at each field angle.

C. WEIGHT - Computes the weight and center of mass of each element and the image.

D. GHOST IMAGE ANALYSIS - Computes all combinations of two-surface reflection ghosts.

E. NARCISSUS ANALYSIS - Computes the out-of-focus blur radius on the detector arising from the cold stop.

Chapter IX: Tolerance Analysis

These options provide for the systematic budgeting and testing of tolerances:

A. TOLERANCE (Primary Aberrations) - Prints table of toleranced lens data. Computes the sensitivity of radii, thicknesses, index, test plate match, irregularity, inhomogeneity, and centering as indicated by first order properties, primary aberrations, Coddington-type foci, and RMS wavefront measures. Computes sensitivity and inverse sensitivity of a designated performance measure. With Monte Carlo techniques, simulates the manufacture of a quantity of systems, printing the statistical distribution of the performance measure. On request, the system may be modified to a given perturbation or to the average system.

B. TOR - TOLERANCE (Ray Based) - Computes tolerances for RMS error or MTF at a designated frequency. Prints sensitivity, inverse sensitivity, plus a statistical summary of combined effects. Each tolerance can include compensating parameters acting over all field positions and wavelengths. Chief ray distortion tolerances may be included.

Chapter X: Fabrication Aids

These options provide support for the mount designer and later manufacturing stages:

A. MODEL DATA - Prints element-by-element data including radii, thickness, separation, clear aperture and materials.

B. LAYOUT - Draws a cross-sectional picture of the lens system and ray bundles.

C. COST FACTORS - Prints approximate number of lenses per tool and cost of material in an element and in the smallest circumscribed block.

Chapter XI: Systems Analysis

These options, largely self-contained, provide for system oriented computation:

A. SPECTRAL ANALYSIS - Cascades specified responses, plots the result if requested, prints and enters spectral weights for polychromatic computations.

B. ILLUMINATION SYSTEMS - Computes the relative intensity on a receiving plane for a given source and optical system.

C. MULTILAYER COATING OPTIMIZATION - Optimizes the structure of a multi-layer stack which will most closely approximate the desired spectral transmission characteristics.

D. IMAGE SIMULATION PROGRAMS - Provides for system performance studies involving structural objects, linear and non-linear components (lenses, film and various types of degradation). Output can be printed or plotted.

Chapter XII: Operation Aids

A number of options to assist in support of CODE V and in providing unattended operation:

END	
EXIT	
FILE	See option description
LOAD, EXECUTE	
EJECT, EON, EOF	
O=TY, O=LP, O=NO, I=CR, I=TY	
RJSTART, RJENT, /*EOF	
RJSTART, RJEND, I=R, O=R	

DATA ENTRY

DATA

I. PURPOSE

Provides for entry of basic optical system data, checking for errors, and supplies any additional data common to all other options.

II. INTRODUCTION - PHILOSOPHY OF CODE V DATA

What kinds of data are there?

Optical data consists of several classes of information:

A. Construction - surface shapes, positions and materials.

B. Usage - definition of object format, optical aperture or speed, and wavelengths.

In addition, the designer may want to provide added information:

C. Label - to identify this particular lens.

D. Clear apertures - defined by the designer instead of by the usage definitions.

E. Generated construction data - produced by solves or by computation from usage data and prior construction data.

F. Special materials - defined by the designer if the program doesn't have access to them.

CODE V permits all of these to be entered through the DATA option. Only A, B, and C must be included for each system; the others are optional, depending on the problem.

Which do I use?

The designer's choice of data is partly dependent on the nature of his task. If he is designing a new lens he may not care to define the clear apertures but, instead, let the conditions of use do it for him. On the other hand, he may be analysing a lens which has been or is to be built with known apertures; in the worst case he may not know the exact condition of usage. These two examples illustrate the way in which several features of CODE V interact to generate the result desired by the designer.

What do I include in the construction data?

Construction data (called SURFACE DATA) consists only of the optical surfaces but these include the object and image surfaces and any dummy surfaces (same material on both sides) the designer chooses to include for mechanical or other control. One surface, dummy or not, is usually declared by the designer to be the aperture stop.

What does the usage data do?

The usage data (called SPECIFICATION DATA), which is always required, defines a set of object points and the operating aperture, with or without vignetting, for each of them. In so doint it specifies a set of reference rays, which are assumed throughout CODE V to define the bundles of light associated with each object point.

What do the reference rays do?

In optimization (AUTOMATIC DESIGN, TEST PLATE), these rays are used to determine edge thicknesses and semi-diameter for several types of constraints. In diagnostic analysis programs (ANALYSIS, RIMRAY, HIGHER ORDER, LAYOUT) the reference rays only restrict the extreme ray fans traced.

In MODEL DATA, the reference rays are traced to determine clear apertures which are printed as part of the data table. These clear apertures serve a very important purpose for they are also determined in the same way in all of the performance evaluation programs (DIFFRACTION MTF, GEOMETRICAL MTF, SPOT DIAGRAMS, TRANSMISSION, etc.); these programs assume the lens has been built according to MODEL DATA and therefore the bundles at each field angle are the shape determined by all of these clear apertures.

Thus a lens may be optimized knowing the edges and clear apertures adhere to the designer's requests and evaluated as if it were built according to MODEL DATA.

Suppose I know the clear apertures but not the exact usage data?

This often happens when a design already exists. The designer can supply the known aperture data for all surfaces (in a section of data called APERTURE DATA) and with a simple request (the SC request in each option), invoke them for determining the beam shape for each field angle in all performance evaluation programs.

But suppose I want to also optimize and use the diagnostic programs?

For these, more accurate usage data must be obtained from the entered APERTURE DATA. The SET option does this; it updates the vignetting and aperture part of the usage data so that the reference rays are those which will generate those clear apertures which actually limit the bundles. The designer can then use optimization and diagnostic analyses in the same fashion as before.

Specifically, which rays are the reference rays?

For a rotationally symmetric lens, the reference rays are the chief ray and the upper and lower extreme meridional rays for all given object points; the upper and lower rays from each object point go through the edge of the entrance pupil unless the designer has defined vignetting factors or has used the SET option to do it.

Each clear aperture is that aperture just large enough to pass all of the reference rays; the aperture stop surface clear aperture is defined only by the extreme rays for the first object point. Optimization and diagnostic programs will limit their meridional tracing dimensions to these same reference rays but skew fans and tracing dimensions will extend to the full edge of the entrance pupil unless specifically restricted by the designer using skew direction vignetting.

Any decentered surface included with the system (whether or not the decenter values are zero) or any object with a non-zero x component will activate the tracing of skew reference rays as well. These may, of course, change the clear apertures used by the performance evaluation programs and MODEL DATA if they are not consistent with the real clear apertures.

Does CODE V handle decentered and non-decentered systems equally well?

CODE V had its early origins in a program (CODE III) for rotationally symmetric systems. It retains a number of efficiencies for both these and for systems bi-laterally symmetric about the Y-Z (meridional) plane. It has many extensions and generalizations to handle decentered or rotationally non-symmetric systems in both optimization and evaluation with equal facility. One example is the fast, convolution-based diffraction MTF program that does not require bilateral symmetry and yet takes advantage of such symmetry when it exists.

A bias in favor of rotationally symmetric systems does show locally in some options. For example, third order aberrations are only calculated assuming surfaces are rotationally symmetric. All first order calculations only incorporate axial shift components of decentered systems. In some cases such as ENVIRONMENTAL ANALYSIS, the extreme complexity implied by decentered systems has dictated that these be modelled ignoring decentrations.

New options may be introduced favoring rotationally symmetric systems with completion of decentered features at a later date. An option such as FIELD is conveniently defined only for rotationally symmetric systems even though it works perfectly well on decentered systems. And, finally, the bias shows in that if a definition of the axial object point or the extreme object point is needed, the first and last, respectively, are chosen.

Is the zoom feature limited to zoom lenses?

The zoom feature permits zooming over 80 types of constructional data (including decenters and tilts), usage data, aperture data, materials, solves, and (locally) even the label. It is thus a versatile multi-configuration design tool. The entries of the DATA option describe only the first position system; the ZOOM DATA option describes the alterations for the other configurations.

III. INPUT DATA

Six types of information can be provided:

1. Title - labels the run and must be present immediately after the DATA option request.
2. SURFACE DATA - must always be present.
3. SPECIFICATION DATA - must always be present.
4. PRIVATE CATALOG - include if special materials are used.
5. APERTURES - include if limiting apertures and/or obscurations are to be invoked in later options.
6. SOLVES - include if special conditions are to be met by altering the data.

Of these, all but the title require a header entry with the names as given (SURFACE DATA, etc.). Each header entry starts in Col. 1 and is alphanumeric format with the first four characters sensed.

In addition to the data given in the cards themselves, the program also obtains information on standard materials from the prestored glass catalogs (see option FILE for instructions on printing this data). For any of the optional items omitted default values are provided.

For a zoom system, the data entered here is considered to be for the first position only; any data required for other positions is entered in the ZOOM DATA option.

A. TITLE CARD - Required

This card must follow the data card. The 80 columns may carry any descriptive information desired:

1	80

This label will be printed out whenever the system data is printed out; in some of the graphics options the titling is derived from columns 1-20 and 21-40 only. See the specific options for instructions.

B. SURFACE DATA - Required

Header card (Col. 1-3 sensed):

SURFACE DATA
1

Data for each ordinary surface is provided on one card per surface; if required, special surface data (aspheric, diffraction grating, thermal gradient surface, cylindrical surface, etc.) is entered on additional cards immediately following the surface.

Whereas some of the data (curvatures, thicknesses, and materials, etc.) is essential to describing the structure for all options, other items (parameter freezes, etc.) are referred to in only a few options. The latter are more conveniently entered here because different values are required for each surface.

The first of the surface data cards is for the object surface while the last surface data card is for the image surface. The object surface can be plano, spherical or any special shape but cannot have its shape be a variable; therefore, some of the data is non-functional. Data for this surface is described in detail later, but uses the same format.

The format for surface data cards is:

CURVATURE	CCY	THICKNESS	THC	GLASS	GLC	GLASS CHAR-ACTERISTICS	STOP	TYPE
1	16	21	36	41	56	61	76	79-80

These entries are explained in detail in the following sections.

Curvature and Its Control

CURVATURE (Col. 1-15) - The reciprocal of the radius of the surface; a positive value designates a surface whose center of curvature lies to the right of the surface. If blank, entry is zero. If special values of CCY are used, this value may have alternate meanings as described below:

CCY (Col. 16-20) - Curvature control. An integer value entered anywhere in the field which designates the meaning of the CURVATURE entry or its variable status in AUTOMATIC DESIGN as follows:

Values of CCY	Meaning of CURVATURE Entry	Variable Status	Effect
Blank	Curvature	Free to Vary	
± 1 ⋮ ± XX ⋮ ± 99	Curvature	Coupled	Changes in AUTOMATIC DESIGN are made equal (+) or opposite (-) to the first of any other curvatures in the same group number (XX). Thus if the value of CCY for surface 7 is 27 and for surface 13 is -27, any changes made to the curvature of 7 will be made, reversed in sign, to the curvature of surface 13. No more than 50 distinct group numbers may be used; they need not be consecutive.
100	Curvature	Frozen	
101 ⋮ 1XX ⋮ 199	None	Assigned Value	Curvature is assigned so that the surface is always concentric to surface XX. Concentricity is maintained throughout all subsequent changes; this value is therefore neither frozen to its input value nor free to vary in AUTOMATIC DESIGN.
200	Radius	Free	Radius is immediately converted to curvature and CCY to 0.
201 . 2XX . 299	Radius	Coupled	Radius is immediately converted to curvature and CCY to XX. Thus, only positive couplings are possible with radius input.
300	Radius	Frozen	

In TOLERANCE:

CCY is used only to indicate those surfaces which are regarded as physically the same surface. Entries from ±1 to ±99 each indicate a group of surfaces which are to be regarded as one tolerance on each type of surface shape error (radius, power, irregularity, tilt and displacement). Other values, including 0, indicate no relationship exists.

Thickness and Its Control

THICKNESS (Col. 21-35) - The distance to the next surface measured along the optical axis. The distance is positive if the next surface lies to the right of the current surface. If blank, entry is zero.

THC (Col. 36-40) - Thickness Control. An integer value entered anywhere in the field which designates the meaning of the THICKNESS entry and/or its variable status in AUTOMATIC DESIGN as follows:

Values of THC	Meaning of THICKNESS Entry	Variable Status	Effect
Blank or 0	Distance to next surface	Free to Vary	
± 1 ⋮ ± XX ⋮ ± 99	Distance to next surface	Coupled	Changes in AUTOMATIC DESIGN are made equal (+) or opposite (-) to the first of any other thicknesses in the same group number (XX). Thus, if the value of THC for surfaces 7 and 13 are the number 27, any change in the thicknesses at surfaces 7 and 13 will be the same. Any number of distinct group numbers may be used; they need not be consecutive. For reflecting systems note that double passage through the same element requires two group numbers of opposite sign.
100	Distance to next surface	Frozen	Not varied in AUTOMATIC DESIGN.

In TOLERANCE:

THC is used only to indicate those thicknesses and separations which are linked together to form one tolerance for thickness error. Entries from ±1 to ±99 each indicate a group of this type. Other values, including 0, indicate no relationship exists.

Glass and Its Control

GLASS (Col. 41-55) - A code designating the material following the surface. Acceptable forms may be decimal values or alphanumeric codes; if the latter they cannot contain a decimal point and must start in Col. 41.

Air

This is designated by either of the alphanumeric entries:

AIR
blank

All indices will be entered by the program as 1.0.

Catalog Glasses

Data from either the pre-stored catalogs or the PRIVATE CATALOG can be retrieved by entering an alphanumeric code for the glass plus an optional alphanumeric code identifying the catalog from which the data is to be taken. The two codes may each contain up to six characters and are separated by a blank. Codes for the glasses are six digit (620603) or alphanumeric (SK16) type; the catalogs codes are:

Code	Catalog
PRIVAT	Private glass catalog
MELT	Synonym for PRIVAT
SCHOTT	Schott
BAUSCH	Bausch and Lomb
CHANCE	Chance
CORNIN	Corning
HOYA	Hoya
KODAK	Kodak
OHARA	Ohara
SOVIRE	Sovirel

If no catalog code is entered with a glass, all glass catalogs are searched for a matching code. The catalogs are searched in the order of the above list, i.e., PRIVATE CATALOG, SCHOTT, etc.

The user can obtain a listing of the pre-stored glass codes and indices calculated for ten wavelengths by using the GLIST request under option FILE.

Some examples of glass codes for catalog glasses are:

(Starting in column 41)

620603 SCHOTT
SK16 SCHOTT
F2
BK7
A-37 MELT

Fictitious Glasses

By means of pre-stored constants, glasses of any practical n_d and V value may be generated. These are designated by numeric value with a decimal point separating the reduced index (n_d-1) and V value:

620.603
621234.60312

Note that, regardless of the wavelengths used in the specifications later, these entries are for the standard n_d and V. The decimal point defines the glass to be a fictitious glass; it cannot be used in any other glass codes.

The digits must be contiguous but may be placed anywhere in Columns 41-55. The number of digits in each section is open to the designer but all output will give 6 digits in front of the decimal point and 5 behind it.

Glasses allowed to vary in AUTOMATIC DESIGN must be converted to this form. All fictitious glasses will have ordinary partial dispersion characteristics.

Reflective Surfaces

Designation of a reflective surface is given by the entry

REFL

This causes the sign of all indices following this surface to be reversed until the next surface is found with REFL as its glass code.

Glass codes are decoded and their indices assigned values according to a pre-set hierarchy which resolves ambiguities:

1. Air values are entered,
2. Fictitious glasses are generated,
3. PRIVATE CATALOG glasses are entered,
4. Prestored catalog glasses are entered.

Any remaining codes are unrecognizable and constitute an error.

GLC (Col. 56-60) - Glass control. An integer value entered anywhere in the field which designates the variable status of fictitious glasses in AUTOMATIC DESIGN as follows:

Values of GLC	Variable Status	Effect
Blank or 0	Free to vary	Both n_d and Δn ($=n_F-n_C$) are allowed to vary in AUTOMATIC DESIGN. V is dependent on both $V = \frac{n-1}{\Delta n}$.
1 ⋮ XX ⋮ 99	Coupled	Changes in AUTOMATIC DESIGN are made equally to all glasses in the same group number (XX). Thus, if the value of GLC on surfaces 5, 9, and 11 are the number 3, any changes made in the n_d or Δn of one will be made to all. No more than 20 distinct group numbers may be used; they need not be consecutive.
100	n_d and Δn frozen	No changes permitted in glass during AUTOMATIC DESIGN.
200	n_d frozen, Δn free	Only Δn can vary in AUTOMATIC DESIGN.
201 ⋮ 2XX ⋮ 299	n_d frozen, Δn coupled	All changes to Δn are made equally to all glasses in the same group number (XX).
300	n_d free, Δn frozen	Only n_d can vary in AUTOMATIC DESIGN.
301 ⋮ 3XX ⋮ 399	n_d coupled, Δn frozen	All changes to n_d are made equally to all glasses in the same group number (XX).
400a	Frozen to boundary a	Freezes glass to boundary A, B, C, D, E as defined in AUTOMATIC DESIGN option. a is the character A, B, C, D, or E. Changes will be made to both n_d and V to keep it on the designated boundary. Only one variable is generated. This is an effective way of reducing the number of variables and constraints. It is also the recommended way of varying glass in a monochromatic system.

401a ⋮ 4XXa ⋮ 499a	Frozen to boundary a, n_d and V coupled	All changes to Δn are made equally to all glasses in the same group number (XX). Index changes are made as needed to meet the boundary freeze condition.

Notes:

1. GLC values need be entered only for fictitious glasses. Catalog glasses are automatically frozen.
2. If GLC is used to freeze the glass to a boundary (400 series), no change in the glass will be made until AUTOMATIC DESIGN is entered. The glass will immediately shift to the boundary and remain there. The principal value in using this type of freeze is to reduce the number of variables and constraints. If runs show a consistent tendency for a glass to be held on one boundary, it is best to convert to a boundary freeze of this type. Of course, if it consistently is held to a corner point, it can be frozen.
3. Typically, the ability to couple glasses is used to keep glasses identical which start as identical.

In TOLERANCE:

GLC is used only to indicate materials which are physically the same element. Entries from 1 to 99 each indicate a group of materials which are to be regarded as one tolerance on each type of material error (index, or inhomogeneity). Other values, including 0, indicate no relationship exists.

GLASS CHARACTERISTICS (Col. 61-75) - An optional catalog glass code to designate a glass from which characteristics such as specific gravity, transmission data, thermal data, etc., may be taken. The codes entered are identical to those described for catalog glasses. Typical entries for the GLASS code and the GCH code are:

GLASS	GCH
620.603	SK16 SCHOTT
A-29 MELT	SF2 OHARA
BK7	
BK7	BK7

Note that the last two examples are identical in their effect; if no GCH is entered for a prestored glass, the GCH is assumed to be the same as the GLASS code.

A GCH entry is especially useful on fictitious and PRIVATE CATALOG glasses when options such as WEIGHT, TRANSMISSION, and ENVIRONMENTAL CHANGE are to be run.

STOP (Col. 76) - A single-column flag (use any character) to designate which surface is to be considered the aperture stop. If no such surface is designated, the first surface after the object is used.

Special Surface Data

TYPE (Col. 79-80) - An integer code which designates surface type for special surfaces. These are as follows:

Codes	Surface Type	Effect
0 or blank	Spherical	No additional data required.
1	Cylinder	Reads one data card.
2	General Aspheric	Reads two additional aspheric data cards.
3	Diffraction Grating	Reads both additional aspheric data cards plus one more with diffraction grating constants.
4	Aspheric Toroid	Reads both additional aspheric data cards plus one with toroidal data.
9	Thermal Gradient Surface	Reads both additional aspheric data cards plus two more with thermal gradient data for the medium following the surface.
10	Special Surface	Temporary special function. Ask for details of currently active function.
12	Spline Aspheric	Reads three additional data cards.
blank	Decentered	These are represented by special cards instead of surface data. See later discussion (Types 5, 6, and 7).

Thus, the type code, TYPE, in Col. 79, 80 plus the additional data define the form of the surface. Each of the special surface types is described in Appendix DATA-A.

Technical Notes - SURFACE DATA:

System Structure and the SURFACE DATA Deck

As previously noted the SURFACE DATA deck is composed of the header card, an object surface card, and lens surface data cards with any optional special surface data. The end of this deck is indicated by the next card being a header card for one of the other data blocks, or an option card. Thus the last surface in the lens deck becomes the image surface.

1. Object Surface

This can be a regular surface entry including spherical, plano or Types 1, 2, 4 or 12. The thickness need not be entered if a RED solve will be used; if not, the value will be used as the distance from object to the first surface. Note that the object cannot be the stop; it is optically impossible for these to coincide.

2. Lens Surfaces

The other surfaces constitute the lens formula. Dummy surfaces (those with identical material preceding and following them) may be inserted for control purposes. In general these do not provide effective variables for automatic design. Thus curvatures and aspheric coefficients of such surfaces are frozen by the program unless they are coupled to other surfaces. The thickness freezes applying to the space before and after the dummy surface are examined and one is frozen; if both are at the aperture stop, both thicknesses can be independent variables and the thickness freezes are left unchanged.

3. Image Surface

The last surface in the deck becomes the image surface and can contain all of the normal data; GLASS, GLC and GCH are non-functional since the material following the image surface is considered to be the same as that preceding it. Also, the STOP entry cannot be used since it is optically impossible for the aperture stop and image surface to coincide.

The thickness preceding this surface (thickness for the next to last surface) becomes the image distance. If the PIM (paraxial image distance) solve is to be used, this value is immaterial; it will be replaced in all options with the Gaussian image distance. If the PIM solve is not to be used, this distance may be coupled or frozen as for any other surface.

The thickness entry on the last surface is interpreted as defocusing from the specified image distance (with the normal sign convention of a + value being a displacement toward the right); all measurements of image quality are referenced to this defocused surface. If the PIM solve is not used, the defocusing can take on quite large values, if allowed to vary in AUTOMATIC DESIGN, in an effort to establish the image surface near the optimum Gaussian image surface; on the other hand, if the PIM solve is used, the defocusing will normally take on rather small values if allowed to vary. There is no point to leaving both the image distance <u>and</u> the defocusing unfrozen without using the PIM solve, since both variables will have the same effect.

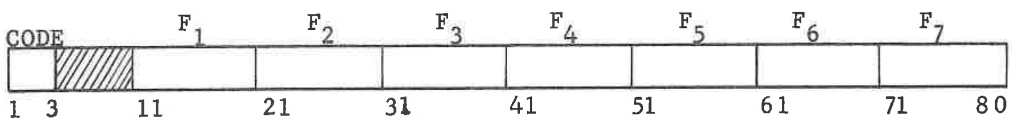
C. SPECIFICATION DATA - Required

Header card (Col. 1-4 sensed):

SPECIFICATION DATA
1

Every optical system requires some information to tell how it is to be used; CODE V requires only that the aperture and wavelengths be supplied. All other specifications such as field angle, vignetting, and magnification are optional. So are control specifications such as whether the system is afocal, the dimensional system (centimeters, millimeters, or inches), which wavelength is the reference wavelength, etc. These are entered in the specification data block.

The format used by all entries is the following:



CODE Col. 1-3	Mnemonic code indicating which specification is being entered. A list of these is given later.
F_1 (Col. 11-20) : F_7 (Col. 71-80)	Fields for entry of data. If one value is required it is entered in F_1; if n values are required they are entered in fields F_1 to F_n. All decimal or integer entries can be anywhere in the field; however, alphanumeric codes must be in the first column of the field.

The specification CODE is a three character code which identifies the specification being entered. In the following sections, the CODES and their meaning are given first, followed by any required usage suggestions.

1. Aperture Specification (F/N, NA, NAO, or EPD) - One Required

F/N	F/no of the image space cone
NA	Numerical aperture in the image space
NAO	Numerical aperture in the object space
EPD	Entrance pupil diameter

These quantities are related to each other through familiar optical equations:

$$NAO = n_o \cdot \sin\left[\tan^{-1}\left(\frac{EPD/2}{\text{Distance from Object to Ent. Pupil}}\right)\right]$$

where n_o is the index of the object space

$$NA = \frac{NAO}{RED}$$ where RED is the reduction ratio (RED = - optical magnification)

$$F/N = \frac{1}{2 \cdot NA}$$

Which combination of values is used is largely a matter of convenience as well as which data is available. Typical cases are the following:

Object at Infinity - Object distance is left blank, entrance pupil distance is immaterial, and reduction ratio SOLVE (RED) is entered. Aperture may then be specified by F/N, NA, or EPD.

Finite Object - If the object distance is entered, the reduction ratio for the input system is thereby established. Aperture may be specified by any of the four forms.

If the reduction ratio SOLVE (RED) is entered to establish the proper magnification, this also establishes the object distance temporarily for the input system. Aperture may then be specified by any of the four forms. Throughout all subsequent optimization the object distance will be modified to maintain the reduction ratio at its solve value, RED. In addition, the aperture specification will designate which property is to be held:

F/N, NA, or NAO entries will adjust the value of entrance pupil diameter to maintain the required value.

EPD entries will allow F/N, NA, and NAO to take on whatever values occur while the entrance pupil is held constant in size.

NOTE: Systems with decentered or cylindrical surfaces must use object space coordinates (NAO or EPD).

2. Wavelength Specification (WL) - Required

WL — Wavelengths to be used in calculation; up to 7 wavelengths may be entered in F_1 to F_7. Values are in nano-meters and are to be entered in descending order (red to blue).

Modern optical systems often used in conjunction with sources, filters and detectors with wavelength bands which do not correspond to measured refractive index data. It is necessary, however, to be able to enter representative wavelengths distributed across the wavelength band of interest in order to properly optimize and evaluate the system. CODE V requires only that the desired wavelength be entered; all interpolation is done automatically. The formula used for interpolation is the Hartmann formula:

$$n_\lambda = n_o + \frac{A}{(\lambda - \lambda_o)^{1.2}}$$

which is a three constant (n_o, A, λ_o) formula. Since melt data is sometimes provided with only three values it is essential that the interpolation formula be a three constant type rather than one of the more complicated forms. In general, interpolation, for catalogs with index data only, is done with the closest three values for each of the wavelengths required, so that high accuracy is achieved.

For prestored catalogs where coefficient data is available from the manufacturer, the standard six constant dispersion formula is used to compute the indices.

3. Reference Wavelength Specification (REF) - Optional

REF — Reference wavelength, the number of the wavelength to be used for all reference and paraxial calculations. Integer value is entered in F1.

One of the wavelengths entered on the WL card will be used as the reference wavelength; the reference wavelength is the one in which all paraxial quantities (EFL, BFL) and distortion calculations are performed. If REF is omitted, the wavelength in the center is chosen, if an odd number of wavelengths is given on the WL card; the one left of center is chosen if there are an even number of wavelengths. For example, if four wavelengths are given, λ_2 will be chosen; if seven wavelengths are given, λ_4 will be chosen.

4. Wavelength Weights (WTW) - Optional

WTW — Integer values of wavelength weights; these values will be used as default values for wavelength weights in all options; one value should be entered corresponding to each wavelength in WL card. If this entry is not made, a weight of 1 is assigned to each wavelength.

When a series of analyses requiring "white" light calculations are made, it is convenient to be able to enter the wavelength weights once for all calculations, rather than entering them in each option; these values can be over-ridden in any option. For compatibility with printer formats, it is best to ensure that the weights lie between 0 and 99.

On request, the option SPECTRAL ANALYSIS can enter weights resulting from its calculations into these values.

5(a). Field Specification (Y, YOB, or YAN) - Optional

Y — Y coordinate of image plane field height
YOB — Y coordinate of object plane field height
YAN — Y component of object space angle in degrees

Up to 5 values may be entered in F1 to F5; if no entries are made, the default is to a single value of 0.0. Each of the three forms uses the position on the card to tell how many field points are to be included. Thus if the entry is made in F_2, (the second available field), this is interpreted as specifying two field points; the entered value is the extreme field point while the blank field F_1 is filled in with a preset fraction of the extreme field point. Using Y as an example these preset fractions are:

Entry in Card Field	Fraction of Field Point Entry Y 1	Y 2	Y 3	Y 4	Y5
F1	1.0				
F2	0.0	1.0			
F3	0.0	.707	1.0		
F4	0.0	.5	.75	1.0	
F5	0.0	.4	.6	.8	1.0

F6, F7 } Not permitted

Overriding of these preset fractions is simply done by entering the desired values in the corresponding card fields. Thus a card of the form

Y .8 1.4 2.0

would specify a total of three field heights

Y 1	.8
Y 2	1.4
Y 3	2.0

The three permissable forms are treated as Gaussian quantities and are related by the familiar optical relations:

YOB = -Y · RED

YOB = -(Distance from Object Plane to Paraxial Entrance Pupil)·tan(YAN)

$$\text{YAN} = \tan^{-1} \frac{\text{Y}}{\text{EFL}}$$ for infinite object distance

Each form of entry internally defines the YOB on the object plane through these equations (care is taken to avoid problems with infinite objects); non-Gaussian conditions such as curved objects or images and spherical aberration of the stop can alter the Y or YAN actually achieved. The choice of which form to use is dependent on the data available as well as which quantity is to be held fixed. The three cases are:

Y specified - YOB is continually adjusted by the program using the first formula.

YOB specified - YOB remains constant.

YAN specified - YOB is continually adjusted by the program using the second formula.

For curved objects the YOB becomes also the Y coordinate on the curved surface; the actual value of Y or YAN will be altered accordingly, depending on the changed distance to the entrance pupil. For curved images, the actual value of Y will be altered, depending on the distance to the exit pupil. Thus, for curved objects YOB is preferred, and for curved images YOB or YAN is suggested; YAN is best reserved for infinite objects since generated values are dependent on both object curvature and spherical aberration of the entrance pupil. The designer is free to use any form as long as he understands these non-Gaussian effects.

NOTE: Systems with decentered or cylindrical surfaces must use object space coordinates (YOB or YAN).

The Y-Z plane is considered to be the meridional plane for rotationally symmetric systems. If an option needs a definition of axis and extreme field points, they are assumed to be the first and last, respectively.

5(b). Field Specification (X, XOB, or XAN) - Optional

X	X coordinate of image plane field height
XOB	X coordinate of object plane field height
XAN	X component of object space angle in degrees

If no entries are made, the defaults are set to 0.0, using the particular form and number of field points corresponding to the Y component field specification. Otherwise up to 5 field points may be entered in F1 to F5 corresponding to entries for Y, YOB or YAN.

The x component of the field specification may be entered in one of the three forms exactly analogous to the Y field specifications. If both x and y components are entered, they must be of the same type, i.e., (X and Y), (XOB,YOB) or (XAN,YAN). If x type specifications are used, the automatic field set up described above will not be used; each field must be set up by the user. The use of nonzero x field components should be avoided, if possible, because they imply lack of symmetry and therefore increase the compute times in most options.

6. Vignetting (VUY, VLY, VUX, VLX) - Optional

VUY	Upper rim ray fraction
VLY	Lower rim ray fraction
VUX	Right (+X) skew ray fraction (as viewed from lens back toward object)
VLX	Left (-X) skew ray fraction (as viewed from lens back toward object)

Vignetting is specified as that portion of the entrance pupil which is to be eliminated from consideration.

Entries are made in the data field corresponding to the field points specified above.

Example:

YAN	1.5	2.0	2.5
VUY	.10	.15	.20
VLY	.30	.40	.50

At an angle of 1.5°, 10% of the upper bundle and 30% of the lower bundle would be removed; likewise, at 2.5° 20% of the upper bundle and 50% of the lower bundle would be removed.

In rotationally symmetric systems with only Y non-zero field points, the reference rays (described in DATA-2 and 3) are traced only for the VUY, VLY specifications unless VUX, VLX are also entered. In that case all four reference rays plus the chief ray are traced.

7. Environment (TEM, PRE) - Optional

All data is assumed to be for 20°C and 760mm Hg unless it has been altered by prior use of the ENVIRONMENTAL CHANGE option or given by either or both of these specifications:

TEM — Temperature of input data in °C, entered in F1.

Example: TEM -10.0

This indicates that the data supplied has previously been converted to that which applies at -10°C.

PRE — Pressure of input data in mm Hg, entered in F1.

Example: PRE 740.0

This indicates that the data supplied has previously been converted to 740mm Hg.

8. Dimensional System (DIM) - Optional

DIM — Dimensions of data:
I - inches (default)
M - millimeters
C - centimeters

The alphanumeric symbol (I,M, or C) is entered in F1. Nearly all operations are scale independent; however, any which involve weight, cost, test plate radii or wave optics must have knowledge of the units.

9. Afocal System (AFO) - Optional

AFO — Designates this as an afocal system.

The presence of this card flags the system as being afocal (telescopic). Afocal systems are those for which the image distance is infinite; object distances may be either finite or infinite for problems run under this program. For such lenses, the system may not have a finite focal length and, therefore, standard definitions of f/no, field angles and heights, etc., may be indeterminate. However, the use of this flag causes the system to be converted into a normal system where standard definitions do apply.

Such a system is interpreted differently in that it is assumed to have a perfect lens behind it whose focal length is the value entered in the position where the image distance normally appears. Thus angular errors in the bundles emerging from the afocal system are converted into transverse errors in the image plane and all other specifications are those which sould apply to the combined system. It is important to note that the value of defocusing in the image surface is a measure of the lack of collimation in the emerging beam.

The perfect lens generated by this flag adheres to the sine condition for accurate simulation in wave aberration calculations; it cannot therefore be faster than f/.5. It is best to choose a perfect lens focal length which is considerably slower than this so that rays which move during optimization do not exceed this aperture. If transverse aberrations are to be considered to be radians in image space, use a focal length of 1.0; if they are considered to be milliradians in image space use a focal length of 1000. Dividing each of these by M, the telescopic magnification, changes the angle measure to object space. If MTF aberrations are to be measured in cycles per milliradians in object or image space use the following value for this focal length:

Cycles/mrad. in image space - 1 meter expressed in lens units

Cycles/mrad. in object space - $\frac{1}{M}$ meters expressed in lens units

where M is the telescopic magnification.

10. Telecentric System (TEL) - Optional

TEL Telecentric entrance pupil

Computing accuracy of telecentric systems is enhanced when this flag is used. The surface flagged as the aperture stop has no bearing on the ray patterns and, in general, the chief ray will not pass through the center of it unless a constraint is applied in AUTOMATIC DESIGN.

11. X-Plane First Order Calculation (XFO) - Optional

XFO First order calculation using X-Z plane data

All first order calculations are normally done using the curvature and data specifications associated with the Y-Z plane (meridional plane for centered systems). Some systems may require that these be done in the X-Z plane instead. The inclusion of this card so flags the system. Included in the first order calculations are the reduction ratio solve and the insertion of image distance, as described earlier. This is useful for anamorphic systems and is often zoomed to obtain Y-Z data in one position and X-Z data in the other.

12. Designer's Initials (INI) - Optional

INI Uses first 3 characters of F1 on all plots

All plots include three characters which are pre-stored initials of the company. These can be modified to the first 3 characters entered in F1. The initials will remain modified until a new lens is entered from DATA or LIBRARY, or until CHANGEd. Any system saved by LIBRARY will keep the modified initials with it, for use on any later runs.

D. PRIVATE CATALOG - Optional

Header card (Col. 1-4 sensed):

PRIVATE CATALOG
1

The PRIVATE CATALOG provides the capability of entering index data for special materials, specific melt indices or other cases where the data is not available from the catalogs on disc.

The PRIVATE CATALOG data is entered in the following format:

CODE		F_1	F_2	F_3	F_4	F_5	F_6	F_7
1	7	11	21	31	41	51	61	71

CODE (Col. 1-6)	Mnemonic code which is either WL or a glass code. (Matching glass codes entered in SURFACE DATA). The first card after the PRIVATE CATALOG must be a WL card.
F_1 (Col. 11-20) : F_7 (Col. 71-80)	Decimal Fields; on a WL card, the wavelengths in nanometers are entered in F_1 to F_7 from longest to shortest wavelength. Cards with a glass code must have the indices corresponding to these wavelengths entered.

The wavelengths of the PRIVATE CATALOG need not correspond with those entered in the SPECIFICATION DATA. If they do, interpolation is not needed; if not, the program interpolates just as it does from the disc catalogs. If interpolation is required, data for at least 3 wavelengths must be available in the PRIVATE CATALOG. If more are available, the 3 nearest a given wavelength will be used in the interpolation.

All of the index data in the PRIVATE CATALOG need not be for the same set or number of wavelengths, i.e. a WL card applies to all glass cards following it until a new WL card is read. Data in the PRIVATE CATALOG remains available throughout the run; consequently glass data may be entered in it which is not used, or which is required by a later CHANGE to the system. Note that due to the sequence of operations, if a glass code is contained in both the PRIVATE CATALOG and the disc catalogs, the index information will be taken from the PRIVATE CATALOG.

The following is an example of a PRIVATE CATALOG data entry:

PRIVATE CATALOG

WL	656.3	587.6	486.1	
A-29	1.51436	1.51684	1.52238	
B-36	1.59874	1.60342	1.61461	
WL	656.3	589.3	546.1	486.1
PLATE	1.51982	1.52259	1.52458	1.52860

The CODES used to identify a glass in the PRIVATE CATALOG may be any characters except that the first three must not be STO or TYP or the same as a CODE V option or a sub-option of DATA. For example, the codes, COSTLY, CATLGA, and MODE1 are all illegal and would be interpreted as calls to options instead of glass codes. STO and TYP are reserved; see description of comma input.

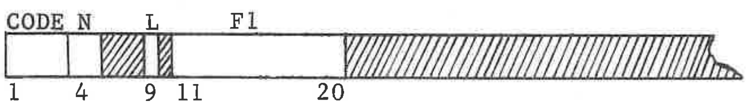
The private catalog may be added to, replaced, or deleted by use of the CHANGE option; see that description for details.

E. APERTURES - Optional

Header card (Col. 1-4 sensed):

The APERTURES provide the capability of entering limiting apertures and/or obscurations on the surfaces (except the object and image).

Three types of apertures may be entered: circles, rectangles, and ellipses. The data for these is entered in the following format:



CODE (Col. 1-3)	A three character mnemonic code identifying the type of aperture and (in the case of rectangles and ellipses) whether the x or y coordinate is being entered. A list of these CODES is given below.
N (Col. 4-6)	The surface number to which this aperture data applies.
L (Col. 9)	An optional one character label to serve as an identifier when more than one aperture of the same type is applied to the same surface. Normally, this will be blank if only one aperture of that type applies to the surface.
F1 (Col. 11-20)	The decimal value of the aperture; the values entered are radii, or half-widths as the case may be. An <u>obscuration</u> is entered by making this value <u>negative</u>.

The following is a list of aperture CODES and their associated types:

CODE	Description
CIR	Circular aperture radius
REX	Rectangular aperture half-width
REY	Rectangular aperture half-height
ELX	Elliptical aperture half-width
ELY	Elliptical aperture half-height

Note that to define a rectangle or ellipse, two cards are required per aperture.

Example:

```
APERTURES
CIR  5          .625   -  Circular outer aperture
CIR  5   A    -.3125   -  Circular obscuration
REX  7          .750   }
REY  7         1.500   }  Rectangular outer aperture
ELX  7         -.250   }
ELY  7         -.500   }  Elliptical obscuration
```

NOTE: It is entirely possible to enter an obscuration larger than the clear aperture; values should be checked.

Functioning of Apertures

As described on p. DATA-2 and 3, reference rays are determined by the SPECIFICATION DATA; these, in turn, determine clear apertures as printed in MODEL DATA and, finally, these clear apertures are used for defining the precise bundle shape in performance evaluation programs. APERTURE DATA permits the over-ride of the apertures used in this last step; the use of the SC request in any of these evaluation options will invoke the use of the entries made here.

With the SET option, these APERTURES can also be made to feed back into the earlier step by changing vignetting and/or aperture specification (F/NO, etc.) to reposition the reference rays.

The following is a summary of the effects of APERTURES in various CODE V options:

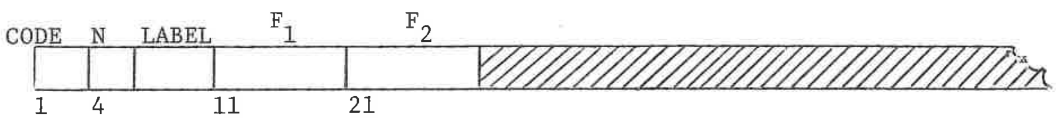
Option	Influence of APERTURES Value
SET	Determine vignetting values when VIG, VIX, VIY requests are used, aperture when F/N, EDP, NAO, or NA are used.
ZOOM, DEZOOM, CHANGE, SCALE	No effect.
AUTOMATIC DESIGN, TEST PLATE, CAM	No effect.
ANALYSIS, FIELD, RIMRAY, HIGHER ORDER ANALYSIS, BEAM PROPAGATION	No effect on these diagnostic analysis options.
ENVIRONMENTAL CHANGE MODEL DATA	Determines contact aperture for spacers. Overrides ray-trace clear apertures for those surfaces with APERTURE data entered when invoked by SC request. Only positive values have meaning and are used.
NARCISSUS ANALYSIS TOLERANCE COST FACTORS	Overrides ray-trace clear apertures for those surfaces with APERTURE data entered when invoked by SC request. Only positive values have meaning and are used.
GEOMETRICAL FREQUENCY RESPONSE RADIAL ENERGY DISTRIBUTION SPOT DIAGRAMS WAVEFRONT CHARACTERISTICS POINT SPREAD FUNCTION DIFFRACTION FREQUENCY RESPONSE TRANSMISSION CATSEYE TOR	Performance evaluation options: Overrides ray-trace clear apertures on those surfaces specified when invoked by SC request. Positive values allow radiation to pass at apertures up to the designated value. Negative values only pass radiation falling outside of the designated value (obscurations).
LAYOUT WEIGHT	Overrides ray-trace clear apertures when invoked by SC request. Positive values limit outer clear apertures; negative values designate the semi-aperture of central holes in optical components such as primary mirrors.

F. SOLVES - Optional

Header card (Col. 1-4 sensed):

In many systems it is possible to save computing time and to reduce the number of independent variables by using system parameters as dependent variables to solve directly for system constraints.

The data for SOLVES is entered in the following format:



CODE (Col. 1-3)	Mnemonic code identifying the parameter being solved (changed as a dependent variable).
N (Col. 4-6)	Surface number of the solved parameter.
LABEL	Mnemonic code separated from the surface number (N) by one or more blanks; this code identifies the values entered in fields F1 and F2 that are being solved for.
F_1 (Col. 11-20)	Data fields 1 and 2; used to enter values required by the CODE and LABEL.
F_2 (Col. 21-30)	

The principal value in using SOLVES is to reduce the number of variables and, thereby, the running time in AUTOMATIC DESIGN. For large systems, it may permit the use of more variables than would otherwise be the case. In general, whenever runs show a consistent tendency for an edge thickness to be held to a minimum or an OAL is required always, it is best to convert them from a constraint in AUTO to a solve in DATA. This usually removes both a variable and a constraint. (The ability to freeze a glass to a boundary, described under "Glass and Its Control," is another similar device).

CODES	SOLVE Description
RED	Reduction ratios: $RED = \frac{\text{Image Height}}{-\text{Object Height}} = -M$ where M is the optical magnification. The object distance is solved to provide the designated value entered in F1. For an object at infinity, use blank or 0.0; any other value establishes a finite conjugate system. Must be zoomed to be active in more than the first position.
PIM	Paraxial image distance insertion. The image distance is solved to focus the marginal paraxial ray on the final surface, ignoring the defocus. No entry is required in F1. Must be zoomed to be active in more than the first position. It is highly recommended that this be used for runs involving optimization; this eliminates a major linear component in all derivatives.
THI n ET	The thickness at surface n is solved to provide an edge thickness, entered in field F_1, at the semi-diameter entered in field F_2. Done separately for each zoom position.
THI n OAL SUR	The thickness at surface n is solved to provide the overall length, specified in field F_1, between the two surfaces specified by a SUR card. The surface numbers are entered both in field F_1, the first in columns 11-15 and the second in columns 16-20. Done separately for each zoom position.
CUY n MRY	The y curvature at surface n is solved to provide an exit angle, u_n, entered in field F_1, of the paraxial marginal ray traced in the Y direction (meridional plane). Active in first zoom position; value retained for use in other zoom positions.
THI n MRY	The thickness at surface n is solved to provide a height entered in field F_1 on the next surface of the paraxial marginal ray traced in the Y direction. Active in first zoom position; value retained for use in other zoom positions.

The following are examples of SOLVE data input:

SOLVES

RED	0.0			- *Solves for infinite object distance*
PIM				- *Inserts paraxial image distance*
THI 4 ET	.075		.625	
THI 7 ET	.0001		.765	
THI 5 OAL	3.18			
SURF	1	6		
THI 8 OAL	10.5			
SURF	1	20		
CUY 15 MRY	-.25			- *Solves for u=-.25 on surface 15*
THI 21 MRY	.4			- *Solves for Y=.4 on surface 22*

Hierarchy of Solves

Solves are done in a particular order which subject some of them to special limitations; in principle no combination of solves can require iteration - cycling back through the problem to converge on a solution. For example, a RED solve depends on the system otherwise remaining unchanged and cannot be combined with first order solves (CUY-MRY or THI-MRY) which depend on the object distance remaining constant.

Thus, the order in which solves are internally performed is:

1. Zero Order
   a. ET
   b. OAL, in order of entry
2. First Order
   a. RED, or
   b. CUY-MRY, then THI-MRY in order of surfaces
3. Image Distance - PIM

First order solves (MRY) are subject to special limitations. They may be used on infinite conjugate systems only with EPD as the aperture specification. Finite conjugate systems must not use a RED solve and must have the aperture specified as NAO, when first order (MRY) solves are used.

First order solves (MRY) are active only in the first zoom position; the solved parameter is then unchanged for remaining zoom positions.

When setting up the OAL solve data, it is important (in some cases) to consider that the order in which they are solved is the order they are entered. Thus, when the solved intervals are nested, the inner groups should be entered first, etc. In the example given above, reversing the order would result in incorrect operation since the correct thickness at surface 5 is required before the summation of thicknesses from 1 to 20 can be done.

Note that if a separation within the range of an OAL solve is zoomed, the solved separation becomes an implied zoom separation because the solve is performed at all zoom positions. This can be used to eliminate a substantial number of constraints and/or variables in AUTOMATIC DESIGN.

In the case of all solves, the solved parameter is not set up as a variable in AUTO, although it will be constantly changing due to other changes. Never request both a solve in DATA and the corresponding constraint in AUTO in the same run. For example, an OAL solve and OAL constraint covering the same interval will cause a blowup.

Solves may be entered or changed via the CHANGE option also. The CODES used are the same; however, the SOLVE header card is not required. Solves may also be deleted through the CHANGE option.

Appendix:

Special Surfaces

Entry of most special surfaces is done by entering the TYPE code referred to previously in Col. 80 of the surface card. The exception to this is the break in data which is generated by decentration. These are internally typed as 5, 6, and 7. These three type numbers are never printed out but are needed when the CHANGE option is used to alter any surface to a decentered surface.

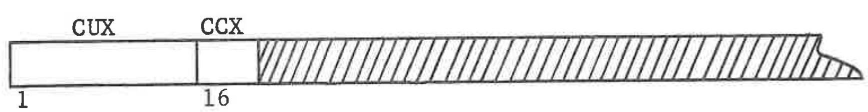
For all other types, the presence of a non-zero code requires that additional data cards follow immediately after the surface card. The particular form depends upon the surface type:

Cylindrical Surface (Type 1)

The regular curvature entry and freeze are assumed to describe the curvature and its control for the Y-Z (meridional) plane. The required additional data card provides the curvature and its control in the X-Z plane:

CUX	(Col. 1-15)	Curvature in X plane (decimal notation).
CCX	(Col. 16-20)	Control.

The permissible range of values for CCX is -99 to 100 with the same meanings as for the normal curvature control. This permits free variables, frozen data and coupled X curvatures. It is not permissible to have both curvatures non-zero or unfrozen. The program will ensure that this is not done, with preference given to the regular curvature (CUY) value and its control. The additional data card is of the form:



Aspheric Surface (Used by Types 2,3,4, and 9), and Fresnel Surface

The form of aspheric surface which can be used is:

$$z = \frac{ch^2}{1 + \left[1 - (1+K)\, c^2h^2\right]^{1/2}} + Ah^4 + Bh^6 + Ch^8 + Dh^{10}$$

where z is the sag of the surface

$h^2 = x^2 + y^2$

c is the curvature at the pole of the surface

K is the conic coefficient ($K = -e^2$):

$K > 0$		for oblate spheroid
$K = 0$		for sphere
$0 > K > -1$		for ellipsoid with major axis on the optical axis
$K = -1$		for paraboloid
$K < -1$		for hyperboloid
A, B, C, D		are the 4th, 6th, 8th, and 10th order deformation terms, respectively.

IC is the intersection code to discriminate between the required intersection with the ray when two intersections of the surface with the ray can exist.

IC blank - intersection closest to tangent plane
IC = -1.0 - intersection farthest from tangent plane

CUF non-zero flags this surface as a Fresnel lens surface on a base curve of curvature CUF; thus to represent a plane base use .0000001. CCF is the control on CUF; 100 is a freeze, 0 is variable. The aspheric is converted to a Fresnel lens surface with infinitely small step sizes. The SLOPE request in MODEL DATA defines the slope for fabrication.

Data is entered on two cards:

K	KC	IC	CUF	CCF	(unused)
1	16	21	41	56	61

A	AC	B	BC	C	CC	D	DC
1	16	21	36	41	56	61	76 80

All values are entered in decimal or floating point format, i.e., .000123456, or 1.23456E-04.

A conic surface can be represented by setting A=B=C=D=0. A cone can be approximated by a hyperboloid with a large curvature and

$K = -(1 + \tan^2 \theta)$ where θ is the cone half angle.

An even order polynomial representation is generated by setting K = -1.

Aspheric Control Codes	Description
KC (Col. 16-20) AC (Col. 16-20) BC (Col. 36-40) CC (Col. 56-60) DC (Col. 76-80)	Entries in these fields are treated like those for Curvature Control. A blank or zero will allow the particular coefficient to vary in AUTOMATIC DESIGN, values between ± 1 and ± 99 are treated as coupling numbers, and a value of 100 freezes a particular coefficient. Note: It is inadvisable, except on strong surfaces, to use K as a variable because it is not defined when c=0, and c becomes non-linear for large K.

Diffraction Grating (Type 3)

This has the form of an aspheric surface on which is ruled a diffraction grating. The rulings are the intersection of a series of parallel planes with the surface. The quantities required to be specified are those of the aspheric plus those relating to the grating, which are:

- n the grating order
- d the spacing between the generating planes
- L, M, N direction cosines of the normal to the generating planes.

For example, if we wish the first order beam from a grating ruled with a space of .001 units with rulings parallel to the x axis, (the normal to generating planes is therefore parallel to the y axis) then the values are:

n = 1

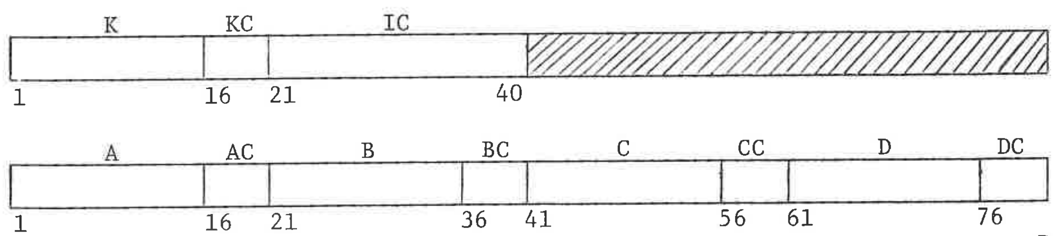
d = .001

L = 0

M = 1.0

N = 0

The data required is entered on three cards (the first two are identical to those for the aspheric surface):



n	d	L	M	N	
1	11	21	31	41	50

The values of n, d, L, M, and N are entered in decimal format.

Aspheric Toroidal Surface (Y-Toroid) (Type 4)

This surface is generated by first defining a normal aspheric contour in the Y-Z plane (meridional plane) and then rotating it about an axis lying in that plane. Thus the surface can be aspheric in one direction and of circular crossection in any X-Z plane. The quantities required to define this surface are those of the aspheric plus the curvature in the X direction and the control for this value:

CUX (Col. 1-15) Curvature in X plane (decimal notation).

CCX (Col. 16-20) Control.

The permissible range of values for CCX is -99 to 100 with the same meanings as for the normal curvature control. This permits free variables, frozen data and coupled X curvatures.

The data required is entered on three cards (the first two are identical to those for an aspheric surface):

K	KC	IC	
1	16	21	40

A	AC	B	BC	C	CC	D	DC
1	16	21	36	41	56	61	76

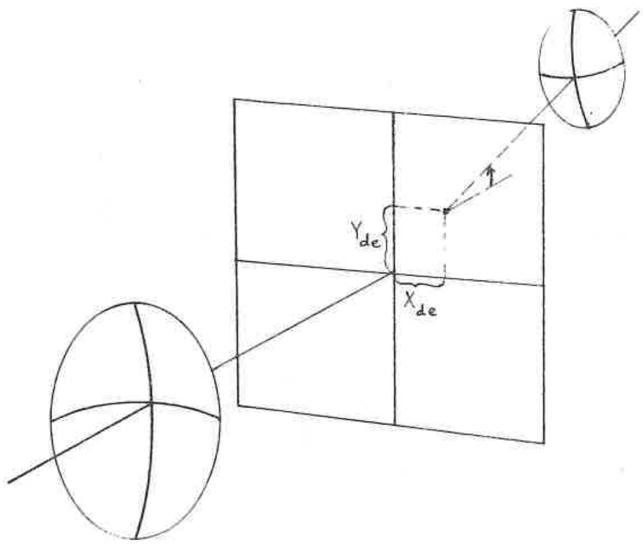
CUX	CCX	
1	16	21

This surface can represent cylindrical surfaces by setting K=A=B=C=D=0 and choosing which curvature is to be zero or non-zero. However, the Type 1 surface is much more efficient for this purpose.

Decentered Surfaces (Types 5, 6, and 7)

Decentered surfaces are provided by declaring a break in coordinate systems rather than defining a regular surface to be decentered. This simplifies the understanding of what occurs as well as providing the opportunity of returning to some prior reference point.

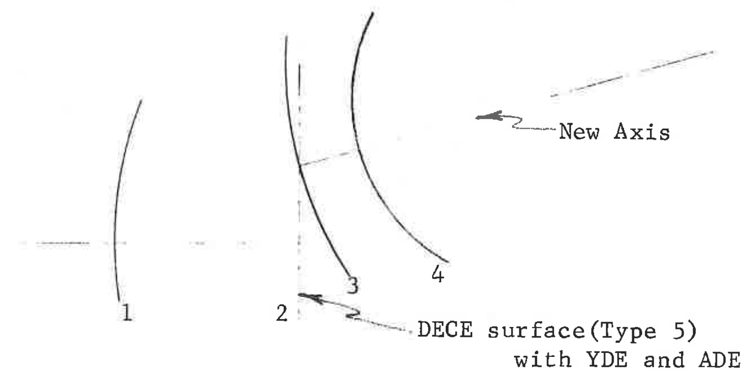
The break is provided by using one of the forms of decentered coordinate cards; these are counted as surfaces so that reference may be made to them in the CHANGE and ZOOM options.



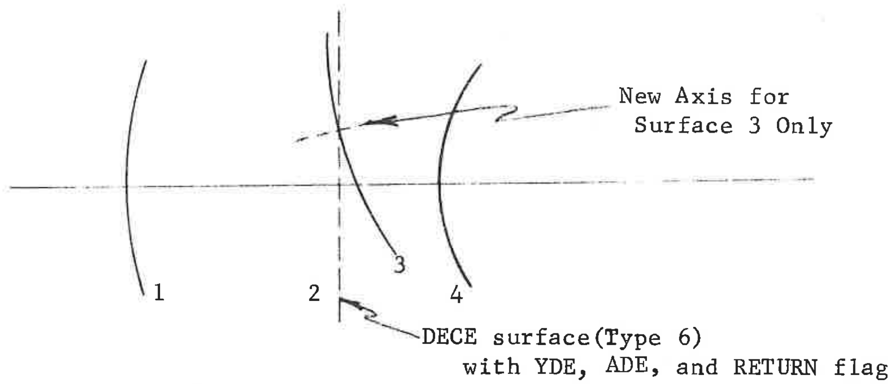
Ray tracing is carried up to the plane of the coordinate break using all data (curvature, index, and distance to next surface) just as if the coordinate break were a normal plane surface. At this point the data for the coordinate break entered in the card are used to describe the penetration point and angle of the new axis in the old coordinate system. All succeeding surfaces are of standard type and are referenced to the new axis until altered by use of a RETURN request as described below, or by another decentered surface.

Three forms are provided; these are:

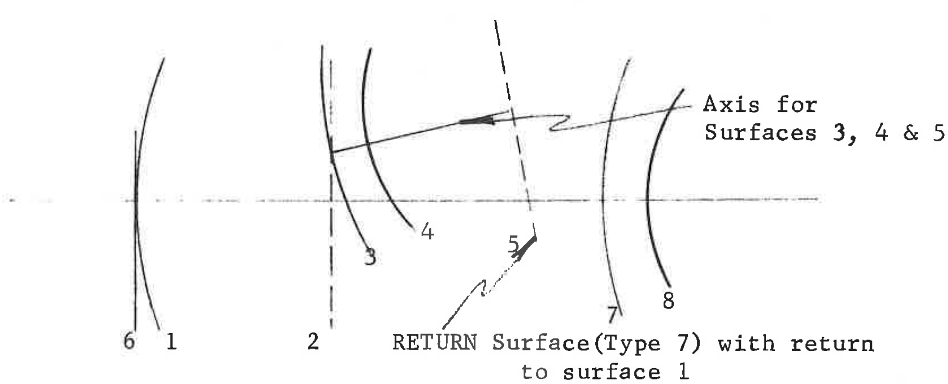
Type 5 - Decenter - A new axis is defined for succeeding surfaces



Type 6 - Decenter and Return - The next surface, only, is decentered, and return to the previous coordinate system is made before translation to the following surface



Type 7 - Return - Return is made to the coordinates of the pole of a designated surface defined prior to the return surface



In the above figure:

2 is a decentering coordinate break (Type 5 surface)

3 and 4 define surfaces in the new coordinate system

5 is the RETURN (Type 7) surface. If the surface number referred to on the card is 1 the new coordinate system for the pole of surface 6 becomes the original coordinate system of surface 1. The thickness of surface 6 is measured from this point.

Type 7 surfaces are most useful when centered components or sub-systems are decentered within a system.

Data Cards (Type 5 and 6)

	XDE	YDE	ADE	BDE	CDE	RETURN	
DECE							//////////
1	11	21	31	41	51	61	71

XDE X displacement of new axis in old coordinate system.

YDE Y displacement of new axis in old coordinate system.

ADE (α) angle of tilt of new axis (degrees) about the X-axis of coordinate system after XDE, YDE (meridional decenter.

BDE (β) angle of tilt of new axis (degrees) about the Y-axis of coordinate system after XDE, YDE, ADE (skew decenter).

CDE (γ) angle of tilt of new axis (degrees) about the Z-axis of coordinate system after XDE, YDE, ADE, BDE (axial rotation.

RETURN this optional word flag indicates that this is a de-center and return coordinate break (Type 6 surface) and only the next surface will be treated in the new coordinate system.

	XDC	YDC	ADC	BDC	CDC	
DECC						//////////////////
1	11	21	31	41	51	60

XDC, YDC, ADC, BDC, CDC are the control codes for XDE, YDE, ADE, BDE, CDE respectively. A value of 0 or blank indicates that the decentering value is to be variable; a value of 100 indicates that it is to be frozen. A value of ± 1 to ± 99 can be used to couple the corresponding variable to any other variable of the same type. Note: This coupling maintains the proper relationships of the sines of the angles, not the angles themselves. Thus, both are maintained if the starting angles are equal in magnitude.

Data Card (Type 7)

	SURF	
RETURN		//////////
1	11	21

SURF — An integer which is the number of the surface whose coordinate system and origin is to be adopted for the succeeding surfaces.

Note:

Some operations, such as paraxial ray tracing and third order analysis are carried out ignoring the decentration except for axial shifts. Functions which depend upon these (such as automatic insertion of image distance, calculation of entrance pupil diameter from EFL and f/no., etc.) will be performed with the system represented by ignoring the decentrations. If these are not suitable, it is best to use object space representations of aperture (EPD or NAO) and field (YAN or YOB) and to place the image distance at the desired value (without using the PIM solve).

Decentrations prior to the aperture stop will give an entrance pupil decentered in both X and Y, as required so that each chief ray passes through the center of the stop.

It is imperative to note that the types of decentration provided here are physically oriented and not just convenient for programming. In particular, the coordinate break concept leaves no doubt that only data following the card is in the new coordinate system; all of the prior data is in the old system. Likewise, on the decenter-and-return surface (Type 6) it is only the physical surface itself which is decentered; separations to later surfaces remain in the old coordinate system.

Thermal Gradient Surface (Type 9)

When lenses are subject to radial thermal gradients (see ENVIRONMENTAL CHANGE option), spherical surfaces are converted to aspheric shapes and information is generated regarding the index of refraction as a function of radius from the axis. While it is generally impractical to generate this information by hand, decks can be punched containing this data. Therefore provision must be made for entering it.

The items of data required are:

K, A, B, C, D - aspheric coefficients of the surface

α_1, α_2 - coefficients of the increase in temperature as a function of lens radius (H) in the medium following the surface.

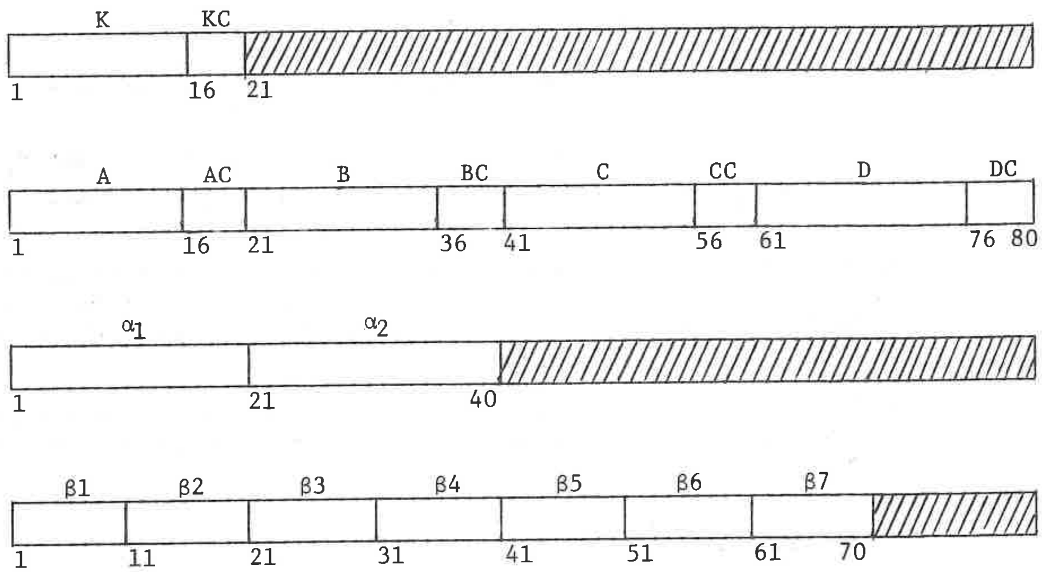
β_λ - values of $\Delta N/\Delta T$ for each of the used wavelengths; values are given for the temperature at the center of the element.

The index coefficients are combined in the following equation for refractive index:

$$N\ (H,\lambda) = N_0 + (\alpha_1 \cdot H^2 + \alpha_2 \cdot H^4) \cdot \beta_\lambda$$

where N_0 is the index of refraction at the axial temperature.

The entries are made as follows on 4 cards:



The values of α_1 and α_2 are entered in <u>decimal</u> or <u>floating point</u> format; $\beta_1 \cdot \cdot \cdot \beta_7$ are entered in decimal format.

Note: It is strongly recommended that, if these entries for thermal gradients must be made with designer generated data, they be made only after thorough familiarization with the use of the ENVIRONMENTAL CHANGE option on the same system. This will give an example of the data entry form.

Thermal gradient surfaces influence ray tracing, but are modeled only to the extent of the primary effect on ray bending and wave aberrations, not as an integral along the ray path. They are therefore useful for ENVIRONMENTAL ANALYSIS, but not for accurate simulation of long paths of variable refractive index.

Spline Aspheric (Type 12)

This alternate form of aspheric is defined by the equation:

$$z = \frac{M_{i-1}}{6} \frac{\left(H_i - h\right)^3}{\left(H_i - H_{i-1}\right)} + \frac{M_i}{6} \frac{\left(h - H_{i-1}\right)^3}{\left(H_i - H_{i-1}\right)} + \left[S_i - \frac{M_i}{2}\left(H_i - H_{i-1}\right)\right] \left(h - H_{i-1}\right) + \left[Z_{i-1} - \frac{M_{i-1}\left(H_i - H_{i-1}\right)^2}{6}\right]$$

where z is the desired sag
h is the radial height at which z is desired
H_{i-1}, H_i are the radial heights at which the spline slopes are defined for the zone containing h
Z_{i-1} is the sag at the defined height H_{i-1}
S_{i-1} is the slope (input data) at the defined height H_{i-1}
M_{i-1}, M_i are the "curvatures" at the defined heights H_{i-1}, H_i

These values are all determined by the input data consisting of pairs of values, namely, H_i, S_i. The aspheric is given by 4 zones which are defined at $H_0(=0)$, H_1, H_2, H_3, H_4; at each point S_i is entered - S_0, S_1, S_2, S_3, S_4.

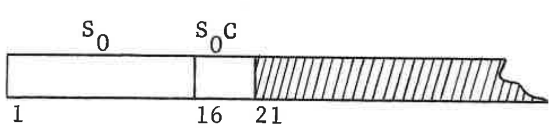
If it is necessary to evaluate the above equation, we can generate the M_i, Z_i recursively by letting $M_0 = c$, the axial curvature, and $Z_0=0$:

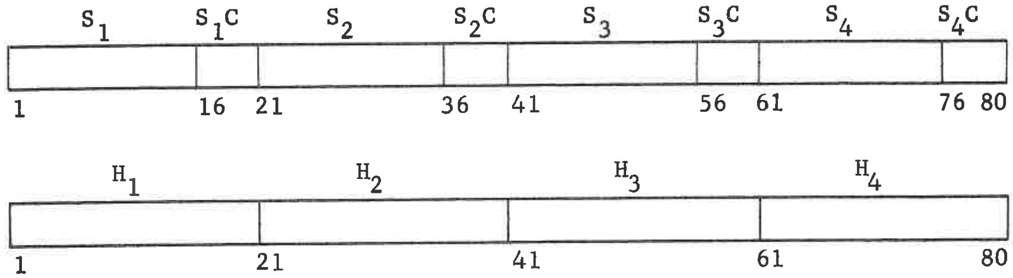
$$M_i = \frac{2\ (S_i - S_{i-1})}{(H_i - H_{i-1})} - M_{i-1}$$

$$Z_i = Z_{i-1} + (H_i - H_{i-1}) \left[S_i - \frac{(H_i - H_{i-1})}{6} (M_{i-1} + 2M_i)\right]$$

$(i = 1, 2, \ldots 4)$

The data is entered on three added cards as follows:





Usually S_0 is zero (first card blank) unless there is an axial slope; $S_0 \neq 0$ provides a cone as a base. H_4, S_4 must be defined outside the largest expected ray intersection point; any attempt to use the surface beyond H_4 will result in the message "RAY MISSED SURFACE i." No two H_i can be the same; also, the zones must be defined in ascending order, $H_1 < H_2 < H_3 < H_4$. All 4 zones must be defined. Otherwise, the designer is free to choose the zones in any appropriate manner he wishes. Typically, the outer zones tend to be narrower than the inner ones.

In AUTOMATIC DESIGN, the S_i are variable and are controlled by their control entries in a manner analogous to the regular aspheric.

The spline aspheric is essentially a low order curve, both odd and even; within any one zone it provides 1st, 2nd, and 3rd order variation of the surface sag. Thus there is no analog to third order aberrations which are created by 4th order variations. In 3rd order, therefore, the spline is treated as a parabola, regardless of the input data. For a parabola, the input data is easily set up:

$$S_i = cH_i$$

From the previous formulas, we can see that, for this case

$$M_i = c$$

This demonstrates that the M_i are not true curvatures but only the second derivative of the surface.

Because it is such a low order aspheric, the spline is most useful as a generator of unusual optical effects which can be generated only with extreme difficulty, or not at all, by spherical or polynomial aspheric surfaces. Examples are special distortion or longitudinal defocus curves. For normal applications, the spline is much less effective than the polynomial form for the same number of defining terms.

DESIGN NOTES

I. Setup of Decentered Systems

A. Sequencing

In setting up decentered systems, it is important to bear in mind the sequence of operation which is done if more than one value of x, y, α, β, γ, are entered on one surface. (x,y) defines the start of the new axis in the tangent plane at the vertex of the DECE surface; either x or y or both may be entered without difficulty, and without concern over the presence or absence of tilt angle entries.

If tilt angle entries are made, computation always occurs in the sequence α first, β second, γ third. Thus if α is entered, β must be defined in the coordinate space generated by the α tilt. Likewise, γ must be defined in the compound space defined by the α and β tilt. For example, suppose we desire to point the axial bundle at an optical system at 80° in the meridional plane from the mechanical centerline and 15° in azimuth from the meridional plane. The entry

	x	y	α	β	γ
DECE	0.0	0.0	80.0	0.0	15.0

would do it, since the 80° swing is made first. This is exactly equivalent to

DECE	0.0	0.0	80.0	0.0	0.0
DECE	0.0	0.0	0.0	0.0	15.0

However, the sequence

DECE	0.0	0.0	0.0	0.0	15.0
DECE	0.0	0.0	80.0	0.0	0.0

is quite different, rotating the pattern of rays in the pupil by 15° before tilting the beam to come in parallel to the meridional (y,z) plane at an angle of 80° to the mechanical axis.

To cancel the effect of a simple tilt is easy:

DECE	0.0	0.0	80.0	0.0	0.0
DECE	0.0	0.0	-80.0	0.0	0.0

To cancel the effect of a compound tilt, the sequence must be done in reverse order. Thus,

DECE	0.0	0.0	80.0	0.0	15.0

can later be removed by

DECE	0.0	0.0	0.0	0.0	-15.0
DECE	0.0	0.0	-80.0	0.0	0.0

Notice that these cancel the decenters in the order γ first, α second. Note also that

DECE	0.0	0.0	-80.0	0.0	-15.0

will not work because α is done first.

B. RETURN Surfaces

Alternatively, the RETURN surface can be used to undo tilts and decenters with fewer surfaces. Thus, in the last example,

5 ----	----	----	----	----	----
6 DECE	0.0	0.0	80.0	0.0	15.0

can be cancelled by

7 RETU 6

This will return to the corrdinate system at the pole of surface 6, before the coordinate change is made. There is no restriction on the order of RETURN surfaces; they may span other RETURNs as well as decentered surfaces. They may also be used with ordinary surfaces just to return to a prior surface as reference point.

C. Reference Axes

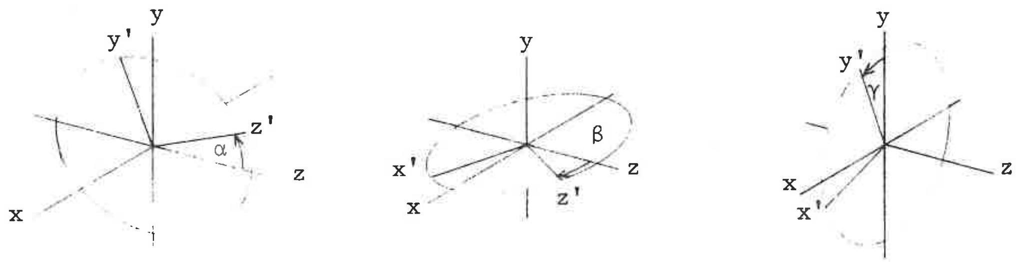
It is essential to realize that the data set up is referenced to a mechanical coordinate system only. There is no guarantee that the optical axis will coincide with the mechanical axis. The designer must see to it that the decenters, reflections, etc., follow the desired optical path. Use can be made of the ray controls in AUTOMATID DESIGN to hold the decentrations properly correlated to the optical axis when necessary; however, it is wise to set up the starting system as close as possible to satisfying the controls requested.

D. Angle Limits

No single tilt angle can be greater than 90°. For changes greater than this use additional DECE surfaces. In AUTOMATIC DESIGN, the variable used is the sine of the angle; it is therefore wise to keep tilt angles that are variables well below 90° so that accuracy is maintained in the sine.

E. Sign Convention

All angles are plus:



Note that these show separate tilt angles; they can, of course, be compound in the order α, β, γ.

ZOOM DATA

Purpose:

Provides a means of entering data for additional configurations (zoom positions) up to a total of seven.

Input Data:

The first time that the ZOOM option is called in a given run the number of zoom positions must be defined by entering the following card:

POSITIONS	N	//////////////////////////////
1	11	

N= number of zoom positions (up to 7).

This is followed by the ZOOM data cards which are punched in the same format as the CHANGE data cards. However, the ZOOM option requires that data for all zoom positions be entered (including position 1). The parameters which can be zoomed are designated by a (z) in the list of CHANGE CODES.

If the ZOOM option is called again to add or change zoom parameters, the POSITIONS card should not be re-entered. If the number of positions is redefined during a run to a value equal to or greater than the current number, all of the zoom data must be redefined. If the number is less, the higher positions are merely removed.

This card should not be confused with the POSITION card used in many options to designate zoom positions to be skipped.

When a parameter which can be a variable in AUTO is zoomed, its control codes are initialized to 100 (frozen); entry of the corresponding control code card (for example THC with a zoomed THI) will modify that initialization.

Function:

In general, once a system has been zoomed, the function of any subsequent option is performed for each of the zoom positions. If optional data cards are entered for any of these options, the zoom positions affected are determined from the fields in which data is entered. For example; data in field F1 (columns 11-20) affects zoom position one, F2 (columns 21-30) affects position two, etc.

Output:

The system data plus a table of zoomed parameters is listed.

Error Conditions:

1. "INVALID CODE (   )" - the zoom data code entered is not acceptable. Check the list of acceptable CODES and rerun.

2. "_____SPECIFIES SURFACE NUMBER LARGER THAN FOCAL PLANE SURFACE" - correct data and rerun.

DEZOOM

Purpose:

Provides a means for removing data from the zoom table or to convert the system to a non-zoom system corresponding to one of the configurations.

Input Data:

A. Dezoom System

The system may be converted to a non-zoom system corresponding to one of the existing positions by entering the following card:

```
          N
POSITIONS |//////////////////////////////////////////////////////
1         11
```

N = number of the position to be adopted as the non-zoom system.

All other zoom data will be removed.

B. Dezoom Data

To remove individual data items from the zoom table, specify the item by the CHANGE code originally used to zoom it; no entries in the data fields are needed or used. For example:

```
DEZOOM
THI 17
F/N
```

Output:

The system data after modification is listed.

DEZOOM

Purpose:

Provides a means for removing data from the zoom table or to convert the system to a non-zoom system corresponding to one of the configurations.

Input Data:

A. Dezoom System

The system may be converted to a non-zoom system corresponding to one of the existing positions by entering the following card:

1	11	
POSITIONS	N	//

N = number of the position to be adopted as the non-zoom system.

All other zoom data will be removed.

B. Dezoom Data

To remove individual data items from the zoom table, specify the item by the CHANGE code originally used to zoom it; no entries in the data fields are needed or used. For example:

```
DEZOOM
THI 17
F/N
```

Output:

The system data after modification is listed.

SET DATA

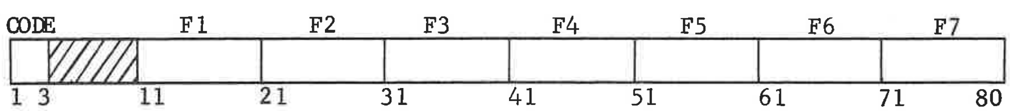
Purpose:

To modify system data selectively as the result of special calculations:

1. To generate APERTURE data from SPECIFICATION DATA
2. To generate vignetting from APERTURE data
3. To generate aperture specification (F/N, EPD, NAO, NA) from APERTURE DATA.

Input Data:

Each request is made in the form:



CODE (Col. 1-3)	Action
APE	From the bundle definitions in the SPECIFICATION DATA previously entered, circular apertures are supplied for any surfaces that do not already have aperture data of some type. They are supplied in the form CIR n ____. These apertures are the smallest required to pass all zoom positions. For zoom systems, the clear apertures on the stop surface(s) will be zoomed.
VIG VIX VIY	From the APERTURE DATA previously supplied, determine minimum vignetting values required to pass light through the system at each field angle and zoom position. VIG sets VUY, VLY, VUX, and VLX. VIX sets VUX and VLX; VIY sets VUY and VLY. If N (or NO) is entered in any field, F1-F7, the calculation is omitted for that zoom position and the values remain unchanged from those used previously.

F/N
EPD
NAO
NA

From the APERTURE DATA previously supplied, determine the largest aperture passable by the system and enter in the form indicated; F/N supplies the data as f/no., EPD as entrance pupil diameter, NAO as the numerical aperture in the object space, and NA as the n. a. for the image space. If N (or NO) is entered in any field, F1-F7, the calculation is omitted for that zoom position and the value remains unchanged from that used previously.

Function:

As each request is entered, it is executed. Thus,

APE
VIG

would set apertures first (based on prior vignetting, field and aperture values) and then the vignetting values would be set from these new apertures. On the other hand,

VIG
APE

would set vignetting first (based on prior apertures) and then reset the apertures based on the new vignetting. In the first of these examples, VUY and VLY will not be changed at the end unless they were physically inconsistent from field angle to field angle (a field angle has more vignetting than could actually be done); however, VUX and VLX will be supplied as well. In the second example, the vignetting will be generated but only the surfaces without prior APERTURE data will have CIR values generated for them. The same type of sequence dependence applies to the aperture specification (F/N, EPD, NAO, NA).

Output:

The modified system data is printed.

Technical Notes:

1. APERTURE DATA is supplied by the designer or by using this option. It presumably will be used by a later analysis option and invoked with the SC request. The presence of such data on surfaces near the final or intermediate image planes will cause clipping of rays at the extreme field angle which are more highly aberrated than the bundle defining rays in an outward direction; this includes outward lateral color or higher order flare. This is

usually apparent in artificially low relative illumination or illogical MTF data at the extreme field angle. Thus, when surfaces lie near intermediate or final images, the designer must make the APERTURE DATA on these surfaces larger so they will not be active, through the CHANGE option.

2. If APERTURE DATA has not been supplied for the surface flagged as the aperture stop, requests for setting F/N, EPD, NAO, or NA will be satisfied by the most limiting APERTURE DATA that is supplied. If APERTURE DATA is supplied on the flagged stop surface as well, a message will be printed if it is not the most limiting surface.

3. If negative vignetting values occur, it is an indication that pupil expansion off-axis exists (if APERTURE DATA has been supplied for the stop) or that the surfaces on which APERTURE DATA has been supplied are not capable of restricting the real bundles at that field angle to any lower value.

4. Any APERTURE DATA supplied for the stop surface is only determined by beam diameters for the first field position of all zoom positions; this is usually the axial beam.

5. Any modifications to these results may be made through the CHANGE option.

<u>Error Conditions:</u>

1. "INVALID CODE ( )" - the CODE entered is not recognizable and is ignored. Check the list of acceptable CODES and rerun.

2. "NOTE - OPTION TERMINATED DUE TO MISSING LENS DATA" - entering system is missing essential data to provide the requested operation.

3. "NOTE - UNABLE TO CALCULATE ____. EITHER NO APERTURES WERE SUPPLIED OR THEY ARE NOT REACHABLE BY RAY TRACING." - Correct data.

4. "NOTE - ____ IS BASED ON SURFACE n RATHER THAN THE STOP SURFACE" - a surface other than the flagged stop is the most limiting for the F/N, EPD, NAO, NA.

5. "NOTE - OPTION TERMINATED DUE TO RAY TRACE ERRORS" - rays defined by SPECIFICATION DATA are not traceable. APE request cannot be fulfilled.

6. "NOTE - AN APERTURE OF _____ HAS BEEN ASSUMED ON THE STOP SURFACE FOR POSITION ____" - For setting vignetting ratios, a temporary circular aperture has been assigned to the flagged stop surface, determined solely by the aperture specification data for that zoom position.

7. "NOTE - VIGNETTING CANNOT BE SET FOR THE nth FIELD ANGLE BECAUSE THE CHIEF RAY IS CLIPPED AT SURFACE NUMBER n FOR POSITION z " - Chief ray is traceable but is outside the designated clear aperture.

8. "NOTE - VIGNETTING CANNOT BE SET FOR ZOOM POSITION z DUE TO AXIAL RAY TRACE ERRORS FOR SPECIFIED BUNDLE" - The F/N, EPD, NAO, or NA gives too large a bundle to be traced to the aperture stop.

DATA ALTERATION

CHANGE

Purpose:

Provides a means of changing individual items of data, inserting and deleting surfaces.

Input Data:

A. Format

The cards containing the data changes are placed immediately after the CHANGE option card and should be punched in the following format:

CODE	N	LABEL	F1	F2	F3	F4	F5	F6	F7
1	4	7	11	21	31	41	51	61	71

CODE (Col. 1-3) — Mnemonic code indicating what data is to be changed. A list and description of the acceptable codes is given later.

N (Col. 4-6) — A number used with some CODES to identify surface numbers, field positions, etc.

LABEL (Col. 7-10) — Separated by one or more blanks from the number N. Used for glass changes to indicate power adjustment; also used as a LABEL for multiple aperture specifications on a surface, and an identifier for SOLVES.

F1 (Col. 11-20)
.
.
.
F7 (Col. 71-80) — Data Fields 1-7; used for alphanumeric, integer and decimal entries depending on parameter being changed. For zoomed parameters the data field number corresponds to the zoom position. If a zoomed parameter is being changed, the values for all zoom positions need not be entered, only those positions which are being changed. However, if a zoom value is to remain unchanged, the letter N should be entered in the first column of the data field which correlates with that position.

B. Change Codes

The CHANGE CODE is a three character code which identifies the data to be changed. In the description list given below, the CODES requiring a number are designated with the letter n. If the number is optional, the designation (n) is used; if the number is omitted on CODES where it is optional, all of the values of the specific parameter (for example: all field heights) are changed. For the object surface, letter O should be used. The (z) codes indicate parameters which can be zoomed.

The surfaces are referred to as follows:

O Object surface (letter O)

1 First optical surface

.
.
.

n-1 Last optical surface (real or imaginary)

n Image surface

I Image surface (equal to n). Convenient when n is not looked up.

S Stop surface. Equivalent to entry of the number.

Each change code is executed immediately before processing the remaining requests.

CODE	DATA
1. TITLE	
TIT	title - when this code is entered the next card is read as the new title card
2. SURFACE DATA	
a. Curvature	
CUY n (z)	curvature - y direction or rotationally symmetric

(z) CODES indicate parameters which can be zoomed.

CUX	n	(z)		curvature - x direction
RAY	n	(z)		radius - y direction or rotationally symmetric
RAX	n	(z)		radius - x direction
CIY	n	(z)		curvature increment y
CIX	n	(z)		curvature increment x
CCY	n	(z)		curvature control y
CCX	n	(z)		curvature control x

b. Thickness

THI	n	(z)		thickness
TIN	n	(z)		thickness increment
THC	n	(z)		thickness control

c. Glass

GLA	n	(z)	L	glass - use the form of codes described in DATA. The code is entered in F1 (to F7 for zooms); if catalog descriptions are to be included, comma input formats will allow the extra characters as long as they fit on one card. <u>Restrictions on zoomed glass</u>: 1. REFL surfaces cannot be zoomed. 2. A fictitious glass may only be coupled within its own zoom position, not across zoom positions. If a letter P is entered in the LABEL field, a simultaneous curvature change will be made to preserve the power of the element whose glass is being changed.
GLC	n	(z)		glass control
GCH	n	(z)		glass characteristics code

d. General Freezes

FRE	Freezes (FRE) or unfreezes (UNF) all variables, if field F1 is blank. If a single surface number is entered in Col. 11-15, only the variables on that surface are affected; if a second surface number appears in Col. 16-20, only the surfaces between and included are affected.

e. Flip, Insertion, Deletion, and Change of Type

FLX FLY	Flips the portion of the lens system between designated surfaces end for end. The starting surface is given in Col. 11-15; the ending is given in Col. 16-20. If no surfaces are designated, they are assumed to be 1 and I-1. Only the order and appropriate signs of surface data are changed; SPECIFICATION DATA and any other usage data must be changed separately. For rotationally symmetric or doubly symmetric (e.g., cylinder) systems, FLX and FLY generate the same result. For decentered systems, however, FLX is a flip rotating about the X axis and FLY is a flip rotating about the Y axis. Results are unpredictable when return (Type 7) or decenter-and-return (Type 6) surfaces are included in or reference surfaces lying in the span of flip surfaces.
INS n	Inserts a new surface at surface n; data from surface n through the end of the surface data is shifted down by one surface. Normally this would be followed by other CHANGE CODES to place the desired data at surface n. This card alone always inserts an unfrozen air space of 0.0 and a spherical surface curvature and CCY equal to the designated surface. This card alone converts a cemented surface into two uncemented ones..
DEL n	Deletes surface n; data in surface n + 1 through the end of the surface data is shifted up by one surface. Note that both insertion and deletion assign new surface numbers to parts of the system data and therefore, special care must be taken in using them. Example: To delete an element located at surfaces 10 and 11 one would use two delete cards (DEL 11 and DEL 10) or (DEL 10 and DEL 10) but not DEL 10 and DEL 11).
TYP n	Surface type - the number representing the new surface type is entered in field F1. Any new surface data values required are initialized to zero. Control Codes are set to 100 (frozen).

f. Special Surfaces - Aspheric

K	n	(z)	conic constant
KC	n	(z)	conic control
A	n	(z)	4th order aspheric
AC	n	(z)	4th order aspheric control
B	n	(z)	6th order aspheric
BC	n	(z)	6th order aspheric control
C	n	(z)	8th order aspheric
CC	n	(z)	8th order aspheric control
D	n	(z)	10th order aspheric
DC	n	(z)	10th order aspheric control
IC	n	(z)	intersection code
CUF	n	(z)	Fresnel base curvature and flag (value in F1-F7 sets flag; 0.0 removes it).
CCF	n	(z)	Fresnel base curvature control

g. Special Surfaces - Decentered

XDE	n	(z)	x decentering displacement
XDC	n	(z)	x decentering displacement control
YDE	n	(z)	y decentering displacement
YDC	n	(z)	y decentering displacement control
ADE	n	(z)	α decentering angle
ADC	n	(z)	α decentering angle control
BDE	n	(z)	β decentering angle
BDC	n	(z)	β decentering angle control
CDE	n	(z)	γ decentering angle
CDC	n	(z)	γ decentering angle control
RET	n	(z)	return surface number

h. Special Surfaces - Spline

S0	n	(z)	spline slope zero
S0C	n	(z)	spline slope zero control
S1	n	(z)	spline slope one
S1C	n	(z)	spline slope one control
S2	n	(z)	spline slope two
S2C	n	(z)	spline slope two control

(z) CODES indicate parameters which can be zoomed.

S3	n	(z)	spline slope three
S3C	n	(z)	spline slope three control
S4	n	(z)	spline slope four
S4C	n	(z)	spline slope four control
H1	n	(z)	spline height one
H2	n	(z)	spline height two
H3	n	(z)	spline height three
H4	n	(z)	spline height four

i. Special Surfaces - Grating

GRO	n	(z)	grating order
GRS	n	(z)	grating spacing
GRL	n	(z)	α grating direction cosine
GRM	n	(z)	β grating direction cosine
GRN	n	(z)	γ grating direction cosine

2. SPECIFICATION DATA

a. Aperture

EPD		(z)	entrance pupil diameter
F/N		(z)	f/no
NA		(z)	numerical aperture
NAO		(z)	numerical aperture - object space

b. Wavelength - (n) refers to the number of the wavelength

WL	(n)		wavelengths. Changing WL drops REF and WTW back to default values.
REF		(z)	reference wavelength
WTW	(n)		wavelength weights - integers only

c. Field - (n) refers to the number of the field

Y	(n)	(z)	Y image height
YAN	(n)	(z)	Y object angle
YOB	(n)	(z)	Y object height
X	(n)	(z)	X image height

(z) CODES indicate parameters which can be zoomed.

XAN	(n)	(z)	X object angle
XOB	(n)	(z)	X object height

d. Vignetting - (n) refers to the number of the field

VUY	(n)	(z)	vignetting Y - upper rim rays
VLY	(n)	(z)	vignetting Y - lower rim rays
VUX	(n)	(z)	vignetting X - plus x rays
VLX	(n)	(z)	vignetting X - minus x rays

e. Stop Surface

STO	(z)	aperture stop surface

f. Special Flags - presence of a blank sets the flag; presence of N or NO restores the normal condition.

AFO	(z)	Indicates afocal system instead of the normal focal condition.
TEL	(z)	Indicates the system is telecentric in the object space instead of the condition of finite entrance pupil.
XFO	(z)	X first order - computes first order properties of the system in the x-z plane rather than the normal y-z (meridional) plane.

g. Miscellaneous

FOC	(z)	focal surface number (must be largest in the first zoom position).
DIM		Dimension - alphanumeric code is entered for new dimension (I,M,C).
TEM		temperature
PRE		pressure
INI		designer's initials

(z) CODES indicate parameters which can be zoomed.

3. APERTURE DATA

CIR	n	(z)	L	circular aperture radius; a LABEL may be entered in column 9 to identify a specific aperture when more than one are entered on a single surface.
REX	n	(z)	L	rectangular aperture half width
REY	n	(z)	L	rectangular aperture half height
ELX	n	(z)	L	elliptical aperture half width
ELY	n	(z)	L	elliptical aperture half height
DAP	(n)			deletes all apertures at surface n; if n is omitted, all apertures are deleted.

4. PRIVATE CATALOG

PRIV	(4 characters)	L	Private catalog - this card should be followed by the normal private catalog wavelength and index cards as described in DATA. This card is used to add a private catalog (when none existed) or completely replace an existing private catalog.
PRA		L	Private catalog addition - the private catalog cards following will be added to the existing private catalog.

NOTE: After entering or adding to a PRIVATE CATALOG through CHANGE, all index data in the lens is deleted and re-entered unless a non-blank entry is made in the LABEL field.

(z) CODES indicate parameters which can be zoomed.
L Allows entry in LABEL field.

5. SOLVES (Second mnemonic falls in LABEL field)

RED		(z)	reduction ratio solve. If zoomed, like constraints in AUTOMATIC DESIGN, presence of a blank in one position avoids entry of the solve; a 0.0. or other value will activate the solve. Active only in zoom positions so designated.
PIM		(z)	paraxial image distance insertion. If zoomed, NO in any field deactivates the solve for that position. Active in all zoom positions not so cancelled.
THI	n	ET	edge solve
THI	n	OAL	overall length solve
SUR			Surfaces of OAL solve interval (must follow THI n OAL card)
THI	n	MRY	paraxial marginal ray height solve
CUY	n	MRY	Paraxial marginal ray angle solve
Deleting a SOLVE:			To delete or deactivate any solve the code DEL should be entered in the LABEL field. Examples are: THI 17 DEL RED DEL

Function:

The system is changed in the order the CHANGE CODES are entered. The data is then checked for consistency and errors, and SOLVES, if any, are performed before proceeding to the next option.

Output:

The data changes are listed.

Error Conditions:

1. "INVALID CODE ( )" - the change CODE entered is not acceptable. Check the list of acceptable change CODES and rerun.

SCALE

Purpose:

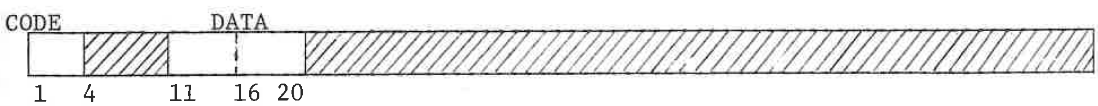
To scale the system or a part of the system, by a given amount or to match given requirements of EFL, TT, or OAL.

Input Data:

The optical system may be scaled with or without the SPECIFICATION DATA, or a portion of the system may be scaled. At least one choice of scaling mode must be made; several may be requested in sequence. The scaling may be applied also to the SPECIFICATION DATA by entry of a request (SPC) or the scaling may be limited to a subsection of the lens by designating the including surfaces (with a SUR request). Applying the scaling of a subsystem as a scale factor to the SPECIFICATION DATA is not often wanted but is permitted.

If a subsection is specified by a SUR request, all of the thicknesses between the two surfaces are scaled but none outside them are changed; however, if the image plane (I) is included, its thickness value (the defocus) will also be scaled.

Input data is provided in the format:



CODE (Col. 1-3)	DATA (Col. 11-20)
Modes (Choose One):	
FACTOR	The desired scale factor. A SUR card may be used to limit the change to a subsection; the default surfaces are 0 and I (total system).
OAL	The desired overall length value. A SUR card may be used to limit the change to a subsection; the default surfaces are 1 and I-1.
FGX FGY	The desired value of effective focal length (X or Y meridian), for infinity object distance. A SUR card may be used to limit the change to a subsection; the default surfaces are 1 and I.
TT	The desired value of object to image distance (total track) for finite conjugate systems. Applied to surfaces 0 to I (the total system).

DIMENSION — The desired dimension code is entered in Col. 11; ex: M for millimeters. The system is scaled from current dimensions to the specified dimension, and the DIMENSION flag is changed.

Controls (Optional):

SUR — Limits the scaling to the surfaces entered in Col. 11-15 and Col. 16-20 and all surfaces in between. Thicknesses connecting these surfaces are included; following thicknesses are not included (unless surface I is used in Col. 16-20).

SPC — The generated scaling factor is applied to linear dimensions of the SPECIFICATION DATA as well.

Operation and Output:

Scaling of the specified system data is performed; the scaling ratio and the resulting system are printed. Any number of mode requests can be made; each will be done in order and each must be followed by its SUR and/or SPC requests if the defaults are not appropriate.

Technical Notes:

There are interesting possibilities in the use of this option. For example, if a reflecting surface is to be inserted, the following sequence would achieve it:

SCALE		
FACTOR	-1.0	*Changes signs on surfaces 10 to I.*
SUR	10 I	
CHANGE		
GLA 10	REFL	*Changes sign of indices from surface 10 to I.*

Error Conditions:

The following error messages can occur:

1. "ZERO SCALING VALUE - NO SCALING" - The scaling mode card is missing or blank in Col. 11-20; correct and rerun.
2. "THE PRECEDING REQUEST IS NOT RECOGNIZABLE" - A SCALE input card does not contain one of the valid codes in Col. 1-3; correct and rerun.
3. "ERROR IN SURFACES" - A SUR card contains integers out of order or not in the range of the system surfaces; correct and rerun.

ENVIRONMENTAL CHANGE

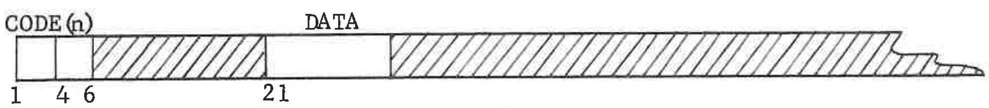
Purpose:

Provides a means for generating in a simple manner the changes in optical parameters associated with an altered thermal and pressure environment.

Input Data:

Because description of the environment is complex, several types of data cards are provided. If data is omitted the program will proceed using assumed conditions as described. If no data cards are provided, the only change is to convert the refractive indices from relative to absolute values.

A. Steady State Conditions



CODE (Col. 1-3)	DATA (Col. 21-30)
TEM	The desired temperature for steady state soak in °C. For radial thermal gradients this can be considered to be the temperature of the mount. If this card is omitted the temperature is unchanged. The temperature assumed in DATA FOR SYSTEM is 20.0°C.
PRE (n)	The desired pressure for steady state in mm Hg. For pressure gradients this can be considered to be the pressure of the object space; inclusion of the surface number n changes the pressure in the space following that surface only. If this card (and an ALT card) are omitted the pressure is unchanged. The pressure assumed in DATA FOR SYSTEM is 760.0 mm Hg.
ALT	The desired altitude; the pressure is then obtained in accordance with the U.S. Standard Atmosphere, 1962. If the system data is in inches, this altitude is entered in feet; for a system in millimeters or centimeters, the altitude must be entered in meters. Altitudes in the range of -5000 meters to 700,000 meters (-16,380 ft. to 2,295,000 ft.) may be used.

These entries must appear before any other data cards. If no additional data is supplied, data changes are made based upon the following assumptions:

1. That the temperature is constant throughout the lens.

2. That the pressure is equal in all spaces.

3. That the mounting rings contact the surfaces at the CA values of MODEL DATA and are made of aluminum ($\alpha = 210.0 \times 10^{-7}/°C$).

4. That the expansion coefficients for elements are those given for Schott glasses and are zero for all others. Coefficients for Schott glasses are obtained by the computer from the built-in glass catalog.

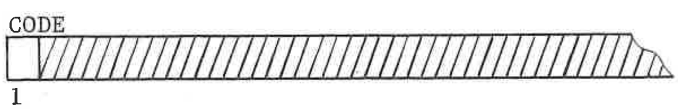
5. That the thermal index constants ($\Delta n/\Delta T$) for elements are given when available (+20 to +40 degrees) and are zero for all others.

6. That the expansion coefficients for mirror substrates are zero.

To alter these assumptions, additional data is necessary.

B. <u>Semi-Aperture Flag</u>

In some circumstances it may be desirable to override the assumption that all mounting rings contact the surfaces at the clear apertures specified. If so, those apertures which are different must have been previously entered and the flag described below set by including the card.

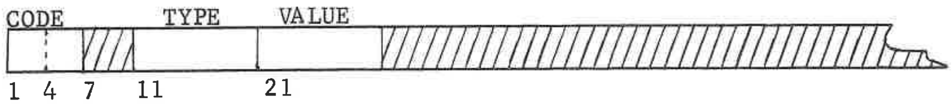


CODE (Col. 1-2)

SC	Indicates that the mounting rings contact the surfaces at the values of the APERTURE data entered previously. Expansion or contraction of these values is retained for future options.

C. Expansion Constants

Two forms of input are allowable. One is general which permits the expansion constant for all mount material (spacers) to be set to the same value or all glasses of a given glass code to the same values. The second form is specific for one surface; the only difference is the presence of a surface number.



CODE
Col. 1-6

A mnemonic code whose first three characters are EXP or EXG. EXP is used for entry of all data except first surface mirrors. For the latter EXG is used to enter the expansion coefficient of the substrate material which is otherwise not represented in the optical data. The remaining three characters are the surface number if the expansion coefficient is to apply only to the material following the one surface. If the surface number is left blank the remaining information is applied as extensively as possible.

TYPE
Col. 11-18

A name of a material. If this is one of the internally stored metals, the stored value of expansion coefficient is applied either to the specific space or to the mount as a whole depending upon the presence or absence, respectively, of the surface number described above.

The stored values are:

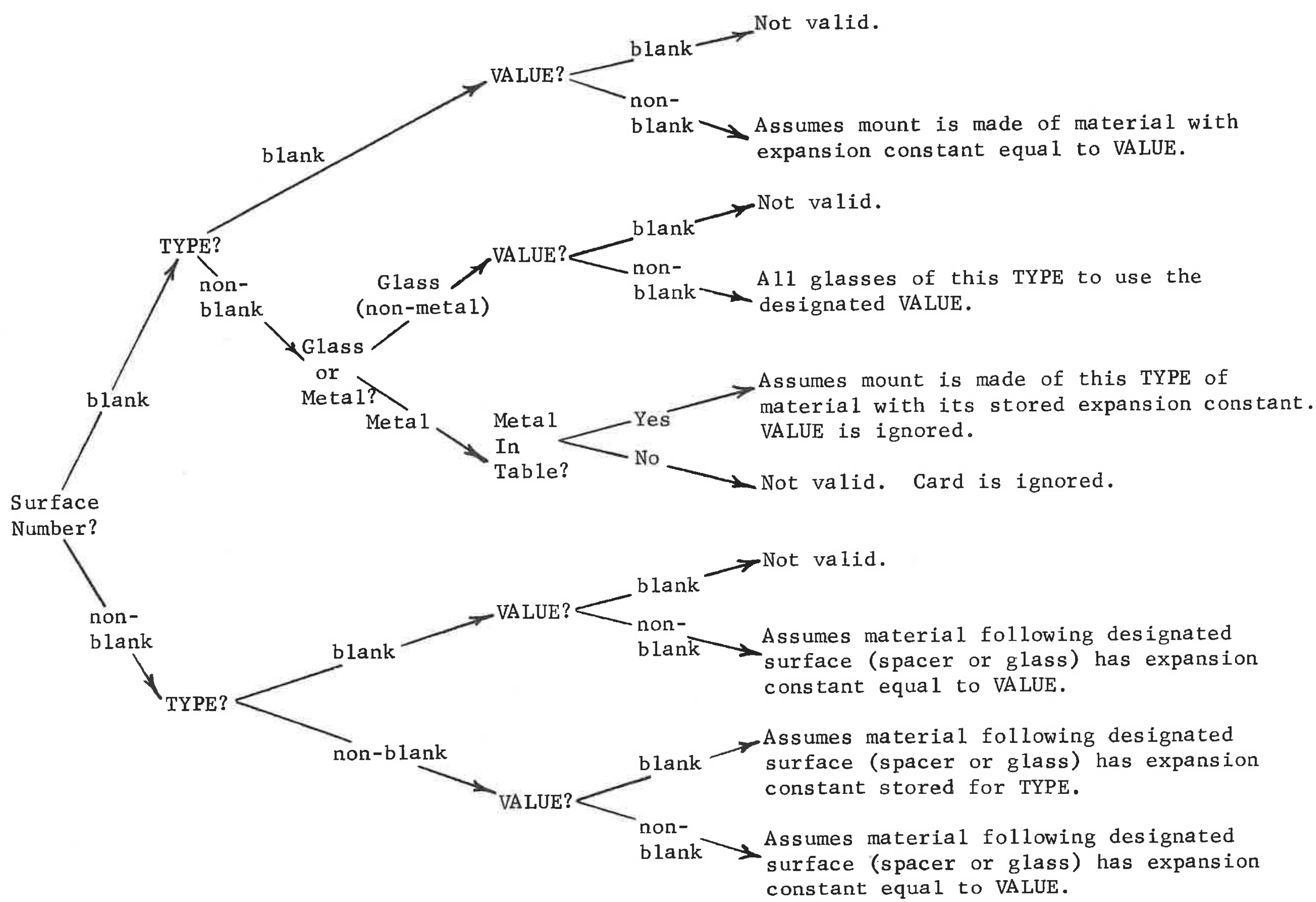
*ALUM	236.0
ALU356	215.0
AL6061	234.0
DUCTIL	117.0
SS303	172.8
SS430	104.4
SS440	100.8
TI6AL4	88.2
MAGAZ3	261.0
*INVAR	9.0
SS416	99.0
TI	85.5

* These values are typical. For precise work obtain exact value for alloy to be used.

If this is a recognized glass code in the Schott catalog, and VALUE (described below) is blank, the expansion coefficient of the designated glass type is supplied to the surface designated in CODE. If VALUE is not blank, its contents is supplied for all glasses with the glass code given in TYPE.

VALUE Col. 21-40	The value of expansion coefficient multiplied by 10^7. Thus an entry of 5.4 would be interpreted as a value of: $= 5.4 \times 10^{-7}/°C$.

The three optional items of data (surface number, TYPE, VALUE) have potentially ten combinations, only some of which are meaningful. These are diagramatically shown in the logic tree on the following page.



Surface Number?
blank
non-blank
TYPE?
blank
non-blank
Glass or Metal?
Glass (non-metal)
Metal
VALUE?
blank
non-blank
Not valid.
Assumes mount is made of material with expansion constant equal to VALUE.
Not valid.
All glasses of this TYPE to use the designated VALUE.
Metal In Table?
Yes
No
Assumes mount is made of this TYPE of material with its stored expansion constant. VALUE is ignored.
Not valid. Card is ignored.
Not valid.
Assumes material following designated surface (spacer or glass) has expansion constant equal to VALUE.
Assumes material following designated surface (spacer or glass) has expansion constant stored for TYPE.
Assumes material following designated surface (spacer or glass) has expansion constant equal to VALUE.

Example 1

EXP 104.

This indicates that all mounting materials are to have an expansion coefficient of 104. $X10^{-7}/°C$.

Example 2

EXP 620603 97.

This indicates that all glasses with glass code 620603 are to have the expansion coefficient 97. $X\ 10^{-7}/°C$.

Example 3

EXP 3 517642

This indicates that the material following surface 3, regardless of its composition, is to have the expansion coefficient associated with glass 517642.

Example 4

EXG 648338

This indicates that all first surface mirrors are to have substrates whose expansion coefficient matches that of glass 648338.

D. Index of Refraction Constants

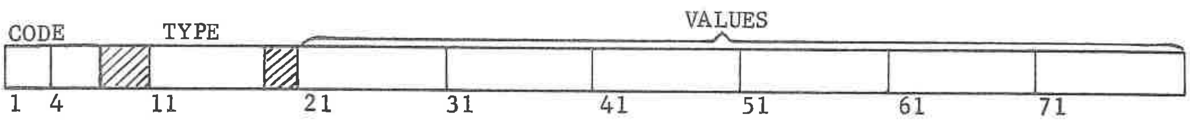
Index of refraction is a function of temperature and therefore must be altered with a change in temperature. Data is available for most of the Schott glasses and some other catalogs. The data is stored and available for the program to use.
However the only data which is available is the +20 to +40 degree dn/dt absolute values. If any other range is desired, or aglass is used that has no data in this range, then the user must supply the values that are to be used. If no data is supplied, the values are assumed to be zero, and a message will be printed.

Pressure does not influence the absolute index of refraction but, since the normal glass catalog values are stated relative to an assumed index of refraction for air equal to 1.00, the relative index of refraction does vary with pressure. Tables are given by Schott for $\Delta n/\Delta T$ for both relative index (sea level - 760.mmHg) and absolute index (vacuum -0.0 mm Hg). A typical table from the Scott Catalog is the following:

Temperature Coefficients of Refractive Index										
Range of temperature	$\frac{\Delta n}{\Delta t}$ relative $\times 10^{6}$ / °C					$\frac{\Delta n}{\Delta t}$ absolute $\times 10^{6}$ / °C				
[°C]	C'	d	e	F'	g	C'	d	e	F'	g
−40 to −20										
−20 to 0										
0 to +20	1.7	1.8	2.0	2.3	2.6	0.1	0.2	0.4	0.7	1.0
+20 to +40	1.7	1.8	2.0	2.3	2.6	0.2	0.3	0.5	0.9	1.2
+40 to +60	1.7	1.8	2.0	2.3	2.6	0.4	0.6	0.8	1.1	1.4
+60 to +80	1.7	1.8	2.0	2.3	2.6	0.5	0.6	0.8	1.1	1.5

For intermediate pressures the chosen values must be the designer's best estimate of the interpolated quantities.

The entries consist of one line from either of the above tables or the corresponding interpolated values.



CODE
Col. 1-6

A mnemonic code of three characters (DN_ or DR_) plus a three digit surface number. DN is used for absolute $\Delta n/\Delta t$'s, DR for relative $\Delta n/\Delta t$'s. As before the remaining three characters are the surface number if the VALUES are to apply only to the material following the designated surface. If the surface number is left blank the remaining information is applied as extensively as possible.

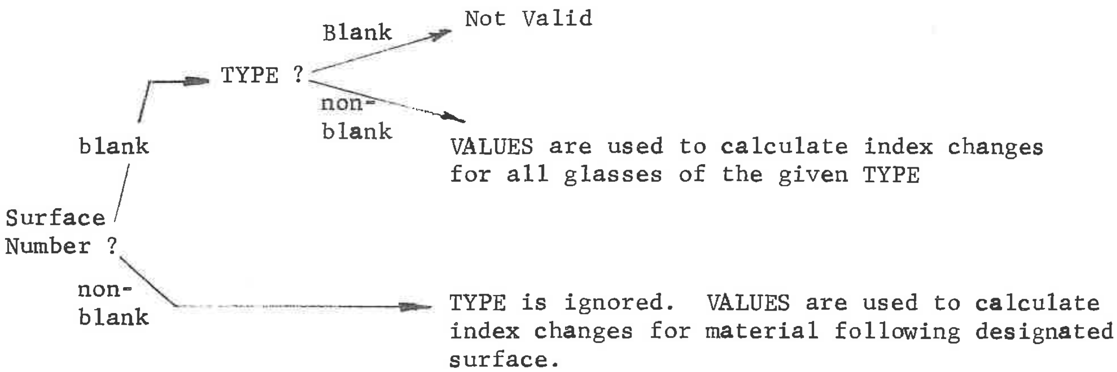
TYPE
Col. 11-18

A name of a recognized glass code. The VALUES are used to alter all representations of this glass type, if the surface number is blank. If a specific surface is designated, TYPE is ignored. If TYPE is blank, VALUES will be used only if the surface number is not blank.

VALUES
Col. 21-30
31-40
41-50
51-60
61-70
71-80

Values of $\Delta n/\Delta T$ for wavelengths corresponding to spectral lines C', d, e, F', g, or to the wavelengths defined by a WL card. These are entered at $10^6/°C$, as in the Schott catalog. Values for all specified wavelengths must be entered suitable to the temperature region being analysed. VALUES must be entered; blank entries are treated as zero values of $\Delta n/\Delta T$.

The following logic tree also shows the valid combinations:



Example 1

DN 620603 .4 .6 .8 1.1 1.4

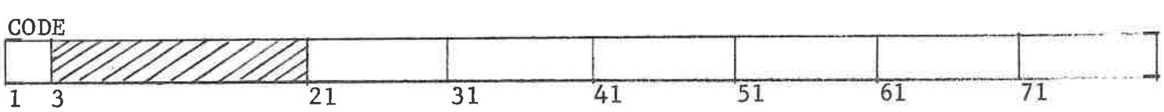
This indicates that all materials with glass code 620603 are to use the values X 10^{-6} as the value of $\Delta n/\Delta T$ for the wavelength at C', d, e, F', g, or the specified wavelengths respectively. (These happen to be the values taken from the absolute table for temperatures between 40° and 60° C.)

Example 2

DN 12 .4 .6 .8 1.1 1.4

This produces the same changes as Example 1 but just for the material following surface 12.

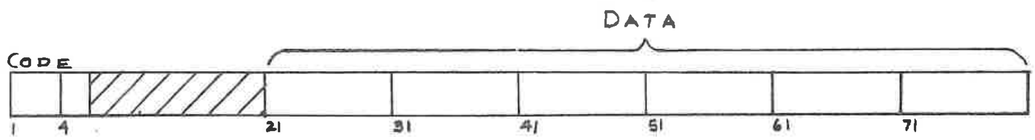
If it is desired to enter $\Delta n/\Delta t$ data at wavelengths other that the standard C', d, e, F', g, a WL card may be used to define the wavelengths for which the $\Delta n/\Delta t$ data is to be entered. After a WL card has been entered, all $\Delta n/\Delta t$ data is assumed to apply to the wavelengths on that card until another WL card is entered. The format of the WL card is:



CODE Col. 1-2	The mnemonic code, WL, designating this as a wavelength card. Wavelengths must be entered in descending order.
VALUES Col. 21-30 . . . 71-80	One to six wavelengths, in nanometers, for which $\Delta n/\Delta t$ information will be input.

E. Thermal Gradients

The effect of radial thermal gradients within a lens element is to change all surface shapes to some aspheric form and to introduce a variation of refractive index which is a function of the radial distance. The form of data is that which is most likely to result from a heat flow analysis, namely, temperature and radial distance for a number of zones in each element. This data is input on a pair of cards for each element.

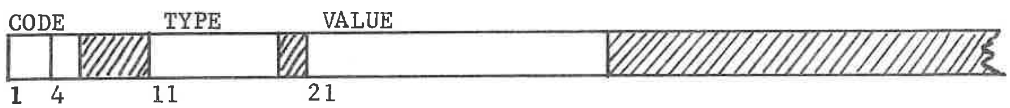


CODE (Col. 1-5)	DATA (Col. 21-30, ...,71-80)
GRR n	Values of distance from the axis for up to 6 zones in the material following surface n. If less than 6 zones are used the remainder are left blank. n is not optional. The letter M may be used, instead of a distance value. If M is used the distance to the mounting ring will be filled into that location.
GRT n	The corresponding values of temperature in °C for the same zones given in the GRR card. There must be a GRT card for each GRR card. The entries in both cards must be in order of increasing radius. If the first value of radius is non-zero, the first value of temperature will be used as the axial temperature as well. If M was not entered in the GRR card the mount radius and temperature will be used as an extra set of values. If M was used, the radius is entered, but the temperature will be the value in the corresponding GRT field; this frees it from having the same edge temperature as the mount.

The effects of axial gradients are not modelled; these can be simulated by breaking up existing elements into a series of thinner elements at different temperatures.

F. Pressure Gradients

Due to sealing of segments of an optical system, spaces within an optical system may have different pressures and therefore different refractive indices. The concept of relative refractive index then becomes more difficult to apply. For this reason, when pressure gradients are applied by the data cards described below, all indices are converted to absolute refractive indices for both glass and spaces.



CODE
Col. 1-6

A mnemonic code whose first three characters are PRE. The three remaining characters are the surface number if the pressure VALUE is to apply to just the space following the designated surface. If the surface number is left blank, the VALUE is applied to all spaces including the object and image spaces. A surface number entry of OBJ designates the object space.

TYPE
Col. 11-18

A name of a gas. This optional entry, starting in Col. 11, may be any of the following:

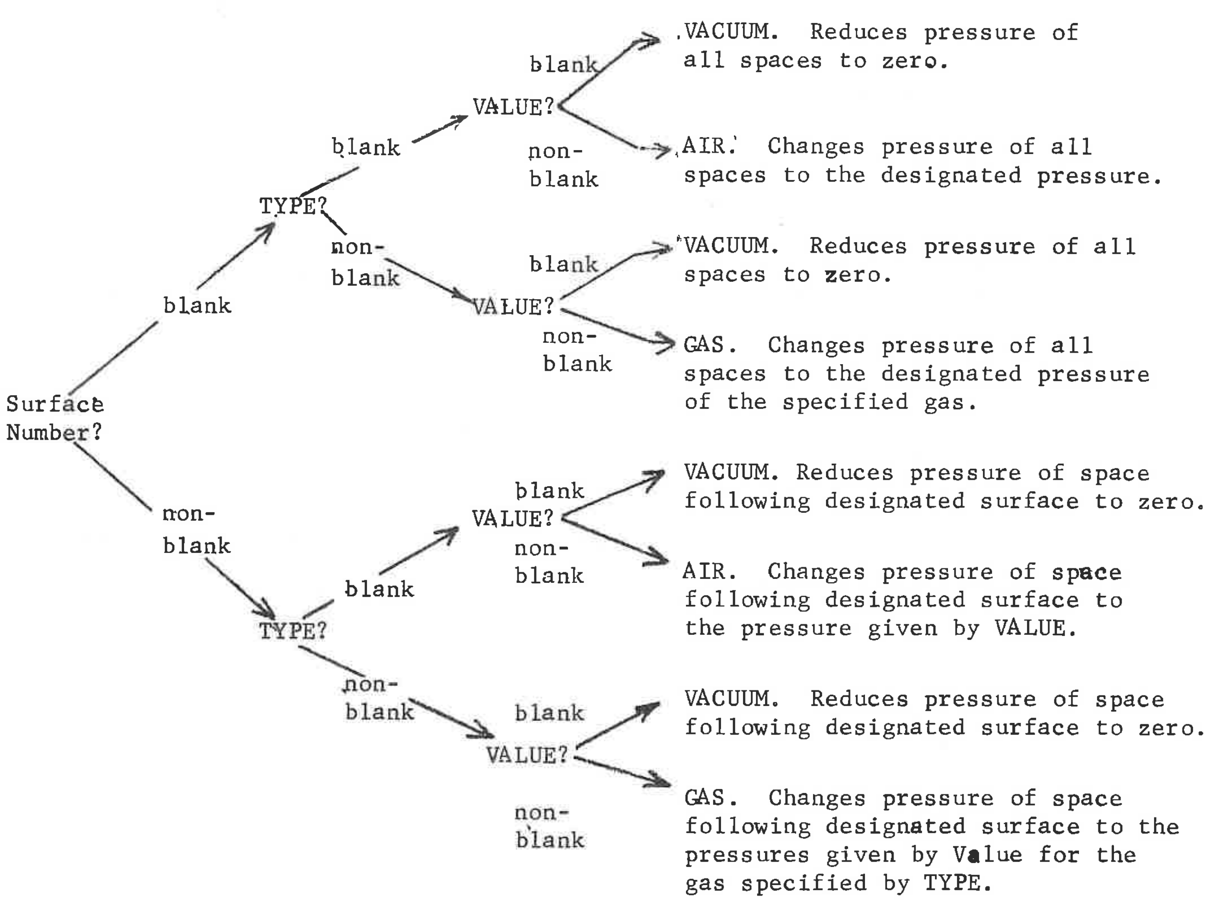
AIR
NITROG
OXYGEN
HYDROG
HELIUM
ARGON
METHAN
ETHANE

If left blank, the gas types will remain unmodified. AIR will be assumed, unless previously changed.

VALUE
Col. 21-40

The value of pressure for the space(s) designated in mm Hg. Thus sea level is 760.0. If left blank, pressure is zero (vacuum).

A logic tree shows the choices:



Example 1

PRE 10.
This indicates that pressure of all spaces is to be changed to 10mm Hg.

Example 2

PRE12 NITROGEN 760.0

This indicates that the space following surface 12 is to be filled with nitrogen at a pressure of 760 mm Hg.

Notes:

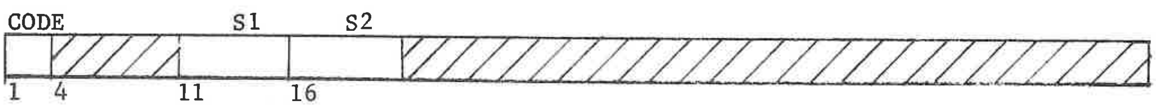
1. At all times information regarding steady state conditions (temperature, pressure, and gas) is retained. Thus it is possible to go from one steady state condition to another directly. However, if radial temperature gradients or pressure gradients have been employed, no history is retained of the sequences which led up to the input system; any new environmental changes therefore, should be made only to some previous system at steady state conditions. If this practice is not adhered to for gradient environments, results are unreliable.

2. The sequence of operations used by the program determines the required order of entry of data cards. Thermal type data cards record their values in a Thermal Environment Table in the order received; thus any given card can be overidden with a later card. Similarly, pressure type data is entered in a Pressure Environment Table and can be overridden with later cards.

All thermal changes are made first, then all pressure changes are made to the thermally modified system. Thus thermal data which is pressure-dependent ($\Delta n/\Delta T$) must be associated with the input pressure; no adiabatic pressure changes are assumed to occur as a result of temperature changes. Likewise, pressure data is associated with the output thermal environment; since none of the pressure data is thermally dependent, the user need not be concerned with this fact. No adiabatic temperature changes are assumed to occur from pressure changes.

G. Physical Structure

Because ENVIRONMENTAL CHANGE is concerned with the physical structure of a lens system rather than the optical structure, sometimes additional data is necessary to define physical characteristics. In particular, a clarification of whether two surfaces are cemented is occasionally necessary. Explicit identification of surfaces as being cemented (or not cemented) may be made with the following card:



CODE Col. 1-3	Mnemonic code, CEM meaning that the two surfaces designated are cemented.
S1 Col. 11-15 S2 Col. 16-20	The surface numbers of the two surfaces whose physical characteristics are being explicitly defined.

Most refracting systems do not require this type of explicit declaration. A case where clarification is needed is the following:

Surface Number	Curvature	Thickness	Glass
2	0.072	0.25	SK16
3	0.003	3.0	AIR
4	-0.076	-2.75	REFL
5	0.011	-0.25	BK7
6	0.003	0.25	REFL
7	0.011	2.0	AIR

In this case a mangin type secondary mirror is cemented to the back surface of a corrector element (surfaces 3 and 6 are cemented) and unless explicitly indicated, the program would not treat them as cemented. The data card for this case would be:

```
CEM    3     6
```

Function:

Analysis of the effects of environmental changes are extremely complicated. Changes, however, can be categorized as primary changes and induced changes. The primary changes are the dominant ones and are considered here. The induced changes are assumed to be less significant and are not included in the calculation.

Thermal Changes - All changes due to thermal effects are considered to arise from two sources. The first is the expansion of all materials, both glass and spacers; the second is the refractive index change with temperature.

Expansion of the elements is assumed to be uniform for the steady state case; expansion of the mounting rings is assumed to be uniform for the temperature given. Air spaces are adjusted so that contact of the mounting ring with the element is maintained as both expand. Refractive index changes are calculated from the five values fed in on the DN card. These are chosen by the designer from the values of $\Delta n/\Delta T$ given in the Schott catalog as being representative of the particular temperature and pressure.

For the case of radial thermal gradients, expansion is the integrated effect from center to edge of the element. The change of curve to an aspheric is assumed to be equally distributed in sag between both surfaces. The center thickness is that associated with the central temperature. The refractive indices are also those associated with the central temperature, but with a multiplicative function of the radial distance generated as well.

Reflective surfaces are assumed to expand according to the expansion coefficient of the substrate, entered on the EXG card. Expansion of cemented components is assumed to occur about either the central contact or the central element depending on whether the number of elements is even or odd, respectively. If elements warp due to differential expansion a warning message is printed out when any surfaces are changed by more than one wavelength; this seldom will be significant in itself but does indicate that some strain is introduced.

The induced changes not considered are:

1. Effects of stress - these can arise from differential expansion of cemented elements and compression of the outer barrel both radially and axially. The effects will be bi-refringence and shape changes.

2. Axial gradients - these can be simulated by breaking up existing elements into a series of thinner elements at different temperatures.

Pressure Changes - All changes in pressure are translated into refractive index changes. Standard procedure is to give in glass catalogs the index of refraction relative to air as 1.0. In reality air does not have this value of refractive index and this program converts all indices to absolute values immediately unless they have already been changed to absolute.

The induced changes not considered are:

1. Humidity changes

2. Strains in the glass due to pressure gradients.

3. Shape changes due to pressure gradients.

Output:

Page 1 - A printout of the input system for thermal change with expansion constants for all materials.

Page 2 - A printout of refractive indices and temperature coefficients before thermal change.

Page 3 - A printout of the system after thermal change, including curvature, thicknesses, semi-diameters and indices of refraction.

Error Conditions:

General

1. "NO SUCH ENVIRONMENTAL CODE (XXXXX)" - the first five characters on the card are not a recognizable input.

2. "THE REQUESTED SURFACE NUMBER DOES NOT APPLY FOR ENVIRONMENTAL CHANGE (XXXXX)" - surface number is less than 1 (not OBJ) or, greater than the number of the last surface preceding the focal plane.

Mounting Material

3. "A NON-EXISTENT MOUNTING RING MATERIAL HAS BEEN REQUESTED" - enter the VALUE instead.

4. "EXPANSION CONSTANT FOR MOUNTING MATERIAL FOR AIR SPACE nn ASSUMED EQUAL TO 210. -7" - no data was provided which altered the standard assumption of aluminum mount material.

5. "THE REQUESTED MOUNTING MATERIAL XXXXXXXX FOR AIR SPACE nn IS NOT IN THE CATALOG" - enter the VALUE instead.

6. " * ASSUMES ALUMINUM SPACERS (EX. COEFF. = 210. X 10-7/DEGREE C.)" - flags the data produced when problem of Error 4 occurs.

7. "**UNCHANGED DUE TO NON-EXISTENT OR NON-FUNCTIONAL DATA" - flags the data produced when problem of Error 5 occurs or when insufficient data is provided.

Semi-Diameters

8. "WARNING -THE SEMI-DIAMETER FOR AIR SPACE FOLLOWING SURFACE nn WAS TOO LARGE, THE THICKNESS WILL NOT BE CHANGED" -the semi-diameter specified was larger than the radius of one of the surfaces surrounding the air space.

9. "*** UNCHANGED DUE TO UNREALISTIC DATA (INPUT SEMI-DIAMETERS WERE TOO LARGE)" - flags the data produced when problem of Error 8 occurs.

Glass Changes

10. "THE REQUESTED GLASS TYPE (XXXXX) IS NOT IN THE CATALOG" - an entry depending upon the glass code for establishing the value of expansion coefficient has been made which does not correspond to an entry in the Schott glass catalog.

11. "THE REQUESTED GLASS TYPE (XXXXX) IS NOT USED FOR ANY ELEMENTS IN THE LENS SYSTEM" - a warning indicating that an expansion coefficient value has been assigned to a glass type that is not represented in the lens data.

12. "EXPANSION CONSTANT FOR SURFACE n TO BE DETERMINED FROM GLASS TYPE XXXXXXX CANNOT BE ENTERED AT THIS TIME AS THE NEW TEMPERATURE HAS NOT YET BEEN ENTERED" - the expansion coefficient which is temperature dependent, cannot be determined until the desired output temperature is obtained. Place TE card first.

13. "EXPANSION CONSTANT FOR SURFACE n ASSUMED EQUAL TO ZERO" - result of data too unsatisfactory or incomplete to come to any other conclusion.

14. "REFRACTION COEFFICIENTS FOR SURFACE n FOR GLASS TYPE XXXXXX ASSUMED EQUAL TO ZERO" - result of incomplete or unsatisfactory data.

15. "WARNING -A STRAIN HAS BEEN INTRODUCED BY CEMENTED SURFACE nn" - due to different expansion coefficients in the cemented glasses a warpage of one or more surfaces has occurred which amounts to more than one wavelength over the clear aperture.

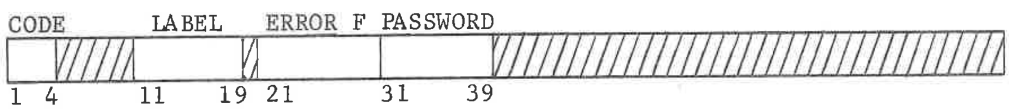
LENS & PROCEDURE LIBRARIES

Purpose:

Provides a means of storing the data for a number of lenses on a rapid access external storage device.

Input Data:

One or more data cards which designate the library operations to be performed should be placed after the Library option card. The format for these cards is:



CODE (Col. 1-4)	Mnemonic code designating the library operation to be performed. A list of the CODES and description of the operations is given below.
LABEL (Col. 11-19)	Mnemonic code assigned by the designer which serves as the identification for the lens in all library operations. If this field is left blank, a label is assigned from the title card.
ERROR F (Col. 21-30)	Error function (optional). This value, if entered, is used as the "condition" error function (rather than the library error function) in the conditional library options. If entered in a SAVE, REST, or REPL library option, it is substituted for the error function of the lens being saved or restored.
PASSWORD (Col. 31-39)	Optional mnemonic code assigned by the designer to provide security for his library lenses. This PASSWORD is never printed out; the designer <u>must</u> remember the PASSWORD he is using. Note that the PASSWORD acts as an extension of the LABEL in all library operations.

CODES	LIBRARY OPERATION
SAVE	Saves the data in the library under the LABEL & PASSWORD specified. If a LABEL is entered which already exists in the library, an alternate label is assigned so that the data is not lost.
RESTORE	Restore the data for lens (LABEL & PASSWORD) to memory.
REPLACE	Replaces the data for lens (LABEL & PASSWORD) with the data in memory; retains the same LABEL. If no lens with the specified LABEL is in the library, the lens is simply saved.
DELETE	Deletes the data for lens (LABEL & PASSWORD) from the library.
CRESTORE	Conditional restore; restores the data for lens (LABEL & PASSWORD) if that lens has a lower error function than the memory data.
CREPLACE	Conditional replace; replaces the data for lens (LABEL & PASSWORD) if the memory data has a lower error function than the library data. If ERROR F value is supplied, data will be saved if the memory data has a lower error function than ERROR F.
CUPDATE	Conditional update; compares the error function of lens (LABEL & PASSWORD) with that of the memory data - retains the system with the lowest error function both in the library and in memory. If ERROR F value is supplied, data will be saved if the memory data has a lower error function than ERROR F. Note: CUPD always results in either a system being saved or a system being restored.
CONDENSE	Condenses library. For operator use, only.
LIST DIRECTORY	Lists library directory. The word DIRECTORY starts in Col. 11. All directory entries stored under a given PASSWORD will be listed. The PASSWORD, however, will not be printed out.

Function:

The above described library operations are performed as called; note that a REPLACE operation is exactly equivalent to a DELETE and SAVE combination. In order to make efficient use of the disc space, the library is always condensed as required to leave maximum room for saving additional lens data.

The intent of this option is to provide a convenient means of storing intermediate forms of a lens design during the design process rather than to create a permanent, ever expanding lens design file. The conditional options involving comparison of the error function are primarily intended for use on unattended runs. Note that the error function must be supplied in a SAVE, REST, or REPL library option or be the result of an AUTOMATIC DESIGN option previously executed; an error function equal to zero will otherwise be entered.

Output:

The library data card is listed along with a message indicating the successful completion of the operations plus a printout of the system data. The data blocks used in save operations are listed so that remaining library space can be easily determined.

Error Conditions:

1. "DUPLICATE LENS LABEL (XXXXXXX) SPECIFIED IN SAVE OPERATION" - a warning that an alternate LABEL has been assigned.
2. "NO LENS WITH LABEL (XXXXXXX) IN LIBRARY - OPERATION TERMINATED" - can occur in any restore operation; correct and rerun.
3. "LIBRARY IS FILLED - SAVE OPERATION TERMINATED" - saving the lens data would over-flow the blocks available; some lenses will have to be deleted.
4. "LENS DIRECTORY IS FILLED - SAVE OPERATION TERMINATED" - some lenses will have to be deleted. It is unlikely that this message will occur.

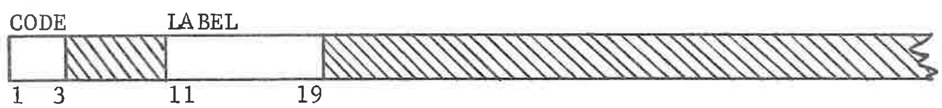
SEQUENCE

Purpose:

To provide access to sequences of option or data cards which are stored in a disc library; this is particularly useful when the same sequence of data cards are needed at several places within the run.

Input Data:

One or more optional data cards may be entered following the SEQUENCE option card. Also, an additional data field (Col. 11-19) on the option card itself is interpreted; the presence of data in that field is important as explained below. These cards (including the SEQUENCE option card) are punched in the following format:



CODE (Col. 1-3)	A mnemonic code which identifies the SEQUENCE option or sub-option. A list of these CODES is given below.
LABEL (Col. 11-19)	A nine character alphanumeric code which labels or identifies the sequence in the various SEQUENCE operations.

CODES

SEQUENCE	The option card; if this card contains an entry in the LABEL field, it acts as a call to the sequence stored on the disc with that label. The cards in that sequence are then inserted into the CODE V data input stream at that point. If the LABEL field is blank, the SEQUENCE card should be followed by any of the other sub-option cards as described below.

DEFINE — Define sequence; the cards following this card until the SEND card is read are saved in the sequence library under the label entered in the LABEL field. If there is a sequence already in the file under that label, it will be replaced.

SEND — Sequence end; this card is used to terminate the sequence being defined. The LABEL field is not used on this card.

DELETE — Delete sequence; the sequence referenced in the LABEL field is deleted from the sequence library.

LIST — List sequence, directory or library; the sequence referenced in the LABEL field will be listed (but will not be inserted into the data input stream). If the label field contains the word DIRECTORY, the directory of sequences stored will be listed. If the label field contains the word LIBRARY, all of the stored sequences will be listed.

CONDENSE — Condenses the sequence library; all blank entries due to previous deletions are eliminated.

Function:

Sequence of cards are saved on disc in a directoried library; when a particular sequence is called in a run, the cards are retrieved from the disc library and transferred to the input data stream. If the input cards are being put onto the disc via the LOAD option, all of the SEQUENCE processing is done at the time the LOAD is executed. This allows a SEQUENCE to be inserted at any point in the run and can contain any CODE V input cards. If the LOAD-EXECUTE cards are not used, a SEQUENCE must begin with a CODE V option and contain all of the input cards for that and any other options in the SEQUENCE.

Output:

Except for the LIST suboption, there is normally no direct output from this option.

Error Conditions:

1. "UNDEFINED SEQUENCE (LABEL) REQUESTED" - the requested sequence cannot be found in the sequence library.

2. "BLANK LABEL FIELD ON SEQUENCE SUB-OPTION CARD (XXX)" - the label field is blank on a sequence sub-option card which requires a non-blank label field.

3. "SEQUENCE LIBRARY IS FULL" - the size limits of sequences and/or data blocks would be exceeded if the current sequence were stored. Some sequences will have to be deleted before more are saved.

4. "A SEQUENCE CARD IS WITHIN A DEFINE SEQUENCE" - The SEQUENCE option card may not be used within a DEFINE sequence operation, i.e. sequences may not be nested.

5. "LOAD CARD OUT OF ORDER" - the LOAD option may not be used within a DEFINE sequence operation.

6. "EXECUTE CARD OUT OF ORDER" - the EXECUTE option may not be used within a DEFINE sequence operation.

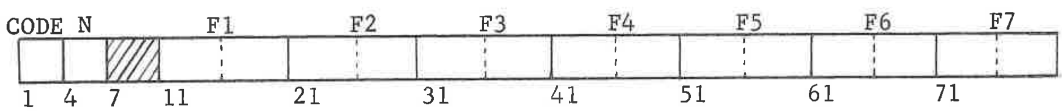
PRINT

Purpose:

To display selected data; to display the system data in single or double space format.

Input Data:

If no input requests are provided, the system data is printed in standard single space format. If any input request is made, this automatic output is deleted and only the requested output is provided; requests take the form:



CODE (Col. 1-3)	A mnemonic code which designates the nature of the print request.
N (Col. 4-6)	If present, identifies the surface number for which the value or values are to be printed.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	For entry of surface numbers (when ranges are needed), or for NO to delete the output for that zoom position.

CODES	OPERATION
DOU	Prints the standard system data with surface data double-spaced.
FGX (z) FGY (z)	Prints EFL of X (or Y) coordinate system which lies between the surfaces given in F1 · · · F7 (Ex: 5 in Col. 11 and 11 in Col. 16 would supply FGX for the portion of the system which includes Surf 5 to, and including, 11 for zoom position 1). N or NO entered in the field will inhibit printout for that position.

Output:

Prints the requested data.

OPTIMIZATION

AUTOMATIC DESIGN

Purpose:

To optimize the lens system while controlling the physical characteristics.

Introduction:

The objective of lens design is to generate a system which, with given requirements or constraints, is the best that can be achieved. Comparison of systems ultimately reduces the definition of "best" to a single overall figure of merit in the designer's mind which somehow includes both image quality and how well the constraints are met. Computer optimization of the lens in a similar manner is driven by numbers which are combined using suitable weightings into a single "error function" which becomes the computer's measure of "best". (See Appendix A for description of CODE V's error function.) The degree to which this definition of "best" agrees with the designer's definition influences how satisfactory the design will be. The standard set of weights provided by the program on aperture, field and wavelength will carry the design well through the initial stages. The detailed agreement with the designer's mental "figure of merit" can be achieved with fine tuning of the weights in a later stage.

Almost all lenses, in addition to the conditions of use defined in SPECIFICATION DATA and SOLVES, are subject to some constraints (such as EFL, image distance, edge thickness, etc.) on any changes that are to be made to the starting design. Some of these (such as EFL) typically are active throughout the design while others (such as edge thickness) need to be imposed only when they will be violated. The handling of constraints is part of the fine art of optimization techniques.

Optimization in CODE V is handled by damped least squares in a manner which leaves to the computer the choice of optimum damping factors and continuous modification of the internal structure of variables for optimum convergence. The designer is free then to concentrate his attention on the optical aspects of the problem. Constraints are imposed when needed by use of Lagrangian multipliers, as absolute requirements so that optimization proceeds within the subspace of acceptable lenses; normally, constraints are not included in the error function which then becomes a meaningful measure of image quality. (See the Preface for a discussion of the historical development of this program.)

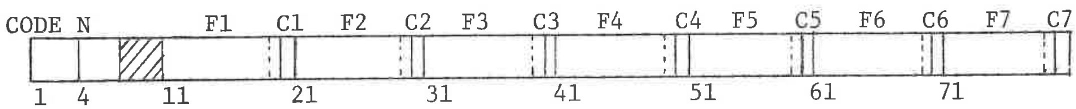
The computations in CODE V are based on real ray tracing. This avoids the limitations of aberration theory (such as third, fifth. . . . order) when dealing with high aperture and wide angle lenses. A major limitation of aberration theory is that, during the course of design, the targets are continuously moving as different balances become optimum; this is because specific aberrations are rarely a direct measure of performance. Another reason for the dependence on ray tracing is that decentered systems, unusual surface shapes, and variation of the aberrations with wavelength can be precisely modelled; the effects of vignetting and obscuration can be simulated more closely, as well.

Two separate sets of rays are used in AUTOMATIC DESIGN. The first is a set of reference rays, traced in the reference wavelength, which are the same bundle defining rays used throughout the program and which are defined in SPECIFICATION DATA. These include, for each off-axis field point in each zoom position, the chief ray (iterated to pass precisely through center of the flagged stop surface), the upper and lower (normally) meridional rays, and (for systems with X components in use or structure) left and right skew rays. For axial field points of rotationally symmetric systems with no X component of use, only the upper meridional ray is traced. Constraints can be imposed, among others, relative to this set of rays only. A record of those rays which are used in constraints is retained and only that set is traced in determining derivatives and improvements for that optimization cycle.

The second set of rays is only used in formation of the error function (described in more detail under Error Function Construction). The same set of rays is traced in each wavelength and field for which the wavelength and field weights are non-zero. The patterns are scaled down for vignetting and are never clipped by clear apertures in order to maintain a consistent definition of the error function in all derivatives and changes.

Input Data:

Optional data cards are used following the AUTOMATIC DESIGN option card to specify constraints on first order parameters, distortion, and physical form, etc., weights affecting the construction of the error function, and other control parameters. These cards are punched in the following format:



CODE	(Col. 1-3)	Mnemonic code identifying the values on the data card or requesting a particular sub-option of AUTOMATIC DESIGN. A list of CODES is given later.
N	(Col. 4-6)	Number used with some CODE's to specify a particular field position or surface.
F1 F7	(Col. 11-19) . . (Col. 71-79)	Data fields 1-7: used to enter the values required by the CODE. For a zoom system the values for a given zoom position are entered in the field corresponding to that position.
C1 C7	(Col. 20) . (Col. 80)	Control flag; used on some constraints to indicate how the constraint should be handled.

The codes are organized in four groups relating to constraints, sensitivity controls, error function construction and convergence controls. Some constraint entries allow or require a SUR or WLN card to immediately follow, providing one or two surface numbers or wavelength numbers for the constraint. The list of codes gives their associated entries; symbols shown after the code have the following meaning:

n or (n)	Entries may be designated as applying to a given field position or surface number. If the parentheses ( ) are present, entry is optional.
(z)	Entries may be made for each zoom position. Note: Like some SOLVES and unlike all other requests in CODE V, the absence of an entry for a constraint means that no constraint will be generated; presence of an entry generates a constraint. A 0.0 target is distinguished from a blank and generates the constraint. For a non-zoom system only, a blank also generates the constraint with a value of zero.

(C) A control flag may be used for this constraint and has the following meaning:

+, blank, or -: the constraint should remain greater than, equal to, or less than the specified value, respectively. Note that to control a constraint within a tolerance requires a request establishing an upper limit (- control flag) and a request establishing a lower limit (+ control flag).

1, 2, 3, 4, 5 or 6: the constraint is referenced to the value of the constraint in the zoom position specified by the integer; this must be a previous zoom position. Ex: With .1 as a value, 2 as the control, the designated constraint will be held to .1 greater than its value in zoom position 2.

±1, ±2, . . . ±6: using Col. 29, 39 . . . 79 for this sign, the constraint is referenced with a greater than, or less than interpretation for the + or - sign, respectively.

P: the constraint is never to be invoked but is to be included in the printed list with each cycle. This allows tracking and/or checking of critical items even though constraints may not be necessary.

(S) A SUR request is needed to supply the surface numbers. If parentheses ( ) are present, the SUR request is optional; defaults then apply.

(R) Two surface numbers may be entered on the SUR request associated with this constraint. If so, the value will be interpreted as the ratio of the constraint values on each of the surfaces: V1/V2.

(W) A WLN request is needed to supply the wavelength identifying numbers (1,2,...) to be used for this constraint. If parentheses () are present, the WLN request is optional; defaults then apply.

A. Constraints

The computer maintains the physical, first order, reference ray and distortion properties of the lens by constraints which are specified by the designer. These constraints, when active, are usually absolute conditions imposed on the solution and therefore can have a rather major effect on the rate and smoothness of convergence as well as the quality of the optimized lens. In general it is good practice to impose the fewest constraints possible, particularly in the early stages of a design. Never use a constraint that is already represented in a SOLVE.

It is also possible to define a range of acceptable values for a constraint by use of the + and - control flags. This does not imply any less absolute control when the constraints are invoked and should not be used with the idea that the lens is less constrained; it is less constrained than a single point only when neither of the two limit constraints is invoked. In particular, it is wise not to eat up a production tolerance on, say, EFL by imposing a range with two limiting values; use the nominal value as the design target instead.

It is sometimes desirable, when constraints are difficult to meet, to include them in the error function rather than requiring that they be solved absolutely. See discussion under WTC code for the use of this capability.

1. Constraints on Optical Definitions

EFL	(z)(C)		Effective focal length for infinity objects (regardless of actual object distance).
FGY	(z)(C)	S	Focal length of a group of surfaces; using the y, z plane system; the first and last surface in the group are specified on a SUR card.
FGX	(z)(C)	S	Same as FGY except it uses the system defined in the x, z plane.
TT	(z)(C)		Total track (distance from object to image). Should be specified only on finite conjugate systems.

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank, -, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request

IMD	(z)(C)		The paraxial image distance plus any defocusing.
IMC	(z)(C)		Image surface clearance; the clearance from the surface preceding the image surface to the image surface. Same as IMD except that the sags of the last surface and image surface are included. Note: Do not include both IMC and IMD in the same run.
RED	(z)(C)		Reduction ratio; the ratio of image to object size. This constraint should be employed only when RED is not included in the SOLVES.
U	(z)(C)	S	Paraxial angle u - marginal ray; controls the paraxial exit angle u (on-axis first order ray in y-z plane) to a specified value at a surface designated in the following SUR request.
INM	(z)(C)	S	Paraxial angle of incidence - marginal ray; controls to the value specified for the surface designated in the following SUR request. Appropriate values may be obtained from the paraxial trace in ANALYSIS; the equation for the angle of incidence is:

$$(ni)_s = n_s(u_s) + n_s Y_s c_s$$

where Y_s, u_s are the paraxial trace values
n_s is the index following the surface
c_s is the curvature of the surface
$(ni)_s$ is the current value of incidence angle to be constrained and is the same value before and after refraction.

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank, -, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request

HNR n (z)(C) S — Narcissus control; the paraxial blur circle radius described in NARCISSUS ANALYSIS (clipping on forward path only). Three surface numbers must be supplied on this and the following SUR request:

- n - the reflecting surface number
- N1 - the clipping surface number
- N2 - the cold stop surface number

N1, N2 are the entries in the SUR request for that zoom position. The clipping surface clear radius is always determined from the largest value required to pass all control rays for that zoom position only; this may require running NARCISSUS ANALYSIS in a de-zoomed mode to determine the current value, from which the target blur radius may be determined. Values of + or - are equally valid.

ENP (n)(z)(C) — Entrance pupil distance; measured from the first surface to the entrance pupil (a positive number when the entrance pupil is to the right of the first surface). Controls the entrance pupil distance for field position n; if n is 0 or blank, the paraxial value is controlled.

EXP (n)(z)(C) — Exit pupil distance; measured from the exit pupil to the image plane (a positive number when the exit pupil is to the left of the image plane). Controls the exit pupil distance for field position n; if n is 0 or blank, the paraxial value is controlled.

X n (z)(C) — Chief ray image height (X) for field position n.

Y n (z)(C) — Chief ray image height (Y) for field position n.

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank, -, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request

DSX n (z)(C) — Distortion in X direction for field position n, expressed as a decimal fraction; thus -5% distortion is entered as -.05.

DSY n (z)(C) — Distortion in Y direction for field position n, expressed as a decimal fraction, as for DSX.

XFO n (z)(C) — X-fan focus (close skew ray) relative to paraxial image surface (as plotted in FIELD option). For rotationally symmetric systems, this is the sagittal image surface. This constraint should only be applied to off-axis images.

YFO n (z)(C) — Y-fan focus (close skew ray) relative to paraxial image surface (as plotted in FIELD option). For rotationally symmetric systems, this is the tangential image surface. This constraint should only be applied to off-axis images.

2. Constraints on Primary Aberrations

Although image quality is best represented in the error function, there are some primary aberrations which can be controlled through constraints in a manner such that computing time can be reduced without serious loss of information during many of the design stages.

Petzval Sum

PTZ (z)(C) — Curvature of the Petzval surface for the reference wavelength, as given in ANALYSIS.

This constraint may be used judiciously, with or without XFO and YFO constraints, to control field performance with fewer field angles.

Chromatic Aberrations

AX (z)(C)(W) — Primary transverse axial color, as defined in ANALYSIS. The wavelength identifying numbers are given in the WLN request following; if no WLN request is included, the first and last wavelength numbers are supplied, giving the same value as ANALYSIS.

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank,-, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request
(W) Wavelength numbers are implied or defined by WLN request

LAT (z)(C)(W) Primary lateral color, as defined in ANALYSIS. The wavelength identifying numbers are given in the WLN request following; if no WLN request is included, the first and last wavelength numbers are supplied. The field height used is the Y component of the last field position, or 1.0 if no off-axis field positions exist; these defaults match those for ANALYSIS if no X component is present in the last field position.

These constraints should be used with color weights (WTW) which eliminate the tracing of rays in the error function formulation for the corresponding wavelengths in order to achieve reduced computing time.

WLN Wavelength identifying numbers for the AX and LAT constraints. These are integers which are entered two per data field corresponding to columns (11-15 , 16-20), (21-25,26-30),...etc.

The wavelengths are counted in order; thus if 5 wavelengths were specified, with 3 as the reference wavelength,

```
WLN   1   5
```

corresponds to the defaults defined above and used in ANALYSIS. If the order is reversed, the value of the constrained aberration will be reversed in sign.

The form of these chromatic aberrations allow independent control of secondary spectrum and secondary lateral color. In the example above

```
AX    ------
WLN   1   3
AX    ------
WLN   3   5
```

would exercise control over secondary spectrum and primary axial color together. It is easy to over-constrain the system (unless WTC requests are included) by including more constraints than are needed. For example, adding

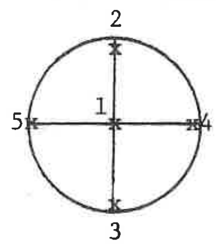
```
AX    ------
WLN   1   5
```

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank,-, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request
(W) Wavelength numbers are implied or defined by WLN request

to the above two constraints provides a third constraint which is only a linear combination of the other two and, thus, the solution will blow up.

3. Constraints on Reference Rays

Reference rays (bundle defining rays) are defined by SPECIFICATION DATA with the aperture and field specification and vignetting values. The chief ray is one of them and is used in some of the optical definitions above; likewise, all of the reference rays for a given zoom position affect the clear aperture and/or edge thickness and thereby influence constraints using these quantities. In addition it is sometimes desirable to control directly the penetration point of such a ray on a given surface. The controls are the X, Y coordinates of the ray on the surface. The rays are designated by number and represent the order implicitly defined by SPECIFICATION DATA:



Ray 1 - Chief Ray

Ray 2 - "Upper" meridional ray (using VUY)

Ray 3 - "Lower" meridional ray (using VLY)

Ray 4 - +X skew ray (using VUX)

Ray 5 - -X skew ray (using VLX)

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank,-, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request

On-axis field points of rotationally symmetric systems generate only Ray 2; Rays 4 and 5 are generated only if VUX and VLX are used or if system or use are bilaterally unsymmetric. Do not request constraints on non-existent rays. The ray designation is contained in the CODE as follows:

X1	n (z)(C)S(R)	Constraint on X coordinate of Ray 1 intersecting surface given in SUR request.
Y1	n (z)(C)S(R)	Constraint on Y coordinate of Ray 1 intersecting surface given in SUR request.
X2	n (z)(C)S(R)	Same for Ray 2
Y2	n (z)(C)S(R)	
.		
.		
.		
X5	n (z)(C)S(R)	Same for Ray 5
Y5	n (z)(C)S(R)	

Entry of the value in the proper column designates the zoom position, as always; n is the field point. A SUR request must immediately follow each constraint with one or two surface numbers specified per zoom position. If one surface number is entered, the value on the ray constraint entry is interpreted as the coordinate for the intersection of the ray with the surface. If two surface numbers are given on the SUR request, the value is treated as the ratio of the coordinate on the first named surface to that on the second (first/second); the surface numbers need not be in ascending order. Example: In a Gregorian telescope an obscuration of 50% could be controlled by:

```
Y2  1    -.5
SUR      2      1
```

If n is left blank, it defaults to the last field position for all ray controls.

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank, -, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request

4. Constraints on Mechanical Structure, Cost and Variables:

There are both general and specific controls for thicknesses, general controls for glass variables, and specific controls for other useful quantities.

Specific Controls

RAX	(z)(C)S(R)	Radius control (X meridian)
RAY	(z)(C)S(R)	Radius control (Y meridian)
		These are useful in limiting the range of variables and in experimenting with test plates. RAX will use RAY if the surface is rotationally symmetric. One or two surfaces are designated by the SUR request.
CT	(z)(C)S(R)	Center thickness
ET	(z)(C)S	Edge thickness
		These controls allow an override of the general thickness controls for the specified surfaces. These center and edge thickness controls must be followed by a SUR request designating the surface to which they apply. If either or both a CT or ET control is entered for a given surface, none of the general controls, MXT, MNT, MNE, or MAE will apply to that surface.
OAL	(z)(C)(S)	Overall length between any two surfaces. SUR request immediately following with both surfaces entered per zoom position, specifies the desired surfaces; the defaults are 1 and I-1.

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank, -, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request

SD (z)(C)S Semi-diameter; controls the semi-diameter at the surface designated on a SUR card. It is best not to enter semi-diameter constraints on any more surfaces than is absolutely necessary; this is due to the fact that the program constrains a violated semi-diameter back to the specified value exactly, and if, for example, two adjacent surfaces are controlled, both are likely to be violated simultaneously. Usually it will be very difficult for the system to solve for clear apertures exactly matching both surfaces. It is best, also, to use ray controls (Y2, Y3, etc.) instead of SD near points where bundle defining rays cross to avoid the oscillations which will occur in picking up the worst violation at the start of each cycle.

BLO (z)(C)S Blocker control; provides control over the number of elements on a blocker in manufacturing for the surface designated in the SUR card following. The value specified is

$$\frac{H}{R} = \sin B'$$

where H is the clear semi-diameter
R is the radius of the surface

Sin B' is related to the values of sin B discussed in Warren Smith, "Modern Optical Engineering", McGraw-Hill, p. 408-410. Tabulated values (courtesy of Warren Smith) are:

No. per tool	Maximum Sin B
2	.707
3	.655
4	.577
5	.507
6	.500
7	.447
8	.398
9	.383
10	.369
15	.309
20	.266
25	.242
35	.204
45	.181

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank, -, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request

Since sin B' does not include stock for mounting, centering or gaps on the tool due to edge thickness, the value of sin B in the table above must be reduced to account for these in arriving at the entered target value for the constraint. For both convex and concave surfaces, obtain the sin B' value by reducing the sin B value by the ratio of blank diameter to clear aperture. For convex surfaces, reduce this further by the ratio of

$$1 - \frac{t}{R}$$

where t is the edge thickness of the blank after grinding the surface. Since this constraint is usually employed only in the later stages of design, sufficient data is in hand to make these judgements. The option COST FACTORS gives values of sin B' for the current system.

General Controls

These apply to classes of variables - glass or thickness (unless overridden with CT and ET constraints on given surfaces). Usually the general controls on thickness are satisfactory unless the elements differ widely in diameter.

MXT	The maximum allowable center thickness of an element (any space with index not equal to 1.0); the default value is 100.00.
MNT	The minimum allowable center thickness of an element; the default is 0.0.
MNAIR	The minimum allowable axial air space; the default is 0.0.
MNEDGE	The minimum allowable edge thickness of an element, measured as the projection of the extreme ray onto the axis; the default is 0.0.
MAEDGE	The minimum allowable airspace at the edge of the airspace, measured as the projection of the extreme ray onto the axis; the default is .0001.

On positive elements MXT may be so small that the resulting edge thicknesses would occasionally violate MNE, as well; in such a situation MNE is invoked and MXT is ignored, preserving the edge thickness without artificially weakening the power of the element. This provides a useful device to generate minimum thickness elements by choosing a small MXT.

If the thickness is frozen these general controls are ignored, allowing negative edges and not restricting power; use the ET constraint if such control is desired.

GLASS

Glass map boundaries; glasses which are allowed to vary are restricted to a region of the n_d versus $n_F - n_C$ map (see illustration) which is bounded by a convex polygon of 3 to 5 sides. This polygon is defined by specifying, in clockwise order, glasses at the corner points; six digit codes (602603) or, as in the surface data cards, with a decimal separator (620.603), should be entered in data fields 1-5. The default polygon is a trapezoid with corners at 487704, 620603, 744448, and 755276. This selection eliminates most of the more expensive glass types from the region. Note that the corner points correspond to real glass types; this is not necessary but is convenient because often the glasses move to the corners and thus the replacement with real glasses becomes simpler.

SUR (z)

Surfaces required by several types of constraints. These are integers which are entered one or two per data field in columns (11-15, 16-20), (21-25, 26-30) . . . etc. If one per zoom position is required, it is entered in the first of the pair. The surfaces are counted as:

O	Object surface (letter O)
0	Entrance pupil surface (number 0) - not represented in surface deck, but may be referred to in this specification.
1	First optical surface
.	
.	
.	
I-1	Last optical surface (real or imaginary)
I	Image surface (including defocussing)

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank, -, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request

Constraints in Error Function

WTC (z) This card flags the previous constraint as one to be included in the error function instead of solved absolutely. Each field corresponds to the zoom position of the constraint to be included. A non-zero weight causes the corresponding constraint error to be included in the error function, while a zero or blank causes the corresponding constraint to be included absolutely. A low weight, about .01, will allow rather wide excursions from the target, while a value of 1.0 will keep it quite close. For close control, it is preferable to allow the constraint to be handled absolutely rather than by the WTC card. The WTC values can be applied to any constraint in the list which is marked with a (C); it is not applicable to the general controls on glass and thickness.

WTC should never be applied to two constraints bracketing the desired value; the run will be terminated. Use the central value without a + or - control flag. Use of WTC even with a single one-sided constraint (employing a + or - control flag) is not recommended; it may lead to erratic convergence.

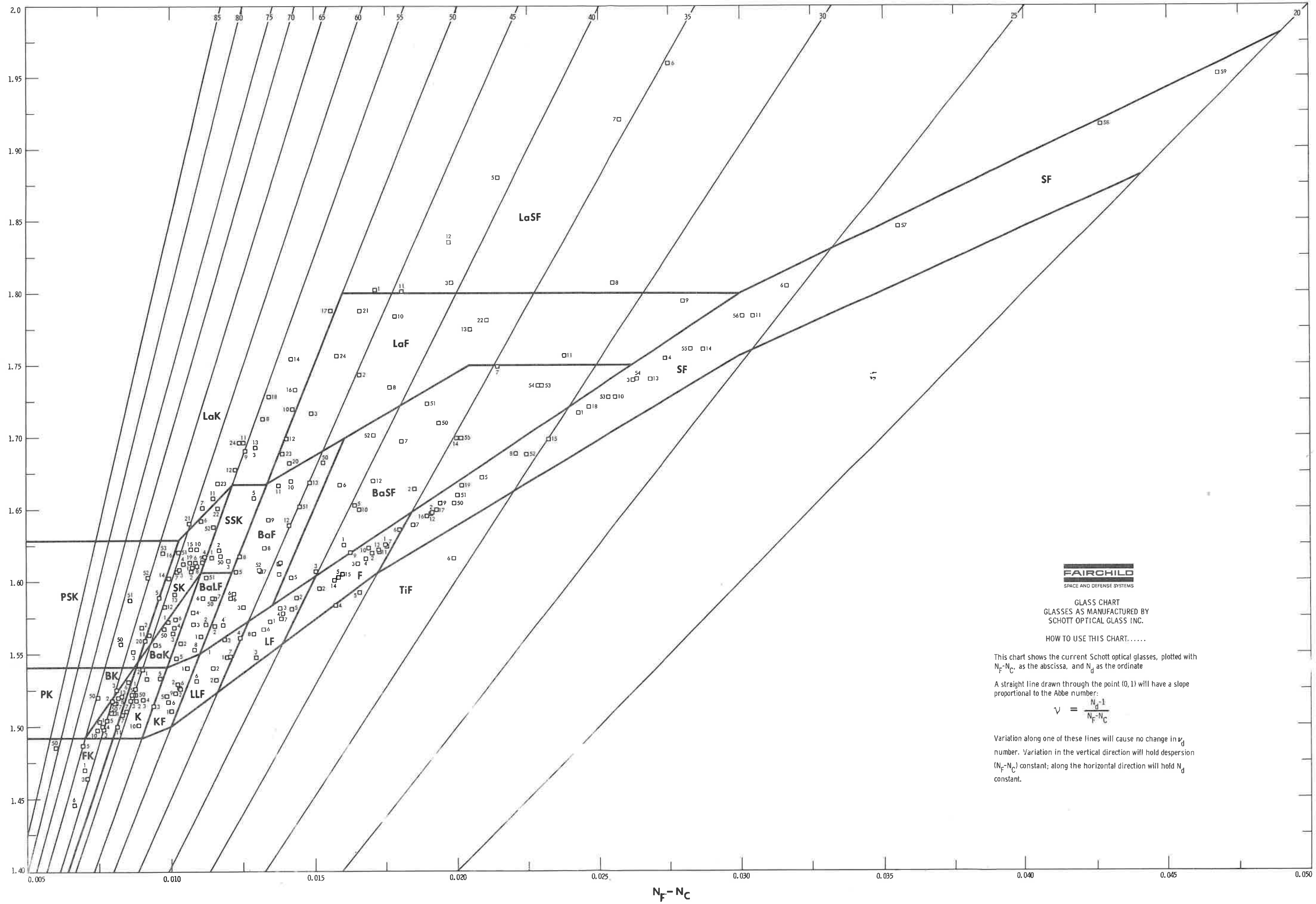
Notes:

1. Distortion is calculated from the standard formula:

$$\text{Dist} = \frac{h_{actual} - h_{target}}{h_{target}}$$

2. Conflicting constraints can be generated. For example, specifying DSX 3 or X 3 on a centered system is redundant since there can be no other value of X than 0. Specifying DSY 3, Y 3 is redundant if EFL is also specified. Specifying OAL over a group of surfaces in which the thicknesses are all frozen, constrained, or controlled by other OAL constraints is redundant. Redundant constraints guarantee failure of the convergence process.

(n) Field or surface designation
(z) Zoomable Entry
(C) Control flag (+,blank, -, prior zoom position, or P) required
(S) Surfaces are implied or defined by SUR request
(R) Ratio capability on SUR request


PSK
PK
FK
BK
K
KF
BaK
SK
BaLF
LLF
SSK
LaK
BaF
LF
F
LaF
BaSF
TiF
LaSF
SF
$N_F - N_C$
FAIRCHILD
SPACE AND DEFENSE SYSTEMS
GLASS CHART
GLASSES AS MANUFACTURED BY
SCHOTT OPTICAL GLASS INC.
HOW TO USE THIS CHART......
This chart shows the current Schott optical glasses, plotted with N_F-N_C, as the abscissa, and N_d as the ordinate
A straight line drawn through the point (0, 1) will have a slope proportional to the Abbe number:
$$\nu = \frac{N_d - 1}{N_F - N_C}$$
Variation along one of these lines will cause no change in ν_d number. Variation in the vertical direction will hold despersion (N_F-N_C) constant; along the horizontal direction will hold N_d constant.

B. Sensitivity Controls

Lenses can be designed which are very sensitive to fabrication errors. It can become important to reduce the sensitivity of the design to these errors, especially for lenses which are to be produced in quantity by methods designed to lower costs.

The quantity used here is the sensitivity to tilting of the optical surface (see H H. Hopkins and H.J. Tiziani, Brit. J. Appl. Phys., 17, 33 (1966) and D.S. Grey, Appl. Optics, 9,523, (1970)). This technique only calculates the tendency to introduce decentered (axial) coma but, for most systems, will adequately represent the sensitivity to decentering over the field. The value printed out is the square root of the variance of the wavefront produced by a radian angular tilt of the surface, measured in the system units. Real tilts are, of course, much smaller and the values may be scaled down by the angle in radians. Thus to convert to waves of aberration

$$W_{RMS} = \frac{\alpha \cdot V}{\lambda}$$

where
- α is the angle in radians
- V is the printed out value of the square root of the variance
- λ is the wavelength in system units

If it is desirable to change the interpretation from tilt sensitivity to displacement sensitivity, multiply each value by the curvature of the surface. Thus the displacement sensitivity is

$$W_{RMS} = d \cdot \rho \cdot \frac{V}{\lambda}$$

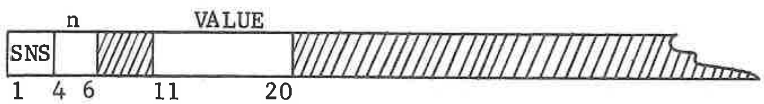
where
- d is the displacement in system units
- ρ is the curvature of the surface

In AUTOMATIC DESIGN, these sensitivity values are derived only from the reference rays and are suitable as constraints to limit or reduce sensitivities. They are unsuited for detailed tolerancing except in the roughest sense; use the tolerance programs of CODE V for this.

If, due to symmetries that exist in the system, not all referency rays have been generated, the use of the SNS request will generate them for use only in this option.

In the computer program, all unused data storage is used for storage of these sensitivity calculations. Thus, for a large system, fewer surfaces can be analysed for sensitivity. The program is set up to include as many sensitivity requests as is possible in the order entered. It will accept requests for analysis until there is no more room.

The code used for all requests is:



<u>SNS</u> (n) — Sensitivity of surface n. n is optional; the VALUE in the first field (Col. 11-20) is also optional. Absence of the VALUE is a request for analysis only; presence of the VALUE is a request for analysis and constraint to the VALUE specified. Absence of n is a request to have the process apply to all surfaces; presence of n restricts it to that surface only. Thus

SNS

is a request for analysis of all refracting and reflecting surfaces. Also,

SNS 6 .01

is a request for constraining the sensitivity value to .01 on surface 6.

Up to 100 requests can be accepted. As with other constraints, it is unwise to apply too many restrictions on the design or to ask for extreme changes in the sensitivity.

C. Error Function Construction

The computer "sees" lens quality in terms of a single number (called the error function) which is a composite of all the image errors, appropriately weighted. The degree to which an experienced lens designer will agree with the quality criterion of the computer for a given design depends upon the set of weightings chosen. Fortunately for most designs the choice is neither very delicate nor very difficult with the approach embodied in this program; all weightings have been expressed such that control is provided over the choice of resolving power vs. contrast, central quality vs. quality at the edge of the field, the relative importance of the various wavelengths, and the relative emphasis on sagittal vs. tangential components.

See Appendix A for the composition of the CODE V error function.

Weights:

WTW (z) — Weight on wavelength; these are single digit integer weights entered as consecutive integers in the order from red to blue - long wavelength to short. They are entered corresponding to zoom position in columns 11-17, 21-27, etc. Any value from 0 to 9 may be used for each weight with greater attention paid to the images in those wavelengths with larger weights. The default weights are the system weights for each wavelength, as determined by DATA option.

WTA (z) — Weight on aperture; this value controls the relative attention paid to the central portion of each bundle relative to the edge of the bundle and therefore has a rather direct relationship to the relative attention paid to resolution and contrast. Typical values are:

0.0 Very high contrast, low resolution.
0.5 High contrast, good resolution.
1.0 Good contrast, high resolution.
1.5 Low contrast, very high resolution.

The default value is .5.

(z) Zoomable entry.

WTX	(n)(z)	Weight on the x components (sagittal), y components (tangential), or both components, respectively, of the aberrations. The default values are:
WTY	(n)(z)	
WTF	(n)(z)	

WTX 1 = 1.0	WTY 1 = 1.0
WTX 2 = .875	WTY 2 = .875
WTX 3 = .5	WTY 3 = .5
WTX 4 = .3	WTY 4 = .3
WTX 5 = .1	WTY 5 = .1

If both x and y components are to have equal weights at each field angle, they can be most conveniently entered with WTF. If different emphasis is to occur at any field angle, use WTX and WTY.

If n (field position) is included, the entries apply only to field position n and the columns correspond to the zoom positions. If n is omitted, the values are interpreted as weights on all field positions of the first zoom position.

The default weights are satisfactory for many applications; however, they may be altered in the "fine tuning" stage of design. Vignetting scales down the portion of the ray grid pattern to which it applies; this usually includes only those rays that would normally pass all real apertures. In cases, however, of highly unbalanced vignetting, rays may be included which will be clipped by real apertures; these may need to be de-emphasized by skew vignetting or down-weighting.

Ray Controls:

OBS (z) — Fractional radius of the entrance pupil through which rays are deleted. Example: value of .5 would eliminate rays through the central one-half of the entrance pupil.

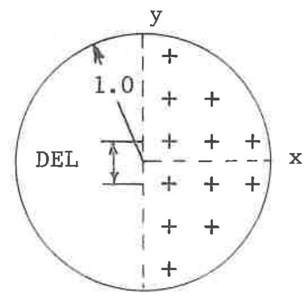
DEL (z) — The interval between rays of the spot diagram array in the normalized entrance pupil. It determines the number of rays used by the computer to evaluate the image quality.

The number of rays per field position per wavelength in the half-pupil considered is as follows:

(z) Zoomable entry.

DELH	No. of Rays
1.414213-.632456	2
.632455-.471405	6
.471404-.392233	8
.392232-.342998	12
.342997-.282843	16
.282842-.262613	22
.262612-.232496	26
.232495-.220864	30
.220863-.210819	34
⋮	⋮
-.1054	152

Ray Pattern



If left blank, the value used is .385 which provides 12 rays. This is suitable for most systems except those with aspheric surfaces; these sometimes require more rays to insure that the aspheric coefficients do not introduce a systematic ripple to the wavefront.

MER (z) — Meridional optimization only: all x pupil components in the ray apttern described above are made zero and redundant rays are eliminated. (This reduces the normal 12 ray pattern to 6 rays lying in the meridional plane). Note that this makes the aperture a meridional slit. Entry of NO for any zoom position suppresses the request for that position.

SAG (z) — Sagittal optimization only; all y pupil components in the ray pattern described above are made zero and redundant rays are eliminated. (This reduces the normal 12 ray pattern to 6 rays lying in the skew plane). Note that this makes the aperture a sagittal slit. Entry of NO for any zoom position suppresses the request for that position.

SAP (z) — Square aperture flag; the ray pattern is extended out to fill a square entrance pupil (or rectangular if vignetting is present). This would include a total of 6 extra rays for the default DEL value, more than normally will be needed. Entry of NO for any zoom position suppresses the request for that position.

(z) Zoomable entry.

D. Convergence Controls

DER — Derivative increment multiplier; entered in data field F1. On some systems, the derivative increments established initially and during the run by the program need to be modified for best results. For example, on some IR systems with high index materials and field lenses, a DER value of .01 or .001 has yielded smoother convergence. The default value is 1.0.

ROUGH — Inclusion of this request causes the program to solve only the constraints on the first cycles until the system has the constraints well satisfied; no aberrational effects are included and therefore no error functions are generated. After these "rough-in" cycles, the normal optimization follows. This feature is usually helpful on systems that have not been previously optimized and which may have constraint values which are far from their targets.

Exit Conditions :

MXCYCLE — Maximum number of cycles permitted; entered in data field F1. The default value is 25. If 0 or blank is entered, the error function will be evaluated and exit will occur with no change in the optical system.

MNCYCLE — Minimum number of cycles permitted; entered in data field F1. The default value is 2, which generally is sufficient to achieve stable optimization.

TIME — Number of CPU minutes after which exit will occur on the next completion of a cycle. Any value, including fractions of a minute, may be entered. This may be coordinated with overall job control time limits in order to ensure that there is an orderly transition and storage of results before the run is terminated by the operating system. No default is supplied or imposed.

TARGET — Value of the error function below which further computation is not desired. Exit will occur on the first completed cycle with the error function below this value; the default is 0.0, which makes this exit condition inactive.

IMP — Improvement percentage; entered as a decimal fraction in data field F1. This number is used as an exit criterion, allowing approximately three cycles which have error function improvements less than the IMP percentage before exit occurs. The default value is .05.

Normal operation only uses MXC, MNC, and IMP all of which are set by defaults unless over-ridden. TIME and TARGET allow additional flexibility.

Exiting is done according to the following hierarchy:

1. Exit if starting system cannot be traced at any aperture and field down to half of the requested values.

2. Exit with first error function if MXC=0.

3. Exit on any cycle that irretrievably produces an untraceable system (IRRECOVERABLE CONDITION).

4. If starting system had to be reduced in aperture and field, exit if aperture and field can't be restored in a reasonable number of tries.

5. Exit on first cycle beyond TIME limit, regardless of following conditions.

6. Continue if cycle number is less than MNC, regardless of following conditions.

7. Exit if error function is less than TARGET, regardless of following conditions.

8. Exit if cycle number is equal to MXC, regardless of following conditions.

9. Exit if "little" progress is being made - several cycles of less than IMP now or earlier.

10. Exit if convergence is unstable (UNSTABLE CONDITION).

On CODE V in-house computer systems run by the user, exit may also be triggered by a switch at will. Exit will occur almost immediately with the optical system of the last complete cycle provided the current cycle is still in the process of developing derivatives.

Function

The option AUTOMATIC DESIGN, using the variables available to it, will optimize a system subject to the constraints specified. The operations, in outline form are as follows:

A. Data Checking

Analyzes the constraint controls and the freezings and couplings on the surface data cards for consistency and completeness. If any errors are found, error messages (see below) will be printed.

B. Construction of Variables

Composite variables are formed from the allowed parameters; for example, bendings of elements and air spaces are generally used instead of individual curvature changes. Any couplings of variables are taken into account here as well.

C. Optimization of Poor Initial Systems

It is desirable to be able to construct any reasonable form of design without reference to any previous data; however, this can often lead to total internal reflection or to having rays miss the surfaces. Most programs give up at this point, but in CODE V the computer performs as many optimization cycles at reduced aperture and field height as are necessary to produce a system which can be run at full aperture and field height. There are safeguards, however, against this being done with excessively bad data.

This phase is most useful when "concocting" a new design but if the initial system can pass the required ray bundles, this phase is skipped.

D. Optimization Cycles

The lens system undergoes a ray tracing analysis at the specified field heights and wavelengths and an evaluation of constraints to determine the work which the computer must do during the optimization cycle. The result is a composite measure of image defects called the error function (which is to be reduced) and a tabulation of the constraints which must be corrected.

Then, with a process called the damped least squares method, the error function is reduced (usually by several orders of magnitude in the early cycles) to as low a value as possible: this is done by using an optimum amount of damping, chosen by the machine; then a new cycle is begun.

As long as the machine is making good progress the process continues; however, if improvements of less than IMP (5% unless changed) are made the computer will be increasingly cautious of continuing. After a few such cycles it will quit unless the rate of improvement picks up (or unless a minimum number of cycles has been designated).

Throughout the cycles, constraints are brought under control when they are found to be violated, are held under control for two cycles and until the program indicates that on release they will move in a direction away from the boundary. The program will exit only when violated constraints are under control.

Output

The normal output of AUTOMATIC DESIGN is shown in Table I. First is a tabulation of constraints, error function construction parameters, and controls including the default values set up by the computer. Following this is the total number of variables used and a time estimate of the number of minutes required by each major cycle. Then each cycle has the following output:

a. Cycle number.

b. Error function - The first value is the composite value, scaled so that it is the mean square of the weighted image radius x 10^{-6}. A pair of lines for each zoom position give the x and y components of the error function (in the same scale) for each of the field angles but with the WTX, WTY and zoom position relative weights removed. Thus the square root of these error functions approximates the RMS spot half-widths in thousandths of an inch (or other scale system) and enables the designer to have an idea of the relative quality level achieved even though the weights are varied from run to run.

   If some constraints are included in the error function by use of the WTC card, the constraint contributions appear as part of the composite error function; in addition, the constraint part of the error function is printed separately. The remaining values are unchanged.

c. Abbreviated system data -- curvatures, thicknesses, glass types, aspheric constants (if any), plus sensitivity values (if requested).

d. For each zoom position, EFL, TT, PIM (paraxial image distance), OAL (first surface to surface ahead of focal surface), entrance pupil, exit pupil, and reduction ratio.

e. Values of potential specific constraints -- a number, usually the present direct value of the constrained quantity. Exceptions to this are the following:

   Ratios (R) - The ratio is printed.

   Referenced constraints - When constraints are relative to the same constraint in an earlier zoom position, it is the value which is printed, not the difference. The referenced value (internally generated) is also printed.

f. Listing of controlled constraints -- these are the constraints currently active. Below each one is printed a count of the minimum number of cycles over which the constraint will be controlled. This number is started at 2 and is reduced if the desired direction of movement of the constraint is toward the acceptable region. Only that one constraint which is most likely to allow improvement of the system is released at each cycle.

g. Warning of frozen violation -- these are violations of edge and center thicknesses whose center thickness values are frozen (in all zoom positions). Thus the most potent correcting variable is unavailable to the program; to control these constraints would cause a violent upset to the system and would give a pessimistic picture of the potential quality of the system. For this reason, these violations are not controlled but should be taken into account when setting up the data for succeeding runs. This printout appears only when such warnings are needed and uses the same codes as the regular violations.

h. Listing of the relative cost of imposing constraints -- a value is printed which represents the relative "cost" or "pressure" each constraint applies to the solution. The magnitude is meaningful relative to others of the same general type; for example, TT, OAL, IMC, IMD, CT, ET, minimum and maximum edges and thicknesses are all measures of length in the direction of the optical axis and the relative magnitude has meaning; glasses are another group where there is meaning within the group. A few constraints (EFL, FGX, FGY, EXP, RAX, and RAY) are handled as reciprocals to improve linearity and to permit infinite values; for these, the "costs" are in the reciprocal domain.

The sign indicates which direction that constraint would move if it were released. On length measures, a + value indicates an algebraic increase if released; for the group treated as reciprocals there is a reversal in these signs. For glasses, a + sign means pressure to go outside the permitted region of the glass map.

If some constraints are included in the error function by use of the WTC card, the "cost" printed out is the departure from the target value for the constraint.

This pattern is followed except on the first cycle, when the initial error function appears after item g.

Error Conditions

The following error messages can occur:

1. "CONSTRAINT ON i POSITION REFERENCES AN ILLEGAL ZOOM POSITION" - a constraint references the same or a later zoom position; correct and rerun.

2. "ERROR IN FIELD NUMBER SPECIFICATIONS" - a constraint references a field number larger than the number of field positions.

3. "ERROR IN OAL SURFACE SPECIFICATIONS" - surface numbers on an OAL constraint are incorrect; correct and re-run.

4. "THICKNESS FREEZING FROM SURFACE i_1 TO i_2 ILLEGAL" - surface i_2 is in front of the first surface or behind the last surface of the system; correct and re-run.

5. "TOO MANY COUPLING NUMBERS" - more that 20 different values of CC (between 1 and 99) are listed on the surface data cards; reduce and re-run (there are probably some that do not have a matching value to couple with).

6. "CENTER THICKNESS TOO GREAT AT SURFACE i" - physical dimensions of system approaching 250000 units; scale it down and re-run.

7. "COUPLING NUMBER i IN 20 GROUPS"-internal table size exceeded; uncouple some of surfaces with i as value of CC. This error is not likely to occur.

8. "GROUP TOO LARGE -SURFACES = i_1 , i_2, ..." - internal table size exceeded; insert some freezings or couplings in the range of i_1 to i_n. This error is not likely to occur.

9. "CONSTRAINT TABLE EXCEEDED - REMAINING CONSTRAINTS IGNORED" - internal table size exceeded; the number of constraints (not including center and edge thickness types) exceeds 24. This error is not likely to occur.

10. "VARIABLE OR PARAMETER TABLES OVERFLOWED" - internal table sizes have been exceeded and some variables may not be used. This error is not likely to occur.

11. "NO IMPROVEMENT POSSIBLE. THE ENTIRE SYSTEM IS FROZEN" - unfreeze some of the parameters before calling for automatic design.

12. "RAY ERROR: MISS i" (A ray missed surface i)
"RAY ERROR: REFL i" (A ray was totally reflected at surface i)
"RAY ERROR: STOP i" (A principal ray couldn't find the stop)
"RAY ERROR: AFOC i" (A ray strikes the perfect lens so far off-axis that it forces the perfect lens to be faster than f/.5. Fix system or lengthen focal length of perfect lens.)

Indicates a system status which will not pass rays. This may be due to (1) system entered in that condition - it will scale down aperture and field and attempt to continue (2) a divergence has occurred - may or may not recover depending on the cause.

13. "ERROR CAUSED BY GROUP i" - indicates that a particular parameter or group of parameters has caused a tracing error of the type mentioned in 12, but undetected in bundle defining rays, on derivatives. May be caused in highly unbalanced vignetting or very insensitive variables.

14. "IRRECOVERABLE CONDITION" - indicates the machine's inability to recover from the situation described in 12. Often time this situation is caused by constraint conditions and costs and how they relate to the available variables; a guilty constraint will often have an extremely large cost. Look for:

  a. No variables available to satisfy an active constraint.

  b. More active constraints than variables that affect them.

  c. Two or more active constraints that are in conflict with each other.

  d. A variable that has no effect on the error function.

15. "UNSTABLE CONDITION" - indicates erratic progress toward a solution. Program terminates to give designer a chance to review his inputs. Look for:

  a. Problems listed in 14.

  b. Use of conic (K) as a variable on a plano or near-plano aspheric.

  c. Rotating from cycle to cycle through a set of nearly incompatible constraints.

AUTO-30

```
 CONSTRAINTS
   EFL          1.000000
   IMD          0.500000  +
   MXT          2.000000
   MNT          0.000000
   MNE          0.000000
   MNA          0.000000
   MAE          0.000100

 ERROR FUNCTION CONSTRUCTION
   WTW          111
   WTA          0.500000
   DEL          0.353009
   WTX  1       1.000000
   WTX  2       0.875000
   WTX  3       0.500000
   WTY  1       1.000000
   WTY  2       0.875000
   WTY  3       0.500000

 CONVERGENCE CONTROLS
   MXC           25
   MNC            2
   TAR          0.000000
   IMP          0.050000

9 VARIABLES

ESTIMATED TIME PER CYCLE IS    31.5 SECONDS (   0.526 MINUTES)


YCLE NO.   0
     OBJ                  INFINITY
       1    0.66900000    0.070000     SILICO              0.000000
       2    0.20000000    0.125000                         0.000000
       3   -0.13500000    0.023000     GERMAN              0.000000
       4    0.16700000    0.467000                         0.000000
       5    0.21600000    0.050000     SILICO              0.000000
       6   -0.17500000    0.620548                         0.000000
       7   -0.50000000    0.000000                         0.000000

                EFL          TT          PIM          OAL        EN PUP      EX PUP        REDU
              1.003512       INF       0.620548     0.735000    0.021136    1.966513     0.000000
   VALUE OF POTENTIAL SPECIFIC CONSTRAINTS
     EFL 0-1      IMD 0-1
   1.0035E+00   6.2055E-01

   CONSTRAINTS CONTROLLED  --   1
     EFL 0-1
      2
```

Table I: Automatic Design Sample Run

```
ERR. F.=        28.73893052
                           X      13.99441433    14.08732700    14.30240440
                           Y      13.99441433    15.03469086    16.26372719

      RELATIVE COST OF IMPOSING CONSTRAINTS
        EFL 0-1
       -0.82E-10 ——(a)
CYCLE NO.  1                    (b)
 ERR. F.=        0.02810030
                           X      0.00047998     0.00142149     0.00492071
                           Y      0.00047998     0.03081780     0.11906526

         OBJ              INFINITY
          1    0.64539917  0.070000     SILICO            0.000000 )
          2    0.19614865  0.046618                       0.000000 )
          3   -0.13769127  0.023000     GERMAN            0.000000 )
          4    0.09079962  0.516997                       0.000000 ) (c)
          5    0.32612630  0.050000     SILICO            0.000000 )
          6    0.00064977  0.653521                       0.000000 )
          7   -0.50000000 -0.000191                       0.000000 )

               EFL          TT          PIM        OAL        EN PUP     EX PUP(d)    REDU
             1.000060      INF      0.653521    0.706615    0.021110    1.696712    0.000000
      VALUE OF POTENTIAL SPECIFIC CONSTRAINTS )
        EFL 0-1      IMD 0-1                  ) (e)
       1.0001E+00   6.5333E-01                )

      CONSTRAINTS CONTROLLED   --   1 )
        EFL 0-1                       ) (f)
         2                            )
```

Table I (Continued)

```
      CONSTRAINTS CONTROLLED   --   2 )
        EFL 0-1      MN  2            )
         2            2               )
```

MN 2 constraint violated during improvement and imposed during re-solution.

```
      RELATIVE COST OF IMPOSING CONSTRAINTS )
        EFL 0-1      MN  2                  ) (h)
       -0.60E-08    -0.93E-08               )
CYCLE NO.  2
 ERR. F.=        0.01767254
                           X      0.00245610     0.00100508     0.00129263
                           Y      0.00245610     0.01502482     0.07245190

         OBJ              INFINITY
          1    0.62081415  0.070000     SILICO            0.000000
          2    0.17461339  0.039425                       0.000000
```

[redacted]

Appendix:

Construction of the Error Function

I. The Error Function

The error function is minimized in automatic design in the least squares sense. Unless constraints have been included with the WTC control, it is composed only of weighted aberration terms. Specifically, such a merit function could be expressed as

$$\Psi\rho = \sum_{zoom} \sum_{field} \sum_{\lambda} \sum_{ray} \left[W_Z^2 \cdot W_F^2 \cdot W_\lambda^2 \cdot W_R^2 \, (\Delta X^2 + \Delta Y^2) \right]$$

where W_Z is a weight for zoom position

W_F is a weight for field position

W_λ is a weight for wavelength

W_R is a weight for the particular ray

ΔX and ΔY are transverse ray aberrations

As a practical matter, such a simple set of weights is not oriented to the designer's needs since it does not allow for cross terms (i.e., a given weight on the second field for the third zoom position). Thus CODE V uses weighting arrays for X or Y components as a function of field and zoom, wavelength weights as a function of wavelength and zoom, and aperture (or ray) weights as a function of ray and zoom position. The composite error function is of the form

$$\Psi\rho = \sum_{Z} \sum_{F} \sum_{\lambda} \sum_{R} \Big[(WTX(Z,F) \cdot WTW(Z,\lambda) \cdot WTA(Z,R) \cdot \Delta X)^2 + (WTY(Z,F) \cdot WTW(Z,\lambda) \cdot WTA(Z,R) \cdot \Delta Y)^2 \Big]$$

In the output, the partial error functions are the two terms above, omitting WTX(Z,F) and WTY(Z,F). These two weights then are applied as above to form the composite error function.

II. Generation of the Weights

The indicated weights are related to, but not identical with, the CODE V entries of the same names. If $\Psi\rho$ and its partials Ψx and Ψy are to have any physical meaning, the weights must be carefully normalized. Thus, wavelength weights of 121 and 242 must produce the same values of $\Psi\rho$, Ψx and Ψy. This means that a change of weights will cause only a redistribution of emphasis without departing from the physical significance.

The aperture weight is

$$WTA(Z,R) = \frac{1}{A} \cdot \frac{1}{(X_o^2 + Y_o^2)^{\alpha}}$$

where Xo, Yo are the ray coordinates in the pupil
α is the CODE V entry, WTA
A is the normalization factor for this weight

The value of α can be used to shift emphasis from the center of the pupil to the edge which has some correlation to shifting the emphasis on MTF from low frequencies to high frequencies, and can be used to fine tune the final performance. The default value of α (.5) gives emphasis to minimizing blur diameter, while values in the range of .65 to .75 correspond to minimizing the variance of the wave front OPD, which is most useful for near-diffraction limited lenses.

WTW corresponds very closely to the wavelength weight entry, except that it has been normalized separately in each zoom position for wavelength. The normalization arising from the differences between zoom position is included in the normalization for WTX and WTY. This means that each partial Ψx and Ψy includes the effect of aperture and wavelength weights but completely excludes field and zoom weights even though the designer has implied a zoom weight in his wavelength weights. The value of Ψx and Ψy are the weighted mean square of the x and y half-widths of the image $x10^6$, respectively.

WTX and WTY are modified by the above mentioned zoom normalization and by their own normalization from the CODE V entries of the same names. The normalization arising from the entries is done so that when WTX = WTY, the composite Ψ represents the weighted mean square radius of the image $x10^6$ and, when WTX or WTY = 0, Ψ represents the weighted mean square of the image half-width $x10^6$. Unequal values of WTX and WTY generate a smooth continuum between these two cases.

III. Inclusion of Constraints (with WTC request)

If WTC is used for any constraint, a term of error function is developed of the form

$$\Psi c = \sum (WTC \cdot \Delta c)^2$$

where Δc is the departure of the constraint from its target

WTC is the value entered for WTC and the composite merit function is

$$\Psi = \Psi \rho + \Psi c$$

Both Ψ and Ψc are printed in the output.

The amount of departure of the constraint from its target will depend on three things:

1. The smallness of the performance component $\Psi\rho$ (or dominance of Ψc)

2. The chosen value of WTC

3. The pressure to violate the constraint

Some experimentation is necessary to find the desirable values for WTC; these may need modification as the design progresses to later versions.

IV. Representation of Chromatic Effects

All ray aberrations are measured from the reference wavelength chief ray intersection with the image plane. This means that each wavelength is being optimized as a full image rather than as a set of isolated chromatic aberrations (axial color, lateral color, etc.). Use of two wavelengths is sufficient to establish correctibility of primary axial and lateral color plus all of the compound effects of spherochromatism, chromatic variation of coma, astigmatism and distortion of all orders. Use of three wavelengths provides the additional secondary chromatic effects such as secondary spectrum and its analogs in the other aberrations. This unified treatment aids in achieving proper balance over the entire spectral band and field.

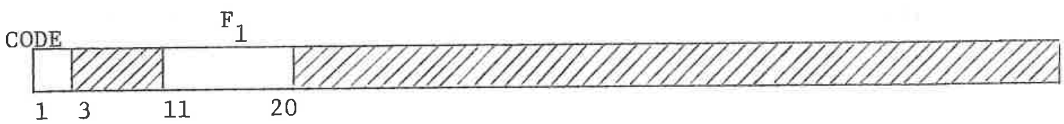
TEST PLATE

Purpose:

To automatically fit a lens system to a specified set of test plates.

Input Data:

By using TEST PLATE, the user is invoking optimization which requires all applicable input that would be used with the AUTOMATIC DESIGN option, plus any of the required data entries described below. The lens system must be one which has been previously optimized and stored with the error function value recorded. Only the PLATES entry must be used; it is followed immediately by the test plate list. Optional data cards follow the TEST PLATE option card to specify the test plate list, the mode of test plate fitting and other control parameters. These cards are punched in the following format:



CODE (Col. 1-3)	Mnemonic code identifying the values of the data card or requesting a particular sub-option of TEST PLATE. A list of CODES is given below.
F_1 (Col. 11-20)	Data field 1: used to enter the value specified in the CODE.

The following list gives the CODES and their associated data entries.

Fitting Strategies: Choose One

POWER	Orders the test plate fitting from strongest surface power to the weakest.
GAP	Orders the test plate fitting from largest power gap in the list to smallest. Criterion is $\|\Delta C\ (n-n')\|$ where ΔC is the gap in the list within which the curvature lies, (n-n') is the index difference across the surface, integrated over the wavelength band. This is the default mode.

STRONGEST	Orders the test plate fitting from strongest lens curvature to the weakest. Similar to POWER except index difference is excluded.
FURTHEST	Orders the test plate fitting beginning with the curvature that is furthest from a test plate.
NEAREST	Orders the test plate fitting beginning with the curvature that is nearest a test plate.

Controls:

ERMAX	The maximum error function that will be allowed before an attempted test plate fit on a surface is rejected; the default is 5% larger than the starting design.
ERINC	The maximum error function increment that will be allowed before an attempted test plate fit on a surface is rejected; the default is 2.5% increase.
PLATES	A header card which indicates that a deck of test plate radii follow this card. This deck should consist of: (1) one title card, i.e., XYZ COMPANY TEST PLATE LIST. The first column of the title card must have an M or C if the plate list is in millimeters or centimeters, respectively; plates will be scaled, if necessary, to match the dimensions of the system. (2) any number (up to 2000) cards containing radius entered in Col. 1-10.
SKIP	Skip the attempt to fit a test plate on surface N (N entered in F1 or as SKI n).

Print Controls: Optional

LIST	List test plates; provides a listing of the test plate radii and curvatures for reference.
FULL	Full printout flag; causes printout of all steps in the test plate fitting including the automatic design cycles. This is the default print mode.

SUMMARY	Summary printout flag; causes only a summary of the test plate fitting process to be printed. The surfaces and curvatures fit on a given pass and the resulting error function are printed plus a notation if the fit was rejected.

In addition to the above CODES and data, the data input applicable to the AUTOMATIC DESIGN requirements is accepted in the TEST PLATE option.

Function:

Using the test plate list entered, the program fits a curvature (or curvatures if coupled) to a test plate, freezes the curvature, and then calls the AUTOMATIC DESIGN options. The system is then optimized in the conventional manner after which control is returned to the test plate fitting program. If the error function is acceptable, based on the ERMAX and ERINC values, the system is accepted. If the error function is unacceptable, the previous system is restored. The process continues until a fit has been attempted on all of the surfaces. The LIBRARY label TESTPLATE is used to save intermediate results during the run; therefore, the label TESTPLATE should not be used in the LIBRARY to save a system without risk of it being destroyed.

Output:

Depending on the output option entered, FULL or SUMMARY, the printout will contain all of the steps including the automatic cycles or just an indication of the surface being fit to a test plate and the resulting error function.

Error Conditions:

Since the AUTOMATIC DESIGN and LIBRARY options are used as slaves to this option, error conditions applicable to either of those options may occur in addition to the following:

1. "NO TEST PLATE LIST ENTERED" - include a test plate list and rerun.

2. "TOO MANY TEST PLATES" - the test plate table size (2000) has been exceeded. The option will be terminated.

CAM

Purpose:

To provide a means of computing a table of separations to be used in constructing the cam for mechanical compensation zoom lenses.

Introduction:

There are two modes of operation of the CAM option which are selected solely by whether the lens is zoomed upon entry to CAM; mode one is a simple interpolation of the data using a spline fit through points represented by the zoomed data. If the system has more than one position upon entering the CAM option, this mode is automatically initiated. Mode two is much more time consuming and generates the cam data by successive optimizations for each step of the cam as some parameter (or constraint) is stepped. This mode requires the CAM option to be entered with the system dezoomed.

Input Data:

Data cards are entered following the CAM option card to specify and control the computation. These cards are punched in the following format:

CODE	L	F_1	F_2	F_3	F_4	F_5	F_6	F_7
1	4	11	21	31	41	51	61	71

CODE (Col. 1-3) — Mnemonic code identifying the values on the data card or requesting a particular sub-option of CAM. A list of codes is given below.

L (Col. 4-10) — Label field

F_1 (Col. 11-20) — Data fields 1-7; used to enter the values specified in the CODE.
.
.
.
F_7 (Col. 71-80)

The following list gives the CODES and their associated data entries.

MODE 1 (Zoomed):

STEP — An integer specifying the number of points in the desired cam data (equals the number of intervals plus one). The maximum number (and the default) is 200.

LIN — Specifies and labels a parameter (such as EFL) to be linearized in the fit. A print-out label should be entered in columns 4-10 and the values of the parameter for each zoom position in fields F1-F7. If this card is not entered, the first zoomed thickness will be made linear.

MODE 2 (Dezoomed):

STEP — An integer specifying the surface number of a separation which is to be stepped in a linear manner; entered in data field F_1. If no surface number is entered, the program assumes that the first constraint (for example, EFL) is to be stepped.

INCR — Increment to be used for the linear step; entered in data field F_1.

LIMIT — Limit (maximum value) of the stepped separation; entered in data field F_1.

LIST — List of surface numbers of separations which are to be listed at each step; up to 7 may be entered in data fields F_1 - F_7.

BASE — Constant base values which are added to the listed separations before printing; a base value for each listed separation should be entered in data fields F_1 - F_7, if this card is included.

In addition to the above CODES and data, any input data cards that are applicable in the AUTOMATIC DESIGN option may also be entered as data for the CAM option when used in Mode 2.

Function:

In Mode 1, a spline fit through the zoomed thickness data is done as a function of one linear parameter, providing a rough cam curve.

In Mode 2, the CAM option generates the cam data by optimizing the system (as a non-zoom) at each step of the cam. This is done by successive passes through the AUTOMATIC DESIGN option incrementing either a separation or a constraint (such as EFL) before each pass. This makes the varying separations a function of one linearly changing separation or a linearly changing constraint. Note that since the AUTOMATIC DESIGN option is used, all parameters that are not to be changed from one cam step to the next should be frozen before calling the CAM option.

There is currently no provision for changing field heights, weights, etc. as a function of the cam step. On most zoom lenses, this presents no particular problem, but may require that the lens be entered in a specific direction; in unusual cases, it may also be necessary to run the cam in a piece-wise fashion.

Output:

Although in Mode 2 the CAM option uses the AUTO option as its slave, all of the output from AUTO is suppressed. The CAM output consists of a header plus one line per step; this line contains a printout of the constraint being controlled of linearized parameter and the value of each zoomed separation that had been requested.

Examples:

A typical deck for a CAM run on a zoom photographic objective would look like the following:

MODE 1

```
LIBRARY
RESTORE     DGZOOM
CAM
STEPS       79
LIN EFL     9.0    14.0    22.0    32.0    48.0
END
```

This deck will produce a listing of all zoomed separations as a function of focal length in increments of .5 mm focal length.

MODE 2

```
LIBRARY
RESTORE     DGZOOM
DEZOOM            - Dezooms lens to first position
CHANGE
FREEZE            - Freezes all variables
THC5        }
THC10       }
THC12       }     - Unfreezes zoomed thicknesses
THC21       }
THC22       }
CAM
EFL         9.0   - First AUTO type constraint (stepped).
OAL         60.0                 }
SUR         1    13              }
BFL         .425                 }
WTA         1.2                  } - Other AUTO type data
DEL         .470                 }
WTF         1.0    .95   .80   .60}
STEP        EFL will be stepped because (n) is missing.
INC         .5    - Increment in EFL
LIM         48.0  - Limit on EFL
LIST        5     10     12     21     22   - Printed separations
BASE                     1.5                - Add 1.5 to THI12 for printing.
END
```

This deck would produce a listing of separations including the BFL and defocussing for focal lengths from 9 to 48 mm in an increment of .5 mm focal length (EFL).

EVALUATION-GEOMETRICAL PERFORMANCE

ANALYSIS

Purpose:

To provide simple diagnostic analyses of the optical system including

First order traces and third order aberrations

Ray tracing and wave aberrations

Input:

If no additional input is provided, output is provided for each zoom position consisting of:

1. First order traces with third order transverse aberrations in the reference wavelength (as in Table I).

2. Partial printout of the third order aberration sums for each of the other wavelengths and their difference from the reference wavelength.

3. Summary ray trace, printing image surface ray aberrations and wave aberration (OPD) for each ray of a standard pattern of ray fans. Distortion, entrance and exit angles, and field focus values are given for each chief ray. Rays are traced for each wavelength. See Table II.

Optional input requests may be made to select these capabilities separately, to extend or shrink the output or to trace a single ray. However, if any input requests are entered, only those operations requested will be performed. Optional input is provided according to the format:

CODE	N		F1	F2	F3	F4	F5	F6	F7
1	4	7	11	21	31	41	51	61	71

CODE (Col. 1-3)	Mnemonic code identifying the values on the data card and/or requesting a particular sub-option of ANALYSIS. A list of CODES is given later.
N (Col. 4-6)	Surface number allowed with some CODES.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields 1-7; used to enter the values specified in the CODE. For a zoom system the values for a given zoom position are entered in the data field corresponding to that position.

CODES	FUNCTION
POSITION	Used in zoom systems to flag those zoom positions which are not to be computed. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the ANALYSIS calculation for that zoom position.

First and Third Order Request:

THIRD	Requests third order analysis; in addition, output controls may be entered in the first seven columns of each data field where each column corresponds to a wavelength. Letter codes entered have the following meaning:

N	No print
P	Partial print; image surface summations are printed.
F	Full print; first order heights and angles plus third order aberrations are printed for each surface as well as image surface summations.
blank	Equivalent to F for the reference wavelength, and P for others.

Pattern Ray Tracing:

RAY TRACE	Requests a ray trace image surface summary; wavelengths may be eliminated from the summary by placing a N in the column corresponding to that wavelength.
SSP	Requests a print out of ray trace coordinates for the reference wavelength at each surface in the system; output controls may be entered in the first five columns of each data field where each column corresponds to a field position. Letter codes entered have the following meaning: N — No print P — Partial print; ray coordinates on each surface are printed for the principal ray and the limiting meridional and skew rays. F — Full print; ray coordinates on each surface are printed for all rays. blank — Same as P.
DELH	Ray interval - the interval between rays in the normalized entrance pupil. This controls the number and relative position of rays for the summary ray trace and the surface by surface ray trace. If a DELH card is not entered, rays will be traced at normalized pupil heights of 1.0, .8, .6, and .4. If DELH is entered, rays will be traced at 1.0, 1.0-ΔH, . . . as long as the pupil height equals or exceeds the DELH. Example: If a DELH value of .200 is entered, rays will be traced at pupil heights of 1.0, .8, .6, .4, and .2.

Trace of a Single Ray:

SIN (n)

Requests a single ray specified by its actual coordinates on the tangent plane to the first surface:

F1	X
F2	Y
F3	X direction tangent
F4	Y direction tangent
F5	Integer corresponding to wavelength at which ray is to be traced; if blank, reference wavelength is used.

The X,Y coordinates, direction tangents and ray length are output for each surface; if (n) is present, output only occurs for surface n.

RSI (n)

Requests a single ray specified by its relative coordinates on the entrance pupil surface and its fractional field coordinates.

F1	X fraction of the pupil
F2	Y fraction of the pupil
F3	X fraction of the last field specification
F4	Y fraction of the last field specification
F5	Integer corresponding to wavelength at which ray is to be traced; if blank, reference wavelength is used.
F6	Special option - if included (as an integer) F6 is the surface number of any surface on which the coordinates are specified; F1 and F2 are actual (not relative) coordinates.

The X,Y coordinates, direction tangents and ray length are output for each surface; if (n) is present, output only occurs for surface n.

Function and Output:

A. Third Order Analysis (THIRD)(See Method for notation)

Two first order rays, the paraxial and the paraxial principal rays, are traced from the object through the system to the image. These provide the information necessary to calculate the five monochromatic third order aberration coefficients - spherical aberration, coma, astigmatism, Petzval sum (field curvature), and distortion - and the two first order chromatic aberrations, axial and lateral color. Output, as shown in Table I, consists of:

1. Paraxial data

The EFL, image distance, image F/NO and image height are printed.

2. Output for each surface

Two lines of output are normally printed for each surface. For an aspheric surface, a third line is printed. The first line contains the surface number, the paraxial ray data and the Petzval sum in the following order:

$$\text{surf. no.} \quad Y_s \quad u_s \quad (ni)_s \quad \overline{Y}_s \quad \overline{u}_s \quad (\overline{ni})_s \quad \text{Petz } \Sigma$$

The second line contains the surface contributions (for the spherical part of the surface if it is an asphere) to the 3rd order transverse aberrations in the following order:

$$\Delta Y \text{ (sph. ab)} \quad \Delta Y_T \text{ (coma)} \quad \Delta Y_T \text{ (astig.)} \quad \Delta X_S \text{ (astig.)} \; \ldots\ldots$$

$$\ldots\ldots \; \Delta Y \text{ (dist.)} \quad Y_F - Y_c \quad Y_{n_f} - Y_{n_c}$$

For an asphere, the third line contains the contributions from the aspheric part of the surface. An extra blank line is added at airspaces in the system so that the printout conveys some sense of the lens construction.

3. Summations

At the end of the surface output, the summations of the Petzval sum and transverse aberrations are printed.

Most systems must be designed to cover a band of radiation rather than a single wavelength. Although the axial and lateral color values already obtained indicate the gross nature of the color correction, many systems eventually are limited by secondary spectrum or chromatic variations of the third order aberrations. To aid in the analysis of these effects, the same first and third order calculations are run in the other wavelengths and the differences taken; these show the chromatic variations.

Third order computations are done correctly for centered systems consisting of plane, spherical, and polynominal aspherics. Third order computations for cylindrical surfaces are done for the equivalent spherical surface in the meridian designated by XFO (Specification Data). Third order computations for aspheric toroids are for the equivalent aspheric. For the gradient index and diffraction grating surfaces, they are for the aspheric without regard to the index variation or diffraction. Splines generate aberrations of all orders (2,3,4....) and are only treated as a parabola of equivalent power. No effect of decentration is included; therefore, for decentered systems, third order computations may or may not be of value, depending on system structure.

B. Summary of Trace Analysis (RAY TRACE)

Ray fans are traced according to a standard pupil pattern, in part determined by the data cards, for the axial field point as well as for each of the previously designated field heights. The normal pupil pattern is shown at the left, where the Y coordinate lines in the meridional plane and the X coordinate is the skew direction; the pupil franctions for X and Y are scaled down appropriately according to the required values of vignetting. The principal ray height in the image surface is subtracted from each of the image surface heights for the ray fans so that the residual aberrations may be listed. Simultaneously, rays are traced in the other wavelengths and the principal ray value for the reference wavelength is also subtracted from these. For the axial bundle of a symmetric system only the X fan is traced; for systems which are bi-laterally unsymmetric, a -X fan is also traced at each field.

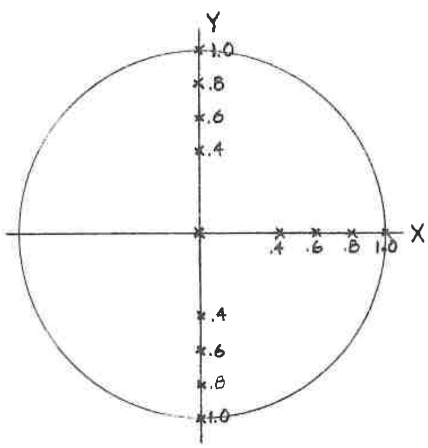


Table II is an example of the output. For each ray the following values are printed:

X Y ΔX' ΔY' OPD

where X and Y are the fractions of the aperture stop surface through which the rays were traced (they will correspond to the entrance pupil fractions only in the absence of pupil aberrations), ΔX' and ΔY' are the X and Y differences of the ray intercept in the image plane from the principal ray and OPD is the wave aberration in wavelength units. If any additional colors are traced the values of ΔX' and ΔY' and OPD are printed out in the same line.

For each principal ray in the reference wavelength, there is given the image plane coordinates (X',Y',Z') values for distortion, entrance pupil distance, entrance angle and exit angle and X and Y focus values. If any additional colors are traced, the values of ΔX' and ΔY' are printed on the same line.

If a negative edge thickness occurs during the tracing of a ray, the characters -ET and printed after the OPD of the image surface.

C. Surface by Surface Printout

For those rays printed in full, the values

X' Y' Z' TAN X TAN Y RAY LENGTH ANG INC ANG REF

for each surface are printed opposite the number of the surface. TAN X is skew direction tangent, TAN Y the meridional direction tangent and the RAY LENGTH is the physical distance along the ray from the preceding surface to the surface. ANG INC and ANG REF are the angles of incidence and refraction. If a negative edge thickness is encountered, the second surface of the intersecting pair is flagged with a -ET following Z'.

D. Single Ray Trace Analysis

The output for each requested ray is identical to that described for the surface by surface rays, above. OPD is printed for the RSI option but not for the SIN option.

Error Conditions:

1. "PR RAY MISSED STOP" - (Principal Ray)

"TOTAL REFLECTION AT SURFACE i"

"RAY MISSED SURFACE i"

The rest of the tracing for that ray is deleted and the next ray is run.

Method:

The third order coefficients are calculated according to the following equations (see MIL - HDBK-141 for comments on a similar scheme:

A. Sign Conventions

All ray heights above the optical axis are positive; all ray angles are positive where the optical axis must be rotated counter clockwise to coincide with the ray.

B. First Order Ray Traces

Paraxial	Principal
$Y_s = Y_{s-1} + \frac{t_{s-1}}{n_{s-1}} (nu)_{s-1}$	$\overline{Y}_s = \overline{Y}_{s-1} + \frac{t_{s-1}}{n_{s-1}} (\overline{nu})_{s-1}$
$(nu)_s = (nu)_{s-1} + (n_{s-1} - n_s) Y_s c_s$	$(\overline{nu})_s = (\overline{nu})_{s-1} + (n_{s-1} - n_s) \overline{Y}_s c_s$
$(ni)_s = (nu)_s + n_s Y_s c_s$	$(\overline{ni})_s = (\overline{nu})_s + n_s \overline{Y}_s c_s$

where c, t, n are the constructional parameters - curvature, thickness, and index

Y_s is the ray height on surface S

$(nu)_s$ is the ray angle times index in the medium after surface S

$(ni)_s$ is the angle of refraction times the index in the medium after surface S. This is also equal to the angle at incidence times the index in the medium preceding surface S.

The starting ray data is chosen so that the paraxial ray corresponds to the marginal real ray in position while the principal first order ray is chosen to correspond to the real chief ray of the last field height.

The values of $\overline{Y}$ and $\overline{nu}$ can then be scaled by the appropriate values to compare them to any actual principal ray. If the last field height is zero, the first order chief ray is traced in this analysis to give an image height of 1.0.

C. Third Order Aberration Coefficients
(for a normalized chief ray)

$$Q = \frac{(nu)_s}{n_s^2} - \frac{(nu)_{s-1}}{n_{s-1}^2} \qquad \overline{Q} = \frac{(\overline{nu})_s}{n_s^2} - \frac{(\overline{nu})_{s-1}}{n_{s-1}^2}$$

$$SC = (ni)_s^2 \, Q \, Y_s$$

$$CC = (ni)_s \, (\overline{ni})_s \, Q \, Y_s$$

$$AC = (\overline{ni})_s^2 \, Q \, Y_s$$

$$PC = c_s \left(\frac{1}{n_s} - \frac{1}{n_{s-1}} \right) = (ni)_s \, \overline{Q} - (\overline{ni})_s \, Q$$

$$DC = (\overline{ni})_s^2 \, Q \, \overline{Y}_s + (\overline{ni})_s \, \overline{Q}$$

Aspheric Third Order Aberration Coefficients

$$PA_s = (K \, c_s^3 + 8 \, A_s)(n_{s-1} - n_s)$$

$$SC_{as} = Y_s^4 \, PA_s$$

$$CC_{as} = \overline{Y}_s \, Y_s^3 \, PA_s$$

$$AC_{as} = \overline{Y}_s^2 \, Y_s^2 \, PA_s$$

$$DC_{as} = \overline{Y}_s^3 \, Y_s \, PA_s$$

D. First Order Chromatic Aberration Coefficients

$$AxC = -(ni)_s \, Y_s \, \Delta n_s$$

$$LatC = -(\overline{ni})_s \, Y_s \, \Delta n_s$$

where $\Delta n_s = \left(\frac{dn_s}{n_s} - \frac{dn_{s-1}}{n_{s-1}} \right)$

E. Transverse Aberrations

The seven aberration coefficients for each surface can be summed for all surfaces in the system to produce seven sums; the transverse aberrations can be easily obtained by multiplying by appropriate factors. These factors are dependent on the particular height in the aperture and the particular image height for which the third order aberration is desired.

Thus

Spherical Aberration:

$$\Delta Y = \frac{-R^3}{2(nu)_r} \sum_1^r SC = R^3 \ f/no \sum_1^r SC$$

Coma:

$$\Delta Y_T = \frac{3}{2} Y_n R^2 \sum_1^r CC$$

$$\Delta Y_S = \frac{1}{2} Y_n R^2 \sum_1^r CC$$

Astigmatism and Field Curvature:

$$\Delta Y_T = \frac{Y_n^2 R(nu)_r}{2} \sum_1^r (3AC+PC) = \frac{Y_n^2 R}{4 \ f/no} \sum_1^r (3AC+PC)$$

$$\Delta X_S = \frac{Y_n^2 R}{4 \ f/no} \sum_1^r (AC+PC)$$

$$\Delta Y_P = \frac{Y_n^3 R}{4 \ f/no} \sum_1^r PC$$

Distortion:

$$\Delta Y = \frac{Y_n^3 (nu)_r^2}{2} \sum_1^r DC = \frac{Y_n^3}{8(f/no)^2} \sum_1^r DC$$

Axial Color:

$$Y_F - Y_c = - \frac{R}{(nu)_r} \sum_1^r AxC = 2\ f/no\ R \sum_1^r AxC$$

Lateral Color:

$$Y_{n_F} - Y_{n_c} = Y_n \sum_1^r Lat.C$$

where R is the ratio of the pupil height considered, to the pupil radius (i.e., the pupil fraction), Y_n is the height in the image plane, f/no is a measure of the aperture in the image space ($f/no = \frac{-1}{2(nu)_r}$), the subscript r refers to the last system surface, and the subscript n refers to the image surface. F and C refer to the shortest and longest wavelengths used.

Table 1. Third Order Output

PARAXIAL VALUES AND 3RD ORDER TRANSVERSE ABERRATIONS FOR 550.0 NANOMETERS

EFL = 1.004999
IMAGE DISTANCE = 0.547221

IMAGE F/NO = 2.000000
IMAGE HEIGHT = 0.269289

SURF	Y(MARG) SPH ABER	U(MARG) TAN COMA (U IS AFTER REFRACTION)	NI(MARG) TAN ASTIG	Y(CHIEF) SAG ASTIG	U(CHIEF) PETZVAL	NI(CHIEF) DISTORTION	PETZ SUM AX COLOR	LAT COLOR
EP	0.251250	0.000000		0.000000	0.267949			
1	0.251250	-0.168068	0.391714	-0.120303	0.233457	0.080390	-0.668927	
	-0.007399	-0.004555	-0.006998	-0.006375	-0.006064	-0.001308	-0.006105	-0.001253
2	0.237638	-0.220054	-0.121164	-0.101395	0.377189	0.334995	0.178547	
	-0.000866	0.007182	-0.018238	-0.005000	0.001618	0.013825	-0.001786	0.004938
3	0.236978	-0.344797	0.325232	-0.100264	0.321006	0.146483	-0.882551	
	0.000376	0.000508	-0.007771	-0.007924	-0.008000	-0.003569	-0.002629	-0.001184
4	0.168019	-0.317658	-0.559328	-0.036062	0.295739	0.520734	0.000000	
	0.003379	-0.009438	0.008787	0.002929	0.000000	-0.002727	0.004869	-0.004533
5	0.155948	-0.112434	0.474975	-0.024824	0.449595	0.356089	1.627492	
	0.004783	0.010757	0.022817	0.017441	0.014752	0.013075	0.006364	0.004771
6	0.149740	-0.112434	-0.112434	0.000000	0.449595	0.449595	0.000000	
	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
7	0.130553	0.104818	-0.545435	0.076721	0.371870	0.195139	1.321055	
	0.013633	-0.014632	0.017210	0.013720	0.011975	-0.004908	0.004703	-0.001682
8	0.134536	0.099687	0.174205	0.090852	0.353665	0.618041	0.000000	
	-0.000049	-0.000524	-0.001857	-0.000619	0.000000	-0.002196	0.000334	0.001185
9	0.142621	-0.058618	-0.370075	0.119533	0.422908	0.161871	-0.934156	
	-0.004518	0.005929	-0.011061	-0.009332	-0.008468	0.004082	-0.002733	0.001196
10	0.142445	-0.066303	0.017966	0.120801	0.214221	0.487856	-0.229984	
	0.000002	0.000155	0.002121	-0.000683	-0.002085	-0.018538	-0.000133	-0.003599
11	0.136805	-0.250000	-0.429435	0.139022	0.238051	0.055709	-0.561057	
	-0.010700	0.004164	-0.005626	-0.005266	-0.005086	0.000683	-0.003043	0.000395
SUMS							-0.149582	
	-0.001359	-0.000453	-0.000617	-0.001110	-0.001356	-0.001582	-0.000159	0.000233

```
  DOUBLE GAUSS EXAMPLE                                                                                POSITION 1

ELATIVE STOP               550.0 NM                              650.0 NM                          450.0 NM
OORDINATES
  X     Y          RAY ABERRATIONS        OPD            RAY ABERRATIONS        OPD         RAY ABERRATIONS        OPD
1.00  0.00     0.000165  0.000000    0.411          0.000368  0.000000   -0.808       0.000488  0.000000   -0.925
0.80  0.00    -0.000143  0.000000    0.316          0.000036  0.000000   -0.518       0.000049  0.000000   -0.333
0.60  0.00    -0.000090  0.000000    0.015          0.000057  0.000000   -0.448       0.000011  0.000000   -0.291
0.40  0.00     0.000000  0.000000   -0.081          0.000105  0.000000   -0.283       0.000047  0.000000   -0.203

0.00  0.00     0.000000  0.189578  0.000000         0.000000 -0.000030                0.000000  0.000045
ISTORTION = -0.3759  PERCENT      EP DIST =      -0.459424        ENTRANCE ANGLES = (  0.0000,  10.7286) DEGREES
-FOCUS, Y-FOCUS = ( -0.001422, -0.000795)                             EXIT ANGLES = (  0.0000,   9.1554) DEGREES

0.00  0.68     0.000000  0.000104   -0.096          0.000000  0.000373   -0.789       0.000000  0.000042   -0.177
0.00  0.55     0.000000  0.000017   -0.014          0.000000  0.000213   -0.411       0.000000 -0.000011   -0.171
0.00  0.42     0.000000  0.000001   -0.002          0.000000  0.000132   -0.183       0.000000  0.000003   -0.185
0.00  0.28     0.000000  0.000002   -0.005          0.000000  0.000073   -0.050       0.000000  0.000028   -0.151

0.00 -0.29     0.000000  0.000030    0.036          0.000000 -0.000071   -0.151       0.000000  0.000038    0.171
0.00 -0.44     0.000000  0.000060    0.110          0.000000 -0.000062   -0.238       0.000000  0.000019    0.234
0.00 -0.59     0.000000  0.000057    0.205          0.000000 -0.000076   -0.328       0.000000 -0.000059    0.204
0.00 -0.74     0.000000 -0.000079    0.217          0.000000 -0.000212   -0.494       0.000000 -0.000299   -0.096

0.99 -0.02     0.000494 -0.000204    0.615          0.000691 -0.000169   -0.544       0.000831 -0.000282   -0.836
0.80 -0.02    -0.000102 -0.000074    0.896          0.000067 -0.000063    0.043       0.000109 -0.000107    0.248
0.60 -0.01    -0.000174 -0.000024    0.532         -0.000037 -0.000030    0.029      -0.000054 -0.000022    0.254
0.40 -0.00    -0.000105 -0.000006    0.204         -0.000008 -0.000025   -0.019      -0.000044  0.000020    0.107

0.00  0.00     0.000000  0.266616  0.000000         0.000000  0.000018                0.000000 -0.000049
ISTORTION = -0.9323  PERCENT      EP DIST =      -0.470795        ENTRANCE ANGLES = (  0.0000,  15.0000) DEGREES
-FOCUS, Y-FOCUS = ( -0.001326, -0.001348)                             EXIT ANGLES = (  0.0000,  12.1904) DEGREES

0.00  0.57     0.000000  0.000364   -0.487          0.000000  0.000699   -1.267       0.000000  0.000078    0.485
0.00  0.46     0.000000  0.000162   -0.165          0.000000  0.000415   -0.679       0.000000 -0.000046    0.492
0.00  0.35     0.000000  0.000059   -0.030          0.000000  0.000240   -0.334       0.000000 -0.000088    0.379
0.00  0.23     0.000000  0.000010    0.011          0.000000  0.000129   -0.134       0.000000 -0.000091    0.240

0.00 -0.24     0.000000  0.000078    0.086          0.000000  0.000028    0.031       0.000000  0.000020   -0.045
0.00 -0.36     0.000000  0.000143    0.227          0.000000  0.000071    0.081       0.000000  0.000054    0.017
0.00 -0.49     0.000000  0.000208    0.462          0.000000  0.000124    0.194       0.000000  0.000069    0.115
0.00 -0.62     0.000000  0.000237    0.754          0.000000  0.000150    0.346       0.000000  0.000026    0.199

0.99 -0.04     0.001320 -0.000128   -1.577          0.001511 -0.000009   -2.306       0.001663 -0.000370   -3.649
0.79 -0.02     0.000296 -0.000024   -0.013          0.000455  0.000058   -0.666       0.000523 -0.000195   -0.986
0.60 -0.01    -0.000009  0.000004    0.226          0.000118  0.000058   -0.189       0.000129 -0.000112   -0.201
0.40 -0.01    -0.000053  0.000006    0.136          0.000037  0.000040   -0.065       0.000023 -0.000072   -0.022
```

ANAL-13

Table II. Ray Trace Analysis Output

FIELD ABERRATIONS

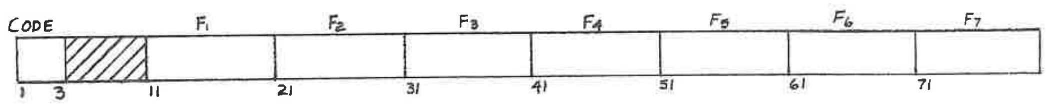
Purpose:

To compute distortion and image focal curves across the field of the lens system.

Input Data:

Tables are generated which give the distortion and focal curves for steps of .1 x the field. The focal curves are the values of X focus and Y focus (sagittal and tangential, respectively, for rotationally symmetric systems). Calculations are done for each zoom position.

An optional data card may be included following the FIELD option card to alter this assumption. This card is punched in the following format:



CODE (Col. 1-3)	Mnemonic code indicating particular FIELD sub-options. A list of the CODES is given later.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields F1-F7; used to enter data for the corresponding zoom positions, i.e. F1 is used for zoom position 1, F2 for zoom position 2, etc.

The following CODES identify the FIELD optional data; the portion of the CODE underlined indicates the characters which are sensed. The letter N (or the word NO) in any field, suppresses the request for that zoom position.

CODE	OPERATION
POSITION	Used in zoom systems to flag those zoom positions which are not to be computed. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the FIELD for that zoom position.
PLOT	Plots distortion, x-focus and y-focus curves. The character N, or NO entered in the data field corresponding to a given zoom position will suppress plotting for that zoom position.
SF	Field curve plotting scale factor. Enter the maximum desired abscissa.
DSF	Distortion plotting scale factor. Enter the maximum desired abscissa. For example, entering 2.0 in F_1 would set -2.0% and +2.0% as the limits of the abscissa.
TITLE n	Temporary title; characters in columns 21-60 (F2, F3, F4, F5) are used. If it is to apply to just one zoom position, enter the zoom position number n in column 11. A title request may be entered for each position.
LINEAR	Prints the actual image height and the $f \cdot \theta$ image height for ten equally spaced field angles plus the percentage difference. This is useful for determining the linearity of image height versus scan angle in scanning systems. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the LINEAR printout for that zoom position.

Function:

This option computes the distortion, x-focus and y-focus across the field of the lens system. These values are computed in steps of 10% of the full field.

Output:

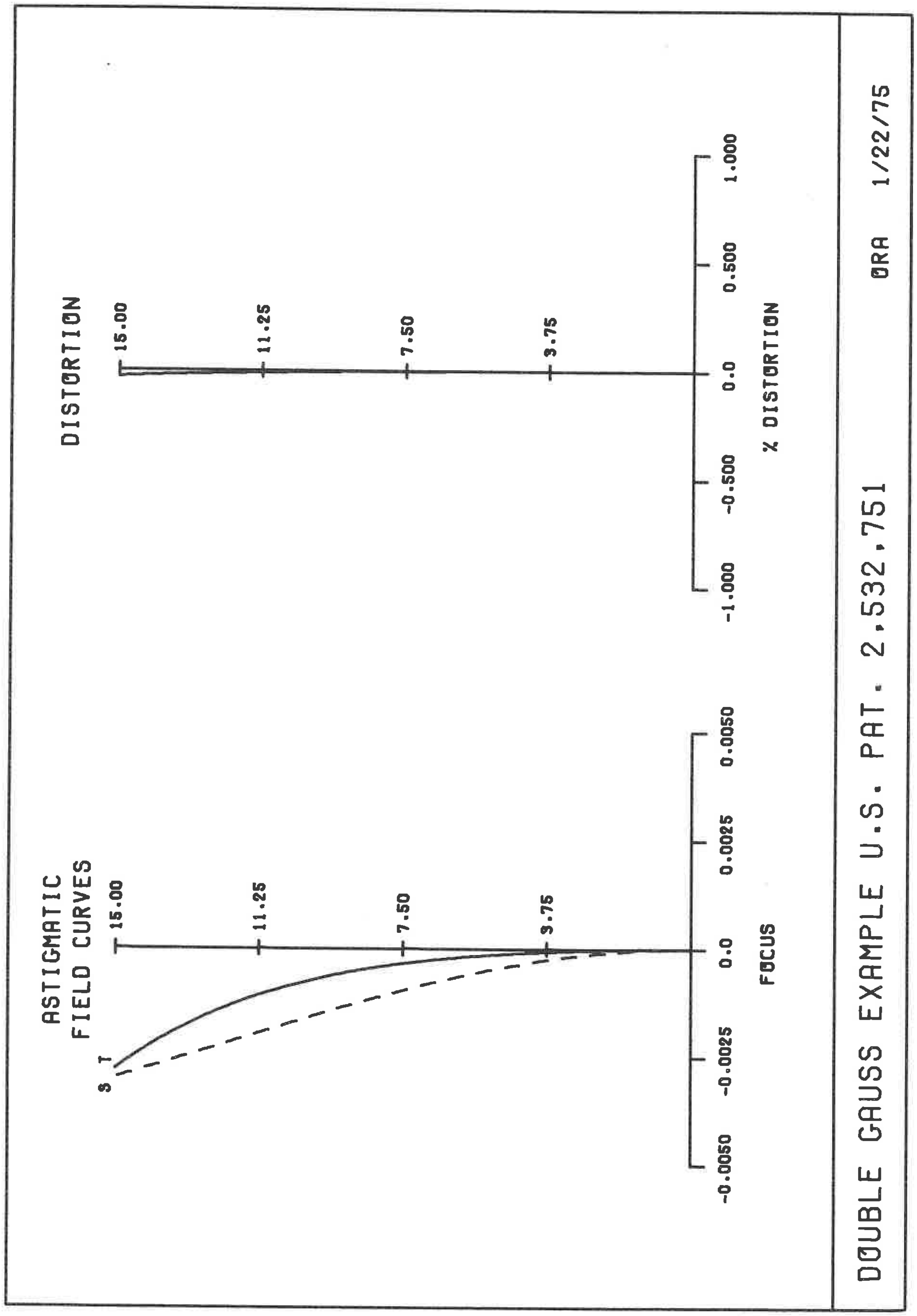
A listing showing the distortion, x-focus and y-focus at the axis, and 10 steps across the field is given. Also the x-focus and y-focus are displaced by the axial defocussing value and the values are listed as separate columns. If requested, a plot like the one shown will be generated.

Error Conditions:

None.

Technical Notes:

The focal curves are determined by tracing real rays close to the chief rays and are thus valid for all of the special surface types and for decentered systems.


ASTIGMATIC
FIELD CURVES
S T
15.00
11.25
7.50
3.75
-0.0050
-0.0025
0.0
0.0025
0.0050
FOCUS
DISTORTION
15.00
11.25
7.50
3.75
-1.000
-0.500
0.0
0.500
1.000
% DISTORTION
DOUBLE GAUSS EXAMPLE U.S. PAT. 2,532,751
ORA 1/22/75

FIEL- 4

Purpose:

To provide plotted output of ray aberrations or wave aberrations for tangential and sagittal fans in a form suitable for reports.

Input data:

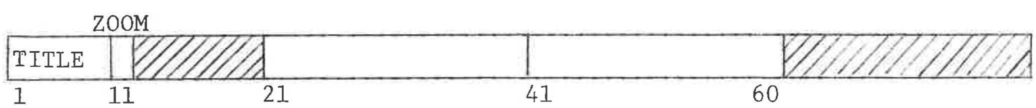
This option, without any additional data, will draw the aberration plots as shown in the example on RIM- 3. The coordinates plotted are the ray aberration vs. the coordinate of the point where the ray strikes the aperture stop. Two fans are traced. One is the fan lying in the y-z plane of the object space (meridional plane in centered systems). The other fan is the fan penetrating the entrance pupil along its x-axis (skew fan in centered systems). Plotting of aperture coordinates is left to right in going from - to +.

It will use a scale of .001 inch of aberration = 1 inch of aberration on the plot; if DIM has been set to M or C in DATA, the default value is .05mm or .005cm, respectively. It will use the first 40 characters of the title card split into two 20 character lines. A single page plot will be generated for each zoom position.

Optional data cards may be used to alter these assumptions.

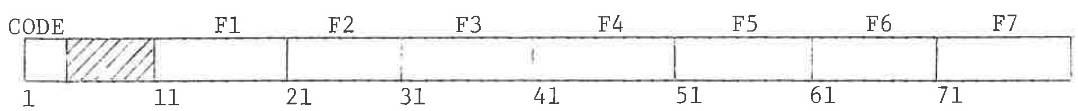
Title

If the title is to be changed it is punched in the following format:



The characters to be substituted are entered in Col. 21-60. If no entry is made in the ZOOM column, the title change is made for all zoom positions. If the title change is to be made for a specific zoom position, this is entered in Col. 11. A TITLE card may be entered for each zoom position.

Additional optional data cards may be included using the following format:



CODE (Col. 1-3) — Mnemonic code indicating particular RIMRAY sub-options. A list of the CODES is given later.

F1 (Col. 11-20)
.
.
.
F7 (Col. 71-80) — Data fields F1-F7; used to enter data for the corresponding zoom positions; i.e. F1 is used for zoom position 1, F2 for zoom position 2, etc.

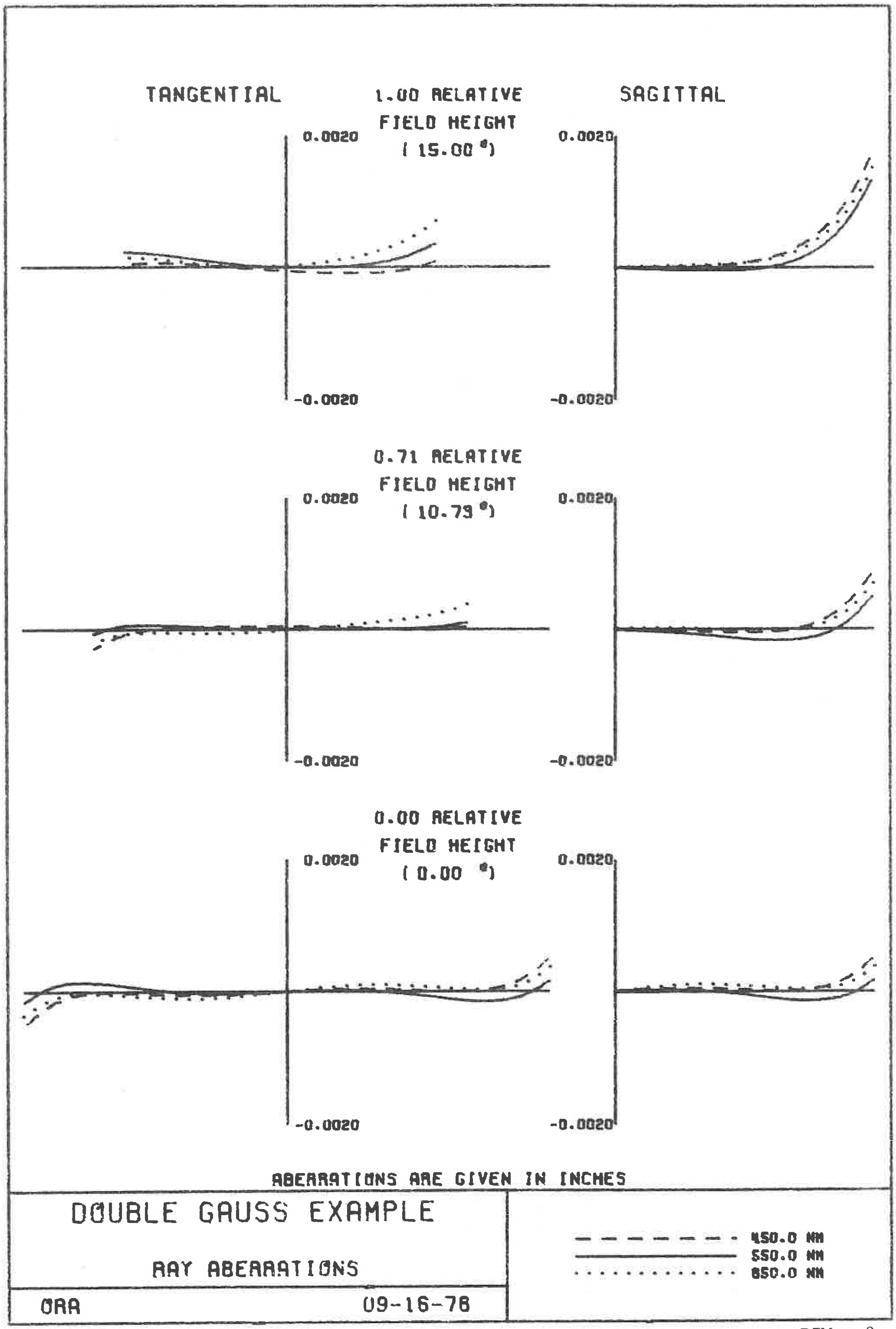
CODES	OPERATION
WFR	This card is entered to generate a plot of the optical path difference rather than the ray aberration plots. Each wavefront is plotted as a fraction of its own wavelength.
EP	Used to designate that the plotting is to be relative to the entrance pupil instead of the aperture stop.
SF	Scale factor; the desired scale for 1 inch of plot for each zoom position is entered in fields F1-F7. This value is in user units for ray aberration plots, and is in waves for optical path difference plots.
POS	Used in zoom systems to flag those positions which are to be computed. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the RIMRAY plot for that zoom position.
NUM	The number of rays traced in each half aperture, to be spline fitted in the plot. The default is 10; any entry less than 10 is set to 10 and any entry greater than 100 is set to 100. This can be used to represent curves with many orders of aberration more accurately.
LABEL	If a quick plot is desired without labelling enter this request with a NO in the fields F1-F7 for each zoom position for which labelling is to be omitted.

Output

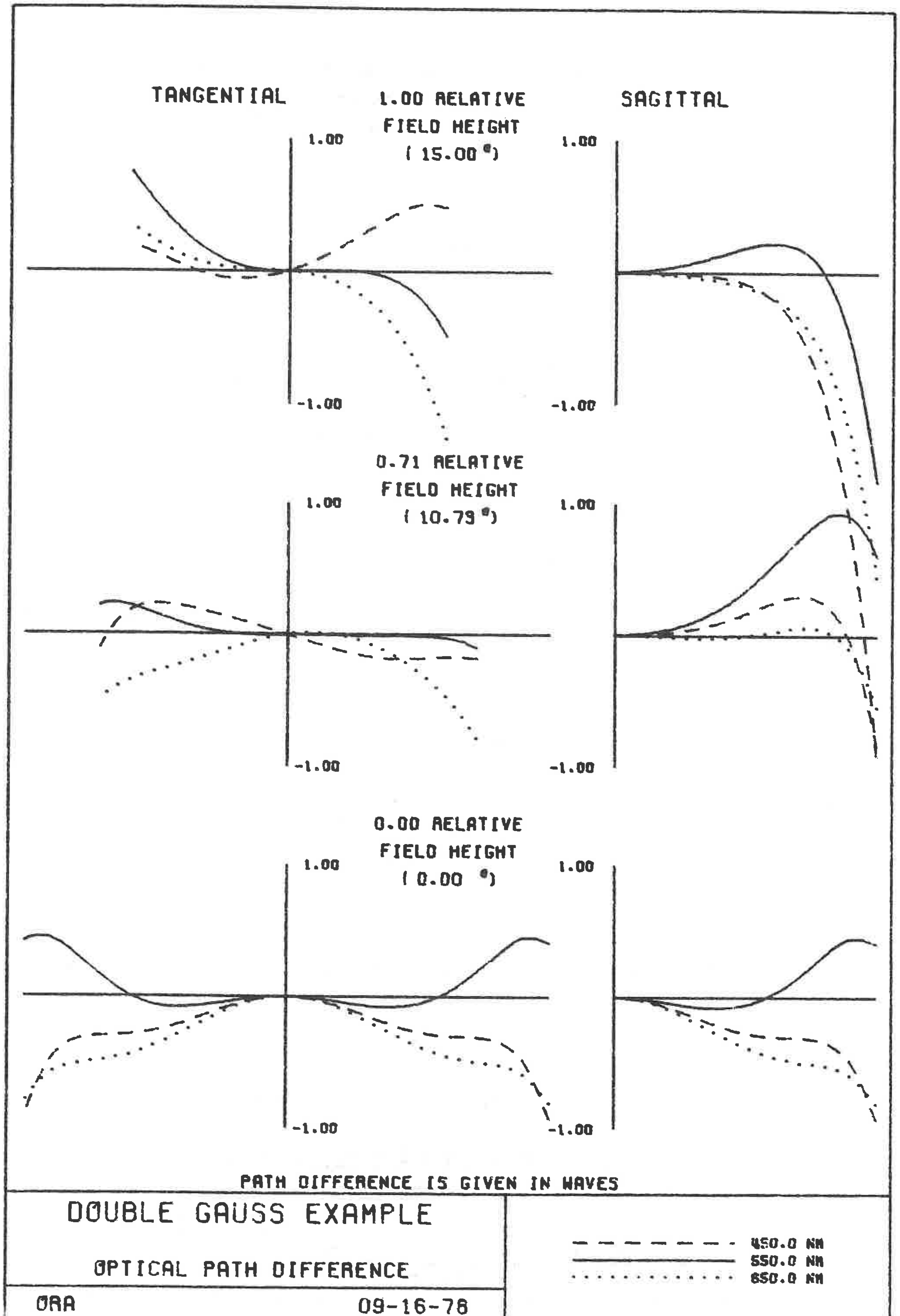
The output is in the form of a labelled plot which is suitable for reference or report. Each wavelength is coded with special line construction; all field positions are included on the plot. Each zoom position is plotted separately. Ray or wave aberrations which are too large to be plotted on the page are ignored; a printed message indicates if any such values have been encountered.

Error Conditions

1. "RAY TRACE ERRORS DURING CLEAR APERTURE TRACE - OPTION TERMINATED" - the meridional rays which are traced to establish the free apertures have encountered either total internal reflection or have missed a surface: correct and rerun.


TANGENTIAL
1.00 RELATIVE
FIELD HEIGHT
(15.00 °)
SAGITTAL
0.0020
-0.0020
0.0020
-0.0020
0.71 RELATIVE
FIELD HEIGHT
(10.73 °)
0.0020
-0.0020
0.0020
-0.0020
0.00 RELATIVE
FIELD HEIGHT
(0.00 °)
0.0020
-0.0020
0.0020
-0.0020
ABERRATIONS ARE GIVEN IN INCHES
DOUBLE GAUSS EXAMPLE
RAY ABERRATIONS
ORA
09-16-78
450.0 NM
550.0 NM
650.0 NM

RIM - 3



TANGENTIAL
1.00 RELATIVE
FIELD HEIGHT
(15.00 °)
SAGITTAL
1.00
-1.00
0.71 RELATIVE
FIELD HEIGHT
(10.79 °)
0.00 RELATIVE
FIELD HEIGHT
(0.00 °)
PATH DIFFERENCE IS GIVEN IN WAVES
DOUBLE GAUSS EXAMPLE
OPTICAL PATH DIFFERENCE
ORA
09-16-78
450.0 NM
550.0 NM
650.0 NM

RIM - 4

HIGHER ORDER ANALYSIS

Purpose:

Provides the surface by surface contributions to the ray aberrations and to the combined fifth and higher order aberrations.

Input Data:

No additional data is required for this option.

Function:

The performance of high quality optical systems is usually limited by aberration residuals higher than third order. Classically, these have been analyzed by special computations of fifth order and seventh order surface by surface contributions. An alternate method would be to calculate the surface by surface contribution to the ray aberrations (i.e., the sum of all orders); subtracting the third order contributions would then give the fifth and higher order ray aberrations.

Heretofore, such a procedure was impossible because no computational method had been published. However, H. L. Aldis developed a method[1] (now called the Aldis theorem) which permits the calculation of these ray aberration contributions - what we call surface aberrations. The computational scheme is embodied in this option.

The computation consists of third order calculations (identical to that in ANALYSIS), the surface aberrations, the difference of these two (giving the higher order contributions) and the ratio of the total ray aberration to the third order aberration. These values can be used in different ways. For example, the higher order contributions reveal the surfaces which are the major sources of aberration tails or higher order astigmatism. If any of these sources are cemented surfaces, then sizable chromatic variations of the higher order aberrations can be expected. The ratio of total to third order aberration is useful in determining which surfaces can be weakened with the least loss in third order balance; thus the work of achieving third order balance can be shifted from one surface to another with a smaller tendency to produce higher order aberrations.

---

1. See A. Cox, "A System of Optical Design", Focal Press, p. 129-133.

Output:

The output is as follows:

1. Third order sums - for reference

2. Surface Aberrations

The first two columns are the contributions to the x and y focal plane ray heights due to the third order aberrations. The second two columns are the corresponding values for the fifth and higher order aberrations (determined from the Aldis theorem). The last two columns are the x and y ratios of the total to the third order contributions.

The rays traced in this option fit the standard pattern used in ANALYSIS. The outer two rays of each group have these six columns printed out for each surface; each principal ray does, too. All other rays are represented by the summation of these values in the image surface only.

Error Conditions:

1. "PR RAY MISSED STOP" - (Principal Ray)
"TOTAL REFLECTION AT SURFACE i"
"RAY MISSED SURFACE i"

The rest of the calculation for that ray is deleted and the next ray is run.

GEOMETRICAL FREQUENCY RESPONSE

(Sine Wave or Square Wave)

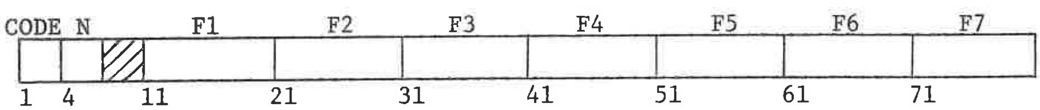
Purpose:

To compute the modulation transfer function (MTF) or square wave response of the lens system ignoring diffraction effects.

Input Data:

If no additional data cards are supplied, geometrical MTF tables will be generated for all field angles and zoom positions, using the focal plane determined by the combination of the paraxial image distance and defocussing. The maximum frequency will be the axial diffraction limit and the increment in frequency will be 1/20th of the axial diffraction limit. Wavelength weights will be those of the system, determined by entries in DATA or CHANGE. Unless specified to the contrary, all clipping apertures will be circular and of the size required to just pass all vignetted field bundles.

Optional data cards may be included following the GEOMETRICAL MTF option card to alter these assumptions. These cards are punched in the following format:



CODE (Col. 1-3)	Mnemonic code indicating particular GEOMETRICAL MTF sub-options. A list of the CODES is given later.
N (Col. 4-6)	Wavelength number for WTW request; code extension for PLOT FOCUS.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields F1-F7; used to enter data for the corresponding zoom positions, i.e. F1 is used for zoom position 1, F2 for zoom position 2, etc.

The following list of CODES identify the GEOMETRICAL MTF optional data; the portion of the CODE underlined indicates the characters which are sensed. The letter N (or the word NO) in any field, on any of the following cards, suppresses the request for that zoom position.

CODES	OPERATION
POSITION	Used in zoom systems to flag those zoom positions which are not to be computed. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the GEOMETRICAL calculation for that zoom position.
WTW n	Wavelength weights. If n is omitted, the values in F1 through F7 are assumed to be weights for the system wavelengths in respective order from long to short. For specific control of each weight in each zoom position, n is the number of the wavelength. The weights are then given in the fields (F1-F7) corresponding to the required zoom positions.
SC	Semi-diameter control; uses the semi-diameters entered as aperture data cards for clear apertures instead of the computed clear apertures. On surfaces where no aperture data was entered, the computed clear apertures are used.

Focus Positions:

Multiple (or modified) focus positions may be specified to display the through-focus (or shifted) characteristics of the image. For a shift of focus only, use the FFO request; for multiple focus positions use NFO, FFO, IFO.

NFO	Number of focus positions requested. Enter a value of 1 to 9 in the required fields (F1 -F7).

FFO — Shift of focus for first focus position as measured from the nominal focus described above.

IFO — The increment in focus to be added to the value of FFO to generate the additional focus positions.

Frequencies:

Geometrical MTF is often required at different frequencies than the default conditions provide. Enter both the MFR and IFR requests to modify the range and spacing to the desired values.

MFR — The maximum frequency in line pairs per millimeter for which the response is required.

IFR — The increment of frequency between each successive printout of response.Must be 1/30th of MFR or larger.

Graphic Output:

Unless requested, no graphical output is generated. Graphical output is triggered by a PLOT or PLOT FOCUS request. Up to 10 of these requests can be used.

a. Modulation vs. Frequency

A PLOT request will generate a single graph of modulation vs. frequency for each zoom position , with all field angles for a given zoom position overlayed on that plot. If multiple focus positions have been calculated, this is done for the position in the middle (NFO odd) or to the left of middle (NFO even).

Usually, plots are desired only for one focus position which has been chosen from a prior run. A specific focus position is selected by using a FOCUS request, with the value of the focus position entered in the fields for each zoom position. Typically, then, unless only one focus position has been calculated, both the PLOT and FOCUS requests will be used, and in that order.

Finally, if the range of frequencies to be plotted is smaller than the range which is calculated, a SPAN request may be used to specify the maximum frequency desired on the plot.

PLOT — Initiates the plotting of modulation vs. frequency graphs.

FOCUS — Specifies the focus position for which plot is requested. Up to 10 focus requests may follow a PLOT request.

SPAN — Specifies the value of the highest frequency plotted, if it is to be different from the maximum calculated frequency. There can be one SPAN request for each FOCUS request.

b. Modulation vs. Focus

For depth of focus studies, a PLOT FOCUS request will generate a single graph of modulation vs. focus for each zoom position, with all field angles for a given zoom position overlayed on that plot. If no specific frequencies are requested, the first frequency at all field angles (both S and T) will be included. It is therefore desirable to limit the number frequencies to just those on which quality judgements are to be made; this is done by FREQUENCY requests. Typically, then, both the PLOT FOCUS and FREQUENCY requests will be used together.

PLOT FOCUS — Initiates the plotting of modulation vs. focus graphs. Uses all focus positions included in the calculation.

FREQUENCY — Specifies the frequency at which the plot is requested. Up to 10 FREQUENCY requests may follow a plot request.

c. Miscellaneous Plot Controls

It may be desirable to temporarily change the title or remove the request to overlay angles. These are done with:

TITLE n — Temporary title; characters in columns 21-60 (F2,F3,F4,F5) are used. If it is to apply to just one zoom position, enter the zoom position number n in column 11. A title request may be entered for each position.

OVERLAY — If NO is placed in any field (F1-F7) then separate plots for each field angle are drawn for that zoom position in standard report form.

Special Computations:

GAUSS — Smoothing is done with the equivalent of an extremely small spot of Gaussian shape at all times. The default value is approximately 1/200 of the image height or width. If simulation of the imaging of an object of this form (such as a CRT display) is required, F1 (through F7) should contain the diameter at which the intensity is 50% of the peak.

LINE — Prints out the line spread function and edge gradient.

QUADRANT — Scanned response of a quadrant detector. Prints the ratio of responses from the two halves of the detector as a function of scan position. Scanning is done for both X and Y directions, assuming proper coupling of the quadrants. Entries in the desired fields (F1-F7) are the size of the scan steps to be taken across the image. Up to 20 QUADRANT requests may be used.

RESPONSE — Quadrant detector positions for a requested value of response and its reciprocal. For example,

```
     RES          .25
```

will give the two scan positions for which the response is .25 and 4.0. Results are given for both x and y directions. Up to 20 RESPONSE requests may be used.

SQW — Request for square wave results. Assumes object is a square wave target rather than sine wave.

Function:

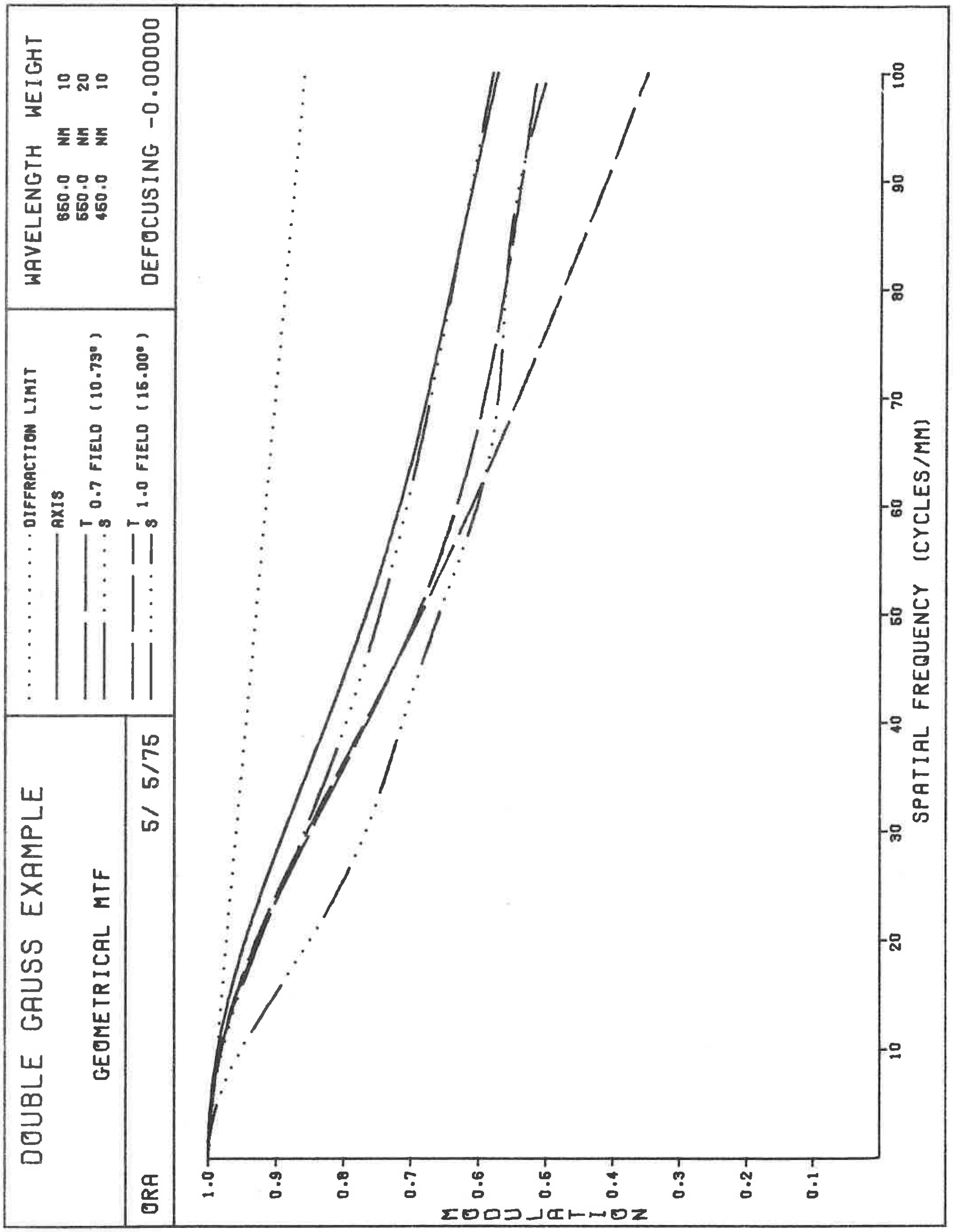
Computation of the geometrical response for both radial and tangential lines is made for all focus positions at each field angle. The relative illumination of each field position is also computed. This illumination is based on the vignetted aperture only and does not include $cosine^4$ effects.

Output:

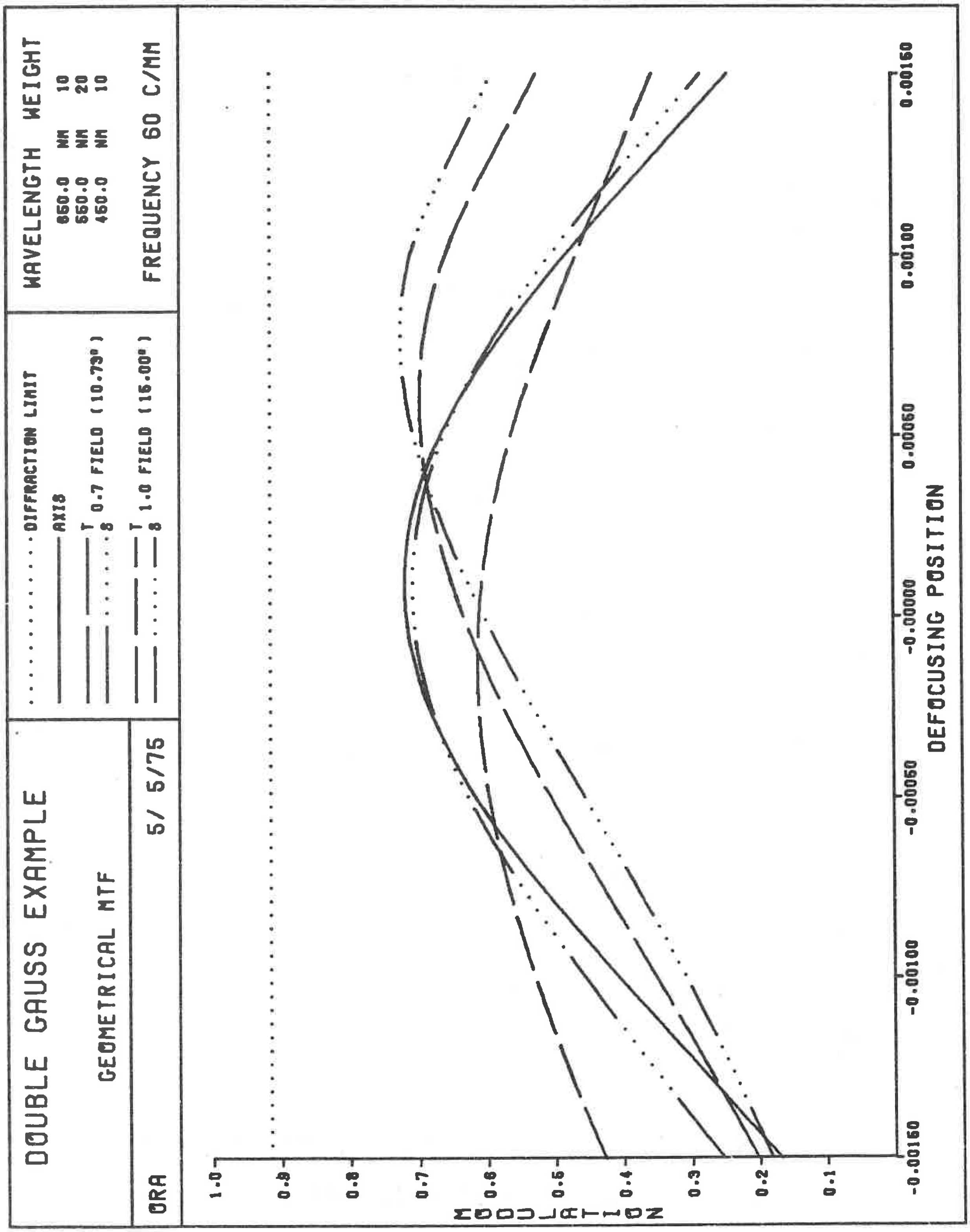
Both a listed and a plotted output are available. The form of the listing output is compact including the radial and tangential responses for all focus positions of one field angle on one page. The response values for a perfect system (diffraction limited) are included to serve as a reference. The relative illumination is listed as well as the distortion. These values are useful since they often appear in optical system specifications along with a quality specification.

Error Conditions:

1. "RAY TRACE ERRORS DURING CLEAR APERTURE TRACE - OPTION TERMINATED" - the meridional rays which are traced to establish the free apertures have encountered either total internal reflection or have missed a surface: correct and rerun.


DOUBLE GAUSS EXAMPLE
GEOMETRICAL MTF
ORA
5/ 5/75
DIFFRACTION LIMIT
AXIS
T
S 0.7 FIELD (10.79°)
T
S 1.0 FIELD (15.00°)
WAVELENGTH WEIGHT
650.0 NM 10
550.0 NM 20
450.0 NM 10
DEFOCUSING -0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10
20
30
40
50
60
70
80
90
100
SPATIAL FREQUENCY (CYCLES/MM)

GEOM-7



DOUBLE GAUSS EXAMPLE
GEOMETRICAL MTF
ORA
5/ 5/75
DIFFRACTION LIMIT
AXIS
T 0.7 FIELD (10.73°)
S
T 1.0 FIELD (15.00°)
S
WAVELENGTH WEIGHT
650.0 NM 10
550.0 NM 20
450.0 NM 10
FREQUENCY 60 C/MM
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
-0.00150
-0.00100
-0.00050
-0.00000
0.00050
0.00100
0.00150
DEFOCUSING POSITION

GEOM-8

RADIAL ENERGY DISTRIBUTION

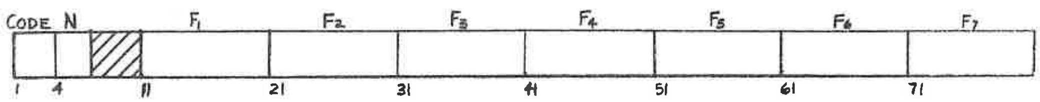
Purpose:

To compute the image diameters within which fixed percentages of light energy are contained. Diffraction effects are ignored.

Input Data:

If no additional data cards are supplied, radial energy distribution tables will be generated for all field angles and zoom positions, using the focal plane determined by the combination of the paraxial image distance and defocussing. These tables give the diameter of the circle which just encloses each successive one-tenth of the image energy (10%,20%, ...90%, 100%). Wavelength weights will be those of the system, determined by entries in DATA or CHANGE. Unless specified to the contrary, all clipping apertures will be circular and of the size required to just pass all vignetted field bundles.

Optional data cards may be included following the RADIAL ENERGY DISTRIBUTION option card to alter these assumptions. These cards are punched in the following format:



CODE (Col. 1-3)	Mnemonic code indicating particular RADIAL ENERGY sub-options. A list of the CODES is given later.
N (Col. 4-6)	Wavelength number for WTW request.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields F1-F7; used to enter data for the corresponding zoom positions, i.e. F1 is used for zoom position 1, F2 for zoom position 2, etc.

The following list of CODES identify the RADIAL ENERGY optional data; the portion of the CODE underlined indicates the characters which are sensed. The letter N (or the word NO) in any field, on any of the following cards, suppresses the request for that zoom position.

CODES	OPERATION
POSITION	Used in zoom systems to flag those zoom positions which are not to be computed. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the RADIAL ENERGY calculation for that zoom position.
WTW n	Wavelength weights. If n is omitted, the value in F1 through F7 are assumed to be weights for the system wavelengths in respective order from long to short. For specific control of each weight in each zoom position, n is the number of the wavelength. The weights are then given in the fields (F1-F7) corresponding to the required zoom positions.
SC	Semi-diameter control; uses the semi-diameters entered as aperture data cards for clear apertures instead of the computed clear apertures. On surfaces where no aperture data was entered, the computed clear apertures are used.

Focus Positions:

Multiple (or modified) focus positions may be specified to display the through -focus (or shifted) characteristics of the image. For a shift of focus only, use the FFO request; for multiple focus positions use NFO, FFO, IFO.

NFO	Number of focus positions requested. Enter a value of 1 to 9 in the required fields (F1-F7).
FFO	Shift of focus for first focus position as measured from the nominal focus described above.
IFO	The increment in focus to be added to the value of FFO to generate the additional focus positions.

Special Requests:

PER	(z)	Entry of requested percentage of energy. Up to 10 PER requests may be entered; the output will only occur for these entered values. If no PER entries are made, the tables will be printed for the spot diameters at 10%, 20%. . . 90%, 100% of encircled energy. Values are entered as integers (i.e., 10 means 10%).
COORDINATES		Each circle (i.e., the 10% energy, 20%, etc.) is moved to find the true circle encompassing the stated percentage of energy. If it is desired to know where the center of each of these circles is located, then by using a COO card, the coordinates of these centers will be printed. For centered systems only the Y coordinate is printed, since the X value is always zero.
XSCAN YSCAN		For decentered systems normally both an X and Y scan is done to determine the center of each circle; with systems symmetrical about the Y axis, no X scanning is done. With a YSCAN request only the Y scan is done; with XSCAN, only the X scan is done. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the scan request for that zoom position.

Function:

The image diameters are computed for 10% intervals of energy up to 100%. A scanning procedure insures that the resultant diameters are minimums for each percentage and focus position.

Output:

A compact listing gives the spot diameters for all energy percentages as a function of focus position. Results for up to three field angles are listed on a single page; additional field angles appear on the next page. See example.

Error Conditions:

1. "RAY TRACE ERRORS DURING CLEAR APERTURE TRACE - OPTION TERMINATED" - the meridional rays which are traced to establish the free apertures have encountered either total internal reflection or have missed a surface; correct and rerun.

(z) Zoomable

3/8/77 R A D I A L E N E R G Y D I S T R I B U T I O N POSITION 1

SPOT DIAMETERS

DOUBLE GAUSS EXAMPLE

WAVELENGTH	650.0 NM	550.0 NM	450.0 NM
WEIGHT	10	20	10

FIELD	PCT	FOCUS -0.00400	-0.00300	-0.00200	-0.00100	-0.00000	0.00100	0.00200	0.00300	0.00400
0.00 YN 0.0 DEG										
	10	0.000778	0.000586	0.000418	0.000139	0.000038	0.000031	0.000154	0.000318	0.000495
	20	0.000985	0.000747	0.000457	0.000204	0.000057	0.000065	0.000298	0.000562	0.000768
	30	0.001144	0.000853	0.000574	0.000318	0.000076	0.000134	0.000413	0.000731	0.001019
	40	0.001287	0.000980	0.000666	0.000392	0.000103	0.000172	0.000500	0.000897	0.001248
	50	0.001406	0.001075	0.000724	0.000418	0.000136	0.000246	0.000603	0.000987	0.001389
	60	0.001572	0.001181	0.000805	0.000427	0.000185	0.000291	0.000666	0.001070	0.001483
	70	0.001795	0.001344	0.000891	0.000487	0.000213	0.000324	0.000722	0.001115	0.001539
	80	0.002010	0.001528	0.001079	0.000631	0.000276	0.000341	0.000738	0.001171	0.001600
	90	0.002410	0.001920	0.001429	0.000939	0.000448	0.000562	0.000976	0.001386	0.001826
	100	0.002966	0.002453	0.001940	0.001428	0.000915	0.000694	0.001114	0.001547	0.001993
0.71 YN 10.7 DEG										
	10	0.000505	0.000356	0.000217	0.000086	0.000031	0.000076	0.000180	0.000304	0.000445
	20	0.000709	0.000509	0.000314	0.000133	0.000073	0.000134	0.000286	0.000489	0.000665
	30	0.000867	0.000632	0.000401	0.000187	0.000094	0.000175	0.000351	0.000605	0.000832
	40	0.001014	0.000747	0.000493	0.000239	0.000120	0.000217	0.000422	0.000667	0.000957
	50	0.001145	0.000865	0.000576	0.000293	0.000147	0.000265	0.000489	0.000771	0.001066
	60	0.001309	0.000985	0.000681	0.000370	0.000191	0.000302	0.000553	0.000857	0.001181
	70	0.001494	0.001144	0.000799	0.000474	0.000245	0.000357	0.000639	0.000961	0.001298
	80	0.001713	0.001334	0.000952	0.000575	0.000324	0.000404	0.000719	0.001045	0.001399
	90	0.001993	0.001605	0.001211	0.000822	0.000456	0.000495	0.000816	0.001168	0.001541
	100	0.002869	0.002422	0.001958	0.001504	0.001056	0.000748	0.001101	0.001500	0.001899
1.00 YN 15.0 DEG										
	10	0.000387	0.000272	0.000175	0.000079	0.000039	0.000076	0.000140	0.000223	0.000308
	20	0.000592	0.000427	0.000269	0.000126	0.000076	0.000104	0.000213	0.000323	0.000458
	30	0.000769	0.000557	0.000361	0.000170	0.000102	0.000141	0.000253	0.000405	0.000616
	40	0.000907	0.000684	0.000460	0.000244	0.000142	0.000173	0.000316	0.000502	0.000714
	50	0.001096	0.000844	0.000589	0.000346	0.000203	0.000230	0.000366	0.000565	0.000815
	60	0.001274	0.001007	0.000730	0.000468	0.000245	0.000287	0.000421	0.000633	0.000896
	70	0.001494	0.001206	0.000895	0.000582	0.000341	0.000345	0.000507	0.000694	0.000976
	80	0.001787	0.001456	0.001141	0.000833	0.000517	0.000428	0.000579	0.000813	0.001077
	90	0.002188	0.001811	0.001526	0.001186	0.000841	0.000533	0.000662	0.000916	0.001206
	100	0.003885	0.003423	0.002961	0.002499	0.002037	0.001579	0.001209	0.001136	0.001465

SPOT DIAGRAM

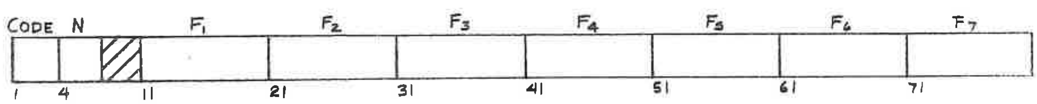
Purpose:

To represent the geometrical structure of the image.

Input Data:

If no additional data cards are supplied, spot diagrams will be generated for all field angles and zoom positions, using the focal plane determined by the combination of the paraxial image distance and defocussing. The scale factor will be .001 units/inch. Wavelength weights will be those of the system, determined by entries in DATA or CHANGE. Wavelength weights determine the number of spots plotted; best appearance usually is obtained when the wavelength weights total about 100. The system weights may not meet this criterion. Unless specified to the contrary all clipping apertures will be circular and of the size required to just pass all vignetted field bundles. The title will be the first 40 characters of the system title card entered in DATA or CHANGE.

Optional data cards may be included following the SPOT DIAGRAM card to alter these assumptions. These cards are punched in the following format:



CODE (Col. 1-3)	Mnemonic code indicating particular SPOT sub-options. A list of the CODES is given later.
N (Col. 4-6)	Wavelength number for WTW request.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields F1-F7; used to enter data for the corresponding zoom positions, i.e. F1 is used for zoom position 1, F2 for zoom position 2, etc.

The following list of CODES identify the SPOT optional data; the portion of the CODE underlined indicates the characters which are sensed. The letter N (or the word NO) in any field, on any of the following cards, suppresses the request for that zoom position.

CODES	OPERATION
POSITION	Used in zoom systems to flag those zoom positions which are not to be computed. (The character N, or NO entered in the data field corresponding to a given zoom position will suppress the calculation for that zoom position).
SF	Scale factor. To alter the default of .001 units/inch on the plot, enter the desired values in F1 through F7.
WTW n	Wavelength weights. If n is omitted, the values in F1 through F7 are assumed to be weights for the system wavelengths in respective order from long to short. For specific control of each weight in each zoom position, n is the number of the wavelength. The weights are then given in the fields (F1-F7) corresponding to the required zoom positions. The value of the weight is proportional to the number of rays attempted; this is approximately 1.5 rays/unit weight. Up to 1680 total rays which clear the apertures can be included for each field point.
SC	Semi-diameter control; uses the semi-diameters entered as aperture data cards for clear apertures instead of the computed clear apertures. On surfaces where no aperture data was entered, the computed clear apertures are used.
TITLE n	Temporary title; characters in columns 21-60 (F2,F3,F4,F5) are used. If it is to apply to just one zoom position, enter the zoom position number n in column 11. A title request may be entered for each position.

Focus Positions:

Multiple (or modified) focus positions may be specified to display the through-focus (or shifted) characteristics of the image. For a shift of focus only, use the FFO request; for multiple focus positions use NFO, FFO, IFO.

NFO	Number of focus positions requested. Enter a value of 1 to 9 in the required fields (F1 - F7).
FFO	Shift of focus for first focus position as measured from the nominal focus described above.
IFO	The increment in focus to be added to the value of FFO to generate the additional focus positions.

Added Output:

LIST	Printed ray coordinates

Function:

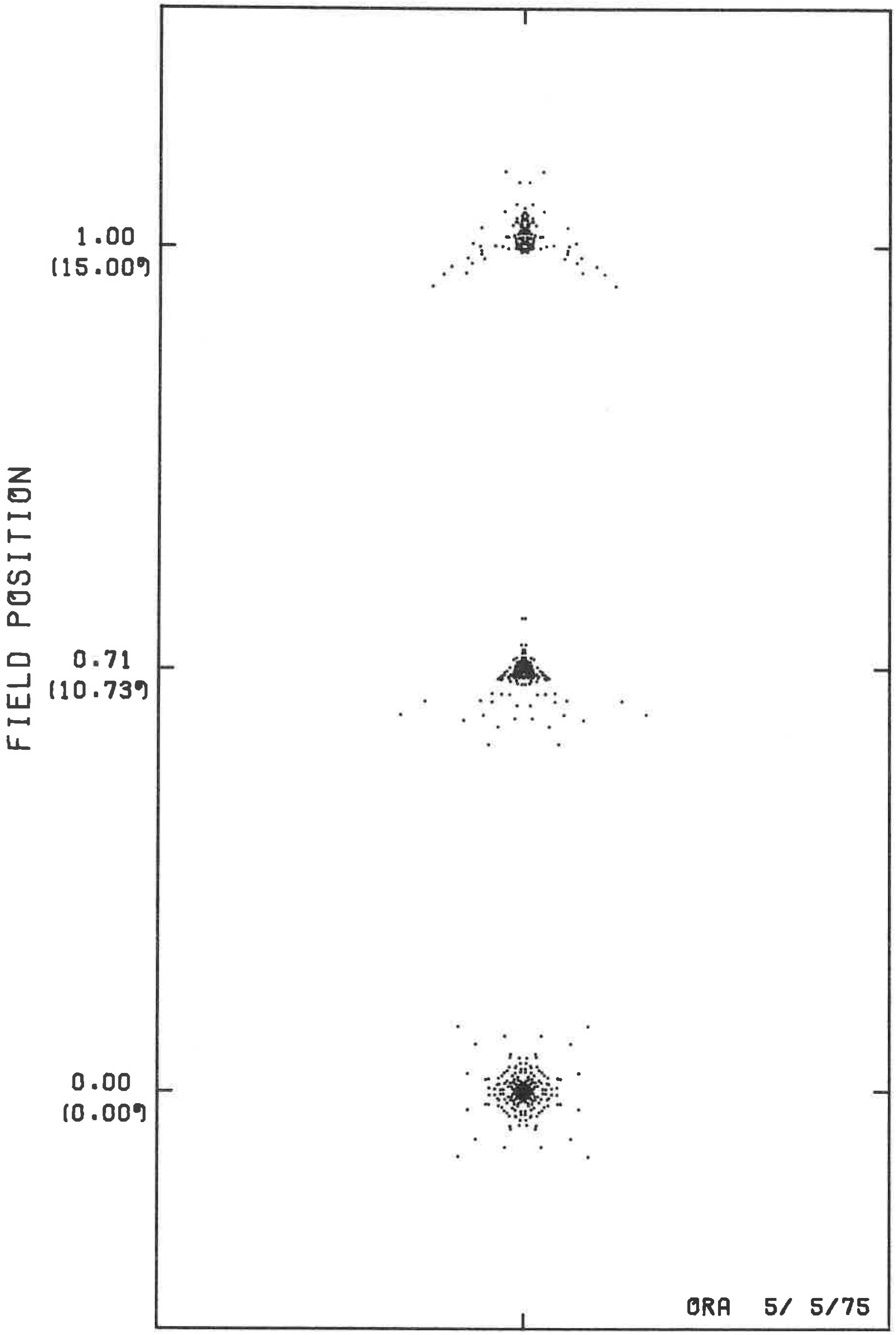
Rays which are evenly spaced in the entrance pupil plane are traced to show their distribution in the image plane.

Output:

The spot diagrams, provided by the plotter, are the principal output. If requested, a printed listing of all rays is provided. A table showing the number of rays traced, and the number of rays plotted is printed on the line printer.

Error Conditions:

If any rays are too far from the center to be conveniently plotted, they are omitted and an error message is printed.



DOUBLE GAUSS EXAMPLE

SPOT- 4

SCALE: 1 INCH = 0.00100 IN

EVALUATION-WAVE
OPTICAL PERFORMANCE

WAVEFRONT CHARACTERISTICS

Purpose:

To calculate wavefront characteristics of the system, including RMS wavefront errors with and without optimum focus and the resulting Strehl definition.

Operations and Input Data:

If no input data is provided, one table is produced for each zoom position giving:

1. For each field angle, the lateral and focus shift of the reference sphere center, the resulting RMS and Strehl definition under two assumptions:

   a. Best individual focus (unrelated to any other image points)

   b. Best composite focus (connected to other image points in a specified manner)

   Each field angle weights the wavelengths according to the system weights unless modified.

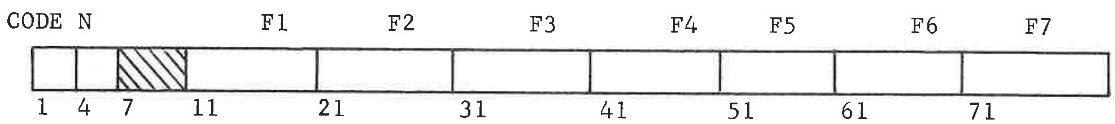
2. The composite RMS value over the fields for that one zoom position, for the best composite focus

At the end, the composite RMS value over all zoom positions is printed, using the relative weighting given in the wavelength weights.

The composite focus is calculated assuming (unless altered) that all fields of all zoom positions share a common focal surface.

Upon request a through-focus table of RMS can be generated, the independent coupling of fields and zoom positions for composite focus can be specified, and weights for field and wavelengths can be entered.

The following format is used:



CODE	(Col. 1-3)	Mnemonic code indicating particular WAVE requests. A list of the CODES is given later.
N	(Col. 4-6)	This field is used as a place to enter the wavelength or field number. (CODES which have this capability will be indicated by a lower case letter n after the CODE).
F1 . . . F7	(Col. 11-20) (Col. 71-80)	Data fields F1 - F7; used to enter data for the corresponding zoom positions, i.e., F1 is used for zoom position 1, F2 for zoom position 2, etc.

The following list of CODES identify the WAVE optional data; the portion underlined indicates the characters which are sensed. Some of these optional cards are flags for various requests - on any of these if the flag is to pertain only to certain zoom positions, the letter N (or the word NO) in the corresponding columns will serve to flag the opposite condition for that zoom position.

CODES	OPERATION
POSITION	Used in zoom systems to flag those zoom positions which are to have RMS tables calculated and printed. The character "N" (or word NO) entered in the data field corresponding to a given zoom position will suppress the RMS printouts for that position.
SC	Semi-aperture control; uses the semi-aperture entered on the surface data cards for clear apertures instead of computed clear apertures. On surfaces where no semi-aperture is entered, the computed clear aperture is used. Semi-apertures which have been entered as negative values are treated as obscurations when this request is used.

Weights:

WTF n

Weight of field position n. If n is omitted, the values entered are interpreted as weights on all field positions of the first zoom position. The default weights are:

WTF1 = 1.0
WTF2 = .875
WTF3 = .5
WTF4 = .3
WTF5 = .1

WTW n

Weight on wavelength n. If n is omitted the values entered are interpreted as weights on all wavelengths for the first zoom position. The wavelengths are assumed to be in the order from red to blue - long wavelength to short. The default weights are obtained from the specification data.

Focus Coupling:

CPL n

Coupling pattern to define focus relations between field angles and zoom positions for composite RMS; the values apply to field n. Values in F1 - F7 are integers representing pairings or groupings of fields to be focused as a group. For example,

CPL 1	1	5	1
CPL 2	1	5	1
CPL 3	1	5	1

would focus as a group the three fields of zoom positions 1 and 3; the three fields for zoom position 2 are focused as a separate group. Note that the values chosen for groups (1 and 5) are unique to the group, but otherwise arbitrary. The default is equivalent to filling in all values with the same number; all fields of all zoom positions are focused together.

Optional Through-Focus Tables:

Entry of any of the following 3 requests will cause the inclusion of through-focus tables.

NFO — This is the number of focus positions for which the RMS values are to be calculated. The default value is 1. The maximum value is 9.

FFO — This is the value by which the back focus is to be defocused for the first focus position.

IFO — This is the delta value by which the back focus is to be incremented from the first focus position for NFO times.

These tables are output, one page per zoom position, and include a composite RMS over the fields according to the field weights.

Console Switches

Sense Switch 1 will cause exit from this option.

Special Error Conditions

1. "* STREHL INTENSITY LESS THAN .64" - RMS errors are large enough (more than .1) that the Strehl intensity is no longer directly related to RMS.
2. "NOTE - MULTI-WAVELENGTH COMPUTATIONS USE A COMMON PHASE SHIFT ADJUSTMENT WITH FOCUS. FOCUS TABLE RESULTS WILL NOT PRECISELY MATCH THE COMPOSITE OF SEPARATE WAVELENGTH RUNS." - Explanatory note of minor computational differences between a multi-wavelength run and the combination of seperate runs. The differences are generally insignificant relative to normal RMS values.

POINT SPREAD FUNCTION

Purpose:

To compute the characteristics of the image of a point including the effects of diffraction.

Input Data:

This option computes the wave aberration of the system and, by Fast Fourier Transform (FFT), the diffraction image shape in the designated focal plane integrated over the wavelengths according to the weights assigned. This image patch is represented in the computer by intensity values in a grid across the image with the chief ray or optical axis as the center point of the grid.

Since the area represented by the output display is only about 10 times the Airy disc diameter, it is apparent that this program is unsuited to systems with large aberrations. For these, use the SPOT DIAGRAM option.

Due to the nature of the FFT process, if the pupil function is represented by many points, such as the default grid interval provides, the diffraction image (say, the Airy disc) will be represented by few points. Thus, asking for a smaller output grid spacing to enlarge the image size will provide more detail in the output but will use less data to represent the lens. This trade-off should be understood when choosing grid sizes. The default grid size should usually be the largest value used while the smallest should be one-half of it. Values outside this range should be recognized as introducing increasingly large errors.

Due to the fact that points on a square grid are used to represent the pupil function which is approximately circular in symmetry, artifacts appear in the output when too small a grid interval is used. Thus, the default grid spacing, for a rotationally symmetric system will produce a rather precise display of the Airy disc. A grid spacing of one-half this amount will enlarge the image but use one fourth as much data to represent the lens. The square grid representation of the pupil function now does not look so circular; it has flats and steps of twice the size on it. This produces slight distortions (a few per cent) in energy in a four-fold symmetric pattern which may give an esthetically unpleasant appearance to what should be a rotationally symmetric image.

Specifically, the default assumptions are:

1. All field angles and zoom positions will be included.

2. Wavelength weights will be those of the system, determined by entries in DATA or CHANGE.

3. All clipping apertures will be circular and of the size required to just pass all vignetted field bundles.

4. The focal plane is determined by the combination of the paraxial image distance and defocussing.

5. The grid size is chosen to be

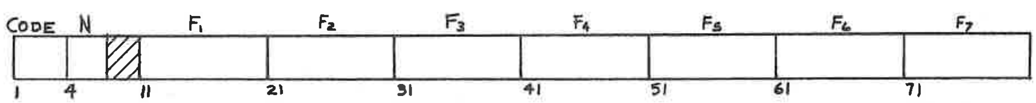
$$\frac{\lambda s \cdot f/no}{2}$$

which results in the Airy disc diameter for the short wavelength being spread over 4.880 output grid elements.

6. Intensity across the pupil is assumed to be uniform.

7. Output is to be only the printer display of intensity relative to 100 for the peak value at each field angle (INTENSITY request).

Optional data cards may be included following the POINT SPREAD FUNCTION option card to alter these assumptions. These cards are punched in the following format:



CODE (Col. 1-3)	Mnemonic code indicating particular POINT SPREAD sub-options. A list of the CODES is given later.
N (Col. 4-6)	Wavelength number for WTW request.
F1 (Col. 11-20) . . . F7 (Col 71-80)	Data fields F1-F7; used to enter data for the corresponding zoom positions, i.e. F1 is used for zoom position 1, F2 for zoom position 2, etc.

The following list of CODES identify the POINT SPREAD optional data; the portion of the CODE underlined indicates the characters which are sensed. The letter N (or the word NO) in any field, on any of the following cards, suppresses the request for that zoom position.

CODES	OPERATION
POSITION	Used in zoom systems to flag those zoom positions which are not to be computed. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the POINT SPREAD calculation for that zoom position.
WTW n	Wavelength weights. If n is omitted, the values in F1 through F7 are assumed to be weights for the system wavelengths in respective order from long to short. For specific control of each weight in each zoom position, n is the number of the wavelength. The weights are then given in the fields (F1-F7) corresponding to the required zoom positions.
SC	Semi-diameter control; used the semi-diameters entered as aperture data cards for clear apertures instead of the computed clear apertures. On surfaces where no aperture data was entered, the computed clear apertures are used.
PROPAGATE	Used in conjunction with a focus shift where the out of focus spot is much larger than the Airy disc. When this option is selected a near-field propagation procedure is used instead of the normal far field diffraction calculation. Typically, this option should be used when the out-of-focus spot is larger than half the output array. If no grid interval is specified (see GRID option), it will be selected so that the geometrical spot will fill about half the output array. Note that this option breaks down, and therefore cannot be used, for zero focus shift.

Focus Shift:

A shifted focus position may be specified to depart from the nominal value.

FOCUS	Enter values representing the desired shift for each zoom position. Only one FOCUS request per run is permitted; multiple image positions must be analysed in multiple runs.

Image Plane Interval:

The default grid interval may not be a convenient size. It can be increased up to a factor of two to shrink the relative size of the image. The lens will be represented by more data which will take longer to calculate by the square of the scale change. The grid interval can also be decreased to expand the relative size of the image. It is unwise to do this beyond a factor of two because the lens will be represented by very few data points in the wavefront, especially in the long wavelengths. The artifacts mentioned previously will also become evident.

The grid size is by the following request:

GRID	The interval in the focal plane between output data numbers.

Gaussian Apodization:

To transform the uniformly illuminated pupil into one with a Gaussian intensity profile, use:

PUA
PUX
PUY

Superimposes an amplitude apodization* of Gaussian cross section across the pupil. It can be circular or elliptical in shape. The Gaussian is described by the absolute (not normalized) entrance pupil coordinates of the major and minor axes at which the amplitude reaches a certain value. The value on the PUX card is the X pupil coordinate (for Y=0) at which the amplitude reaches the value given on the PUA card. The PUY card should contain the Y pupil coordinate (for X=0) at which the amplitude reaches the value given by the PUA card.

Thus	PUX	0.2
	PUY	0.3
	PUA	0.1

would indicate that at (0.2, 0) and at (0, 0.3) in the pupil the amplitude would be 10% of the value at (0,0). A rotationally symmetric apodization is obtained if the PUX value equals the PUY value, or if the PUY value is omitted, a rotationally symmetric apodization is assumed.

*Note that this is the amplitude, which is the square root of the desired intensity distribution. Thus, the example given would be used to simulate a measured intensity of .01 at each of the designated pupil coordinates.

A one dimensional apodization is obtained by making one value much larger than the other. For example:

PUX	0.3
PUY	100000.

Output Requests:

Wave Aberration.

WFR — Output of wave aberration in the exit pupil is produced, separately for each wavelength and field angle. The grid spacing is that required to give the required grid in the diffraction image when the FFT process is used.

Intensity (Choose one - INTENSITY is the default).

INTENSITY — Output of relative intensity distribution in the image, on a scale of 100.

If a numerical value is placed in a data field (F1-F7), the intensity is scaled to the value read in, rather than to 100.

INTENSITY STREHL — The presence of the word STREHL in any of the data fields (F1-F7) gives output of the intensity distribution in the image, (for that zoom position) relative to a perfect lens image whose peak would be 100. This is valid for both monochromatic and polychromatic images.

INTENSITY DB — The presence of the symbol DB starting in any of the data fields (F1-F7) gives output of the relative intensity distribution in the image, for this zoom position, expressed as db fall off from the peak value.

Image Phase Distribution.

PHASE — Output of phase distribution in image. See Born and Wolf "Principles of Optics", p. 445-448 for discussion of phase behavior as a function of focus.

Altered Display.

The normal output for the above requests produce printer output for each zoom position which is dimensionally proportionate in X and Y to the image plane or exit pupil dimensions. To alter this use:

COMPACT	Suppresses blank lines in printer output.
LIST	Suppresses printer plots in zoom positions corresponding to fields (F1-F7) with N or NO entered. Useful for suppressing printed output on graphical runs and special image analyses.

Special Image Analyses.

LINE	Output of line spread function and edge gradient for X and Y scan of the diffraction image.
MTF	Output of modulation transfer function for X and Y scans of the diffraction image. (This is equivalent to the results computed by another, usually more accurate, method in DIFFRACTION MTF). The frequencies are values which result from the choice of image grid interval.
DEX DEY	Output of energy falling within a detector of designated size and shape centered about the chief ray. If DEX, only, is entered, the detector is circular of diameter DEX. If DEX and DEY are entered, the detector is rectangular, with the X (skew) dimension equal to the value on the DEX card, and the Y (meridional) dimension equal to the value on the DEY card.
ENC	Output of encircled energy image diameters within which fixed percentages of light energy are contained. Each circle is shifted in the Y direction to find the minimum diameter enclosing the given percentage. The Y coordinate of the center of the circle is also printed.
PER	Entry of requested percentage of energy. Up to 10 PER requests may be entered; the output will only occur for these entered values. If no PER entries are made, the tables will be printed for the spot diameters at 10%, 20%...., 90% of encircled energy. Values are entered as integers (i.e., 10 means 10%). Note that 100% is not meaningful and should not be entered since the diffraction spot goes to infinity.

Graphic Output:

Unless requested, no graphical output is generated. Graphical output is triggered by a PLOT or CONTOUR request. The title, unless altered, is derived from the first 40 characters of the title card entered in DATA or CHANGE. To alter, use:

TITLE n — Temporary title; characters in columns 21-60 (F2, F3, F4, F5) are used. If it is to apply to just one zoom position, enter the zoom position number n in column 11. A title request may be entered for each position.

a. Oblique Projection Plots

PLOT — Causes WFR or INTENSITY results to be output in "three dimensional" oblique projection plots.

This type of output requires prior entry of a WFR or INTENSITY request. For a WFR request the vertical height is scaled so that maximum deviation for all field angles of a zoom position is one inch. This may be reduced to improve visibility of the surface or altered to match a desired scale.

Use:

SF — Vertical scale factor; enter the number of waves to correspond to one inch of vertical height in the field corresponding to the desired zoom position (F1-F7). These values will be overridden if any entered value would cause a vertical excursion of greater than 2 inches; the scale will be reduced to allow 2 inches as the maximum value.

There is automatic scaling for the oblique projection plots of INTENSITY. The INTENSITY, INTENSITY DB, and INTENSITY STREHL plots are drawn so that 100% has a vertical deviation of 4 inches. For INTENSITY STREHL, the vertical height is less than 4 inches for a non-perfect lens; the vertical height, therefore, is a measure of absolute intensity. The Strehl ratio may be determined by taking the vertical height and dividing by 4.

Occasionally, the detailed structure of the image is hidden by the peaks of the oblique projection plot. To rotate 90° use:

ROTATE — Rotate X, Y coordinates 90°.

b. Contour Plots

CONTOUR — Causes WFR or INTENSITY results to be output in contour "maps".

This requires prior entry of a WFR or INTENSITY request. Unless otherwise requested, the interval between contour lines is chosen to give a maximum of 10 contour levels for the field angle with maximum excursion. This may not be a convenient number, and can be altered by using:

SF — Contour interval. Expressed in waves of aberration for WFR requests; expressed in relative height for INTENSITY requests (10. would place them at 10% intervals). Enter in required zoom position columns (F1-F7).

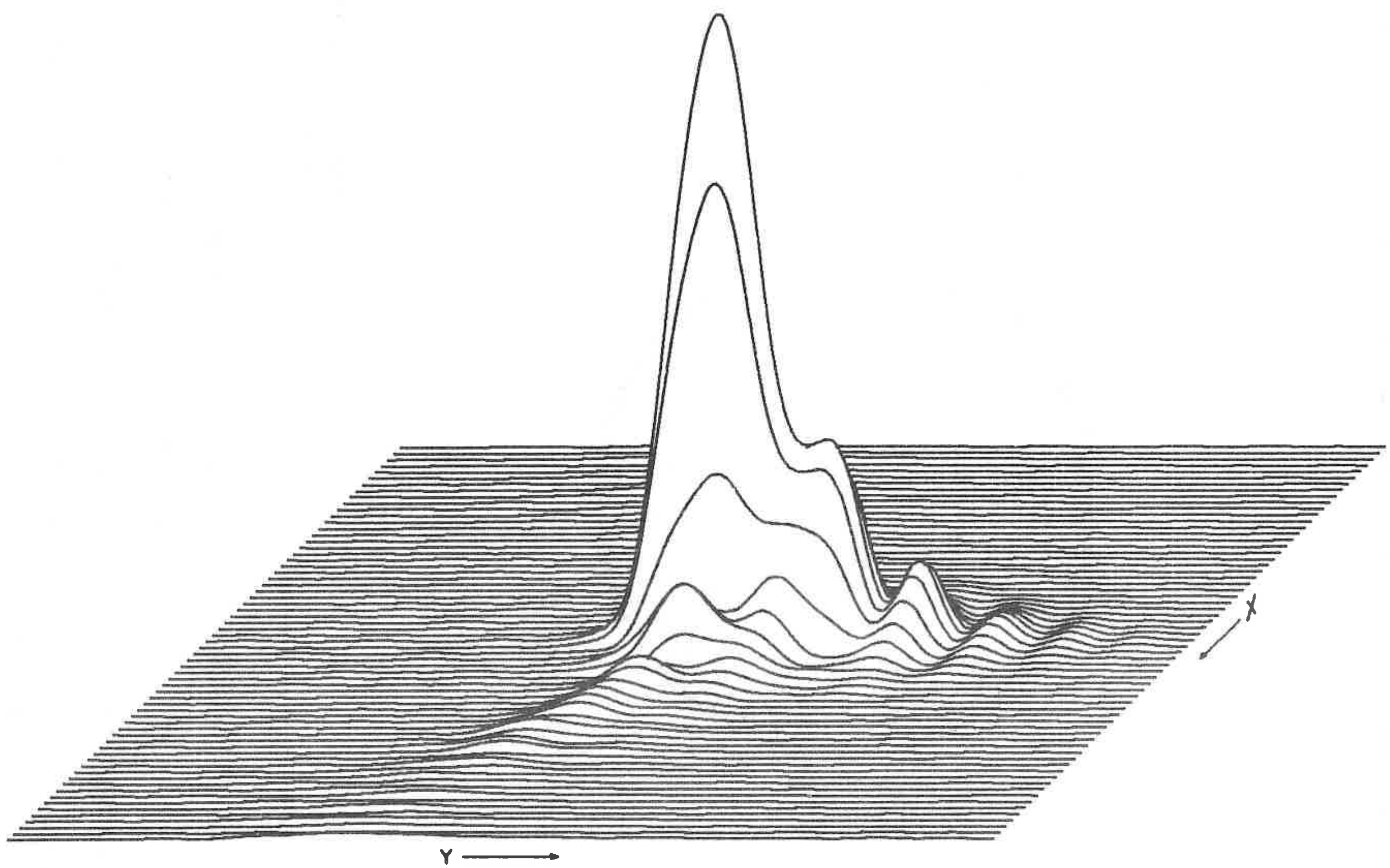
Function and Output:

Computes, by FFT, the diffraction image shape for the designated focal plane. Output and analyses of this image are performed according to the operations requested. The sub-option INTENSITY and PHASE print out values on a two dimension grid which represents the focal plane with the grid interval as specified. The sub-option WFR prints out values on a two dimensional grid representing the exit pupil. The sub-options LINE, MTF, and ENC print out tables of values. The sub-option DEX, DEY prints out the per cent energy falling within the designated detector.

Error Conditions:

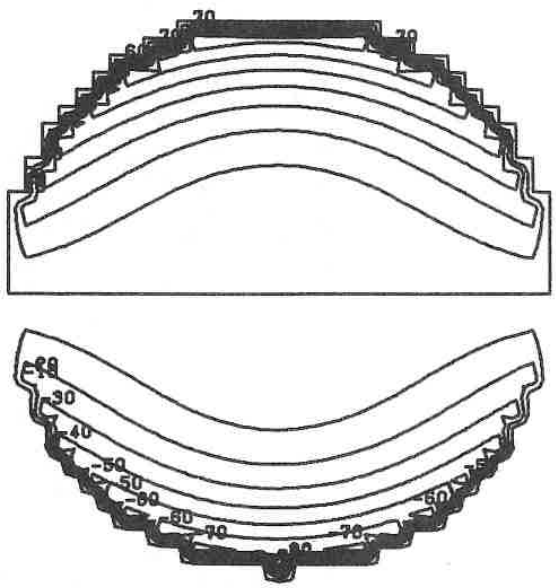
1. "RAY TRACE ERRORS DURING CLEAR APERTURE TRACE - OPTION TERMINATED" - the meridional rays which are traced to establish the free apertures have encountered either total internal reflection or have missed a surface. Correct and rerun.

2. "DETECTOR DIMENSIONS ARE TOO LARGE FOR IMAGE INCREMENT" - some portion of the detector area lies outside of the displayed area.



DOUBLE GAUSS EXAMPLE	DIFFRACTION INTENSITY SPREAD FUNCTION	WAVELENGTH	WEIGHT
	FIELD ANGLE - 15.00 DEGREES	650.0 NM	10
	DEFOCUSING - 0.000000 IN.	550.0 NM	20
ORA 5/ 5/75	HORIZONTAL SCALE - 1 INCH = 0.0001769 IN.	450.0 NM	10

POIN-9



MAX - -0.82
MIN - 0.81

PARABOLIC MIRROR
F/2

WAVE ABERRATION

ORA 5/ 5/75

WAVELENGTH - 500.0 NM

FIELD ANGLE - 0.25 DEGREES

DEFOCUSING 0.000000 IN.

ONE CONTOUR INTERVAL IS 0.10 WAVES

POIN-10

DIFFRACTION FREQUENCY RESPONSE

(Sine Wave or Square Wave)

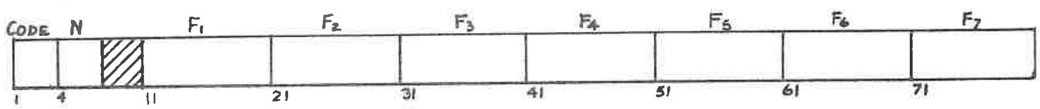
Purpose:

To compute the modulation transfer function(MTF) of the lens system including diffraction effects, assuming either a sine wave object or a square wave object.

Input Data:

If no additional data cards are supplied, diffraction MTF tables will be generated for all field angles and zoom positions, using the focal plane determined by the combination of the paraxial image distance and defocussing. The maximum frequency will be the axial diffraction limit and the increment in frequency will be 1/30th of the axial diffraction limit. Wavelength weights will be those of the system, determined by entries in DATA or CHANGE. Unless specified to the contrary, all clipping apertures will be circular and of the size required to just pass all vignetted field bundles.

Optional data cards may be included following the DIFFRACTION MTF option card to alter these assumptions. These cards are punched in the following format:



CODE (Col. 1-3)	Mnemonic code indicating particular DIFFRACTION MTF sub-options. A list of the CODES is given later.
N (Col 4-6)	Wavelength number for WTW request; code extension for PLOT FOCUS.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields F1-F7; used to enter data for the corresponding zoom positions, i.e. F1 is used for zoom position 1, F2 for zoom position 2, etc.

The following list of CODES identify the DIFFRACTION MTF optional data; the portion of the CODE underlined indicates the characters which are sensed. The letter N (or the word NO) in any field, on any of the following cards, suppresses the request for that zoom position.

CODES	OPERATION
POSITION	Used in zoom systems to flag those zoom positions which are not to be computed. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the DIFFRACTION MTF calculation for that zoom position.
WTW n	Wavelength weights. If n is omitted, the values in F1 through F7 are assumed to be weights for the system wavelengths in respective order from long to short. For specific control of each weight in each zoom position, n is the number of the wavelength. The weights are then given in the fields (F1-F7) corresponding to the required zoom positions.
SC	Semi-diameter control; uses the semi-diameters entered as aperture data cards for clear apertures instead of the computed clear apertures. On surfaces where no aperture data was entered, the computed clear apertures are used.

Focus Positions:

Multiple (or modified) focus positions may be specified to display the through-focus (or shifted) characteristics of the image. For a shift of focus only, use the FFO request; for multiple focus positions use NFO,FFO, IFO.

NFO	Number of focus positions requested. Enter a value of 1 to 9 in the required fields (F1 - F7).

FFO — Shift of focus for first focus position as measured from the nominal focus described above.

IFO — The increment in focus to be added to the value of FFO to generate the additional focus positions.

Frequencies:

Diffraction MTF is often required at different frequencies than the default conditions provide. Enter both the MFR and IFR requests to modify the range and spacing to the desired values.

MFR — The maximum frequency in line pairs per millimeter for which the response is required.

IFR — The increment of frequency between each successive printout of response. This should be between 1/15 and 1/48 of the diffraction limit for proper accuracy. The time of calculation is inversely proportional to the square of the interval. If the system is decentered, or the 45° orientation request is included, the smallest increment allowed is 1/32 of the diffraction cut-off.

Graphic Output:

Unless requested, no graphical output is generated. Graphical output is triggered by a PLOT or PLOT FOCUS request. Up to 10 of these requests can be used.

a. Modulation vs. Frequency

A PLOT request will generate a single graph of modulation vs. frequency for each zoom position, with all field angles for a given zoom position overlayed on that plot. If multiple focus positions have been calculated, this is done for the position in the middle (NFO odd) or to the left of middle (NFO even).

Usually, plots are desired only for one focus position which has been chosen from a prior run. A specific focus position is selected by using a FOCUS request, with the value of the focus position entered in the fields for each zoom position. Typically, then, unless only one focus position has been calculated, both the PLOT and FOCUS requests will be used, and in that order.

Finally, if the range of frequencies to be plotted is smaller than the range which is calculated, a SPAN request may be used to specify the maximum frequency desired on the plot.

PLOT	Initiates the plotting of modulation vs. frequency graphs. Uses all focus positions included in the calculation.
FOCUS	Specifies the focus position for which plot is requested. Up to 10 focus requests may follow a PLOT request.
SPAN	Specifies the value of the highest frequency plotted, if it is to be different from the maximum calculated frequency. There can be one SPAN request for each FOCUS request.

b. Modulation vs. Focus

For depth of focus studies, a PLOT FOCUS request will generate a single graph of modulation vs. focus for each zoom position, with all field angles for a given zoom position overlayed on that plot. If no specific frequencies are requested, the first frequency at all field angles (both S and T) will be included. It is therefore desirable to limit the number frequencies to just those on which quality judgements are to be made; this is done by FREQUENCY requests. Typically, then, both the PLOT FOCUS and FREQUENCY requests will be used together.

PLOT FOCUS	Initiates the plotting of modulation vs. focus graphs. Uses all focus positions included in the calculation.
FREQUENCY	Specifies the frequency at which the plot is requested. Up to 10 FREQUENCY requests may follow a plot request.

c. Miscellaneous Plot Controls

It may be desirable to temporarily change the title or remove the request to overlay angles. These are done with:

TITLE n	Temporary title; characters in columns 21-60 (F2,F3,F4,F5) are used. If it is to apply to just one zoom position, enter the zoom position number n in column 11. A title request may be entered for each position.
OVERLAY	If NO is placed in any field (F1-F7) then separate plots for each field angle are drawn for that zoom position in standard report form.

Optional Forms of Computation:

SQW	Request for square wave results. Assumes object is a square wave target rather than sine wave.
45	Request for additional MTF calculation at a target orientation of 45°, half way between radial and tangential.
PHASE	Request for spatial phase table to be added. Together with the modulus (MTF) table normally printed, this provides the complete OTF. If the 45 request has also been given, the phase table for this orientation will also be included. This request is the only sure way to detect spurious resolution.

RAY — Request to convert the diffraction calculation to a geometrical (ray theoretic) calculation. This provides the special features of this option (45, PHASE and accurate relative illumination calculations) for the geometrical domain as well. Restrictions on frequency increment are removed; calculations, in general, run faster than the corresponding GEOM option. Do not use this request together with SQW; use GEOMETRICAL FREQUENCY RESPONSE option instead.

WFR — Output of wave aberration in the exit pupil is produced, separately for each wavelength and field angle. The grid spacing is that required to give the requested frequencies in the Diffraction MTF calculation for each wavelength. The background around the image is filled in with 9's. For centered systems only half of the wavefront is displayed.

Function:

The diffraction MTF is calculated for radial and tangential lines utilizing H. H. Hopkins method[1] for the numerical evaluation of the auto correlation integral of the pupil function. The canonical pupil coordinates, suggested by Hopkins, are also employed.

For off-axis field positions, an adjustment in the tangential calculation is made to compensate for the error caused by the inclination of the principal ray.

The relative illumination of each field point is computed including all effects of vignetting, pupil expansion and $\cos^4$.

Output:

A compact listing of radial and tangential responses for all focus positions of one field angle is produced on one page. If requested,

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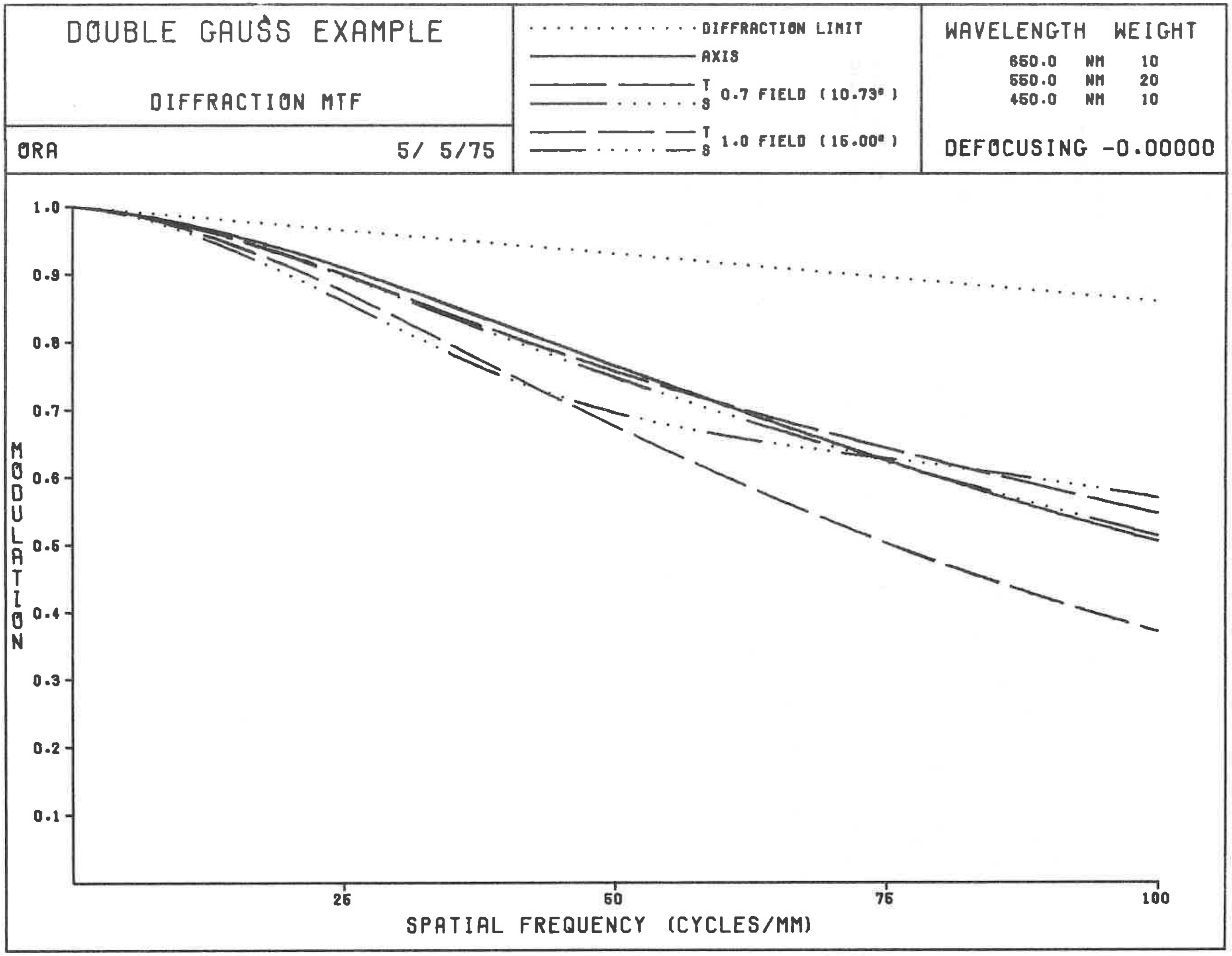
[1] H. H. Hopkins, Proc. Phys. Soc. 70 B 1002 (1957).

the listing for the 45° target orientation will be printed out on the same page. Also, if requested, the phase will be included. For reference, two calculations of the diffraction limit responses are included. The first is the analytical calculation (by formula) for the system wavelengths and f/no.; the second, under the heading OBSCURED, is a numerical calculation using the actual rays traced for the system under evaluation, but with zero wavefront errors. Thus the effects of any vignetting and/or obscurations in the system are included in this calculation. If the SQW request has been included, all values including the diffraction limit responses are converted to square wave response.

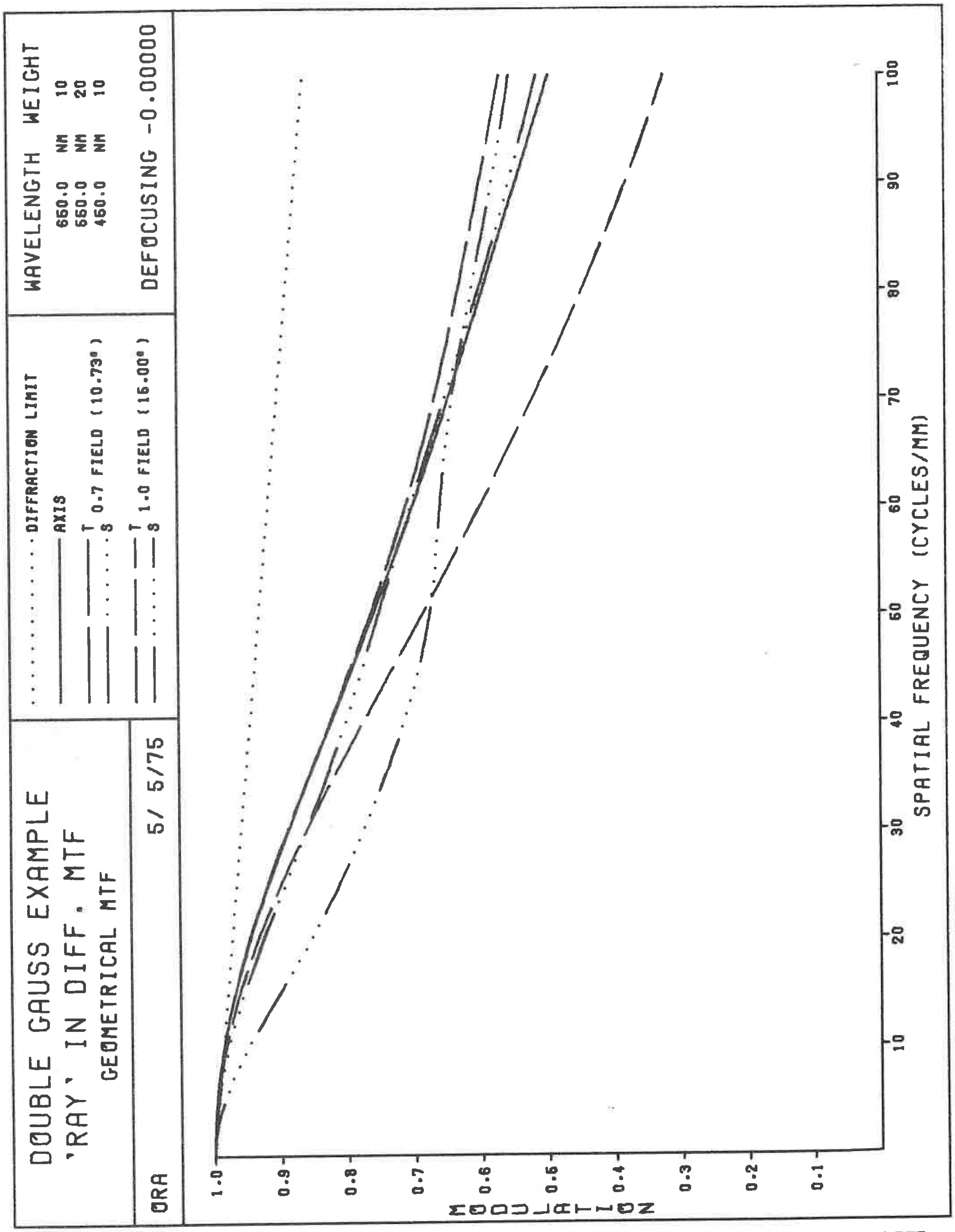
The relative illumination including $\cos^4$ effects and distortion are listed at each field position. Plotted output is produced, if requested.

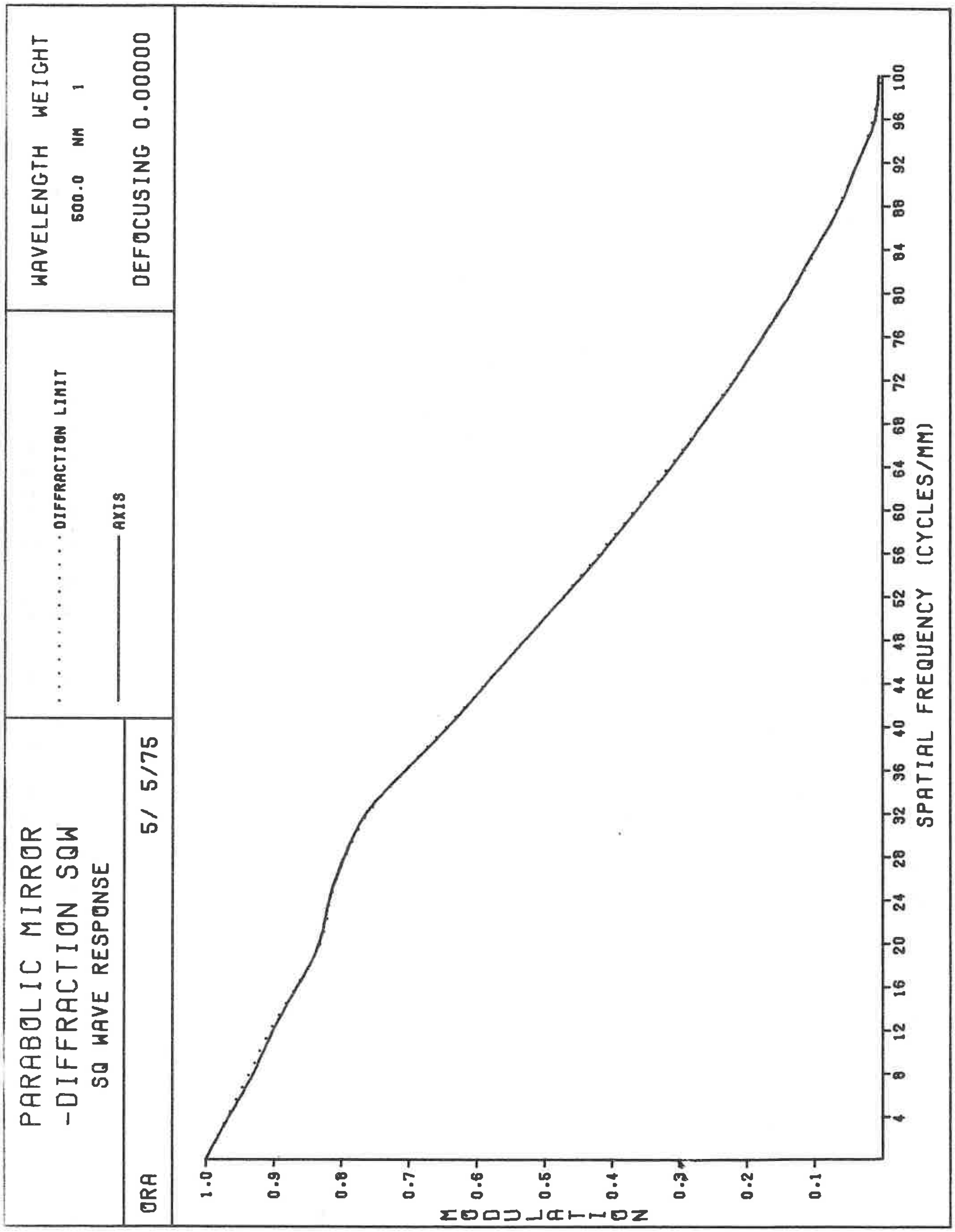
Error Conditions:

1. "RAY TRACE ERRORS DURING CLEAR APERTURE TRACE - OPTION TERMINATED" - the meridional rays which are traced to establish the free apertures have encountered either total internal reflection or have missed a surface; correct and re-run.


DOUBLE GAUSS EXAMPLE
DIFFRACTION MTF
ØRA
5/ 5/75
DIFFRACTION LIMIT
AXIS
T
S
0.7 FIELD (10.73°)
T
S
1.0 FIELD (15.00°)
WAVELENGTH WEIGHT
650.0 NM 10
550.0 NM 20
450.0 NM 10
DEFOCUSING -0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
25
50
75
100
SPATIAL FREQUENCY (CYCLES/MM)

DIFF- 8


DOUBLE GAUSS EXAMPLE
'RAY' IN DIFF. MTF
GEOMETRICAL MTF
ORA
5/ 5/75
DIFFRACTION LIMIT
AXIS
T 0.7 FIELD (10.73°)
S
T 1.0 FIELD (15.00°)
S
WAVELENGTH WEIGHT
650.0 NM 10
550.0 NM 20
450.0 NM 10
DEFOCUSING -0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10
20
30
40
50
60
70
80
90
100
SPATIAL FREQUENCY (CYCLES/MM)



PARABOLIC MIRROR
-DIFFRACTION SQW
SQ WAVE RESPONSE
ORA
5/ 5/75
DIFFRACTION LIMIT
AXIS
WAVELENGTH WEIGHT
500.0 NM 1
DEFOCUSING 0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100
SPATIAL FREQUENCY (CYCLES/MM)

DIFF-10

BEAM PROPAGATION

Purpose

To trace a "slow" Gaussian beam through an optical system, using propagation equations and calculate at each surface the beam radius, wavefront curvature, waist position and waist radius.

Introduction

The representation of a lens as a Fourier transform device which is the heart of theory underlying all diffraction MTF and point spread function calculations is an approximation which is valid so long as (1) the diffraction spot is small in angular subtense, and (2) the geometrical ray paths through the lens fully represent the used area of the lens surfaces. This is generally true of lenses used at normal apertures (perhaps f/50 or faster). With the introduction of the laser, applications of optics have arisen where much slower beams are practical and inherent in the function of the system. With these, the two conditions for validity of the Fourier transform representation of a lens may no longer be fulfilled adequately and this option must be used for evaluation.

A perfect lens will always form a minimum diffraction spot diameter on a fixed image surface when the normal first order equations show that the lens is focused on that surface. However, if the beam is so slow that the used area on the lens is comparable (within an order of magnitude) to the diffraction spot size, another point between the fixed image surface and the lens can be found where the spot size is smaller yet. The shift necessary to find this smaller beam cross-section (waist) is dependent on the relative size of the bundle at the lens aperture and at the fixed image surface; if they are equal, the waist will be found midway between them. If later elements are intended to relay such beam cross-sections, they cannot be designed by normal first order optics; this behavior must be accounted for by the techniques available in this option.

The waist phenomena occurs whether or not the beam is uniform or apodized; only the diffraction characteristics and size change. If the beam is Gaussian in distribution, essentially without truncation, it will remain Gaussian throughout its passage through the system as long as it is unaberrated. This program calculates the waist location and characteristics for such beams and therefore can be considered to provide the first order beam propagation effects. Since it expands those about the designated chief rays (in a fashion analogous to Coddington's equations) it does include the effects primary and higher order astigmatism and field curvature.

See texts on lasers for a fuller discussion of thin lens beam propagation (i.e. "An Introduction to Lasers and Masers", A. E. Seigman, McGraw-Hill, p. 293-345).

If "slow" beams exist in the object and image spaces this option should be used to check image positions. If "slow" beams exist within a system and long separations are present (particularly, intermediate images), this option also should be used. Since none of the other options include these beam propagation effects, the designer must establish the particular correlation in his system between these results and other results to optimize and evaluate his system.

Currently, this option does not include the effects of aberrations other than astigmatism. If the system does not include spaces with "fast" beams (small f/no's), there will be little or no other aberration and the results will represent the dominant characteristics of the system. Later extensions of this option will include the full effect of all aberrations.

Operation and Input Data

It is assumed that a lens has already been entered. The input beam has a Gaussian intensity profile with the waist at the object plane. Thus, if the source is a laser, the object surface must be at the laser cavity waist; for example, with a spherical cavity it would be half way between the cavity mirrors. The beam radius at the waist ($1/e^2$ intensity points) must be given. Other data are optional as indicated. The Gaussian beam is propagated along the chief ray using paraxial propagation equations.

One table is produced for each zoom position and field position. All calculations are done at the reference wavelength. Output is provided for the X and Y sections of the beam.

The following restrictions apply:

1. The results are for the first order (power) properties around the chief ray at each field angle of the system; thus, astigmatism is represented but no other aberrations are included.

2. Only spherical, cylindrical, aspheric and toroidal surfaces may be used (types 0, 1, 2 and 4). On aspheric and toroidal surfaces, only the power terms are used, not the A, B, C, and D values or the conic constant.

3. Off-axis and/or tilted beams may be evaluated in one meridian only. That is, the beam must lie in either the meridional or sagittal section of any optical surface and must be refracted or reflected in the plane defined by that section. Plane mirrors are an exception to this restriction. This means that the ray representing the center of the beam cannot be a skew ray and that all optical surfaces, elements, sub-systems, etc. must have bilateral symmetry.

4. Tilts and decenters may be used only if they don't violate restriction 3 above.

The following format is used to enter data:

CODE		F1	F2	F3	F4	F5	F6	F7
1	4	11	21	31	41	51	61	71

CODE (Col. 1-3) — Mnemonic code indicating particular request. A list of codes is given later.

F1 (Col. 11-20)
.
.
.
F7 (Col. 71-80) — Data fields F1-F7; used to enter the data necessary for each request.

CODES		OPERATION
WRY	(z)	This is the waist radius at the $1/e^2$ intensity point in the Y direction.
WRX	(z)	This is the waist radius at the $1/e^2$ intensity point in the X direction.

Note: Either WRX or WRY is required; both may be entered. If both are omitted, the calculation will be terminated. If one is omitted, it will be set equal to the other (for the first zoom position only). For a zoom system, if all the radii are the same, then only the first zoom position needs to be entered.

POSITION — The character "N" (or word NO) entered in the data field corresponding to a given zoom position will suppress the calculation for that position.

Output

The output consists of the Gaussian beam parameters in the X and Y sections at each surface. The parameters are propagation length to next surface, beam radius on the surface, waist radius before refraction, distance from waist to surface, radius of curvature of the wavefront before refraction. See example.

Error Condition

The run is terminated if there are any errors in tracing the chief ray.

(z) Zoomable entry

BEA- 4

10/31/77

G A U S S I A N   B E A M   P R O P A G A T I O N

TEST LENS WITH CYLINDRICAL ELEMENTS AND ANAMORPHIC INPUT BEAM — POSITION 1

WAVELENGTH = 632.8 NM — FIELD POSITION = 0.00

SURF	PROPAGATION DISTANCE TO NEXT SURFACE	BEAM RADIUS ON SURFACE X	BEAM RADIUS ON SURFACE Y	WAIST RADIUS BEFORE REFRACTION X	WAIST RADIUS BEFORE REFRACTION Y	DISTANCE FROM WAIST TO SURFACE X	DISTANCE FROM WAIST TO SURFACE Y	WAVEFRONT RADIUS OF CURVATURE BEFORE REFRACTION X	WAVEFRONT RADIUS OF CURVATURE BEFORE REFRACTION Y
0	1.0000	.000736	.015000	.000736	.015000	0.0000	0.0000	0.0000	0.0000
1	.3346	.010800	.015009	.000736	.015000	1.0000	1.0000	-1.0047	-805.0063
2	.8720	.012936	.015013	.000736	.015000	2.0191	2.0191	-2.0256	-1133.2964
3	.2530	.022323	.015040	.000736	.015000	2.0706	2.0706	-2.0729	-390.8423
4	.1360	.023837	.015045	.000736	.015000	3.9777	3.9777	-3.9815	-658.8324
5	.2840	.022576	.015051	.000854	.015000	-2.4308	2.3473	2.4343	-345.2991
6	.7650	.021112	.015058	.000854	.015000	-4.0887	4.5064	4.0954	-582.5403
7	.7650	.014021	.012190	.000854	.002090	-1.5080	-3.1651	1.5136	3.2609
8	.2840	.006948	.009344	.000854	.002090	-.7430	-2.4001	.7544	2.5265
9	1.3470	.005497	.008388	.000854	.001296	-1.0525	-2.4367	1.0785	2.4963
10	.0102	.007122	.001297	.000854	.001296	.7619	-.0076	-.7730	5.9199
11	.1583	.007216	.001296	.000854	.001296	.7721	.0020	-.7831	-17.2126
12	.0102	.008028	.000559	.000854	.000552	1.5472	.0115	-1.5649	-.4259
13	5.4216	.008122	.000545	.000854	.000545	.8703	.0015	-.8800	-.9145
14	.3000	.058399	.078936	.000854	.000545	6.2919	5.4231	-6.2932	-5.4234
15	.2000	.056073	.076156	.000633	.000531	-7.2325	-8.2483	7.2334	8.2487
16	.4000	.058147	.079402	.000765	.000490	5.6058	4.9066	-5.6068	-4.9068
17	4.6666	.060521	.083177	.000882	.000555	10.1983	8.8150	-10.2005	-8.8154
18	17.1704	.046787	.073355	.002691	.003764	-15.8505	-34.7676	15.9031	34.8594
19	.5000	.004730	.037259	.002691	.003764	1.3199	-17.5972	-1.9517	17.7785
20	9.2500	.005381	.036578	.003141	.003764	2.6220	-26.1613	-3.9765	25.4413
21	.2500	.027903	.017307	.003141	.003764	10.9806	-8.0172	-11.1215	8.4151
22	8.2500	.028317	.016958	.003141	.003764	16.8866	-11.8968	-17.0969	12.5123
IMG		.049074	.003856	.003141	.003764	19.3956	.3978	-19.4754	-8.4173

EVALUATION-PHYSICAL
PERFORMANCE

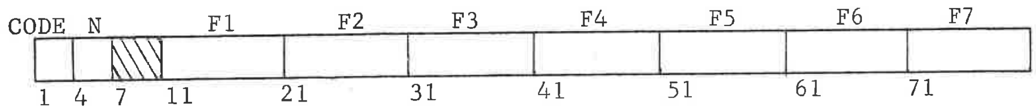
TRANSMISSION

I. Purpose

To compute the transmission of an optical system, including the effects of absorption and single layer anti-reflection coatings.

II. Input Data - Optional

All input data is optional. If provided, it uses the following format:



CODE Col. 1-3	A mnemonic code which designates the nature of the entered value.
N Col. 4-6	If present, identifies the surface number to which the value or values entered in fields F1-F7 is applied.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	The value or values of refractive index, wavelength, or transmission as required.

CODES

POSITION	Used in zoom systems to flag those zoom positions which are not to be computed. The character N or NO entered in the data field corresponding to a given zoom position will suppress the TRANSMISSION calculation for that position.
CEM (n)	Cement at surface n has the refractive index given by the value entered in F1. If n is omitted the value is applied to all cemented surfaces.
CIN (n)	Coating at surface n has the refractive index given by the value entered in F1. If n is omitted the value is applied to all coated surfaces.

CTH (n) — Coating at surface n has the thickness (in fractions of a wavelength) given by the value entered in F1. If n is omitted the thickness is applied to all coated surfaces.

TRN n — Transmission excluding surface reflection losses of a 5mm thick sample of material at surface n (n must be included). A tranmission value should be entered in fields F1-F7 corresponding to the system wavelengths.

WL — The wavelength for which all coatings are quarter-wave; this is therefore the wavelength for which coating transmission is peaked.

SC — Semi-diameter control; uses the entered aperture data to designate the clear apertures defining the transmitted bundles. On surfaces where no aperture data was entered, the computed clear apertures are used.

FUL — Full printout of off-axis transmission analysis is requested by including this card.

III. Function

Each field angle is traced by a group of rays which represent to a sufficient degree of accuracy the integrated bundle of light. At each air-glass surface the angle of refraction in the coating layer is computed. The path length within each coating is calculated and the reflection losses are determined from standard equations for single layer dielectric coatings at oblique incidence; the coating is assumed to have a uniform thickness measured normal to the optical surface. Losses from cemented surfaces are calculated in a similar manner but without interference effects. These are both accumulated as reflection losses.

The absorption losses in each element are dependent on the integrated path lengths, the material, and the wavelength. For materials with known absorption vs. wavelength data, the absorption is calculated and accumulated as absorption losses.

IV. Output

For the on-axis field point, transmission values are printed out at each of the wavelengths in groups which represent the component-by-component structure of the system. The ratio of output to input is given for each source of loss; this ratio for reflection losses is designated REF while, for absorption losses, it is given as ABS. A summary printout of the accumulated products for reflection and absorption are then given, followed by the total for the system arising from both sources.

For off-axis field angles only the summary printouts are given unless the FUL card is entered. It should be noted that this analysis only gives the ratio of output to input and therefore no measure of relative illumination caused by vignetting or $\cos^4$ effects is represented; the effect of transmission variations with field angle must be combined with relative illumination calculations obtained from DIFFRACTION MTF to obtain accurate relative illumination values.

V. Technical Notes

The transmission of a system is dependent upon both absorption losses in the light as it passes through refractive materials and in reflection losses at the various interfaces in the system. If the materials used are from the Schott catalog, the prestored transmission values are used for the losses in the refractive materials. For other materials, including fictitious glasses, no loss is assumed unless values are specifically entered in the data cards of this option.

Air-glass surfaces are assumed to be coated with a single layer of index 1.38 unless this index value is altered by data card; this corresponds to magnesium fluoride (MgF_2). The thickness of this single layer coating is assumed to be one-quarter of the reference wavelength unless some other peak wavelength is specified by data card. In broad band systems significant losses will be noted for those wavelengths far from the peak wavelength. For shorter wavelengths, the thickness exceeds one-quarter wavelength until at a wave length one half of the peak wavelength, the thickness represents a half wave layer. At this point, the loss is a function only of the indices of the substrate and air, and not of the coating material. For longer wavelengths the thickness approaches zero wavelengths and therefore the reflection losses asymptotically approach those associated with an uncoated substrate. See "Principles of Optics", Born & Wolfe, p. 61 for a fuller treatment.

Cemented surfaces can be treated as a thin film between two media. However, they are typically at least twenty wavelengths thick. Thus the maximum and minimum transmission wavelengths, which correspond to differences of one-quarter wavelength in thickness, will differ by only 1 1/4%. It would therefore be misleading to calculate the transmission for a given wavelength, assuming a definite thickness of cement, since chance determines how close this wavelength corresponds to the maximum or minimum value. Instead, the program calculates the average of the two values as representative of the reflection loss at a cemented surface. The index of refraction for the cement, unless modified by data card, is assumed to be 1.576. V is assumed to be 60. No particular thickness is assigned to the cement; in practice, the thickness is assumed to be part of the glass thickness involved.

Comparison of losses at cemented surfaces with the Fresnel losses at an interface between the two materials (a "fused" surface, as it were) shows that there is a loss higher than the Fresnel loss where both media are either higher or lower in index than the cement. If one medium is higher and the other lower, then the losses are less than the Fresnel losses.

If systems contain steep angles of incidence on coated surfaces and also possess some vignetting, the transmission analysis will ofter show higher transmission off-axis than on-axis. The path lengths within the coatings are far from the quarter-wave near the edge of an uncoated surface. However, the off-axis bundles vignette a portion of these steeply incident rays and are therefore not degraded in ratio of output to input as much as the on-axis bundles.

CATSEYE DIAGRAM

I. Purpose:

To plot the appearance of designated surface edges as viewed in the entrance pupil. This is often called a catseye diagram.

II. Input Data:

Surfaces to be plotted must be designated by the designer; a bordered, labelled plot showing the entrance pupil and the image of the surface edges at each field point and zoom position will be drawn. The plot shows where the image of edges lie with respect to the entrance pupil circle.

With scaling or title data added the size and labelling can be changed. These entries are described as follows:

CODE		ENTRY		
TITLE	//////			//////
1	11	21	41	60

A. Title

A card of the above form will use the characters in columns 21 - 60 as the title for the plot in place of the first 40 characters of the lens deck title card.

All other entries are made with the format:

CODE		F_1	F_2	F_3	F_4	F_5	F_6	F_7
	//////							
1	4	11	21	31	41	51	61	71

B. Scale Factor

The scale of the plot is adjusted if necessary so that the entrance pupil circle will fit into the plotted area for each zoom position. If other scalings are needed this is done by using one of the two following methods:

CODE (Col. 1-3)	F_1 - F_7 (Col. 11-20, 21-30, . . . , 71-80)
SF	Factor by which the plot is scaled relative to full scale. Thus SF .025 will scale the first position to +1/40 of full scale. Each zoom position used must have an entry.
EPD	This designates the distance in inches on the plot to which the entrance pupil diameter is scaled. Thus EPD 1.0 2.5 will scale the plot so that the first zoom position entrance pupil will have a diameter of 1 inch and the second position will have a corresponding diameter of 2.5 inches. Each of the used zoom positions must have an entry.

C. Edge Size

If it is desired to use aperture data previously entered, use the SC card:

<u>CODE (Col. 1-3)</u>

SC

This will use any previously entered apertures as the surface edge limit. If none has been entered for a surface used in the analysis, the clear aperture normally required to pass all field angle bundles will be used; this is the clear aperture printed out in MODEL DATA.

If the SC flag card is omitted previously entered apertures will be ignored.

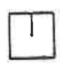
For obscurations to appear, at least one aperture must be entered as negative and the SC card must be used.

D. Designation of Surfaces

Surfaces must be designated; only the entrance pupil aperture shape and the edges of the designated surfaces are plotted. The cards are of the following form:

CODE (Col. 1-3)	F_1 (Col. 11-21)
SUR	Number of surface to be plotted. Up to 10 surfaces may be included. Any more will be ignored. <u>Do</u> <u>not</u> designate a surface at any intermediate or final focal surface.

The plot produced for each edge will be a solid line interrupted by a code as follows:

	1st surface requested
	2nd surface requested
	3rd surface requested
	4th surface requested
	5th surface requested
	6th surface requested
	7th surface requested
	8th surface requested
	9th surface requested
	10th surface requested

Only that part of each edge will be plotted which lies within an appropriate plot space around the pupil; no overlaping of adjacent plots will occur.

III. Output:

A typical plot is included. This was produced by the following data cards:

```
SUR     24
SUR      1
SUR     15
SUR     23
SF      2.0
```

Surface 24 lies near the focal plane and is too large to appear in any of the plots. Surface 1 is the front edge and only appears at the maximum field position. Surface 15 is the aperture stop surface and shows the expansion of the pupil common to wide angle lenses. Surface 23 is near the back of the lens and vignettes the top of the bundles off axis. The scale is twice full scale.

IV. Error Conditions and Warnings

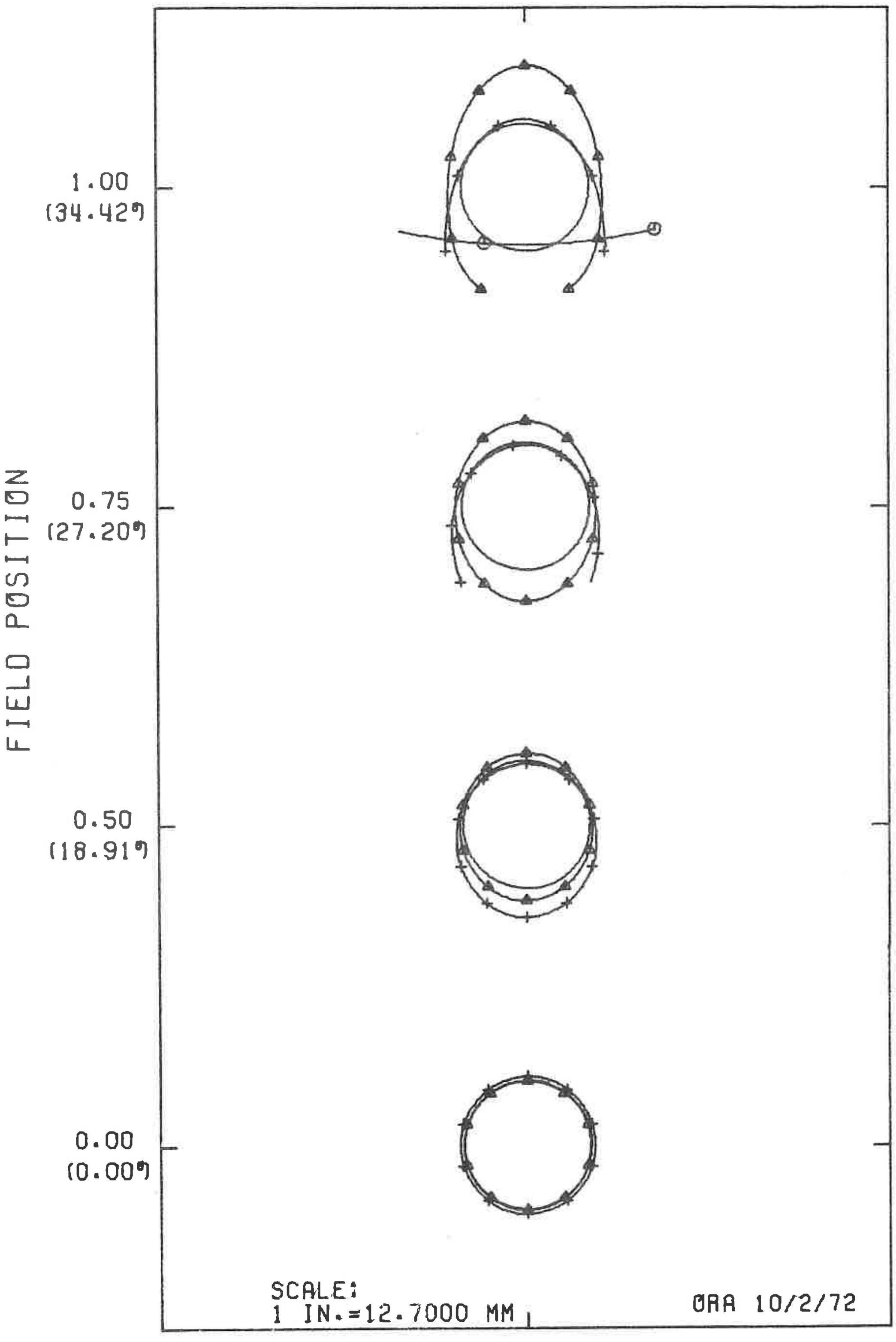
1. "RAY TRACING ERRORS DURING CLEAR APERTURE TRACE - OPTION TERMINATED" - System not traceable. No plotting is done.

2. "EDGE OF SURFACE n NOT VISIBLE IN PLOT FOR FIELD POSITION k, ZOOM POSITION i" - Warning. A requested surface does not appear within the plotted area.

3. "EDGE OF SURFACE n CANNOT BE FOUND FOR FIELD POSITION k, ZOOM POSITION i, DUE TO EXCESSIVE SEMI-DIAMETER." - Warning. Rays to the edge of surface n cannot reach it anywhere on the periphery.

Technical Notes:

All plots are drawn as projected onto the entrance pupil plane which is normal to the optical axis. The view from the direction of the object is different, however. This view would require plotting the clear aperture plots on a plane normal to the chief ray. This would essentially foreshorten the plots, as produced, by the cosine of the angle subtended by the object point.



20MM WA CAMERA LENS

CAT- 5

WEIGHT

Purpose:

To calculate the weight and center of each element and of the total system.

Input Data:

With no input data, the clear apertures are determined by tracing the standard clearance rays. To these are added the same increment in diameter and chamfers as are drawn by the LAYOUT option. Then the weight and center of mass of each element are calculated and printed. Finally, the total weight of all elements and the center of mass of the elements as spaced is calculated and printed.

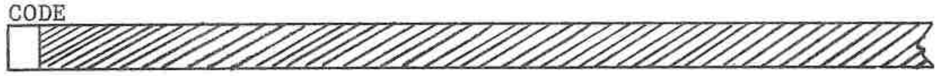
If any non-recognizable material is encountered a specific gravity is assumed which is a function of the index of refraction and approximates the specific gravity of common glasses (Schott K, SK, F, SF series). If a first surface mirror is encountered, its weight is treated as zero.

If these assumptions are to be modified, data cards are required.

A. Semi-Diameter Flag

This flag allows recognition of specified free apertures.

CODE



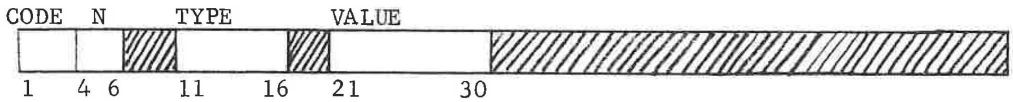
1

CODE (Col. 1-2)	Entry
SC	Indicates that all values of aperture data previously entered are to be used as the clear apertures. To these are added the mounting clearance and chamfers as outlined in the process above.

B. Specific Gravity

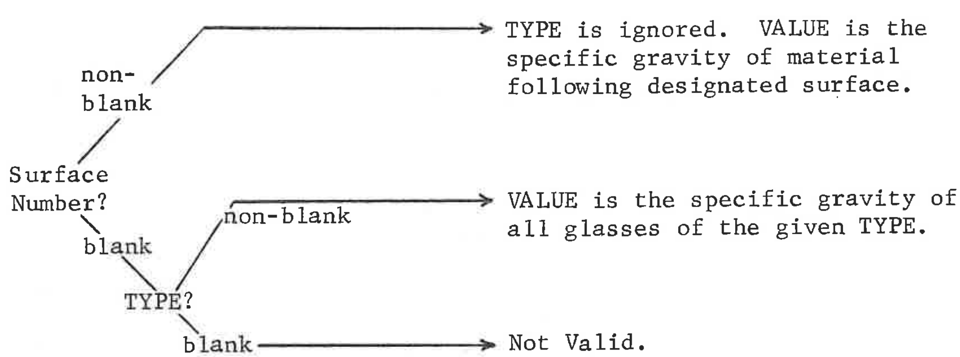
This card permits the designer to over-ride the specific gravity used by the program on each surface or each glass type.

Two forms are allowable. One is general which permits the specific gravity of all glasses of a given glass code to be set to the same changed value. The second form is specific for one surface; the only difference is the presence of a surface number.



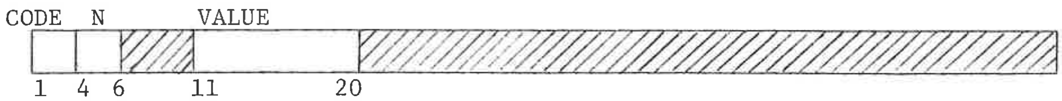
CODE Col. 1-3	A mnemonic code whose three characters are SPG.
N Col. 4-6	The surface number; if present, the specific gravity is to apply only to the material following the one surface; if the surface designated is a first surface mirror, the value is assumed to apply to the substrate. If the surface number is left blank the remaining information is applied as extensively as possible.
TYPE Col. 11-16	A name of a recognized glass code. If the surface number is blank, all representations of this material are assigned the specific gravity of VALUE. If TYPE is blank, VALUE will be used only if the surface number is not blank.
VALUE Col. 21-30	Value of specific gravity. A blank is treated as zero.

The following logic tree shows the valid combinations:



C. First Surface Mirrors

There is no representation of the substrate in the optical data and, in lieu of additional data, no weight is calculated for the substrate. To calculate substrate weight requires the additional items of thickness, specific gravity and back curve. Specific gravity is entered by the card described above. Thickness and back curve are entered as follows:



CODE (Col. 1-3)		Entry
THM	n	Thickness of substrate for first surface mirror at surface n is entered in VALUE.
CUM	n	Back curve of substrate for first surface mirror at surface n is entered in VALUE.

Function:

The mounting edges and chamfers determined from the clear apertures are combined with the radii and thickness of each element to provide the data necessary to calculate the volume and center of mass. From the specific gravity of the material, the weight of the element is computed. Finally, the total weight and system center of mass is calculated.

The handling of outside diameters, edges and chamfers is identical to LAYOUT option used in the same manner. Therefore this analysis is for elements as drawn in that option. If negative semi-diameters (CIR) are present and invoked by SC, the obscuration removes a core of material.

Simplified formulas are used. Elements are assumed to be rotationally symmetric with spherical surfaces. Aspherics and other unusual surfaces are therefore not accurately represented.

Output:

A table is output containing, for each element, the following data:

Element number
Volume
Weight
Center of Mass (measured from surface 1 of element)

After completion of this for all elements, the total weight and center of mass of the total system of elements are calculated.

Technical Notes:

This program assumes that the surface types are all spherical and performs the calculation ignoring all other surface data. Extension to all surface types has not yet been made.

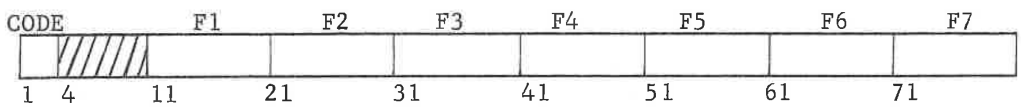
GHOST IMAGE ANALYSIS

Purpose:

To determine the location and size of images produced by surface reflections in a lens.

Input:

Optional data cards punched in the following format may be input after the GHOST option card.



CODE (Col. 1-3)	Mnemonic code indicating particular GHOST sub-options. A list of the CODES is given later.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields F1-F7; used to enter data for the corresponding zoom positions, i.e., F1 is used for zoom position 1, F2 for zoom position 2, etc.

In the list of CODES, the portion underlined indicates the characters which are sensed. Some of the requests are for various sub-options; on any of these, the letter N (or the word NO) in the columns corresponding to a given zoom position will serve to delete the request for that zoom position.

CODE	OPERATION
POSITION	Used in zoom systems to flag those zoom positions which are to be skipped. The character N, or NO, entered in the data field corresponding to a given zoom position will delete all calculations for that position.
SSP	Surface by surface print flag; presence of this card causes a surface by surface

printout of the first order trace. The character N, or NO, entered in the data field corresponding to a given zoom position will delete the surface by surface printout for that zoom position.

SUR — Surface numbers: limits the surface by surface printout (requested by the SSP sub-option) to the surfaces entered in P1 and P2. Use the format:

	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
SUR														
1	11	16	21	26	31	36	41	46	51	56	61	66	71	76

Function:

The program traces (first order) all combinations of two surface reflections within a lens, i.e., a ray is traced to the second surface from which it reflects back to the first surface and then, reflecting from it, travels on through to the image. This process is continued for all combinations of two surfaces.

Output:

For each surface pair combination, five values are printed in addition to the two surface numbers. They are:

1. DBFL: the distance from the primary image plane to the reflected image.

2. EFL: the focal length of the system including the two extraneous reflections.

3. DISC: the semi-diameter of the reflected beam (from an on-axis object point) at the primary image plane.

4. PUPIL RATIO: the maximum ratio of first order reflected ray heights at the stop surface to the stop semi-diameter. The paraxial marginal ray will pass through the stop once or three times prior to, between, or after the pair of surfaces causing the ghost. Maximum ratios greater than 1.0 will be clipped by the stop and, therefore, real disc semi-diameters will be reduced from the printed values by the reciprocal of these ratios.

5. MAGNIFICATION: the size of the reflected image relative to the size of the primary image.

[redacted]

NARCISSUS ANALYSIS

Purpose:

To determine the impact of re-imaging of a cold stop or detector onto the detector (principally of concern in scanning infra-red systems).

Introduction:[1]

Infra-red systems have detectors which are sensitive, of course, to thermal radiation (heat) and which are typically mounted in a cryogenically cooled space. Any heat source in the lens structure itself, including the elements and lens mount looks like a bright source to the detector. Since the elements and mount are usually not cryogenically cooled, the detector will "see" its intended source within an out-of-focus self-radiating surround. The wanted signal could be swamped by this surround, except that such systems typically contain a cryogenically cooled cold stop some distance ahead of the detector but still within the cooling system.

If the detector is a point, the cold stop may be anywhere ahead of the detector and of sufficient size to limit the axial bundle to the used aperture; this would eliminate the direct signal from the mounting structure. For an extended detector the ideal location for the cold stop would be at the exit pupil of the optical system; with the cooled detector, and in the absence of vignetting this would give complete baffling to unwanted direct radiation. However, it is seldom possible to locate the cold stop at the exit pupil and therefore the system aperture is limited by a "warm stop" forward of the cold stop. The front face of the cold stop is usually reflecting, so that, viewed from the front, the hole of the cold stop appears cold while the surround is the reflection of the warm lens mount.

In the infra-red all objects have a "brightness" associated with their temperature and emissivity; they are "black" to a given detector only if all emission occurs outside of the wavelength band of the detector sensitivity. In particular, if the object is colder than the threshold temperature of the detector, all of its radiation will be longer in wavelength than the band of sensitivity of the detector.

If the detector is a point, a full picture is generated by two dimensional scanning; if it is a line of point detectors, the full picture is generated by one dimensional scanning. Hybrid systems exist where the sensor is a widely spaced line of point detectors; one dimensional scanning with interlace generates the picture. If a mosaic sensor is used, the full picture may be generated with no scanning action.

With scanning systems, time is an integral part of the picture formation. Any steady state, non-moving, condition (such as emission from

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1. See J. M. Lloyd, "Thermal Imaging Systems", Plenum Press, particularly p. 275-281 for additional information.

[redacted]

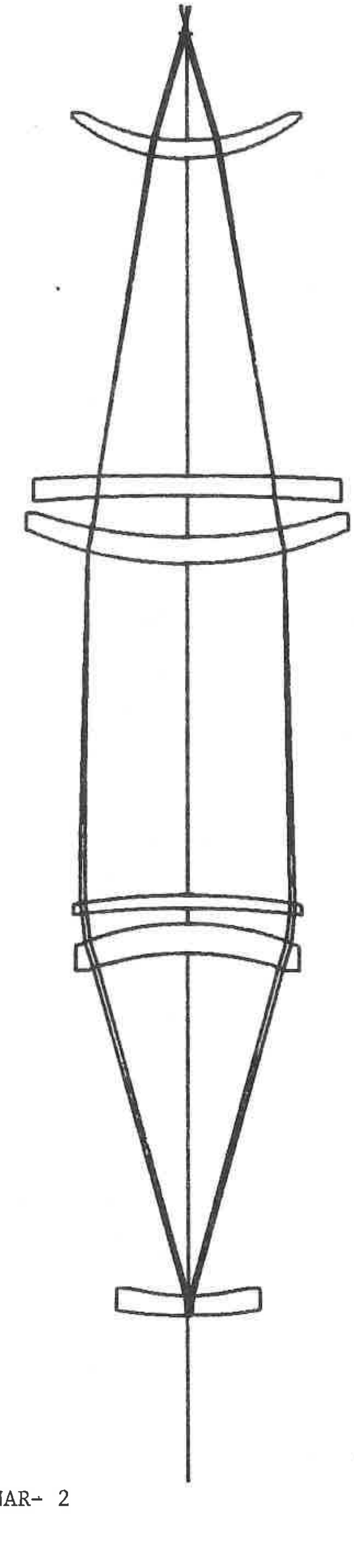


Figure 1a - Narcissus Created By Surface At Beam Focus

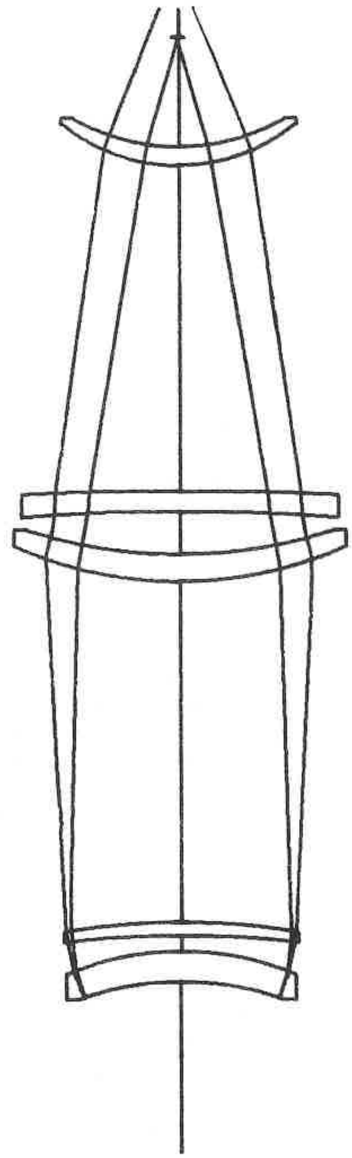


Figure 1b - Narcissus Created By Surface Normal To Beam

NAR- 2

the warm stop) can be removed electronically so that only signals that vary in time are sensed; such sensed signals include changes of vignetting or other relative illumination effects during scan. Another more serious false signal is called narcissus and consists of an image of the cold stop and detector formed by reflection off of an optical surface and back onto the detector. This image consists of a black hole (image of the cold stop and detector) with a bright surround (image of the warm stop).

If the surface causing the reflection is between the scanner and the detector, this reflected image will be stationary and will be usually of little concern. If the reflecting surface is ahead of the scanner, the image will move across the detector and provide a moving, usually out of focus, blur; this is detected along with any of the intended images as a supposed signal of interest. Since only one surface is causing the reflection, this image can be far brighter than any normal, two-reflection ghost image, regardless of the use of efficient anti-reflection coatings.

In-focus narcissus images may be formed either by having the offending surface normal to the marginal ray or lying at an intermediate image in the system. For a cold stop that is in contact with the detector, this is strictly true and is the basis in other programs for narcissus analysis and control. With a cold stop displaced from the detector, these two conditions must be modified increasingly as the displacement increases. Examples of these two cases are shown in Figure 1a and b. This program and the corresponding control in AUTOMATIC DESIGN provide for separated cold stop and detector to more accurately simulate systems where this is an important feature. Note that narcissus is associated with refractive surfaces; reflective surfaces cannot cause a refractive and a reflective component to be superimposed on the same detector.

This option permits the estimation of blur sizes falling on the detector plane, interpreting the cold stop as the object and each surface, in turn, as the reflector. The cold stop is chosen as the object because it usually possesses the sharp discontinuities in temperature (edge of the hole, etc.). The degree of defocus in its image is determined by the ray emerging forward from its center at an angle just large enough to clip the most limiting clear aperture, reflecting from the designated surface, and passing back through the intervening surfaces and cold stop to the detector. Its height on the detector is the out-of-focus blur radius; an edge or other detail on the cold stop would be blurred over a total length of twice this amount. From this and the magnification of the cold stop to the closest image near the detector, the image contour of any detail in the cold stop can be approximated.

In reality, clipping also occurs after reflection as the ray heads toward the detector. Such a clipped beam calculation is necessary to compute instantaneous intensity of the narcissus effect. Ignoring clipping after reflection will approximate the contour of energy which is scanned across the detector by the action of the scanner. Again surfaces which lie between the scanner and detector do not cause moving reflections and are usually of little concern.

The present output gives the blur radius for clipping only on the forward pass, as well as for clipping on both passes. The former provides a value for use in minimizing narcissus during optimization (HNR constraint in AUTOMATIC DESIGN) and can be used as well for the development of the scanned pattern. The blur radius with clipping on both passes can be used for instantaneous relative comparisons by generating a "figure of merit" of:

$$\psi_i = \left(\frac{U_i}{R_i}\right)^2$$

where

U_i = the cold stop "emission" angle for reflections from surface i

R_i = the blur radius for reflections from surface i

ψ_i = the relative intensity for the narcissus image generated by reflection from surface i

This "figure of merit" is included in the output.

Restrictions:

-This program is dependent on first order computations and thus does not include effects of decentered surfaces. Clipping apertures arise from ray tracing and/or APERTURES input data.

Future development will address photometric properties of the scanned signal using real ray computations.

Input Data:

If no data is input, the program will make the following assumptions:

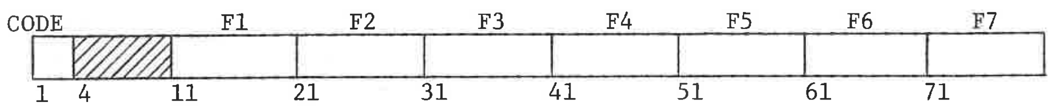
1. The cold stop is in contact with the detector.

2. Standard ray-traced clear apertures will be used to define clipping diameters.

3. All zoom positions will be computed.

4. Output for all surfaces preceding the image surface will be generated.

If these assumptions are to be changed, input data is entered in the following format:



CODE (Col. 1-3) Mnemonic code indicating particular NARCISSUS sub-options. A list of the CODES is given later.

F1 (Col. 11-20) Data fields F1-F7; used to enter data for the corresponding zoom positions, i.e., F1 is used for zoom position 1, F2 for zoom position 2, etc.
.
.
.
F7 (Col. 71-80)

In the list of CODES, the portion underlined indicates the characters which are sensed. Some of the requests are for various sub-options; on any of these, the letter N (or the word NO) in the columns corresponding to a given zoom position will serve to delete the request for that zoom position.

CODE	OPERATION
COLD	Cold stop surface number. This may be any surface including the image plane.
SCN	Scanner surface number. Default is the I-1 surface. Limits printout to those surfaces prior to and including the scanner. This must be less than the cold stop surface number.
POSITION	Used in zoom systems to flag those zoom positions which are to be skipped. The character N, or NO, entered in the data field corresponding to a given zoom position will delete all calculations for that position.
SC	Semi-aperture control. Uses the APERTURE data for clear apertures instead of computed clear apertures; the smallest X or Y dimension is used depending whether XFO was entered or not, respectively, in the lens DATA. Negative APERTURES (obscurations) are ignored.

Output:

A sample run is shown in Table I. This resulted from the input:

```
NARCISSUS ANALYSIS
COLD      I-1     Cold stop just prior to focal plane (=24).
SCN       17      Limit printout to surface prior to and
                  including the scanner on surface 17.
```

In Table I, the worst offender is seen to be the narcissus blur formed by reflections from surface 12, where the radius is .3643mm (clipping on forward path only). This would logically be removed by re-optimizing in AUTOMATIC DESIGN with an HNR constraint to raise this to a value of, say 5.0; of course, as with all constraints, variables must be available to accomplish this change. Note that the printout is terminated after the scanner (surface 17).

NARCISSUS ANALYSIS
BLUR CIRCLE RADIUS FOR COLD STOP - FIRST ORDER

NARCISSUS EXAMPLE

	CLIPPING ON FORWARD PATH ONLY			CLIPPING ON FORWARD AND REFLECTED PATH			
REFLECTING SURFACE	CLIPPING SURFACE	BLUR RADIUS MM	COLD STOP EMISSION ANGLE RADIANS	CLIPPING SURFACE	BLUR RADIUS MM	COLD STOP EMISSION ANGLE RADIANS	RELATIVE INTENSITY ESTIMATE
1	16	-7.1256	0.2759	16	-7.1256	0.2759	0.001499
2	16	-7.2257	0.2759	16	-7.2257	0.2759	0.001458
3	16	19.5947	0.2759	12	9.8599	0.1415	0.000206
4	16	30.2564	0.2759	12	10.0554	0.0938	0.000087
5	16	28.5742	0.2759	12	10.0423	0.0992	0.000098
6	16	-5.4625	0.2759	14	-5.0690	0.2569	0.002569
7	16	-22.2824	0.2759	12	-11.0542	0.1395	0.000159
8	16	35.2287	0.2759	12	10.3599	0.0831	0.000064
9	16	2.1619	0.2759	16	2.1619	0.2759	0.016287
10	16	4.8969	0.2759	14	4.3041	0.2439	0.003211
11	16	1.0432	0.2759	16	1.0432	0.2759	0.069952
12	16	0.3643	0.2759	16	0.3511	0.2664	0.575765
13	16	4.5623	0.2759	17	4.4539	0.2697	0.003666
14	16	31.2066	0.2759	22	11.6079	0.1049	0.000082
15	16	-2.3913	0.2759	16	-2.3913	0.2759	0.013312
16	16	23.3670	0.2759	22	11.1794	0.1346	0.000145
17	17	1.5151	0.2760	17	1.5151	0.2760	0.033180

NOTES:

1. FIRST ORDER RAY TRACING IS USED TO DETERMINE BLUR RADIUS AND COLD STOP EMISSION ANGLE. THESE RESULTS ARE THEREFORE LIMITED TO FIRST ORDER ACCURACY. CLEAR APERTURES FOR CLIPPING ARE DETERMINED BY STANDARD REAL RAY BUNDLES AND/OR APERTURE INPUT DATA.

2. FIRST ORDER TRACING IGNORES DECENTERED SURFACES.

3. NARCISSUS REFLECTING SURFACES FORWARD OF THE SCANNER GIVE RISE TO MOVING IMAGES AND MUST BE CONTROLLED TO AVOID NARCISSUS EFFECTS. NARCISSUS REFLECTING SURFACES FOLLOWING THE SCANNER CREATE STATIONARY IMAGES WHICH USUALLY ARE OF LITTLE CONCERN.

4. RELATIVE INTENSITY ESTIMATE IS COMPARATIVE ONLY. IT ASSUMES ROTATIONAL SYMMETRY AND DOES NOT INCLUDE REFLECTIVITY OR SOURCE EMISSIVITY. UNITS ARE IN $RADIANS^2/MM^2$

Table I - Narcissus Output

TOLERANCE ANALYSIS

TOLERANCE - Introduction

CODE V offers two programs to assist in tolerancing lenses:

I. TOL - TOLERANCE (Primary Aberrations)

This is the comprehensive tolerancing program previously included in CODE V, with features for sensitivity, inverse sensitivity, tabulated tolerances and Monte Carlo analysis of budgets. It includes a large variety of performance measures including first order quantities, third order aberrations and their RMS wavefront equivalents, primary aberrations of image displacements plus astigmatic foci determined by ray tracing and their RMS wavefront equivalents. In addition, several additional composite performance measures for combined image quality at center or edge of the field are included.

The assumptions, for the image quality performance measures, are that:

1. The system is centered, without vignetting or obscuration (or suitably represented thereby).

2. The performance changes are well represented by monochromatic primary aberrations (third order equivalent accuracy), centered or decentered.

Tolerances of astigmatic foci do use ray tracing and are not limited to centered systems.

While the program is flexible and comprehensive, some optical systems are not properly represented by primary aberration tolerances and need a fuller treatment using performance measures derived from tracing real rays. For this a second program has been developed.

II. TOR - TOLERANCE (Ray Based)

This program, using either RMS error or MTF at a given frequency and orientation as its performance measure, computes the tolerances of centered and decentered fabrication errors with features for sensitivity, inverse sensitivity, and statistical combination of effects. Each tolerance can use compensators to simulate production alignment procedures which optimize performance over the field. Being ray-based, it includes:

1. The total aberration (not just third order).

2. Vignetting and obscuration.

3. Polychromatic effects, if desired.

Using differential ray tracing techniques, it generates changes without re-tracing the rays and is computationally much faster than a finite difference procedure.

In general, use TOL for those applications requiring tolerances of first order quantities or its special features (TABLE, Monte Carlo, inhomogeneity). If it is necessary to depend on the RMS effects, (AXI, EDG, EDF) be sure to test the results with TOR to uncover any significant departures between ray-based and primary aberrations. If RMS tolerance effects are needed but the special features of TOL are not, or if MTF tolerancing is to be done, use TOR. As development continues, TOR will be expanded with additional performance measures and features to make this choice less significant.

The manual sections are written so that TOL provides a more comprehensive discussion of tolerancing; it is expected that the user of TOR is familiar with the overall concepts discussed in TOL.

Tolerancing of a system can seem formidable to the lens designer and cause him to avoid the subject. It is our aim to make this process so easy that it can be done routinely on any system to provide a release of data, including tolerances, as well as to permit the routine check of tolerances and their control during the design process.

TOLERANCE

Purpose:

To provide tools for tolerancing of lens systems, analyzing the effects of these tolerances and optimizing tolerance budgets.

Specifically, the designer can:

1. Get sensitivity of one or more system parameters (EFL, image distance, spherical aberration, tangential focus, RMS wave error at field point, etc.) to the errors in construction parameters (radii, fringe error, thickness, index, irregularity, inhomogeneity, tilts and decenters).

2. Get inverse sensitivity. This is the amount of tolerance necessary to generate equal amounts of degradation. Very sensitive or insensitive tolerances are automatically restricted to practical limits.

3. Run Monte Carlo simulations of manufactured lenses to determine the effect of the chosen tolerance budget.

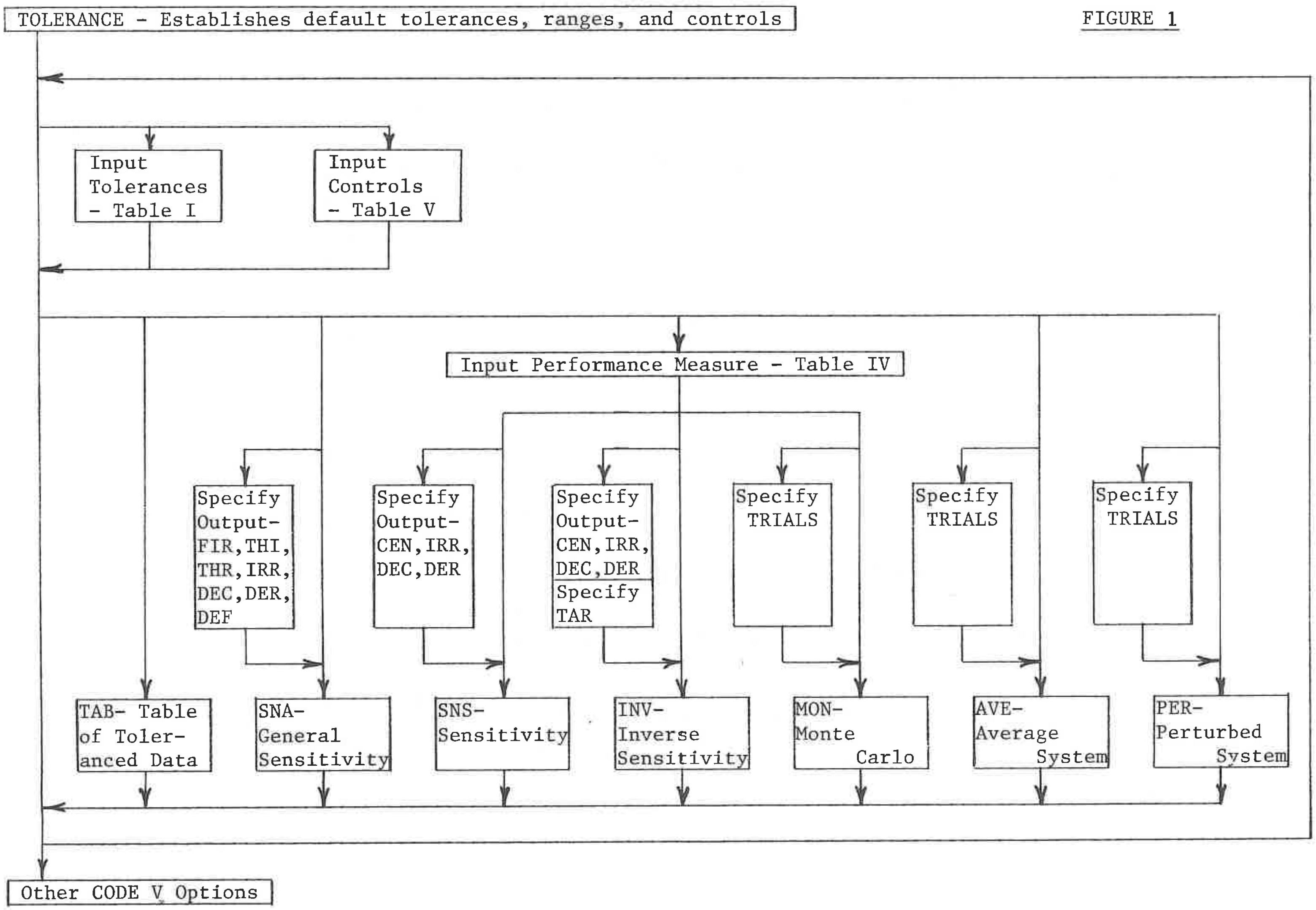
4. Print a table of the lens construction data with tolerances.

5. Modify the current tolerance budget and limits either from the default values or from previous entries so that the new budget may be tested or printed.

6. Output the lens system as the average of all manufactured lenses or as a specific perturbation so that other computations may be run (MTF, re-optimize, etc.).

Figure 1 shows the overall flow of operations. Tables I - V in the text are quick reference guides to the input requests.

FIGURE 1


TOLERANCE - Establishes default tolerances, ranges, and controls
Input Tolerances - Table I
Input Controls - Table V
Input Performance Measure - Table IV
Specify Output- FIR,THI, THR,IRR, DEC,DER, DEF
Specify Output- CEN,IRR, DEC,DER
Specify Output- CEN,IRR, DEC,DER
Specify TAR
Specify TRIALS
Specify TRIALS
Specify TRIALS
TAB- Table of Toler- anced Data
SNA- General Sensitivity
SNS- Sensitivity
INV- Inverse Sensitivity
MON- Monte Carlo
AVE- Average System
PER- Perturbed System
Other CODE V Options

Introduction:

A. Lens Data Base

Throughout almost all of CODE V, the lens data is the primary data acted upon by the various options; it is the data base for the program. It can be modified by user input, by optimization, or by special options; it can be used for performance and structural analyses.

B. Tolerance Data Base

In tolerancing, we add another major data base - the set of manufacturing tolerances - by program defaults or by user input. It is this data base which is used for analyses or is modified and re-analysed in this option. The ultimate purpose is to arrive at a set of tolerances which is balanced between the usually conflicting requirements of low manufacturing cost and sufficient performance.

C. Process of Tolerancing

The process of tolerancing is described in Appendix TOL-A. Within that overall outline is the opportunity to introduce many computational tools and aids to manufacturing. This option currently addresses many of these needs and is aimed at providing a comprehensive tolerancing tool.

D. Ease of Use

In spite of the apparent complexity of tolerancing, it is simple to initiate. The option

TOLERANCE

alone, will set up default tolerances and run a general sensitivity analysis. This provides an overview for detecting sensitive points in the lens structure during intermediate design stages.

For development of the actual tolerance budget, we need to enter tolerances and limits, and requests for various computations. Entry of any of these will delete the automatic computation of general sensitivity tables; only the requested computations will be done.

For example, adding the two cards

EDG
MON

will do only the Monte Carlo analysis for the RMS wavefront error at the edge of the field of view, without refocusing relative to the axis.

All entries are processed as they are received. At any point, tolerances may be modified and all succeeding analyses will use this revised budget. Thus, several trial budgets may be analysed within the same run, with only the changes to budgets supplied between analysis requests.

Structure:

A. Lens Data Base

Standard CODE V system with any data (such as SOLVES and couplings) necessary to generate compensation features expected in assembly.

Couplings are used to inform TOLERANCE that two or more surfaces, thicknesses or materials are physically the same item; this may differ from their use for AUTOMATIC DESIGN and may require changes of couplings between optimization and tolerancing.

CCY, THC, and GLC are the only couplings used in TOLERANCE and have the meanings described in DATA. Only optical surfaces which are the same physical surface should be coupled with CCY; this will generate a grouped tolerance on radius, power, irregularity, tilts and decenters. Only thicknesses which are physically the same thickness should be coupled with THC (using - signs for negative thicknesses, + for positive); this will generate a grouped tolerance on thickness. Only materials which are physically the same element should be coupled with GLC; a grouped tolerance will be generated for index and inhomogeneity.

For surfaces coupled by CCY, the largest clear aperture of the group will be used in tolerancing power, irregularity, and inhomogeneity.

Each zoom position is toleranced separately; thus no coupling across zoom positions is recognized.

B. Tolerance Data Base

Consists of:

1. Tolerances on:

Radii Power Irregularity (cylinder) Thicknesses (and separations) Index Inhomogeneity Tilts and Decenters Special sources of degradation	Used by all functions.

2. Ranges - Practical limits on how large or how small tolerances can be. Used by functions (such as INVerse sensitivity) which temporarily re-define tolerances.

3. Statistical Distributions - Curves describing the expected distribution of part dimensions for each type of tolerance. Used by functions involving Monte Carlo analysis.

Each of these is established by defaults; tolerance data can be modified by the user.

C. Functions

Analysis requests (sensitivity, inverse sensitivity, Monte Carlo, perturbed system, table of toleranced lens data, etc.). These are the computation requests - the main purpose of TOLERANCE.

D. Performance Measures

Declaration of a specific aberration, physical property, image point or combination to be used as the measure of degradation in inverse sensitivity and Monte Carlo analyses.

E. Controls

Declaration of assumptions used during succeeding functions (active zoom positions, activate the entered clear apertures, etc.).

TABLE I: TOLERANCES

CODE	Default In	Default Cm	Default Mm	Description
a. Centered Tolerances				
DLC (n)	.001	.001	.0001	Tolerance on curvature
DLR (n)				Alternate to DLC - Tolerance on radius
DLF (n)	------------5 Fringes------------			Tolerance on test plate fit (power) in fringes at 546.1 nm over the clear aperture.
DLT (n)	.001	.0025	.025	Tolerance on thicknesses and separations
DLN (n)	--------------.001----------------			Tolerance on index of refraction
b. Irregularity Tolerances				
CYL (n)	------------1 Fringe-------------			Tolerance on cylinder irregularity in fringes at 546.1 nm over the clear aperture.
HOM (n)	-----------$\pm 5 \times 10^{-6}$-------------			Tolerance on non-refocusable inhomogeneity

c. Decentering Tolerances (See text for surface specification with SUR card.)

CODE	Description
TILT	Tolerance on tilt (in radians) of each surface about its pole in group P1-P2 of SUR card.
BTILT	Tolerance on tilt (in radians) of the group of surfaces P1-P2 about P1 specified in the SUR card(s).
DISPLACE } BDISPLACE }	Tolerance on lateral displacement of each surface P1-P2 specified by SUR card (plus the tilt in surfaces S1 to S2 induced by P2, if any.)
ROLL	Tolerance on roll of surfaces P1-P2 on seat of P1 (P1 itself does not tilt), plus the tilt in surfaces S1 and S2 induced by P2, if any. Expressed as amount of lateral shift(usually half the difference between I.D. and O.D.).

d. Special Added Tolerances (listed by TAB, used by MON)

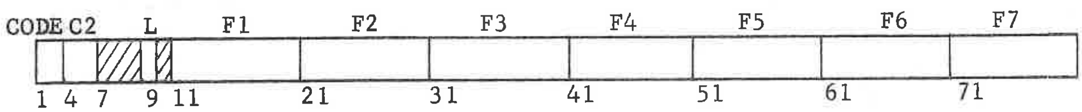
CODE	Description
ADD	Effect of component in tolerance budget - see text.

(n) If n is blank, the value applies to all surfaces. If n is present, the value applies only to that surface.

Input Data:

If no additional input data is provided, the program generates a request (SNA) for sensitivity analysis of all standard performance measures using the default tolerances given in Table I. If any input data is provided, this automatic request is not issued.

Optional input data is provided using the following format:



CODE (Col. 1-3)	Mnemonic code indicating particular TOLERANCE sub-options. A list of the CODES is given later.
C2 (Col. 4-6)	Code extension or surface number. Enter the surface data when the information is to apply to only one surface. (CODES which can be entered for only one surface will be indicated by a lower case letter n after the CODE).
L (Col. 9)	Label field (seldom used).
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields F1-F7; used to enter data for the corresponding zoom positions, i.e., F1 is used for zoom position 1, F2 for zoom position 2, etc.

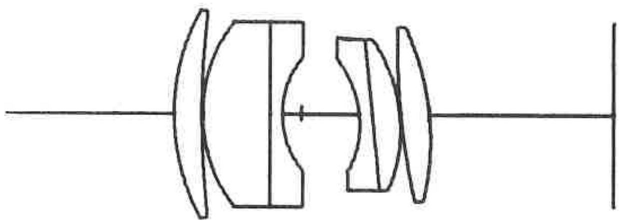
In the list of CODES below and in Tables I, III, IV and V, the portion underlined indicates the characters which are sensed.

A. Tolerance Data Base Input

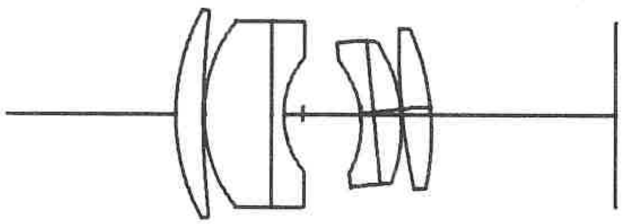
1. Tolerance Input

The codes are listed, with defaults in Table I.

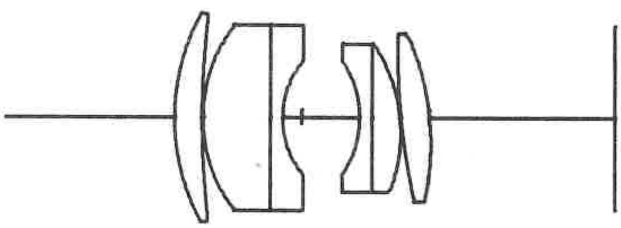
For centered and irregularity tolerances DLS, DLR, DLF, DLT, DLN, CYL, HOM, the surface number is optional. If this number is absent, the values in F1-F7 will apply to all surfaces of the corresponding zoom position; if the number is present, the values apply only to that surface. When surfaces, thicknesses, or materials are coupled, only the value on the first of the coupled items is used. For example, if CCY 2, 5 and 8 are a group, then only DLR 2, or DLF 2 are used; DLR 5 would be ignored.



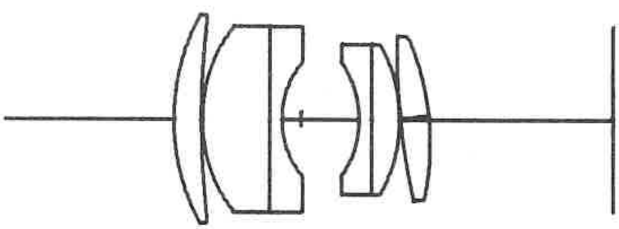
TILT: Shearing Tilt of
Last Three Elements



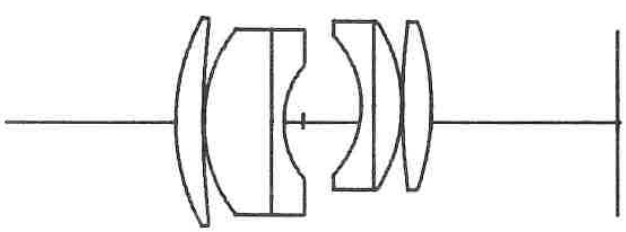
BTILT: Barrel Tilt of
Last Three Elements
About Their First Surface



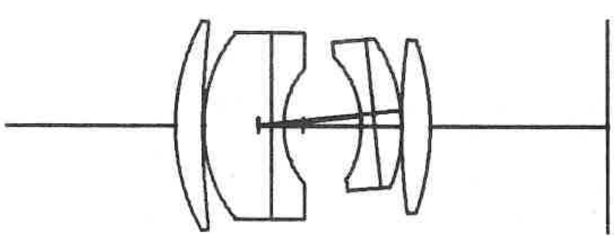
TILT: Wedge in Fifth
Element Plus Induced
Tilt In Last Element



BTILT: Tilt of Last
Element



DISP (or BDISP): Displacement
of Last Three Elements



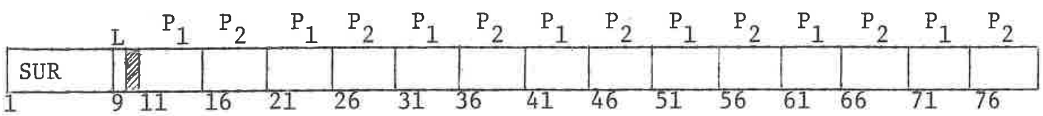
ROLL: Roll of Fourth and
Fifth Elements About The
Center of Curvature of
Their First Surface

FIGURE 2: EXAMPLES OF DECENTERING

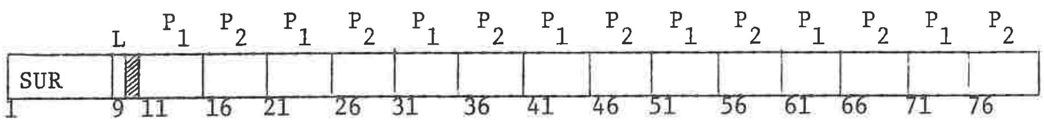
For <u>decentered</u> tolerances, a type (<u>TILT</u>, <u>ROLL</u>, <u>DISPLACE</u>, etc. as shown in Figure 2) is specified along with values in F1-F7 as required; up to 100 such type specifications can be supplied. The span of surfaces to be covered by this error is given in a SUR card immediately following giving the primary surfaces, P1 to P2, affected. In addition, the tilt of P2 may induce a tilt in a second group of surface stacked on the first, as shown (exaggerated) in Figure 2; this secondary set of surfaces, S1 to S2 may be specified in a second SUR card.

The SUR cards have the special format:

<u>PRIMARY SURFACES</u>



<u>SECONDARY SURFACES</u> (If required)



If no SUR cards are included, the values of P_1 and P_2 will be set to the first and last physical surface (1 and I-1) respectively for each zoom position; S_1 and S_2 will be ignored and no induced tilt will take place. If only the first SUR card is entered, S_1 and S_2 will be ignored and, again, no induced tilt will take place. The only way induced tilts will be included is by specifically including them in the request. SUR cards <u>must</u> immediately follow the Type card to which they apply.

Example: If it is desired to have a displacement with surfaces 3 through 5, with the tilt of surface 5 induced in surfaces 6 through 7, then the following three cards must appear

```
DIS          .001
SUR          3  5
SUR          6  7
```

Surfaces may be input backwards or forwards if necessary to define roll conditions or induced tilts. Thus

```
DIS          .001
SUR          5  3
SUR          1  2
```

would have indicated that the tilt of surface 3 (P2) generated by displacing surfaces 3-5 would be used in tilting surfaces 1-2.

When surfaces are coupled through CCY entries, and at least one member of the group lies within the span of surfaces designated by a SUR card, the effect of all members of the group are included in the tolerance, even though some lie outside the span. For example, in the first case described above, if CCY 4 and 9 are coupled, the effect of surface 9 will be included with surface 4; this is done because, according to the meaning of couplings in tolerance, surfaces 4 and 9 are actually the same physical surfaces.

If a SUR card has an S in the label field, it is treated as if there was a set of cards included for each surface individually. For example, in each of the following three examples the cards on the left are equivalent to inputting the cards on the right.

			↔		
DIS		.001	↔	DIS	.001
SUR	S	3 4		SUR	3 3
				DIS	.001
				SUR	4 4

			↔		
DIS		.001	↔	DIS	.001
SUR		3 4		SUR	3 4
SUR	S	3 4		SUR	3 3
				DIS	.001
				SUR	3 4
				SUR	4 4

			↔		
DIS		.001	↔	DIS	.001
SUR	S	3 4		SUR	3 3
SUR	S	3 4		SUR	3 3
				DIS	.001
				SUR	3 3
				SUR	4 4
				DIS	.001
				SUR	4 4
				SUR	3 3
				DIS	.001
				SUR	4 4
				SUR	4 4

Each of the <u>generated</u> decentered type cards is counted toward the limit of 100.

For a detailed discussion of decentering effects, see Appendix TOL-B.

Special tolerances may be needed to represent additional sources of error in Monte Carlo analyses. These are represented as errors in the specified performance measure AXI, EDG, EDF (not tolerances) with a truncated Gaussian distribution of production effects. They are input as:

CODE	Z		ERROR	CUT-OFF	DESCRIPTION
ADD		//////			
1	4	6	11	21	31

where:

ADD (Col. 1-3)	Specifies this to be an additional source of error.
Z (Col. 4-6)	Zoom position in which the special tolerance is active. If left blank, the error is active in all positions.
ERROR (Col. 11-20)	Value of the error produced at the cut-off; it is in units of the performance measure.
CUT-OFF (Col. 21-30)	Fraction of the peak at which the Gaussian is truncated. Typical values would be: .6065 (1σ) .1353 (2σ) .0111 (3σ)
DESCRIPTION (Col. 31-80)	Any 50 character descriptor (without commas) for labelling of output. It is desirable to include the value of the physical error that is associated with the performance measure ERROR.

Example:

ADD 2 .031 .25 MIRROR ASSY NO. 2 (1FR POW/.5 FR IRR)

Specifies that the second zoom position is to include .031 RMS wave front error, with a Gaussian distribution which decreases to .25 at that point and truncates to zero. Note: ADD effects will be included only with performance measure AXI, EDG, and EDF.

The Gaussian distribution is shown in Figure 3F for three typical cut-off points. The values which generated these are:

Value of CUTOFF	DESCRIPTION
.6065	1 sigma
.1353	2 sigma
.0111	3 sigma

Thus, the value of .25 used in the above example lies between 1 and 2 sigma.

TABLE II: RANGES (TOLERANCE LIMITS)
(Fixed - Not Alterable)

LIMIT	TOLERANCE	VALUES In	Cm	Mm	COMMENTS
a. Centered Range Limits					
Upper (sag)	DLR	.001	.0025	.025	Expressed as largest sag change at edge of aperture
Lower (rad)	DLR	.001	.0025	.025	Expressed as smallest radius change
Upper	DLF	--10 Fringes at 546.1 nm--			
Lower	DLF	--.5 Fringes at 546.1 nm--			
Upper	DLT	.010	.025	.250	
Lower	DLT	.0005	.00125	.0125	
Upper	DLN	----------.0100----------			
Lower	DLN	----------.0001----------			
b. Irregularity Range Limits					
Upper	CYL	----4 Fringes at 546.1----			
Lower	CYL	---.2 Fringes at 546.1----			
Upper	HOM	--------$\pm 1 \times 10^{-5}$--------			
Lower	HOM	--------$\pm 1 \times 10^{-7}$--------			
c. Decentered Range Limits					
Upper	TILT, BTILT	10 minutes (.00291 radians)			For diameters <1 inch
		.003	.0075	.075	TIR's (Total indicator runout) for diameters >1 inch
Lower	TILT, BTILT	.34 minute (.00010 radians)			For diameters <1 inch
		.0001	.00025	.0025	TIR's for diameters >1 inch
Upper	ROLL, DISP, BDISP	.010	.025	.25	Lateral shift
Lower	ROLL, DISP, BDISP	.0005	.00125	.0125	Lateral shift

2. Ranges

When operations such as inverse sensitivity (INV) are performed, tolerances are temporarily re-calculated. On insensitive parameters, these values can be so large that there is no cost advantage in such a loose tolerance; this tolerance can be reduced to a default maximum value that represents the point at which no further cost advantage is significant.

On the other hand, a sensitive parameter may generate a tolerance so tight it is not practical. This tolerance can be increased to a default minimum value representing the point at which manufacture becomes practical; the increased degradation must be accepted.

The ranges and defaults are listed in Table II; they cannot be reset by the user.

ERROR DISTRIBUTIONS FOR:

Figure 3a

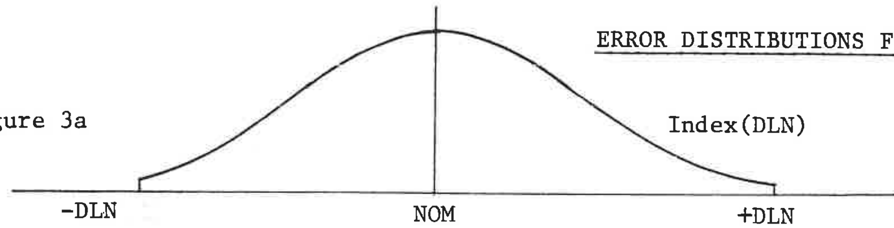


Figure 3b

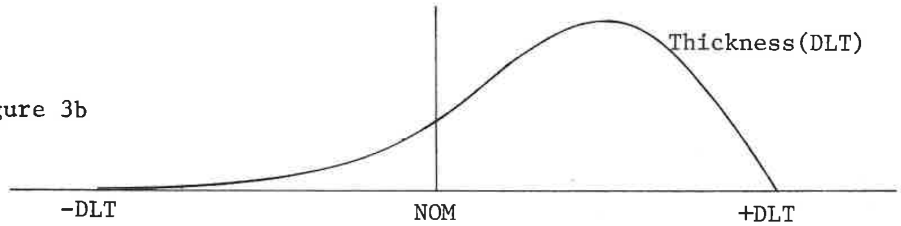


Figure 3c

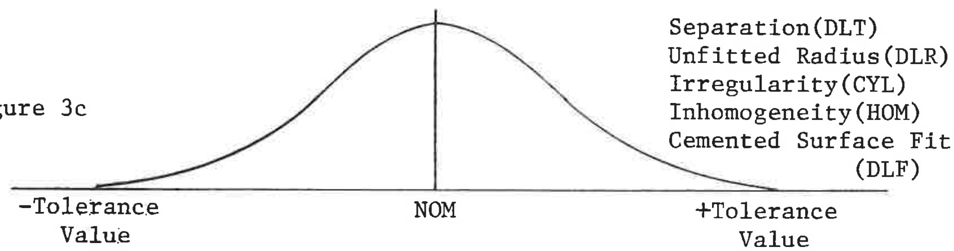


Figure 3d

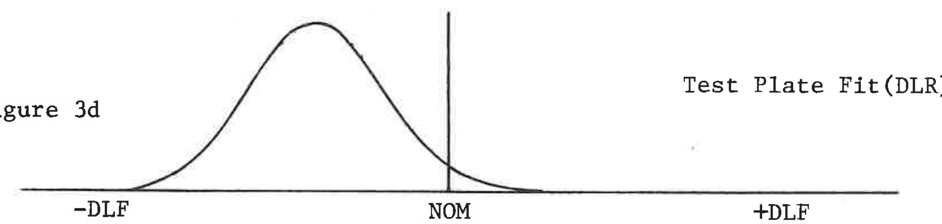


Figure 3e

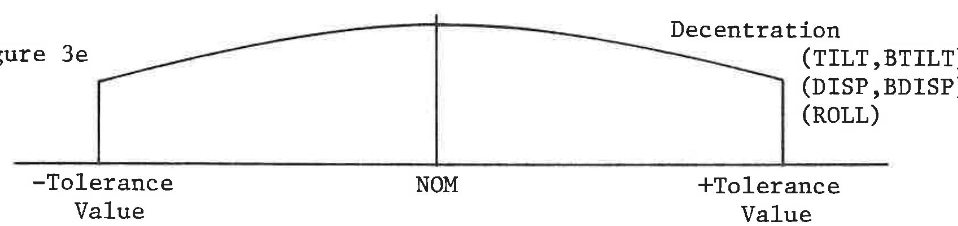
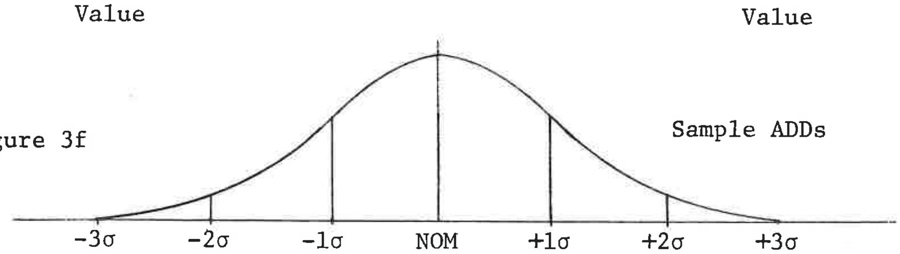


Figure 3f



3. Statistical Distributions

Simulation of manufacturing is done using Monte Carlo analysis. For this, a necessary part of the tolerance data base is the statistical distribution of each manufacturing error. Each constructional parameter has associated with it a particular distribution which is determined by the nature of the processes that are used to arrive at the desired value.

Index of Refraction - There is assumed to be an equal probability of the index being too high or too low. Thus, a Gaussian distribution would be expected. However, since glass is annealed to bring its index up, and there is an upper limit for each melt, there may be a slight skew to this distribution. Presumably, the distribution is truncated, because out of tolerance glass can be re-annealed to bring it into tolerance. Talks with glass manufacturers reveal that they apparently have insufficient data of the type needed to establish an accurate distribution.

A Gaussian distribution (Figure 3a) is therefore assumed, which is truncated at the 5% points, represented by the DLN value. If the design will be fitted to melts, the DLN value can be made small, representing the variation within one melt. If the design will not be re-computed for melts, the DLN value can be set to a value which makes the Gaussian fairly represent the expected melt-to-melt variation.

Center Thickness - There is a tendency in the optical shop to leave elements on the high side of the thickness tolerance, on the theory that more can always be removed in processing out scratches and surface irregularities. From discussions with fabricators, the best guess is that the distribution is a Gaussian skewed to the high side and truncated to represent the fact that rejects have been removed. Specifically, the assumption (Figure 3b) is a Gaussian with its peak at the midway point between the nominal value and the high side tolerance, truncated at the 3 sigma points which lie at the tolerance limits defined by DLT. This means that approximately .26% of the parts will be rejected, before assembly, for center thickness error.

Separation - Actual distributions are difficult to establish and depend on whether the lenses are separated by spacers or mounted individually with retaining rings or shoulders. The assumed distribution, however, is a Gaussian symmetrical about the nominal value (Figure 3c), with its 3 sigma points at the tolerance limit given by DLT.

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1 ORA is especially grateful for information from Warren Smith, Infrared Industries, Inc., and Robert Chamberlain, Schott Optical Glass, Inc. in preparing this section.

Unfitted Radius - Lenses are usually fitted to test plates before fabrication and therefore only the "fit" error itself is normally included in Monte Carlo analysis (see next paragraph). However, sometimes a few curves are left unfit or the design will be fabricated without test glasses. In these cases, values can be supplied which will establish tolerances on the expected radius (or curvature) errors. A Gaussian distribution (Figure 2c), symmetrical about the nominal value, is assumed with the 3 sigma points at the tolerance limit defined by DLR. No change is made to dummy surfaces.

Test Plate Fit - The assumption is made, for production lenses, that test plates exist or have been made for every curve. In fabrication, there is a strong tendency to go toward a "hollow" test glass fit, where there is contact at the edge of the surface. Thus, convex curves tend to be weaker and concave curves are stronger. The distribution is assumed to be a displaced symmetrical Gaussian (Figure 3d) with its peak at 40% of the tolerance defined by DLF on the hollow side and at 20% of the tolerance limit on the "full" side. No change is made to dummy surfaces. Cemented surfaces are intentionally made hollow to ease the cementing process. The symmetrical distribution of Figure 3c is used on the assumption that the two "hollow" surfaces, filled with cement will have an optical effect of a single surface which can be deformed either way with equal ease.

Irregularity - Both cylinder and non-refocusable in-homogeneity are assumed to follow the Gaussian distribution of Figure 3c with the 3 sigma points being at the tolerance limits.

Tilt and Decentering - These errors are assumed to have a symmetrical Gaussian distribution (Figure 3e) with the 1 sigma points being at the tolerance limits.

Special Tolerances - The added tolerances allow input of the distribution height at cut-off and assume a symmetrical Gaussian distribution. Three such cut-offs are shown in the curve, Figure 3f.

The above descriptions are the defaults. Currently there is insufficient data to identify valuable user inputs for modifying these distributions.

C. Functions

These are listed in Table III; they are performed in the order requested. The only acceptable entry in fields F1 to F7 is "NO" to indicate that the function is not to be performed for that zoom position. The function is performed for all zoom positions not so cancelled, or cancelled by a prior POS control (described later). As shown in Figure 1 and Table III, some of these (SNS, INV, MON) require the prior designation of a performance measure.

Some (SNA, SNS, INV) allow selection of reduced output by designation, previous to the function request, which tables are to be printed; these output codes are also shown in Table III. For each of these, the contents of field F1 - F7 are normally blank, causing the specific output request to be active for all succeeding functions that use it. If it is necessary to reset the request to its original condition, this may be done by entering "NO" in the applicable field F1 - F7.

D. Performance Measures

These are listed in Table IV. The last one entered designates the only measure of concern for any subsequent calculation in INV, SNS, or MON. Thus, separate Monte Carlo analyses of image distance and axial RMS wave error would be obtained by:

IMA
MON
AXI
MON

E. Controls

These are listed in Table V; they remain active over all following functions until they are modified.

TABLE III: FUNCTIONS AND OUTPUT REQUESTS

Function CODE*	Prior Output CODE*	Description
TAB	None	Generates a table of toleranced lens data using the tolerances previously established.
SNA	None	Generates sensitivity tables of all standard performance measures.
	FIR	Prints only first order tables
	THI	Prints only third order and x, y focus tables
	THR	Prints only third order and x, y focus data converted to RMS
	IRR	Prints only sensitivities of CYL and HOM tolerances
	DEC	Prints only 0 and 2nd order decenter aberrations
	DER	Prints only 2nd order decenter aberrations converted to RMS
	DEF	Prints full diagnostic development of DEC and DER tables
SNS**	None	Generates sensitivity of the last requested performance measure; prints only the applicable tables.
	CEN	Prints applicable FIR, THI or THR table
	IRR	Prints IRR table if applicable
	DEC	Prints DEC table if applicable
	DER	Prints DER table if applicable
INV**	Same as SNS	Generates inverse sensitivity of the last requested performance measure; prints only the applicable tables. The target effect may be entered previously on a TAR request; the default is .010.
MON**	None	Generates cumulative distribution tables of the effect on the last requested performance measure in a large number of systems fabricated to the current tolerance budget. The number of systems may previously be specified by TRIALS request; the default is 100, and the maximum is 1000.
AVE	None	Alters the lens system to the average of the Monte Carlo systems and prints the lens data. TRIALS may be specified as in MON.
PER	None	Alters the lens system to the last system of the Monte Carlo systems and prints the lens data. TRIALS may be specified as in MON.

*A "NO" in fields F1 to F7 deletes the request for that corresponding zoom position. For prior output codes, "NO" will reset the request to its original setting.

**Requires prior designation of performance measure (See Table IV).

TABLE IV: PERFORMANCE MEASURES

CODE	Description
a. First Order	
IMA	Image distance
EFL	Effective focal length
EP	Entrance pupil distance
OBJ	Object distance
TT	Total track (object to image) Finite conjugate systems
RED	Reduction ratio
b. Third Order, Primary Color and Astigmatic Fields	
SA	Transverse spherical aberration (radius) - without refocus
COM	Transverse sagittal coma (radius)
ASS	Transverse sagittal astigmatic blur (half-width)
AST	Transverse tangential astigmatic blur (half-width)
DST	Transverse (radial) distortion
AX	Transverse axial color
LAT	Transverse lateral color
X-F	Longitudinal focus at field edge x fan (close real ray)
Y-F	Longitudinal focus at field edge y fan (close real ray)
c. Third Order RMS Wave Front Error	
RSA	RMS conversion of SA - with refocus
RCO	RMS conversion of COM
RAS	RMS conversion of astigmatic departure from best compromise field curve
RFC	RMS conversion of best compromise focus field curve
RFI	RSS of RAS and RFC
RMA	Equivalent to RAS, using X-F, Y-F
RMF	Equivalent to RFC, using X-F, Y-F
d. Decentration Image Errors	
DDI	Lateral image displacement
DDT	Decentered distortion - tangential (field edge)
DDR	Decentered distortion - radial (field edge)
DCO	Decentered sagittal coma (radius)
DAS	Decentered astigmatic tilt (radians)
DTI	Decentered average tilt (radians) - best compromise tilted focal surface

Continued....

TABLE IV: PERFORMANCE MEASURES (Continued)

d. Decentration Image Errors (Continued)

DRC	RMS conversion of DCO
DRA	RMS conversion of astigmatic departure from best compromise field tilt
DRN	RMS conversion of astigmatic and tilted image - no compensating tilt
DFT	RSS of DRC and DRA
DFN	RSS of DRC and DRN

e. Compound Measures (See Appendix TOL-B)

AXI	Expected axial RMS wavefront error - with refocus
EDG	Expected full field RMS wavefront error - without removal of tilt and field curvature changes
EDF	Expected full field RMS wavefront error - with focusing to remove tilt and field curvature changes

TABLE V: CONTROLS

CODE	Description
POSITION	Used in zoom systems to flag those zoom positions which are to be skipped. The character "N" (or the word NO) entered in any data field F1-F7 will delete all output and calculations for that zoom position.
SC	Semi-aperture control; uses the semi-apertures entered with the lens data instead of computed clear apertures. On surfaces for which no aperture data was entered, the computed clear aperture is used. Use "N" (or NO) in fields F1-F7 to ignore the input semi-apertures for that zoom position.
TRIALS	Number of trials used in statistical function requests (MON, AVE, PER). The default value is 100; the maximum value is 1000. As the number increases, the results converge towards their true values. If TRIALS is used, an entry must be made in each field F1-F7 that will be used in computation; blank is zero trials.
TARGET	Required effect (on the designated performance measure) of the scaled tolerances generated by inverse sensitivity (INV). The default is .01 (change of EFL, axial RMS wave error, etc.). If TARGET is used, an entry must be made in each field F1-F7 to be used in computation; blank is zero.

Computation and Output:

A. TAB

For each surface, one line of print is generated. For the surface quality, the radius is printed with its radius tolerance; this is followed by the test plate fit - both power and irregularity - expressed as fringes at 546.1 nm. The thickness is followed by the thickness tolerance. The glass code is given with the index tolerance and the tolerance on inhomogeneity, both expressed as change of index.

After the surface data, the tilt and decenter tolerances (and special ADD tolerances, if any) are listed. See Table VI.

B. SNA

Three categories of analysis are performed:

Centered Effects

Irregularity Effects

Decentered Effects

and are described in detail below. Unless otherwise specified all are printed out. There are, however, a series of output requests which may be specified before calling SNA (see Table III). If any of these prior output codes are issued, only those tables requested will be printed.

C. SNA - Centered Effects

Each parameter of the lens system is varied individually and the third order aberrations are calculated; the nominal aberration values are then subtracted to determine the changes. A defect of manufacturing will cause a modification in image quality which is dominated by the change in primary aberration correction. For this reason, SNA indicates the relative sensitivity of each constructional parameter as well as the degradation to be expected from a given departure from the nominal design data.

Four tables are printed. These are:

1. Curvature (Radius) Sensitivity
2. Fringe (Test Plate fit) Sensitivity
3. Thickness and Separation Sensitivity
4. Index Sensitivity (see Table VIIa)

Each of these includes three sub-divisions.[1] The first contains the

---

1. The three letter codes in parentheses in the following sentences are the way in which each is called out as the performance measure of interest. These are all listed in Table IV.

change due to each tolerance in the first order parameters; these are image distance (IMA), effective focal length (EFL), and entrance pupil distance (EP). For finite conjugate systems, the changes in object distance (OBJ), total track (TT), and reduction ratio (RED) will also be listed. As a statistical estimate of random effects, the RSS (root-sum-square) is printed out for these measures.[1]

The second of the three sub-divisions lists the changes due to each tolerance on the primary centered aberrations. These are transverse spherical aberration radius without refocus (SA), transverse coma radius - sagittal coma (COM), transverse sagittal astigmatism half width (ASS), transverse tangential astigmatism half width (AST), transverse distortion (DST), transverse axial color radius (AS), and transverse lateral color (LAT). In addition, the longitudinal shift in sagittal (X) and tangential (Y) foci at the edge of the field, relative to the axis, is determined by ray tracing and included in this section. For some lenses, particularly wide angle lenses, the dominant effect of tolerances is to alter these foci so that they no longer lie within the permitted depth of focus.

The third sub-division is the conversion of these primary transverse and longitudinal aberrations into RMS wavefront aberration equivalents in various practical combinations. These are, in order, spherical aberration - assuming refocus (RSA), coma (RCO), astigmatic departure from circle of least confusion - field curvature - (RAS), best compromise focus field curve (RFC), astigmatism and field curvature combined (RFI), the astigmatic departure from circle of least confusion - determined by X and Y ray traced foci (RMA) and a similarly determined value for the best compromise focal curve (RMF). Finally, two values are given for the composite at the edge of the field of spherical aberration, coma, astigmatism and field curvature - with refocus (EDF) and without refocus (EDG). Note that vignetting is ignored at all field angles - see Appendix TOL-B.

Unless otherwise specified, all three sub-divisions will be printed in the four tables. If only one or two are wanted, they may be selected by the prior output codes FIR, THI, THR (see Table III).

D. SNA - Irregularity Effects

Table VIIb shows the sensitivity of RMS wavefront error to irregularity and inhomogeneity. Irregularity is defined as cylinder in the test plate fit; it is the most common form of irregularity in multiple blocked production elements. Although cylinder tolerances may be imposed independently of fringe tolerances, it should be borne in mind that the optician cannot readily measure cylinder if it is smaller than 1/5 of the fringe tolerance.

---

1. RSS is a better measure for the practical upper limit of tolerance effects than is worst case tolerancing. It is a rough measure; Monte Carlo analysis is a better simulation of manufacturing.

Inhomogeneity is defined as a residual variation of refractive index after any quadratic (focusing) and tilt (boresight) variation has been removed. The RMS wavefront effect is linearly proportional to the fraction of the clear aperture used by any beam, and proportional to the element thickness. Note that the number entered (and glass catalog specification, as well) represent a ± excursion of index rather than a peak-to-peak error.

As indicated by the notes on Table VIIb, the glass catalog specification on inhomogeneity is greater than the values to be entered as input. First, the catalog value represents the upper limit of the glass shipped to the fabricator; much of it will be better than the catalog limit. This is particularly true of unselected glass; specified selected glass will be much closer to the tighter catalog limit. Secondly, the catalog inhomogeneity specification is not concerned with whether any of the variation can be reduced by removal of a quadratic (focus) or tilt (boresight) effect; such an effect only causes a slight shift of image position and does not degrade the performance of the shifted image. This model of inhomogeneity is based on currently available information (which is scarce) and will be updated as more information becomes available.

The prior output request code for this section is IRR. It is unnecessary if no such codes have been used.

E. SNA - Decentered Effects

Three forms of output are available for decentered tolerances. The first two are the effect on image position and shape (DEC output request) and the effect on RMS wavefront error (DER output request); one line per tolerance is printed. Each tolerance may involve contributions from several surfaces (tilt of a cemented doublet involves three surfaces). The third form of output (DEF output request) is a full surface-by-surface printout of the contributions for each of the decentered effects; this is normally of little interest to the user, except to see how each surface contributes to the size of some particularly troublesome decentering tolerance. If no prior output request codes are entered, all three forms of output will be provided - if decentered tolerances exist.

If no decentered tolerances are entered by the user, the computer will generate two of them. The first is a simple tilt (TILT) of each surface from first to last, and the second is a displacement of each surface from first to last. Neither of these should be regarded as a valid tolerance with a valid summation, but only as a table of surface-by-surface tilt and decenter sensitivities. If any decentered tolerances are entered by the user, these automatically constructed tolerances will not be generated.

The sample run includes tabulated results for all three forms of output. Table VIIc is the summary table for image position and shape; the six image errors relate to the descriptions in Appendix TOL-B. Table VIId is the summary table converting these to RMS wavefront errors, representing degradation in imaging and not position. Table VIIe is an example of one of the two self-generated tolerances (TILT from first to last surface) showing the surface-by-surface contribution. Note that the final line represents summing of the contributions, not an RSS of them; likewise, the last three entries in this line are the conversions of other sums to the RSS wave aberration rather than the sum of the (unsigned) columns above them.[1]

Table VIII represents an example of entering specific decentering tolerances, with the RMS wavefront output request (DER).

F. SNS

If a performance measure has been previously specified (from those listed in Table IV), the sensitivity of that performance measure to each of the tolerances may be computed and printed as shown in Table IX. If performance measures AXI, EDG, or EDF are chosen, sensitivity to irregularity, inhomogeneity, tilts and decenters are provided in two additional tables; if only one or two of these tables are desired they may be selected with the appropriate prior input codes CEN, IRR, or DER.

G. INV

Inverse sensitivity is the choice of each tolerance so that it, by itself, will generate an effect of a designated magnitude. Table X shows as an example the inverse sensitivity needed to generate .01 shift of image distance. The tables are similar to those generated for SNS. If any such tolerances exceed the upper or lower ranges specified by Table II, they are limited to the range default values, which are printed on the output.

H. MON

Monte Carlo analysis is a simulation of the fabrication process. A number of lens systems (determined to be 100 or the TRIALS entry) are generated by randomly perturbing the system, with the perturbations adhering to the distributions and tolerances previously discussed. The effect on a previously designated performance measure is recorded, ordered from lowest to highest and the cumulative distribution is printed out. This is done for each of the contributing groups of parameters (radii,

---

1. Since the RMS values are derived from signed contributions, we can retain this sign even though the usual definition of RMS implies a positive value. When this is carried into a Monte Carlo analysis, we can get a true simulation of potential cancellation of tolerances. Therefore the signs are retained in tolerance effect tables as well.

fringes, thicknesses, indices, and where applicable, irregularity, inhomogeneity, decenters, and ADD effects) plus the composite of all.

This not only gives the degradation expected from the worst of these units (far better than the performance of a worst case system), but also gives an idea of the performance when a given percent is rejected. The separation into source types allows diagnosis and rebalancing of the budget.

Table XI gives such an analysis for image distance (IMA) and Table XIIa, b are for EDG.

I. PER and AVE

Any one of the systems (designated by the count given in the TRIALS entry) may be generated for later treatment by other options by using PER. Likewise, the average of all of the systems may be generated by using AVE. This will differ from the nominal system only because some of the distributions are skewed; thus only thicknesses and radii will be modified. This system may then be evaluated, or modified by adjusting parameters so that the new average system becomes the nominal design. Please note that this system does not represent the most probable lens system, which would include deviations from all tolerances.

Output for PER and AVE consists of the standard lens data for the revised system.

Note: In all systems for which there are couplings, the first tolerance in the group will represent the effect of the entire group and a + sign will be printed to denote it or its effect as a grouped tolerance.

Example:

The tolerance run which produced the sample output in Tables VI to XIII, following, is constructed with the following run:

```
After DATA deck,
TOLERANCE            - Calls for the tolerance option (produces SNA
                       output if no other entries are made)
TAB                  - Print table of toleranced lens data (Table VI).
                       This shows the default tolerance values.
SNA                  - Print tables of sensitivity of all standard
                       sensitivity measures:
                       Table VIIa - Sensitivity of centered measures to
                         index tolerances; curvature (radius), fringes,
                         thickness are similar.

                     Table VIIb - Sensitivity of RMS wavefront
                                    error to cylinder and inhomogeneity.
                     Table VIIc - Summary printout of effect on
                                    image position and shape of each
                                    decentered tolerance.
                     Table VIId - Summary printout of effect on
                                    primary RMS wavefront aberrations
                                    of each decentered tolerance.
                     Table VIIe - Sensitivity of decentered errors
                                    to decentered tolerances - full
                                    printout of surface-by-surface
                                    contributions.
```

Put in more appropriate tolerances.

```
DLR      0.0     - Set radius tolerances to 0.0 (fitted to test gl.)
DLF      3.0     - Assume 3 fringe fit on all surfaces
DLT 1    .002   )
DLT 2    .001   |
DLT 3    .0005  |
DLT 4    .0005  |
DLT 5    .001   } - Set more balanced thickness tolerances
DLT 6    .001   |
DLT 7    .0005  |
DLT 8    .0005  |
DLT 9    .001   |
DLT 10   .002   )
BTILT    .0006  )
SUR      2  1   |
BTILT    .0006  |
SUR      5  3   |
BTILT    .0006  } - Construct component mounting tilts of 2 minutes
SUR      7  9   |
BTILT    .0006  |
SUR      10 11  )
```

```
TILT     .0003  \
SUR      2  2    |
TILT     .0003   |
SUR      3  3    |
BTILT    .0003   |
SUR      4  3     > - Construct element wedges of 1 minute.
BTILT    .0003   |
SUR      8  9    |
TILT     .0003   |
SUR      9  9    |
TILT     .0003   |
SUR      11 11  /
DISP     .001   \
SUR      1  2    |
DISP     .0005   |
SUR      3  5     > - Construct component displacements.
DISP     .0005   |
SUR      7  9    |
DISP     .001    |
SUR      10 11  /
DER                 - Set for printing of decentered RMS effects
                      in SNA.
SNA                 - Do calculations (Table VIII).
DER      NO         - Reset output to original defaults.
IMA                 - Designates image distance as the performance
                      measure of interest for the next function
                      requests.
SNS                 - Print sensitivity of IMA to all tolerances
                      (Table IX).
INV                 - Print inverse sensitivity - amount of each
                      tolerance needed to generate .01 shift of
                      image distance (Table X).
MON                 - Do Monte Carlo analysis for IMA:  Table XI -
                      Image distance errors due to centered
                      system tolerance components and composite
                      of all tolerance effects.
ADD      .031         .25      FOLD MIRROR (1 FR POW/.5 FR IRR)
                    - Construct special effect of fold mirror
                    Note:  This was not inserted earlier because
                      it could have been included in functions
                      in which it was not wanted.
EDG                 - Designates RMS wavefront error at the edge
                      of the field, without refocus as the per-
                      formance measure of interest for the next
                      function requests.
MON                 - Do Monte Carlo analysis for EDG:  Table XIIa -
                      RMS wavefront errors (without refocus) due
                      to centered system tolerance components
                      Table XIIb - RMS wavefront errors (without
                      refocus) due to decentered or special
                      tolerance components, plus the composite
                      of all tolerance components.
```

TAB	- Print table of lens data with revised tolerances (Table XIII).
END	- Completion of tolerance run.

If testing of an average system or random perturbation had been desired, this could have been done by using AVE or PER and then going into the option AUTO to test, for example, the ability to recover using spacings.

T O L E R A N C E S

DOUBLE GAUSS EXAMPLE

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL	GLASS	INDEX TOL	INHOMO-GENEITY
OBJ								
1	0.64141	-0.0004	5.0/ 1.00	0.08099	.00100	747.377	.00100	0.0000050
2	2.40305	-0.0058	5.0/ 1.00	0.00300	.00100			
3	0.43459	-0.0002	5.0/ 1.00	0.20000	.00100	620.603	.00100	0.0000050
4	INF		5.0/ 1.00	0.03800	.00100	755.276	.00100	0.0000050
5	0.26548	-0.0001	5.0/ 1.00	0.05521	.00100			
6				0.17064	.00100			
7	-0.30151	-0.0001	5.0/ 1.00	0.03800	.00100	657.329	.00100	0.0000050
8	INF		5.0/ 1.00	0.08110	.00100	744.448	.00100	0.0000050
9	-0.45791	-0.0002	5.0/ 1.00	0.00300	.00100			
10	1.85997	-0.0035	5.0/ 1.00	0.08505	.00100	744.448	.00100	0.0000050
11	-0.76242	-0.0006	5.0/ 1.00	0.54722				
12				-0.00076				

TILT AND DECENTER TOLERANCES

TILT OF	0.001000	FROM 1 THROUGH 11
DISPLACEMENT OF	0.001000	FROM 1 THROUGH 11

TABLE VI: TOLERANCED LENS DATA

TOL-30

INDEX SENSITIVITY

DOUBLE GAUSS EXAMPLE

TABLE VIIa - SNA - Index Sensitivity

	DELTA INDEX	IMAGE DISTANCE	EFL	EP
NOMINAL		0.547221	1.004999	-0.448976
1	0.001000	-0.001161	-0.000526	-0.000193
3	0.001000	-0.001685	-0.001012	-0.000035
4	0.001000	0.001529	0.001087	0.000079
7	0.001000	0.000912	0.001329	0.000000
8	0.001000	-0.000697	-0.001132	0.000000
10	0.001000	-0.000561	-0.001026	0.000000
RSS		0.002856	0.002566	0.000212

	SA-T	COMA-T	AST-S	AST-T	DIST-T	AX COL-T	LAT COL-T	X-FOCUS	Y-FOCUS
NOMINAL	-0.001359	-0.000151	-0.001110	-0.000617	-0.000395	-0.000159	0.000233	-0.001326	-0.001348
1	-0.000012	-0.000008	-0.000006	-0.000011	0.000008	-0.000000	0.000003	-0.000014	-0.000017
3	-0.000036	-0.000011	-0.000008	-0.000009	0.000009	0.000005	0.000002	-0.000018	0.000010
4	0.000037	0.000006	0.000012	0.000015	-0.000008	-0.000007	-0.000003	0.000037	0.000020
7	0.000036	-0.000001	-0.000001	-0.000024	0.000001	-0.000004	-0.000001	-0.000013	-0.000103
8	-0.000031	-0.000001	0.000001	0.000015	-0.000001	0.000001	0.000001	0.000011	0.000064
10	-0.000021	-0.000002	-0.000003	0.000002	-0.000004	0.000000	0.000000	-0.000007	-0.000002
RSS	0.000074	0.000016	0.000016	0.000035	0.000016	0.000010	0.000004	0.000047	0.000124

	SA-RMS	COMA-RMS	AST-RMS	FC-RMS	FIELD RMS	X,Y AST-RMS	X,Y FC-RMS	MAX FIELD RMS WITH FOCUS	MAX FIELD RMS NO FOCUS
1	-0.0026	-0.0113	-0.0062	-0.0144	-0.0157	-0.0008	-0.0063	0.0116	0.0132
3	-0.0078	-0.0153	-0.0006	-0.0139	-0.0139	0.0079	-0.0017	0.0189	0.0190
4	0.0079	0.0087	0.0033	0.0228	0.0231	-0.0049	0.0117	0.0127	0.0172
7	0.0078	-0.0012	-0.0266	-0.0200	-0.0333	-0.0260	-0.0238	0.0271	0.0361
8	-0.0067	-0.0014	0.0162	0.0125	0.0205	0.0154	0.0155	0.0168	0.0229
10	-0.0045	-0.0033	0.0056	-0.0011	-0.0057	0.0017	-0.0019	0.0058	0.0061
RSS	0.0160	0.0213	0.0324	0.0385	0.0503	0.0316	0.0315	0.0413	0.0519

2/24/77 POSITION 1

IRREGULARITY AND INHOMOGENEITY SENSITIVITY

DOUBLE GAUSS EXAMPLE

	IRREGULARITY		INHOMOGENEITY	
SUR	CYL	RMS	DN	RMS
1	1.00	0.0981	0.0000050	0.0052
2	1.00	-0.1022		
3	1.00	0.0883	0.0000050	0.0158
4	1.00	0.0197	0.0000050	0.0060
5	1.00	-0.1079		
6				
7	1.00	0.0834	0.0000050	0.0049
8	1.00	0.0079	0.0000050	0.0046
9	1.00	-0.0637		
10	1.00	0.0490	0.0000050	0.0041
11	1.00	-0.0439		
RSS		0.2352		0.0193

NOTES: IRREGULARITY IS DEFINED AS FRINGES OF CYLINDER POWER IN TEST PLATE FIT

INHOMOGENEITY IS THE NON-FOCUSABLE RADIAL VARIATION OF INDEX; THIS IS A FRACTION OF THE CATALOG HOMOGENEITY LIMITS. FOR UNSELECTED GLASS, THE AVERAGE EXPECTED VALUE IS WELL BELOW THE UPPER LIMITS GIVEN IN THE CATALOG AND IS FURTHER REDUCED BY REFOCUSING; FOR H4 GLASS, THE AVERAGE EXPECTED VALUE IS CLOSER TO THE CATALOG UPPER LIMITS.

TYPICAL VALUES: $5*10^{-6}$ FOR UNSELECTED GLASS TO $5*10^{-7}$ FOR H4

TABLE VIIb - SNA - Irregularity Sensitivity

2/24/77 POSITION 1

IMAGE POSITION AND SHAPE

DOUBLE GAUSS EXAMPLE

TYPE	AMOUNT	SURFACES	INDUCED TILT	LATERAL DISP (C0)	DISTORTION TANGENTIAL (C3*Y**2)	DISTORTION RADIAL (C4*Y**2)	SAGITTAL COMA (C1)	ASTIGMATIC TILT(RAD) (C2)	AVERAGE TILT(RAD) (2*C2+CP)
TILT	0.001000	1 TO 12		0.000231	-0.00000	-0.00001	-0.000010	-0.000430	-0.000793
DISPLACEMENT	0.001000	1 TO 12		0.001000	0.00000	0.00000	0.000005	-0.000018	-0.000036
RSS				0.001026	0.00001	0.00001	0.000011	0.000431	0.000793

TABLE VIIc - SNA - Decentered Image Position and Shape

2/24/77 POSITION 1

PRIMARY RMS WAVEFRONT ABERRATION

DOUBLE GAUSS EXAMPLE

TYPE	AMOUNT	SURFACES	INDUCED TILT	RMS COMA	ASTIGMATIC RMS TILTED	ASTIGMATIC RMS NO TILT	RSS--MAX FIELD TILTED	RSS--MAX FIELD NO TILT
TILT	0.001000	1 TO 12		-0.0131	-0.0669	-0.1106	0.0682	0.1113
DISPLACEMENT	0.001000	1 TO 12	0 TO 0	0.0074	-0.0028	-0.0048	0.0079	0.0088
RSS				0.0150	0.0670	0.1107	0.0686	0.1117

TABLE VIId - SNA - Decentered RMS Wavefront Aberrations

2/24/77 POSITION 1

D E C E N T E R I N G   A N A L Y S I S

DOUBLE GAUSS EXAMPLE

TILT OF 0.001000 FROM 1 THROUGH 12

	LATERAL DISP (C0)	DISTORTION TANGENTIAL (C3*Y**2)	DISTORTION RADIAL (C4*Y**2)	SAGITTAL COMA (C1)	ASTIGMATIC TILT(RAD) (C2)	AVERAGE TILT(RAD) (2*C2+CP)	RMS COMA	ASTIGMATIC RMS TILTED	ASTIGMATIC RMS NO TILT	RMS--MAX FIELD TILTED	RMS--MAX FIELD NO TILT
1	0.000755	0.00002	0.00002	0.000031	-0.000216	-0.000825	0.0420	-0.0336	-0.0975	0.0538	0.1062
2	-0.000714	-0.00005	-0.00007	-0.000018	-0.000497	-0.000245	-0.0240	-0.0773	-0.0819	0.0809	0.0854
3	0.000590	0.00002	0.00001	0.000002	-0.000414	-0.001886	0.0031	-0.0643	-0.2191	0.0644	0.2191
4	0.000093	0.00001	0.00001	0.000011	0.000224	0.000225	0.0146	0.0348	0.0429	0.0377	0.0453
5	-0.000475	-0.00003	-0.00003	-0.000014	0.000459	0.001693	-0.0196	0.0713	0.2010	0.0740	0.2020
6	0.000000	0.00000	0.00000	0.000000	0.000000	0.000000	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.000346	0.00002	-0.00000	0.000041	0.000348	0.001114	0.0553	0.0541	0.1350	0.0774	0.1459
8	0.000046	0.00001	0.00001	0.000003	-0.000040	0.000021	0.0038	-0.0061	0.0066	0.0072	0.0076
9	-0.000426	-0.00002	-0.00000	-0.000038	-0.000277	-0.001188	-0.0515	-0.0430	-0.1388	0.0670	0.1480
0	0.000426	0.00005	0.00006	0.000016	0.000149	0.000437	0.0224	0.0232	0.0538	0.0322	0.0582
1	-0.000409	-0.00002	-0.00002	-0.000044	-0.000168	-0.000137	-0.0592	-0.0261	-0.0302	0.0647	0.0665
									--CONVERSION OF SUMS---		
UM	0.000231	-0.00000	-0.00001	-0.000010	-0.000430	-0.000793	-0.0131	-0.0669	-0.1106	0.0682	0.1113

TABLE VIIe - SNA - Surface-by-Surface Decentered Aberration Contributions

2/24/77 POSITION 1

PRIMARY RMS WAVEFRONT ABERRATION

DOUBLE GAUSS EXAMPLE

TYPE	AMOUNT	SURFACES	INDUCED TILT	RMS COMA	ASTIGMATIC RMS TILTED	ASTIGMATIC RMS NO TILT	RSS--MAX FIELD TILTED	RSS--MAX FIELD NO TILT
BARREL TILT	0.000600	2 TO 1		0.0076	-0.0640	-0.0907	0.0644	0.0911
BARREL TILT	0.000600	5 TO 3		-0.0022	0.0462	0.0847	0.0463	0.0847
BARREL TILT	0.000600	7 TO 9		0.0127	0.0097	0.0196	0.0160	0.0233
BARREL TILT	0.000600	10 TO 11		-0.0182	0.0000	0.0210	0.0182	0.0277
TILT	0.000300	2 TO 2		-0.0072	-0.0232	-0.0246	0.0243	0.0256
TILT	0.000300	3 TO 3		0.0009	-0.0193	-0.0657	0.0193	0.0657
BARREL TILT	0.000300	4 TO 3		0.0049	0.0000	-0.0264	0.0049	0.0269
BARREL TILT	0.000300	8 TO 9		-0.0116	-0.0125	-0.0342	0.0170	0.0361
TILT	0.000300	9 TO 9		-0.0154	-0.0129	-0.0416	0.0201	0.0444
TILT	0.000300	11 TO 11		-0.0178	-0.0078	-0.0091	0.0194	0.0200
DISPLACEMENT	0.001000	1 TO 2	0 TO 0	0.0554	-0.0845	-0.1758	0.1011	0.1843
DISPLACEMENT	0.000500	3 TO 5	0 TO 0	-0.0333	0.0604	0.1281	0.0690	0.1324
DISPLACEMENT	0.000500	7 TO 9	0 TO 0	-0.0356	-0.0428	-0.0745	0.0557	0.0826
DISPLACEMENT	0.001000	10 TO 11	0 TO 0	0.0897	0.0467	0.0656	0.1012	0.1112
RSS				0.1217	0.1498	0.2864	0.1930	0.3112

TABLE VII - SNA - RMS Wavefront Aberrations for Defined Tolerance Budget

S E N S I T I V I T Y

IMAGE DISTANCE

DOUBLE GAUSS EXAMPLE

	RADIUS		FRINGE		THICKNESS		INDEX	
	TOLERANCE	EFFECT	TOLERANCE	EFFECT	TOLERANCE	EFFECT	TOLERANCE	EFFECT
1			3.00	-0.0007	0.002000	-0.0016	0.001000	-0.0012
2			3.00	-0.0007	0.001000	-0.0008		
3			3.00	-0.0007	0.000500	-0.0015	0.001000	-0.0017
4			3.00	-0.0001	0.000500	-0.0014	0.001000	0.0015
5			3.00	-0.0008	0.001000	-0.0002		
6					0.001000	-0.0002		
7			3.00	-0.0006	0.000500	-0.0001	0.001000	0.0009
8			3.00	-0.0001	0.000500	-0.0001	0.001000	-0.0007
9			3.00	-0.0004	0.001000	-0.0001		
10			3.00	-0.0003	0.002000	-0.0002	0.001000	-0.0006
11			3.00	-0.0003	0.000000	0.0000		
RSS		0.0000		0.0017		0.0028		0.0029

TABLE IX - SNS - Sensitivity of Image Distance to Centered Tolerances

2/24/77 POSITION 1

I N V E R S E   S E N S I T I V I T Y

IMAGE DISTANCE

DOUBLE GAUSS EXAMPLE

	RADIUS		FRINGE		THICKNESS		INDEX	
	TOLERANCE	EFFECT	TOLERANCE	EFFECT	TOLERANCE	EFFECT	TOLERANCE	EFFECT
1			-10.00*	0.0024	0.010000*	-0.0079	-0.008610	0.0100
2			-10.00*	0.0024	0.010000*	-0.0078		
3			-10.00*	0.0023	-0.003241	0.0100	-0.005934	0.0100
4			-10.00*	0.0004	-0.003518	0.0100	0.006541	0.0100
5			-10.00*	0.0028	0.010000*	-0.0020		
6					0.010000*	-0.0020		
7			-10.00*	0.0019	0.010000*	-0.0029	0.010000*	0.0091
8			-10.00*	0.0002	0.010000*	-0.0028	0.010000*	-0.0070
9			-10.00*	0.0014	0.010000*	-0.0005		
10			-10.00*	0.0011	0.010000*	-0.0012	0.010000*	-0.0056
11			-10.00*	0.0009	0.010000*	0.0000		
RSS		0.0000		0.0057		0.0187		0.0215

* THESE VALUES ARE RESTRICTED TO LIE IN THE RANGE:

	MAXIMUM	MINIMUM
RADIUS :	0.0010 IN SAG AT CA	0.0010 RADIUS CHANGE
FRINGE :	10.0 FRINGES	0.0 FRINGES
THICKNESS:	0.0100	0.0005
INDEX :	0.0100	0.0001

AND GENERATE LESS THAN 0.0100 CHANGE IN IMAGE DISTANCE

TABLE X - INV - Inverse Sensitivity of Change Distance To Centered Tolerances (.01 Target Change)

2/24/77 POSITION 1

M O N T E   C A R L O   A N A L Y S I S

DOUBLE GAUSS EXAMPLE

SAMPLES: 100
COMPONENTS FOR ERROR BUDGET
ON IMAGE DISTANCE

CUMULATIVE PERCENT	RADIUS	FRINGE	THICKNESS	INDEX	COMPOSITE TOTAL ERROR
0	0.000000	0.001091	-0.003809	-0.002964	-0.003735
2	0.000000	0.001112	-0.003723	-0.002382	-0.003295
4	0.000000	0.001282	-0.003345	-0.002094	-0.003070
6	0.000000	0.001334	-0.003240	-0.001995	-0.002713
8	0.000000	0.001340	-0.003122	-0.001918	-0.002314
10	0.000000	0.001433	-0.003119	-0.001594	-0.002273
20	0.000000	0.001533	-0.002768	-0.000967	-0.001470
30	0.000000	0.001601	-0.002480	-0.000720	-0.000913
40	0.000000	0.001691	-0.002181	-0.000540	-0.000683
50	0.000000	0.001791	-0.002027	-0.000153	-0.000481
60	0.000000	0.001835	-0.001761	0.000304	-0.000069
70	0.000000	0.001950	-0.001563	0.000610	0.000493
80	0.000000	0.002066	-0.001219	0.000739	0.001101
90	0.000000	0.002275	-0.000651	0.001412	0.001698
92	0.000000	0.002290	-0.000511	0.001577	0.001862
94	0.000000	0.002304	-0.000459	0.001725	0.002137
96	0.000000	0.002361	-0.000340	0.001792	0.003000
98	0.000000	0.002402	-0.000092	0.002056	0.003167
100	0.000000	0.003109	0.000218	0.002269	0.003252
MEAN	0.000000	0.001806	-0.001941	-0.000093	-0.000229
VARIANCE	0.000000	0.000000	0.000001	0.000001	0.000002
SIGMA	0.000000	0.000330	0.000885	0.001116	0.001520

TABLE XI - MON - Monte Carlo Analysis for Image Distance Effects (IMA)

M O N T E   C A R L O   A N A L Y S I S

TOL-38

DOUBLE GAUSS EXAMPLE

SAMPLES: 100
COMPONENTS FOR ERROR BUDGET
ON MAX FIELD RMS - NO REFOCUS

CUMULATIVE PERCENT	RADIUS	FRINGE	THICKNESS	INDEX
0	0.000000	0.023026	0.029091	0.004147
2	0.000000	0.023162	0.036084	0.005117
4	0.000000	0.030911	0.046063	0.005548
6	0.000000	0.031664	0.057590	0.006734
8	0.000000	0.033691	0.064436	0.006961
10	0.000000	0.034953	0.072929	0.008141
20	0.000000	0.039458	0.091137	0.011253
30	0.000000	0.042433	0.104303	0.013378
40	0.000000	0.046123	0.119198	0.015406
50	0.000000	0.049540	0.129993	0.017081
60	0.000000	0.054394	0.140084	0.022464
70	0.000000	0.058154	0.153346	0.024879
80	0.000000	0.063574	0.169222	0.027178
90	0.000000	0.072177	0.198790	0.030622
92	0.000000	0.073054	0.201009	0.032829
94	0.000000	0.073599	0.211035	0.035118
96	0.000000	0.074504	0.219057	0.035744
98	0.000000	0.082209	0.229150	0.042656
100	0.000000	0.085380	0.251670	0.049757
MEAN	0.000000	0.051383	0.132251	0.019752
VARIANCE	0.000000	0.000189	0.002216	0.000090
SIGMA	0.000000	0.013763	0.047076	0.009504

TABLE XIIa - Monte Carlo Analysis for EDG - Centered Tolerance Effects

M O N T E   C A R L O   A N A L Y S I S

DOUBLE GAUSS EXAMPLE

SAMPLES: 100
COMPONENTS FOR ERROR BUDGET
ON MAX FIELD RMS - NO REFOCUS

CUMULATIVE PERCENT	IRREGULARITY	INHOMOGENEITY	TILTS AND DECENTERS	SPECIAL TOLERANCES	COMPOSITE TOTAL ERROR
0	0.034574	0.001596	0.068517	0.000380	0.137105
2	0.035612	0.001852	0.078489	0.000382	0.164811
4	0.039387	0.002234	0.084339	0.000816	0.164941
6	0.042287	0.002919	0.096959	0.001314	0.166762
8	0.043058	0.003125	0.106517	0.001761	0.176191
10	0.044144	0.003257	0.110363	0.002137	0.178431
20	0.055583	0.003641	0.126410	0.003759	0.197609
30	0.063568	0.004306	0.134253	0.006170	0.214001
40	0.069964	0.004721	0.143193	0.007362	0.224659
50	0.076700	0.004997	0.160820	0.010262	0.236765
60	0.082799	0.005455	0.167955	0.011934	0.247211
70	0.086579	0.006208	0.187845	0.014614	0.260781
80	0.093203	0.007151	0.199744	0.018012	0.271213
90	0.100445	0.008211	0.214461	0.021822	0.286402
92	0.110473	0.008629	0.216883	0.023010	0.289040
94	0.113584	0.009053	0.226087	0.023748	0.295196
96	0.115127	0.009307	0.234037	0.026284	0.297358
98	0.122532	0.009977	0.243798	0.027488	0.305275
100	0.137354	0.012171	0.248216	0.030130	0.332045
MEAN	0.076128	0.005476	0.160930	0.011225	0.235720
VARIANCE	0.000484	0.000004	0.001715	0.000056	0.001562
SIGMA	0.022004	0.001998	0.041412	0.007465	0.039520

TABLE XIIb - Monte Carlo Analysis For EDG - Non-Centered and Composite Effects

POSITION 1

T O L E R A N C E S

TOL-40

DOUBLE GAUSS EXAMPLE

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL	GLASS	INDEX TOL	INHOMO-GENEITY
OBJ								
1	0.64141		3.0/ 1.00	0.08099	.00200	747.377	.00100	0.0000050
2	2.40305		3.0/ 1.00	0.00300	.00100			
3	0.43459		3.0/ 1.00	0.20000	.00050	620.603	.00100	0.0000050
4	INF		3.0/ 1.00	0.03800	.00050	755.276	.00100	0.0000050
5	0.26548		3.0/ 1.00	0.05521	.00100			
6				0.17064	.00100			
7	-0.30151		3.0/ 1.00	0.03800	.00050	657.329	.00100	0.0000050
8	INF		3.0/ 1.00	0.08110	.00050	744.448	.00100	0.0000050
9	-0.45791		3.0/ 1.00	0.00300	.00100			
10	1.85997		3.0/ 1.00	0.08505	.00200	744.448	.00100	0.0000050
11	-0.76242		3.0/ 1.00	0.54722				
12				-0.00076				

TILT AND DECENTER TOLERANCES

BARREL TILT OF	0.000600	FROM 2 THROUGH 1
BARREL TILT OF	0.000600	FROM 5 THROUGH 3
BARREL TILT OF	0.000600	FROM 7 THROUGH 9
BARREL TILT OF	0.000600	FROM 10 THROUGH 11
TILT OF	0.000300	FROM 2 THROUGH 2
TILT OF	0.000300	FROM 3 THROUGH 3
BARREL TILT OF	0.000300	FROM 4 THROUGH 3
BARREL TILT OF	0.000300	FROM 8 THROUGH 9
TILT OF	0.000300	FROM 9 THROUGH 9
TILT OF	0.000300	FROM 11 THROUGH 11
DISPLACEMENT OF	0.001000	FROM 1 THROUGH 2
DISPLACEMENT OF	0.000500	FROM 3 THROUGH 5
DISPLACEMENT OF	0.000500	FROM 7 THROUGH 9
DISPLACEMENT OF	0.001000	FROM 10 THROUGH 11

TABLE XIII - TAB - Toleranced Lens Data
Revised Tolerances

SPECIAL TOLERANCES	MAXIMUM ERROR	GAUSSIAN AT MAXIMUM ERROR
FOLD MIRROR (1FR POW/.5FR IRR)	0.0310	0.250

Appendix A:

Systematic Tolerancing of Optical Systems

Tolerancing remains an art of lens design, requiring extensive judgement on the part of the designer, combined with an awareness of the capability of the fabricator. The optical designer has generated a design which, if optimized, manufacturing errors can only degrade. The manufacturer can only fabricate a lens whose acceptable errors are within his capability. It is the responsibility of the optical designer to bridge this gap. This introduction to the option TOLERANCE aims to provide a systematic approach to this task.

In tolerancing, the designer is attempting to answer two questions:

- How can I get the best hardware article?
- How bad are the systems likely to get?

The end result can be considerably enhanced if, during the design, investigations of sensitivity have been made and modifications introduced to reduce the more troublesome errors. Tolerancing thus plays a role both during design and at the completion. In answering the first question, sensitivity tables are valuable in designing a compensation strategy and in setting tolerance budgets. Monte Carlo analysis of the system under the proposed tolerance budget can establish the answer to the second question.

The following discussion is a procedure for approaching the budgeting of tolerances for a given optical system. It breaks the process down into the details. In few cases, will all these steps be necessary. In most cases, the stages will be grouped together in a logical sequence depending on the expected volume of manufacturing, target cost, and desired performance.

I. List All Possible Sources of Error

- Potentially Compensatable

  A. Index and dispersion departures from catalog values
  B. Radii errors - tolerances on test plate fabrication
  C. Test plate fit and coating non-uniformity
  D. Thickness errors
  E. Separation errors

- Non-Compensatable

  F. Inhomogeneity of material
  G. Surface irregularity
  H. Decentering in elements, seats, and assembly
  I. Errors in measurement

The first five are departures from the nominal design data and can be analyzed directly if necessary. The rest are random errors which can only be treated statistically.

II. Select Compensatable Errors

Of the listed errors, it will be possible to group them into compensatable errors and non-compensatable errors. The first five errors are potentially compensatable; the choice, however, depends on the application and the practicality of individually compensating each lens or group of lenses. For example, lenses for high volume manufacture must be designed so that no compensation is needed, or that sufficient compensation will occur automatically; it is usually only possible to remove radii errors (by test plate fitting). For low quantities, it may also be feasible to fit to glass melts, thereby putting A and B into the category of compensatable errors. For prototypes, it may be desirable to respace for measured thicknesses, as well. For critical state-of-the-art prototypes it may even be necessary to correct for test plate fit or to respace the remaining separations for errors in the separations of partial assemblies.

Once this choice of compensatable errors has been made, all other errors fall into the category of non-compensatable errors. Each group is handled differently.

III. Run Tolerance Sensitivity Tables (SNA, SNS or INV functional requests)

This data will reveal the relative sensitivities of indices, thicknesses, curvatures and decenters. This becomes input in the choices to be made.

IV. Choose Compensation Strategy - Confirm with Worst Case Optimizations

The first step of compensation has the largest number of free variables available. The last step has few. Some errors can best be compensated by certain types of variables - index and dispersion errors are best compensated by curve changes, thickness errors are best compensated by separation changes. Choose the sequence accordingly.

Each step must be compensatable by the remaining variables.

To guarantee that compensation is possible at any given step:

1. Choose preliminary tolerances on the items expected to be in error.

2. From sensitivity tables, select the sign of the tolerances to add to each other. Use RMS versions of SA, COMA, AST+P at the dominant part of the field (edge of field for wide angle systems, on-axis for narrow angle systems).

3. With these changes introduced into the system, re-optimize for the available variables. If performance is still satisfactory accept these tolerances; if not, alter the tolerances or the strategy and repeat.

The most extensive strategy which might be applied would be the following:

1. Choose index tolerances. Confirm acceptability for melt recomp with worst case re-optimization. Order glass.

2. Melt recomp with curvatures, thicknesses, separations.

3. Test plate fit. For any new test plates, choose radius tolerance. Confirm acceptability of new radii with worst case re-optimization. If recomputation for new plates is desirable the worst case re-optimization can be on thicknesses and separations. If there is to be no special recomp for new plates, the worst case re-optimization is to be that of step 4, using only separations to compensate both radius errors and thickness errors. Specify new test plates.

4. Fit measured values of new plates. Choose thickness tolerances. Confirm acceptability of thickness tolerances with worst case re-optimization of separations. Release for element fabrication.

5. Respace to measured thicknesses. Choose separation tolerances. Confirm with worst case re-optimization of defocus. Release for assembly. If necessary, this may be broken down into two or more stages of assembly with recomputation in between for measured separations.

In order to establish tolerances prior to this process, each step can be simulated separately in advance. In the case of radii tolerances this will provide guidance in the sequence of test plate fitting. It is unrealistic to perform worst case re-optimization over all of the errors since the statistical chance of this occurring is insignificant. Practical limits can be investigated with Monte Carlo techniques.

V. Non-Compensatable Errors - RMS Analysis

The virtue in using RMS wavefront errors for tolerancing is that for moderate errors up to .07 waves RMS (corresponding to .80 Strehl definition or approximately the Rayleigh criteria), all aberration sources of equal RMS value have identical impact on MTF and can be combined statistically without regard to the specific form of the aberration. For somewhat larger aberrations this is sufficiently true that tolerancing can be still done using RMS wavefront errors.

Assign the RMS tolerance budget as follows:

1. Cut off frequency = $\frac{1000}{\lambda \cdot f/no} = \omega_c$ (λ in μ)

2. Choose frequency of interest, ω.

   Fractional frequency $F = \frac{\omega}{\omega_c}$

3. Choose allowable relative loss in MTF at the frequency of interest. From graph (Figure 2) determine allowable RMS error.

Example:

f/4.5 lens with reference λ at .7μ

Specification calls for 40% response at 40 c/mm.

Design produces 50% nominally.

$$\omega_c = \frac{1000}{.7 \cdot 4.5} = 320 \text{ c/mm}$$

$$F = \frac{40}{320} = .125$$

Allowable degradation factor = $\frac{40\%}{50\%} = .8$

From graph, .8 degradation factor at .125 of cut off occurs with .090 waves of RMS error.

The non-compensatable errors must combine to be less than this amount. The combination is the root-sum-square of the RMS errors:

$$E = \left[\sum_{1}^{n} (e_i)^2 \right]^{1/2}$$

VI. RMS - MTF Graph

RMS analysis is of value for three reasons:

1. Many varieties of errors may be evaluated on a common basis.

2. It is a natural approach to use on surface irregularity and inhomogeneity of glass.

3. Moderate RMS degradation correlates well with Strehl definition, the Rayleigh criteria and MTF.

The correlation between RMS error and MTF reduction is good up to about .10 λ RMS error and is somewhat useful up to .20 λ RMS error. Figure 1 shows the reduction of MTF for a number of values of RMS wave-front error.[1] From this, a plot of degradation factors can be made, which is to be used as given in the example previously; this is plotted in Figure 2.

---

1. From: R. R. Shannon, "Some Recent Advances in the Specification and Assessment of Optical Images," Optical Sciences Center Technical Report 49, University of Arizona, 1969.

FIGURE 1

Family of averaged MTF's for varying amounts of rms random wavefront error.

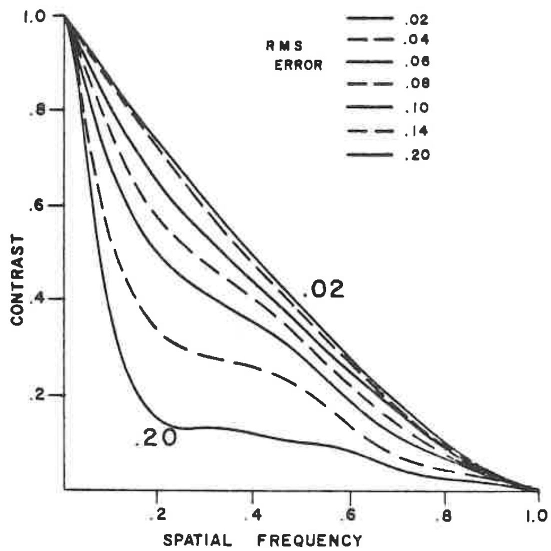
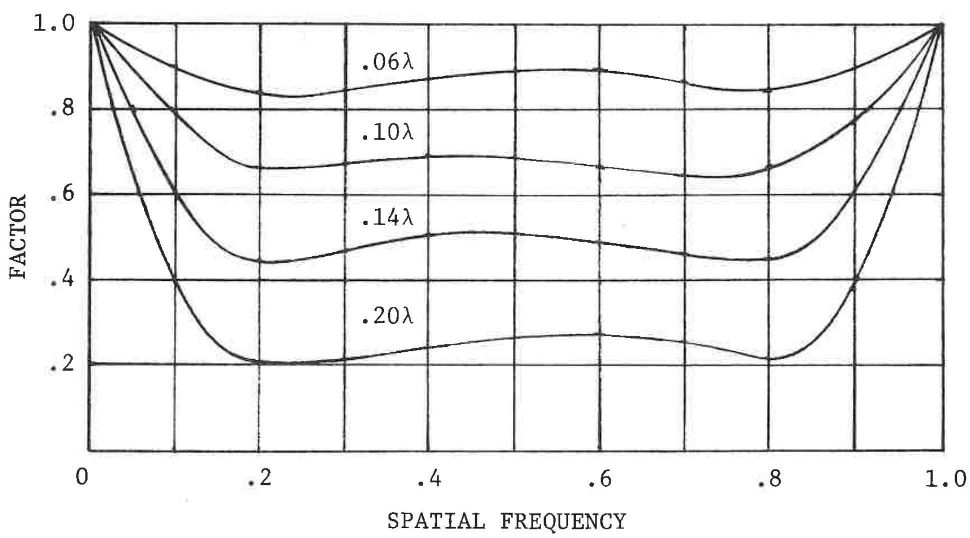


FIGURE 2 - MTF MULTIPLYING FACTOR



TOL-A6

Appendix B:

Technical Notes

I. Effects of Small Decentrations on Image Quality

It is possible to analyze the effects of small decentrations by expanding decentered ray trace equations in a power series and neglecting any terms higher than second order. When this is done a group of coefficients analogous to the third order (Seidel) aberrations are produced which can be summed in any grouping to find the effects of required decenterings. There is one zero order effect plus five second order decentering aberration coefficients.

These are:

D_0 a zero order shift of the entire image, without degradation, in the plane of the decentration movement.

D_1 a second order comatic flare which is uniform over the whole field and symmetrical about the plane of decentration movement.

D_2 a second order astigmatic separation of the focal plane into two tilted intersecting focal planes in the plane of decentration, coupled with a circular blurring in the plane perpendicular to the plane of decentration.

D_P a second order tilting of the focal plane (or planes, if $D_2 \neq 0$).

D_3 a second order displacement of the image which bends the radial lines (called tangential distortion); no image degradation occurs from D_3.

D_4 a second order displacement of the image which is connected with D_3; no image degradation occurs from D_4.

These coefficients represent the relative sensitivity to tilting of the surfaces. The amount of tilt of each surface depends upon the type of decentering movement which the mounting allows. Thus, summing up these coefficients does not necessarily give a useful value. When they are properly combined, however, a set of aberrations are obtained which have the following characteristics[1].

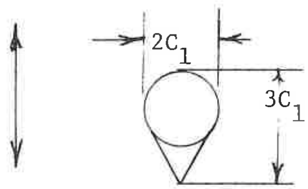
C_0 The displacement of the image uniform over the field, is equal to C_0 in the direction of the decentering movement.

---

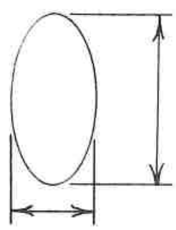
1. The letters C_0, C_1, C_2, C_P, C_3, and C_4 are the coefficients referred to in the output headings for decentered primary aberrations.

C_1 The comatic flare, uniform over the field, has the following dimensions:

Direction of decentering movement



C_2 and C_P Case I: Decentration in direction of meridional plane

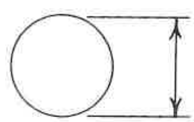


$(3C_2 + C_P)\ Y/\ (f/no)$
$= (\text{Average Tilt} + \text{Astigmatic Tilt}) \cdot Y/\ (f/no)$
where Y is the field height

$(C_2 + C_P)\ Y/\ (f/no) = (\text{Average Tilt} - \text{Astigmatic Tilt}) \cdot Y/\ (f/no)$

This is an ordinary astigmatic image which changes shape as the lens is focused, and possesses a sagittal and tangential focus.

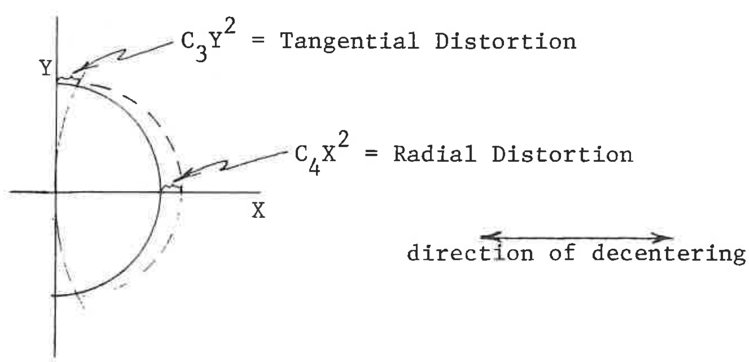
Case II: Decentration perpendicular to meridional plane



$C_2 \cdot Y/\ (f/no) = (\text{Astigmatic Tilt}) \cdot Y/\ (f/no)$

This is a circular image which is the circle of least confusion between two astigmatic lines oriented at $\pm 45°$.

C_3 and C_4 Tangential distortion



Because of the many possible orientations of decentering movement which can exist simultaneously in a complex lens system, the above representations are necessarily limited to special cases.

Decentering Movements

There are six types of errors which can occur in a lens which give rise to tilts of the surfaces:

Wedge	This is the tilt introduced in one surface of an element due to one edge being thicker than the other.
Tilt	This is the tilt of an entire element.
Roll	This occurs when one surface of a component remains in contact with the lens seat, but undergoes a rotating displacement about its center of curvature. The other surfaces of the component thereby become tilted.
Displacement or Barrel Displacement	This is the lateral shift of a single component or group of surfaces.
Barrel Tilt	This is a rotation of a group of surfaces about the vertex of the first as would occur if a subassembly of a lens could be tilted as a unit.

Any proposed lens mount design can be broken down into groupings of these six types of decentering motions and the effects determined individually by using this program; the worst case effects can then be obtained by combining unfavorably all possible combinations. If there is no established form for the lens mount design (as would be the case in the development of a new lens design) it is useful to examine the sensitivity of the lens design to decentering. This can be adequately done by examining the default groupings of tolerances defined by the program.

II. Compound Measures of Performance

The compound measures of performance given in Table IV are all composites of the contributing RMS wavefront errors that apply. Specifically:

AXI — The RSS of the RMS contributions of spherical aberration (RSA), cylinder, inhomogeneity, decentered coma, and ADD effects.

EDG The RSS of the RMS contributions of spherical aberration (RSA), coma (RCO), astigmatism (RMA), and field curve (RMF), cylinder, inhomogeneity, decentered coma, astigmatism, tilt, and ADD effects.

EDF Same as EDG, but excludes field curve (RMF) and decentered tilt to give the edge of field effect with refocusing.

In general EDG would be used for lenses where no compensating curvature or tilt of the image plane could be done; EDF would be used for systems (as in visual systems) where such compensation would be expected. EDG and EDF are for the last field position; if evaluation is desired at an intermediate field angle, the field specification will have to be reduced to that angle.

It should be noted also that these compound performance measures are mono-chromatic; they do not include axial or lateral color changes.

III. Vignetted Systems

None of the coefficients except cylinder and inhomogeneity include the effects of vignetting. For significantly vignetted systems, the tolerance effects will be pessimistic and allowance must be made for this. For systems with highly asymmetric vignetting, it is better to choose another stop position where vignetting is more nearly balanced.

[redacted]

TOR - TOLERANCE (RAY-BASED)

Purpose:

To calculate the changes in either the RMS wavefront error or the MTF at a given frequency due to perturbations to the constructional parameters of the lens.

Description:

The calculations are based on a differential ray trace which provides the derivatives of the wave aberration with respect to each of the perturbations.[1,2] Grids of rays are traced through the lens as needed. For each ray, the wave aberration derivatives are calculated for each perturbation and appropriately summed. The final result is a set of coefficients defining a function which describes the variation of RMS or MTF with respect to each of the parameters of interest (perturbations). The function is basically a Taylor series expansion about the nominal (unperturbed) system so that it is most accurate for small departures from the nominal system. The variation of the square of the RMS or MTF is quadratic in the parameter.

The RMS calculation is equivalent in accuracy to the WAVE option and the MTF values are equivalent in accuracy to the DIFFRACTION MTF option but without the restriction on frequency choice. Thus MTF tolerance may be computed for very low frequencies, if needed. Because of the formulation of both computations, the accuracy of the predicted computation does not depend on the lens system being near diffraction limited.

The basic output of the program is the predicted change in RMS or MTF due to a change in the parameter. In addition, a statistical summation of the change for all of the parameters is given. An option is available to allow one or more parameters to be compensating parameters, i.e., they are set to the value which optimizes the merit function (RMS or MTF). For example, this option is used when finding best focus or best image plane tilt. The compensation may be done independently at each field and zoom or simultaneously over field and zoom.

For the tolerances, compensated as required for optimum MTF, a table of predicted changes in chief ray distortion is also available. This includes data for both nominal and calibrated focal length cases.

---

1. M. Rimmer, Appl. Opt., 9, 533 (1970)
2. M. Rimmer and J. Vanderhoff, J. Opt. Soc. Am., 67, 1429 (1977)

Input data:

If no data is entered, the program generates the standard set of tolerances most often needed for a centered system which will be fitted to test plates. It then proceeds with a computation using the image distance as a compensating parameter to minimize the performance loss weighted over the field.

Specifically, the default assumptions are:

1. A standard set of tolerances (DLF, DLT, DLN, CYD, DLA and DLY from Table I) are used.
2. Image distance (DLT I-1) is used as a compensating parameter.
3. Polychromatic RMS wavefront tolerance sensitivity is computed.
4. All wavelengths, field angles and zoom positions are included.
5. Wavelength weights are those of the system, determined by entries in DATA or CHANGE.
6. Field weights are uniform (=1) in arriving at the value for the compensating parameter separately in each zoom position.
7. All clipping apertures are circular and of the size required to just pass all of the vignetted field bundles determined by previously entered SPECIFICATION DATA. In each zoom position, the aperture stop surface is limited to that circle required to pass the first field angle.
8. Approximately 320 rays are traced through the pupil at each wavelength.

Input may be provided to override any or all of these assumptions. In general, overriding one assumption will leave the others unaffected. Once input is made to override the default tolerances, all must be entered. The compensating parameters, which are defined like tolerances, may be selected without eliminating the default tolerances.

[redacted]

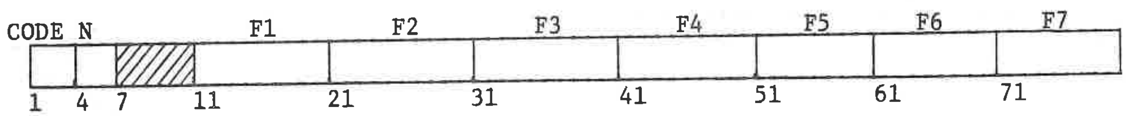
Restrictions:

1. A maximum of 200 parameters (tolerances plus compensators) may be entered.
2. Wavefront derivatives are computed by differential ray tracing giving a much higher speed computation than with finite differences; the following features have not yet been implemented:

   -Coupled parameters are not considered. For example, if two curvatures are coupled and a change is entered for the first one, the second one will not be changed.

   -SOLVES are ignored.
3. Currently, only rotationally symmetric systems with the field in the meridional section are operational. An early future release will extend the program to cover non-symmetric systems.

Optional input data is provided using the following format:



CODE	(Col. 1-3)	Mnemonic code indicating particular TOR requests. A list of the CODES is given later.
N	(Col. 4-6)	This field is used as a place to enter the wavelength, field number or surface number. (CODES which have this capability will be indicated by a lower case letter n after the CODE).
F1 . F7	(Col. 11-20)	Data fields F1 - F7; used to enter data. A zoomable entry is indicated by (Z).

In the list of CODES to follow and in the Tables, the portion underlined indicates the characters which are sensed. Some of these optional cards are flags for various requests - on any of these if the flag is to pertain only to certain zoom positions, the letter N (or the word NO) in the corresponding columns will serve to flag the opposite condition for that zoom position.

TABLE I: TOLERANCES AND COMPENSATORS

CODE	Default In	Default Cm	Default Mm	Description
a. Centered Tolerances				
DLS (n)	.001	.0025	.025	Surface sag at edge of clear aperture
DLC (n)	.001	.001	.0001	Alternate to DLS - Tolerance on curvature
DLR (n)	.001	.0025	.025	Alternate to DLS - Tolerance on radius
DLF (n)	5 Fringes			Test plate fit (power) in fringes at 546.1 nm over the clear aperture
DLT (n)	.001	.0025	.025	Thicknesses and separations
DLN (n)	.001			Index of refraction
b. Irregularity Tolerances				
CYL (n)	1 Fringe			Cylinder irregularity in fringes at 546.1 nm over the clear aperture - 0° orientation
CYD (n)	1 Fringe			Cylinder irregularity in fringes at 546.1 nm over the the clear aperture - 45° orientation
c. Single Surface Decenters and Displacements (No change to locations of other surfaces)				
DLX (n)	.001	.0025	.025	Lateral displacement of the surface in the X direction
DLY (n)	.001	.0025	.025	Lateral displacement of the surface in the Y direction
DLZ (n)	.001	.0025	.025	Axial displacement of the surface in the Z direction
DLB (n)	.001 Radians			Tilt (in radians) of the surface about its pole in the X-Z plane
DLA (n)	.001 Radians			Tilt (in radians) of the surface about its pole in the Y-Z plane
TIR (n)	.001	.0025	.025	Alternate to DLA - Tolerance on total indicator run-out at the edge of the clear aperture

d. Group Decentering Tolerances (See text for surface specification with SUR card.)

CODE	Description
TILT	Tilt (in radians) of each surface about its pole in group N1-N2 of SUR card.
BTILT	Tilt (in radians) of the group of surfaces N1-N2 about N1 specified in the SUR card(s).
DISPLACE	Lateral displacement in Y of the group of surfaces N1-N2 specified by SUR card.
ZDISPLACE	Axial displacement in Z of the group of surfaces N1-N2 specified on the SUR card.
ROLL	Roll of surfaces N1-N2 on seat of N1 (N1 itself does not tilt).
OAL	Change in overall length between surfaces N1 and N2 specified on the SUR card. The change is distributed equally among all the spaces involved.

[redacted]

A. Tolerance Data Base Input

1. Tolerance Input

The codes are listed, with defaults in Table I.

Tolerances are defined as either simple or group parameters. A simple parameter is one which refers to a single surface, such as a curvature thickness, index, etc. In this case, the parameter name (CODE), a surface number (N) and a value (F1) for the change in the parameter are required.

- -If the surface number is omitted, the change will be applied to each surface in the system.
- -If the value is omitted, the default value will be used.
- -If both are omitted, the default value will be applied to each surface of the system.

Note that the value in F1 applies to all zoom positions. Simple variables of a given parameter type are only defined once for any surface. For example, if a change in curvature on surface 4 is entered twice, only the second value will be used. Sections a, b, c of Table I are simple parameters.

Group parameters are defined by two surfaces. An example of this is a decenter of an element where surfaces 4 and 5 are decentered by the same amount. Section d of Table I lists the group parameters.

Group parameters require a SUR card (immediately following the parameter card) which defines the two surfaces. The SUR card has the special format:

	N_1	N_2	
SUR			//////////
1	11	16	21

Example: If it is desired to have a displacement with surfaces 3 through 5, then the following cards must appear:

```
DIS      .001
SUR      3  5
```

If no SUR card is included, the values of N1 and N2 will be set to the first and last physical surface, respectively (1 and I-1).

2. Compensation Input

It is logical to assume that, during assembly of the lens, certain adjustments will be made to partially remove the effect of accumulated tolerances. Such things as seeking best focus by shifting the image distance and tilting the image plane to remove the defocus effects of centering tolerances are commonly done; refocussing of relays, objectives and eyepieces is common, also. Less often but feasible is the change of one curve to compensate for one or more glass changes. These are all called compensators.

Compensators are input in exactly the same form as tolerances and may be any of the types listed in Table I. They are distinguished from tolerances by being entered first in the list of parameters and by using the CMP request to give the number of compensators. The following assumptions apply:

1. If any parameters are entered, no compensation will occur unless the CMP request below is included.

2. If just the number of parameters are entered that are called out in the CMP request, they will all be compensators and the default set of tolerances will be included.

3. If more parameters are input than are designated in the CMP request as compensators, the excess will be regarded as tolerances and no default tolerances will be generated.

CODE	OPERATION
CMP (n)	This specifies that the first one or more parameters will be used as compensating parameters. The number of compensating parameters is specified by n, which is limited to a maximum of 2. If n is omitted, 1 will be assumed. The compensating parameters are obtained from the list of parameters defined by the user and must be the first entries in the list. For example, if n is 2, the first 2 parameters defined will be the compensators. F1 is a code to specify whether the compensation will be done independently or simultaneously over field. If F1 is omitted, the compensation will be simultaneous over all fields and zoom positions. If it is +1, the compensation will be independently done at each field.

Compensators are not allowed to improve the performance of the nominal design, which they might otherwise do since the lens is not subject to the same constraints as were imposed during design. Instead, they optimize only for the degradation added by the tolerance itself.

[redacted]

B. Functions

1. Sensitivity

With no function request, sensitivity of the performance measure (RMS or MTF) to each tolerance will be supplied. This includes any reduction which can optimally be achieved with the designated compensators.

2. Inverse Sensitivity

Inverse sensitivity can be specified instead with:

CODE	OPERATION
INV	Requests inverse sensitivity. F1 contains the desired change in MTF or RMS. Each tolerance will be scaled to give the value specified, based on the first field only. The scaled tolerance will be applied to the other fields. Use a negative value for MTF (drop in MTF) and positive for RMS (change in RMS).

Currently no ranges limit the changes. A totally insensitive parameter will remain at its input value.

C. Performance Measures

1. Polychromatic RMS Wavefront Aberration

With no other designation for performance measure, the effect of each tolerance on RMS wavefront aberration is computed including wavelength as weighted.

2. Polychromatic MTF

By including a FREquency request, MTF is computed at that frequency, including wavelengths as weighted. An optional AZImuth request allows input of the orientation of the spatial frequency. The default azimuth is tangential.

CODE	OPERATION
FREQ (n) (z)	The spatial frequency in 1/mm for the MTF calculation; n is the field position. If n is omitted, the values correspond to the different fields of the first zoom position. If only one value is entered, it will apply to all fields and zoom positions.

[redacted]

CODE	OPERATION
AZIM (n) (z)	The azimuth of the spatial frequency; n is the field position. If n is omitted, the values correspond to the different fields of the first zoom position. If only one value is entered, it will apply to all fields and zoom positions. The value may be entered as an angle in degrees or as a mnemonic for the specific values 0 and 90 degrees. For 0, use RAD and for 90 use TAN. The default is 90 degrees (TAN).

3. Chief Ray Distortion

This can be obtained with MTF only and is evaluated for the compensation required for that calculation.

CODE	OPERATION
DST	This request causes the change in distortion due to each parameter change to be printed as a separate table after the MTF changes. Values are given for each field. The value is the change in the position of the chief ray averaged over wavelength and thus includes scale change (due to change in focal length), distortion change and shift of the entire format (for tilts and decenters). If there are 2 or more fields, a calibrated distortion will also be printed in which the effects of focal length change and image shift have been removed.

D. Controls

1. Weights

The wavelength weights determine the relative importance of each wavelength in defining the performance measure in each image point:

WTW (n) (z)	Weight on wavelength n. If n is omitted the values entered are interpreted as weights on all wavelengths for the first zoom position. The wavelengths are assumed to be in the order from red to blue - long wavelength to short. The default weights are obtained from the SPECIFICATION DATA.

The field weight determines the relative importance of each field position in defining the balance achieved by the compensators:

<u>WTF</u> (n) (z) — Weight of field position n. If n is omitted, the values entered are interpreted as weights on all field positions of the first zoom position. The default weights are 1.0.

2. Print Controls

Normal printout consists of tables suitable for inclusion with design data. Extended printout for diagnostic purposes is obtained with:

<u>PR</u>F — Full printout. This option results in a more detailed printout as described in the sample output. If omitted, the compact printout will result.

3. Other Controls

<u>RA</u>YS — The approximate number of rays to be traced through the pupil in each wavelength is entered in F1. The default is 320 rays.

<u>POS</u>ITION (z) — Used in zoom systems to flag those zoom positions which are to be omitted. The character "N" (or word NO) entered in the data field corresponding to a given zoom position will suppress the computation for that position.

<u>SC</u> (z) — Semi-aperture control; uses the APERTURE DATA instead of computed clear apertures. On surfaces where no semi-aperture is entered, the computed clear aperture is used. Semi-apertures which have been entered as negative values are treated as obscurations when this request is used.

Computation and Output:

Tables II and III show output for two sample calculations. Input for the first example is:

```
TOR       - Calls for TOR option
FRE,100   - Triggers MTF output for 100 cycles/mm tangential azimuth
DST       - Include distortion table
CMP2      - First 2 parameters are compensators, rest are tolerances
DLT11     - Compensate with image distance
DLA12     - Compensate non-symmetric degradation with image tilt
DLF3     ⎫
BTI      ⎪
SUR,3.5  ⎪
DIS      ⎬ - Tolerances
SUR,1,2  ⎪
DLT1     ⎪
DLT3     ⎭
```

Various parts of the output are labeled and are:

Table IIa - MTF Sensitivity

a. The wavelength, weight and number of rays for each color. The number of rays is that which gets through the convolved pupil. This will vary with wavelength, being higher for the shorter wavelengths (since the frequency is a smaller fraction of the cutoff frequency). It is a good check on whether there is any unsuspected clipping of rays.

b. The spatial frequency and azimuth for the MTF calculation.

c. The MTF value if there were no aberrations, but using the vignetted pupil as traced.

d. The value of the MTF for the system.

e. Description of the parameter, giving surface number, type and change.

f. The change in MTF due to the manufacturing error. The changes for both plus and minus changes in the parameter are given.

g. The change in the compensating parameters.

h. Probable change in MTF is a statistical value arrived at by assuming that each parameter is distributed uniformly within its given range. For example, if the change in a thickness is given as .001, it is assumed that if many elements were made there is equal probability that the

[redacted]

departure from nominal will be anywhere in the range ±.001 and no probability that it will be outside. For tilts, decenters and cylinders, the additional assumption is made that the direction of the tilt or decenter is uniformly distributed in 360 degrees. A mean value and spread (1 sigma) are calculated. The probable change is defined as the mean plus 2 sigma meaning that, statistically, 97.7 of the cases will have a smaller change.

i. The RSS and the sum of the absolute values of the compensators give an indication of the probable and worst case values for each compensator. The criterion for determining the compensation is the minimization of the sum of the changes in MTF over the field. Field weights can be used to emphasize one field over another.

In addition to the output shown in Table IIa, a separate page precedes this with a listing of the meaning of each code for inclusion in the data packet.

<u>Table IIb - Chief Ray Distortion Sensitivity</u>
(Added by DST request)

j. The boresight error is the change in chief ray height at the first field angle. The data in row A is the change with respect to the unperturbed chief ray. The data in row B is after the values across the field have been modified by a scale change and lateral shift of the image plane.

k. In row A, the values are the changes after the boresight error has been subtracted out. Row B contains the residuals after scale change and shift.

l. The RSS of each of the A and B quantities, indicating the most probable change before and after adjustment.

m. The RSS of the components of scale change, only.

The second example is similar except that RMS is the performance measure instead of MTF, the distortion calculation is not available, and the expanded printout is used; this is accomplished by removal of FRE,100. and DST from the input and inclusion of PRF.

<u>Table III - RMS Wavefront Sensitivity</u>

The labelled sections are:

n. The nominal RMS wavefront error.

p. The form of the RMS as a function of the parameter as obtained from the wavefront differentials. The coefficients A, B and C are given in the output. C is common to all the parameters (it is the square of the nominal RMS) and A and B are given for each parameter. T is a scale factor on the parameter value. When T=1, the equation gives the RMS for the given value of the parameter change. If the result for twice the given value is needed, then evaluate the equation with T=2.

q. The change of RMS for plus and minus manufacturing errors. The difference between these two values is more thoroughly discussed in the Technical Notes.

r. The RMS of the change in the wavefront. This number gives an indication of the size of the aberration which is introduced. It is equivalent to the number used in Grey's tolerance analysis program and is analagous to the third order equivalent RMS values of the TOLERANCE option.

This value may be significantly larger than the change of RMS if the nominal RMS is large. One way to use this number is to calculate the RSS for all the parameters plus the nominal RMS; the result is a statistical estimate of the RMS including the effect of manufacturing errors.

s. The probable change in RMS for four different probability levels. These numbers are based on the assumptions described in h. The footnote gives a 97.7 probable change for a distribution in which the parameter can only take on the extreme values of its range. This condition is sometimes approached when the tolerances are very tight and are at the limit of the shop's capability or when there are one or two very sensitive parameters which account for most of the error.

[redacted]

Technical Notes:

The designer usually submits for tolerancing a lens that he expects to be optimum. He is therefore unprepared to see RMS or MTF values improve as a result of tolerance changes. The explanation is that, although the lens is an optimized balance for all fields, zoom positions and MTF azimuths, any single field angle (or azimuth for MTF) in any zoom position will not be in general, separately optimum. Thus, a given tolerance can, in fact, enhance the performance for one image point (and azimuth) but presumably degrades other image points even more. An example of this is shown in Figure 1.

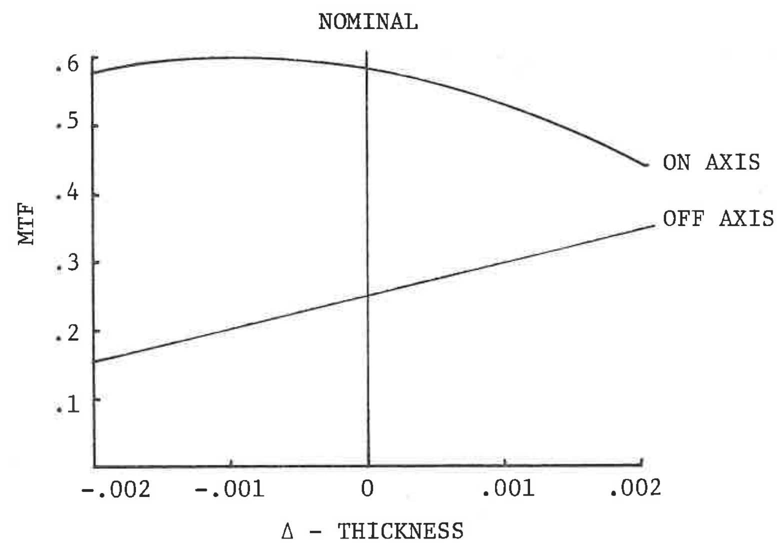


FIGURE 1 - MTF VS. CHANGE IN THICKNESS

In addition, the original design was subjected to constraints which are not imposed in tolerancing (EFL, image distance, etc.). Thus, conceivably there may be tolerances that will enhance performance at every field point since the lens is unrestricted by constraints.

The changes in MTF which are calculated depend on the focal position thus making it possible to have widely differing sensitivities to a particular perturbation at two different focal settings. When using TOR, the lens should be at its best focus position.

Table IIa - MTF Sensitivity

8/ 3.78 C O D E V POSITION 1

TOR-14

S E N S I T I V I T Y A N A L Y S I S
POLYCHROMATIC MODULATION TRANSFER FUNCTION

DOUBLE GAUSS EXAMPLE

FIELD POSITION = 1.00 Y MAX. (15.00 DEGREES)
FIELD WEIGHT = 1.00

WAVELENGTH	WEIGHT	NO. OF RAYS
650.0 NM	10	102
550.0 NM	20	104
450.0 NM	10	116

(a)

FREQUENCY = 100.00 L/MM
AZIMUTH = TANGENTIAL (b)

DIFFRACTION LIMITED MTF = 0.729 (c)
NOMINAL MTF = 0.354 (d)

MANUFACTURING ERROR TYPE	SURF NO.	CHANGE (e)	CHANGES IN MTF FOR PLUS AND MINUS MANUFACTURING ERRORS (+)	(−) (f)	COMPENSATING PARAMETERS DLT 11	DLA 12 (g)
DLF	3	5.000000	0.024	-0.029	-0.001118	-0.000000
BTI	3- 5	0.001000	-0.001	-0.002	0.000001	0.002658
DIS	1- 2	0.001000	0.029	-0.040	-0.000002	-0.002229
DLT	1	0.001000	0.025	-0.027	-0.000818	-0.000000
DLT	3	0.001000	0.082	-0.136	-0.003073	-0.000000

PROBABLE CHANGE IN MTF -0.148 (h)

	DLT 11	DLA 12
RSS OF COMPENSATORS	0.003371	0.003469
WORST CASE SUM OF COMPENSATORS	0.005012	0.004887

(i)

UNITS - LINEAR DIMENSIONS ARE IN INCHES
ANGLES ARE IN RADIANS
FRINGES ARE IN WAVELENGTHS AT 546.1 NM

NOTE - THE PROBABLE CHANGE IN MTF IS A MEAN PLUS 2 SIGMA VALUE (97.7 PERCENT)
AND ASSUMES A UNIFORM DISTRIBUTION OF MANUFACTURING ERRORS OVER THE RANGE

Table IIb - Chief Ray Distortion Sensitivity

5/24/78 CODE V POSITION 1

DISTORTION SENSITIVITY

DOUBLE GAUSS EXAMPLE

A - UNCALIBRATED DISTORTION
B - ADJUSTED FOR SCALE AND SHIFT

MANUFACTURING ERROR TYPE	SURF NO.	CHANGE			(j) BORESIGHT ERROR	(k) DISTORTION	
			FIELD ---		0.000	0.707	1.000
DLF	3	5.000000		A	-0.000000	-0.000094	-0.000120
				B	0.000000	-0.000005	0.000005
BTI	3- 5	0.001000		A	-0.000217	-0.000098	-0.000182
				B	0.000091	-0.000007	-0.000091
DIS	1- 2	0.001000		A	0.000881	0.000067	0.000112
				B	-0.000056	0.000011	0.000056
DLT	1	0.001000		A	-0.000000	0.000067	0.000106
				B	0.000000	-0.000005	0.000005
DLT	3	0.001000		A	-0.000000	0.000020	0.000065
				B	0.000000	-0.000015	0.000015
RSS			(l)	A	0.000908	0.000167	0.000275
				B	0.000107	0.000021	0.000108
RSS SCALE CHANGE			(m)		0.000000	0.000119	0.000169

TOR-15

TOR-16

Table III - RMS Wavefront Sensitivity

8. 3778 CODE V POSITION 1

SENSITIVITY ANALYSIS
POLYCHROMATIC RMS WAVEFRONT ABERRATION

DOUBLE GAUSS EXAMPLE

FIELD POSITION = 1.00 Y MAX. (15.00 DEGREES)
FIELD WEIGHT = 1.00

WAVELENGTH	WEIGHT	NO. OF RAYS
650.0 NM	10	148
550.0 NM	20	146
450.0 NM	10	144

NOMINAL RMS = 0.307 (n)

RMS=SQRT(A*T**2 + B*T + C)

(T=SCALE FACTOR FOR CHANGE)

C = 0.094449

MANUFACTURING ERROR TYPE	SURF NO.	CHANGE	CHANGES IN RMS FOR PLUS AND MINUS MANUFACTURING ERRORS (q)		RMS OF CHANGE IN WAVEFRONT (r)	COMPENSATING PARAMETERS (p) DLT 11 / DLA 12	A	B
DLF	3	5.000000	-0.004	0.006	0.024	-0.001153 0.000000	0.000569	-0.003274
BTI	3- 5	0.001000	0.013	-0.004	0.053	-0.000000 0.001213	0.002816	0.005259
DIS	1- 2	0.001000	-0.017	0.024	0.049	0.000000 -0.001169	0.002443	-0.012785
DLT	1	0.001000	-0.007	0.008	0.018	-0.000837 -0.000000	0.000337	-0.004504
DLT	3	0.001000	-0.009	0.027	0.075	-0.003166 0.000000	0.005685	-0.011330
RSS					0.109			

PROBABLE CHANGE IN RMS 0.034

RSS OF COMPENSATORS 0.003472 / 0.001685

WORST CASE SUM OF COMPENSATORS 0.005155 / 0.002382

```
UNITS - LINEAR DIMENSIONS ARE IN INCHES
        ANGLES ARE IN RADIANS
        FRINGES ARE IN WAVELENGTHS AT 546.1 NM.
        RMS IS IN WAVELENGTHS (AVERAGED OVER SPECTRAL REGION)

NOTE  - THE PROBABLE CHANGE IN RMS IS A MEAN PLUS 2 SIGMA VALUE (97.7 PERCENT)
        AND ASSUMES A UNIFORM DISTRIBUTION OF MANUFACTURING ERRORS OVER THE RANGE.
```

CUMULATIVE PROBABILITY	CHANGE IN RMS FOR UNIFORM DISTRIBUTION
50.0 PCT.	0.004
84.1 PCT.	0.019
97.7 PCT.	0.034 *
99.9 PCT.	0.048

(S)

* IF IT IS ASSUMED THAT THE ERRORS CAN ONLY TAKE ON THE EXTREME VALUES OF THE TOLERANCES, THE 97.7 PERCENT PROBABLE CHANGE IN RMS IS 0.063

Table III (Cont) - RMS Wavefront Sensitivity

FABRICATION AIDS

MODEL DATA

Purpose:

To tabulate the lens constructional data including radii and clear apertures in a format convenient for use by lens mount designers.

Data Input:

Optional data cards may be entered following the MODEL DATA option card to specify additional fabrication-related computations. These cards are punched in the following format:

CODE	N		F1	F2	F3	F4	F5	F6	F7
1	4	6	11	21	31	41	51	61	71

CODE (Col. 1-3)	Mnemonic code identifying the MODEL DATA sub-option; a list of the CODES is given later.
N (Col. 4-6)	Number used with some codes to identify a surface number.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields used to enter data appropriate to the particular CODE entered.

The following list gives the CODES, their associated data entries (if any), and a description of the sub-options.

SC	Inserts previously entered APERTURE DATA for clear apertures.
HEADER	Changes the table heading from the pre-stored company name to the contents of the next complete card. Spacing and centering is up to user; the 80 columns are centered over the table.
SAG (n)	Computes a sag table for surface n; if n is not entered, sag tables are computed for all aspheric surfaces. The maximum height to which sag tables are printed is entered in data field F1; if blank, the semi-clear aperture is used. The delta (step size) for the sag table print-out is entered in F2. The default provides 20 to 40 steps out to the maximum height.

A reference curvature may be entered in field F3 from which sag differences (excess material) will be computed. The default is the base curvature. A constant to be added to the excess material column may be entered in data field F4.

BEST	Find the reference curvatures which best fit the aspherics printed out by the SAG request, contacting at two zones on the air side of the surface.
SLOPE	Adds a print-out of the surface slope in degrees, minutes and seconds and radius increment/sag increment to the sag tables requested by SAG.
FRINGES	Adds a print-out of the number of fringes (visual wavelength units, 546.1 nm) departure from spherical to the sag tables requested by SAG.
SPACER	Computes and prints the length along the mounting ring from element to element.
REFRACTIVE INDICES	Prints out a table of the refractive indices; normally only the glass codes are listed in MODEL DATA.
ZPR (z)	Prints MODEL DATA as a non zoom lens system for each zoom position. The letter N in any field omits the printing for that position.

Function:

First order properties are computed and the limiting upper and lower rim rays are traced at each field angle to determine the required clear apertures. For Fresnel lenses, SLOPE will provide the surface definition.

Output:

The date and title are listed followed by a tabulation of element radii, thicknesses, clear apertures, and glass type with separations between elements. The aperture stop position and diameter, image radius and size, EFL, F/no, OAL (overall length from front to rear vertex), angular coverage, and size and position of entrance and exit pupils are all printed in appropriate formats. For finite conjugate systems, the object distance, magnification (reduction ratio), and total track are included.

A note indicating the sign convention for radii (+ for center of curvature to the right, - to the left) is printed to avoid possible confusion.

Error Conditions:

1. "WARNING - SOME LIMITING RAYS NOT TRACED - CLEAR APERTURES MAY BE IN ERROR" - Either a ray missed a surface or encountered total reflection; check data and rerun.

(z) Zoomable

LAYOUT

Purpose:

To provide a layout of the optical system on the plotter.

Input Data:

This option, without additional data, will provide a layout of the optical system on the plotter. It will include the meridional cross-section of the surfaces, edges, center-line in air spaces, the image surface and the rays limiting the optical bundle at each field angle. The plots for each zoom position will be centered within the width of the paper and placed in sequence along the paper. The default scale factor is full scale or, if necessary, reduced to restrict the total length of the plot to 36 inches.

Optional data cards may be included following the LAYOUT option card to alter these assumptions. These cards are punched in the following format:

CODE	F1	F2	F3	F4	F5	F6	F7
1	11	21	31	41	51	61	71

CODE (Col. 1-9)	Mnemonic code indicating particular LAYOUT sub-options. A list of the CODES is given later.
F1 (Col. 11-20) . . . F7 (Col. 71-80)	Data fields F1 - F7; used to enter data for the corresponding zoom positions, i.e. F1 is used for zoom position 1, F2 for zoom position 2, etc.

The following list of CODES identify the LAYOUT optional data; the portion of the CODE underlined indicates the characters which are sensed.

OFFSET	The offset in inches from the margin of the paper to the axis of the optical system is entered in data fields F1 - F7. The default value is 5.0.

SF — Scale factor; the desired scale factor is entered in the data fields F1 - F7. The default value is 1.0 (full scale) unless the layout will not fit the paper width or exceed the length boundary (36 inches unless modified by LENGTH option below).

LENGTH — The maximum paper length in inches on which the drawing must fit is entered in data fields F1 to F7. If the layout exceeds this length, it will be scaled down until it fits. The default value is 36 inches.

SURFACES — The surfaces entered here define the portion of the optical system to be drawn; the number of the first surface to be drawn is entered in columns 11-15, 21-25, etc. The last surface is entered in columns 16-20, 26-30, etc. If no surface card is entered, the system is drawn from surface 1 to I; if the second number in each pair is omitted, I is supplied.

TITLE n — The title to be plotted with the layout is entered in columns 21-60. If this card is not entered, the title is taken from the first 40 characters of the title entered in DATA FOR SYSTEM. The zoom position number n is entered in column 11 if the title is to apply to a specific zoom position. A TITLE card may be entered for each position.

The following optional cards are flags for various sub-options; the letter N, or the word NO in the first columns of any field suppresses the request for that zoom position.

SC — Semi-aperture control; uses the semi-apertures entered on the surface data cards for clear apertures instead of the computed clear apertures. On surfaces where no semi-aperture was entered, the computed clear apertures are used.

POSITION — Used in zoom systems to flag those zoom positions which are not to be plotted. The character N, or NO entered in the data field corresponding to a given zoom position will suppress the layout for that position.

OBSC — Eliminates rays from the layout which strike an obscuration or which lie outside a semi-diameter.

REPORT — Causes layout to be drawn in a special 8 1/2 X 11 inch bordered format which is useful for reports. If no scale factor is entered, the system is automatically scaled to fit the 8 1/2 X 11 inch format.

LABEL — The title, scale factor and date will be printed on the plot; this is the default condition.

TITLE TOP — The title is placed on top (away from the origin) of the layout instead of the bottom.

LENS — The lens surfaces are drawn; this is the default condition.

RAYS — The chief ray, upper and lower meridional rays at each field angle are drawn. This is the default condition.

EDGES — Edges are drawn on the optical elements; this is the default condition.

RETURN — Returns the pen to the origin after the layout for the zoom position is complete.

Alternate Views and Perspective Layouts

The LAYOUT option normally provides a drawing of the Y-Z section of the lens system or subsystem, with or without rays or surfaces, as specified by requests.

With non-rotationally symmetric systems, it is desirable to show other sections and/or a perspective view. For any system, a specific section may be requested by using:

XZ (z) — Requests the X-Z section for plotting. This is the projection of the local X-Z section of the surfaces and the rays onto the X-Z plane of the first surface. The letter "N" in any field eliminates the request for that zoom position.

YZ (z) — This is the default condition. Requests the Y-Z section for plotting. This is the projection of the local Y-Z section of the surfaces and the rays onto the Y-Z plane of the first surface. The letter "N" in any field eliminates the request for that zoom position.

For a perspective view (approximately isometric) with the Y axis vertical, use

PER — Plots both the X-Z and Y-Z local sections of the surfaces and the rays.

The point chosen for projective viewing is half-way between the X and Z axes, then elevated 30°. If this causes the drawing, with its defined starting point on the first surface to extend beyond the plot area

(z) Zoomable

of the paper, the starting point is shifted, with scaling performed if necessary, to bring the plot back within the confines of the paper. If REPORT mode is requested, the drawing of the system is scaled and centered top and bottom as well as left and right.

If these standard assumptions are to be altered to give a better point of view or position on the paper, this can be done by request. All references are to the position of the pole of the first surface and to the direction of the mechanical axis prior to it. Thus, the default is 0.0, 5.0 for the pole and 45., 30., 0. for the axis orientation. These can be altered by one card substantially identical in form to the DECE surface card:

DEC	Fields F1 to F5 respectively contain the LDE, WDE, ADE, BDE, CDE values, defined below, and apply to all zoom positions.

If these values are to be zoomed they must be referenced individually, transforming the fields F1 to F7 into their standard zoom position references:

LDE (z)	The distance along the length of the paper that the pole of the first surface is shifted. Default value is 0.0.
WDE (z)	The distance across the width of the paper that the pole of the first surface is shifted. Default value is 5.0. (This is identical in function to the OFFSET request).
ADE (z) BDE (z) CDE (z)	The Euler angles for the direction of the optical axis preceding the pole of the first surface. This establishes the direction of view; ADE, BDE, CDE are the angles α, β, γ in degrees, analogous to the same angles for the new axis in the DECE surface form. Default values are 45., 30., 0. Any change in ADE or BDE will be compensated so that the Y axis remains vertical; any change in CDE will cause the expected rotation of the Y axis.

Three examples are given; the first is a centered system with only a REPORT request. The second is an anamorphic system showing the two cross-sections. This was generated by

```
LAYOUT
XZ
OFFSET    7.0
LABEL     NO
RETURN
LAYOUT
YZ
OFFSET    3.0
```

(z) Zoomable

The third is a perspective view of a folded scanning system, generated by

```
LAYOUT
PER
REPORT
RAY    NO
SUR    0  I
```

Function and Output:

The optical system is ray traced to determine clear apertures. Unless otherwise specified, the system is then drawn with the axis parallel to the long (rolled) dimension of the plotter paper; the optical system is drawn (with edges) at full scale from the first surface to and including the image surface; chief rays, upper and lower meridional rays are drawn and the first 40 characters of the system title are plotted for the title.

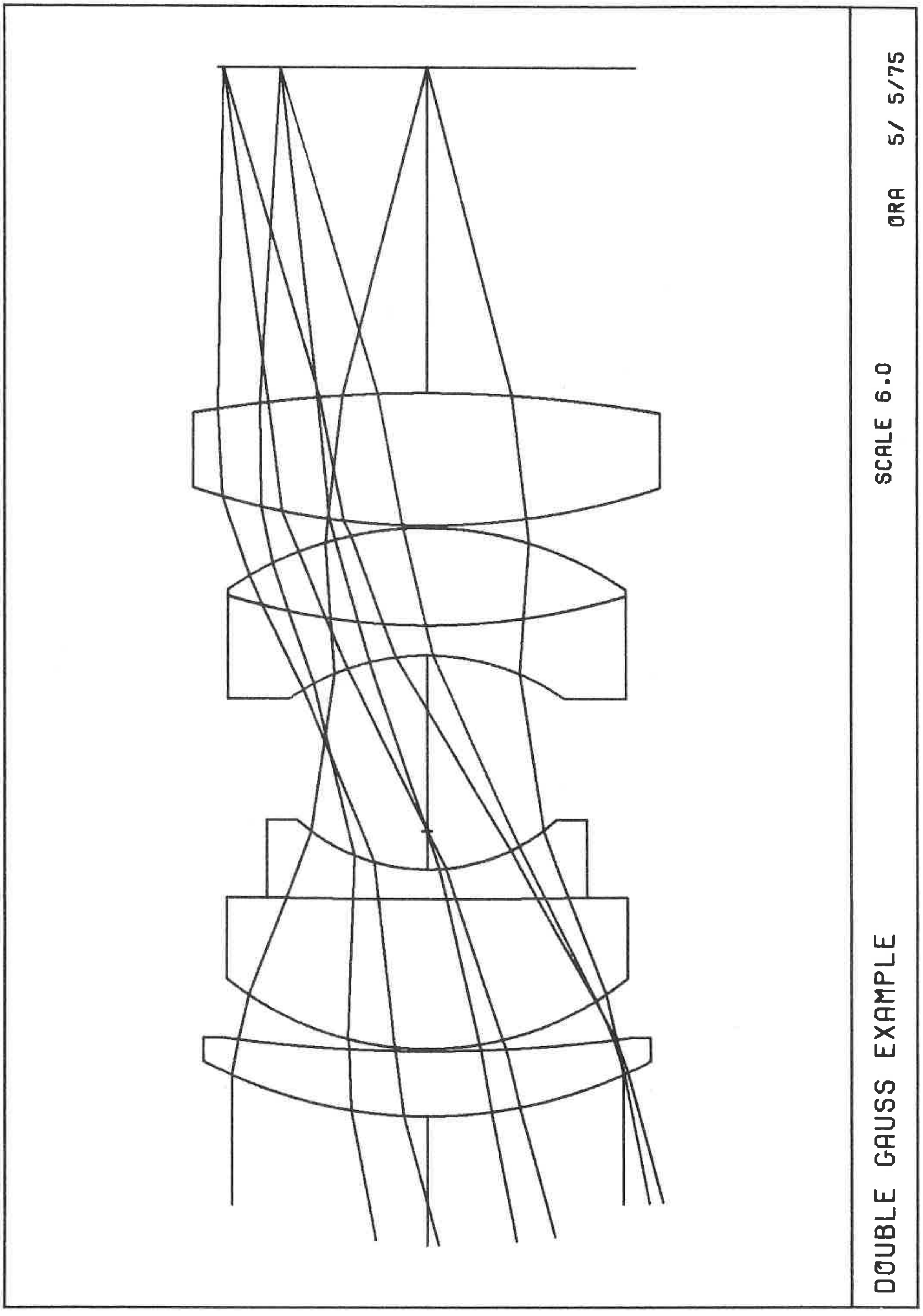
Error Conditions:

1. "NOTE - LAYOUT OPTION HAS BEEN TERMINATED DUE TO THE SIZE OF THE ERROR FUNCTION." - The system is the result of an irrecoverable condition in AUTO and is therefore not plotted.

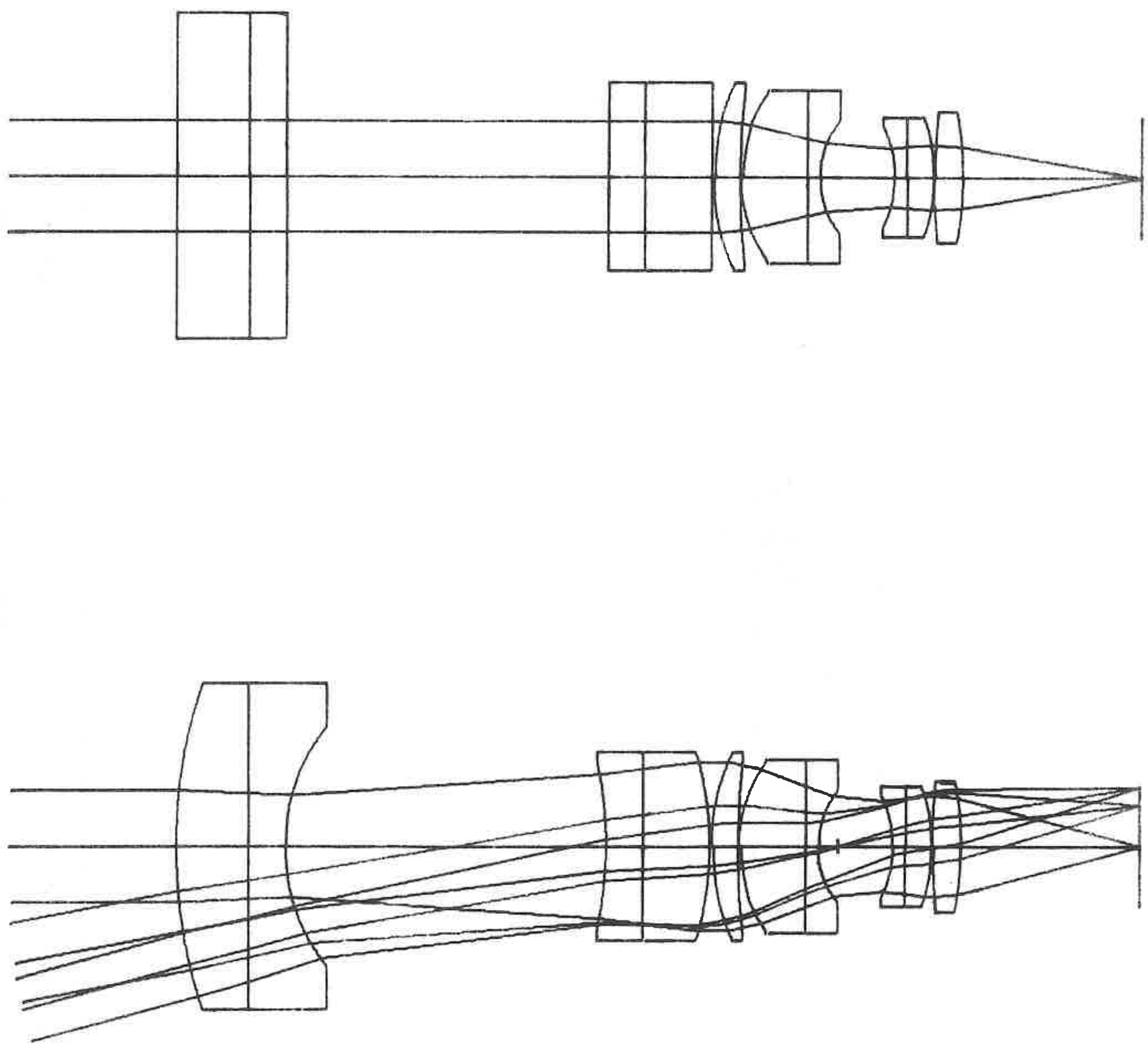
2. "SYSTEM HAS UNTRACEABLE SURFACES. LAYOUT IS SUPPRESSED." - The rays which are traced to determine clear apertures have encountered either total internal reflection or have missed a surface: correct and rerun.

3. "NOTE - THE SCALING FACTOR HAS BEEN CHANGED FROM XXXX TO XXXX." - Diameters or length exceed the allowable paper size. Scaling is done automatically.

4. "SCALE FACTOR MUST BE SMALLER THAN ALLOWED MINIMUM OF 0.01; SET SCALE FACTOR AND SUBMIT AGAIN." - Automatic scaling is excessive, suggesting an error. Correct or specify your own scale factor.



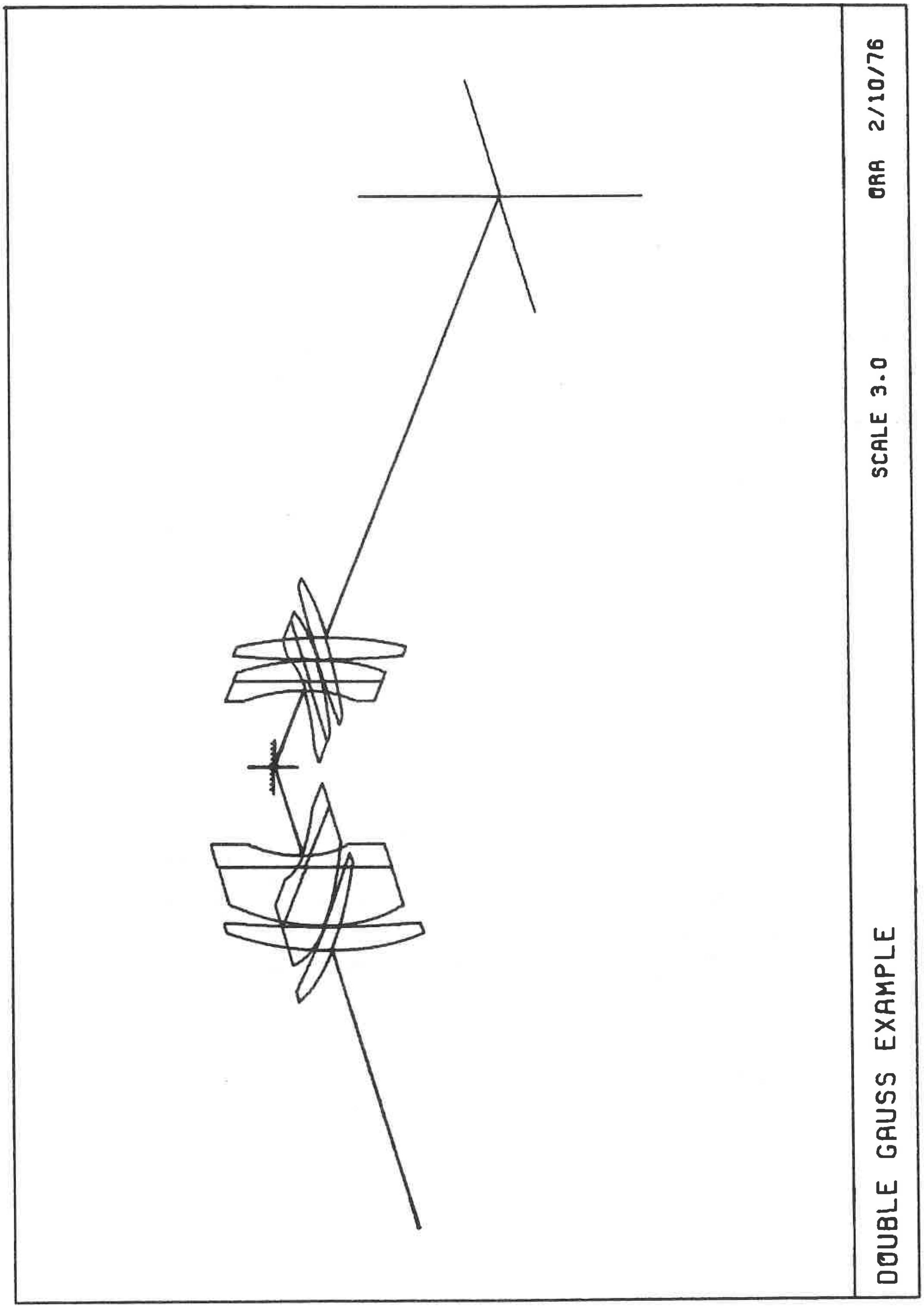
LAY- 6



ANAMORPHIC AFOCAL
ATT. ON DOUBLE GAUSS

SCALE 2.0
ORA 2/3/76

LAY- 7



LAY- 8

COST FACTORS

Purpose

To compute factors which affect the cost of a lens. These include:

A. Blocking Factors

Computes the blocking factor sin B' (see AUTOMATIC DESIGN under BLOC control) and the resulting approximate number of lenses on a tool. Sin B' does not include stock for mounting, centering or gaps on the tool.

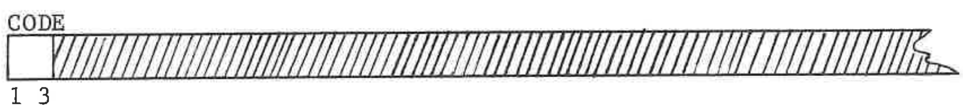
B. Price

The cost of material in an element, and in the smallest block from which an element can be made.

Input Data

1. Clear Apertures

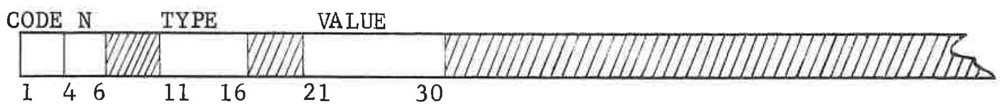
The clear aperture, unless changed, is the circular aperture required to just pass all vignetted bundles. If desired, aperture data including the best guess for the required excess may be entered. If such aperture data has been entered in DATA or CHANGE, the calculation will use it if requested by the following:



CODE (Col. 1-3)	OPERATION
SC	Semi-diameter control; uses the semi-diameters entered as aperture data cards for clear apertures instead of the computed clear apertures. On surfaces where no aperture data was entered, the computed clear apertures are used.

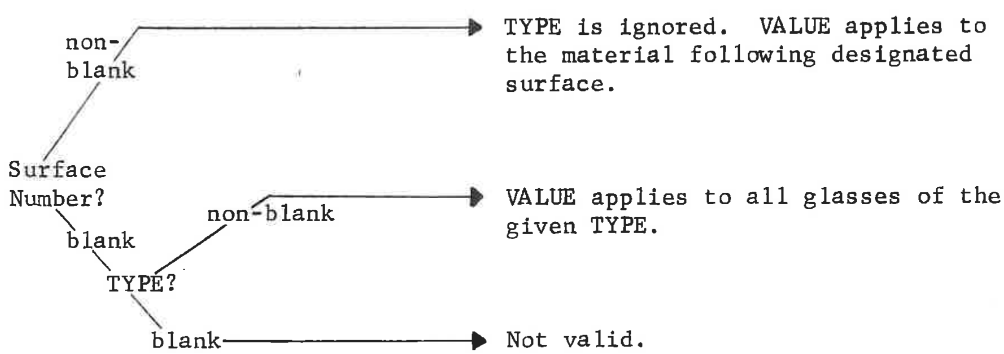
2. Additional Data

Specific gravity and cost are stored for the Schott catalog materials. To override these, to supply values for non-Schott material or for mirror substrates, additional data must be supplied, using the format:



CODE Col. 1-3	A mnemonic code whose three characters are one of the CODES listed below.
N Col. 4-6	The surface number; if present, the VALUE is to apply only to the material following the one surface; if the surface designated is a first surface mirror, the value is assumed to apply to the substrate. If the surface number is left blank the remaining information is applied as extensively as possible.
TYPE Col. 11-16	A name of a recognized glass code. If the surface number is blank, all representations of this material are assigned the amount given in VALUE. If TYPE is blank, VALUE will be used only if the surface number is not blank.
VALUE Col. 21-30	Value of the quantity. A blank is treated as zero.

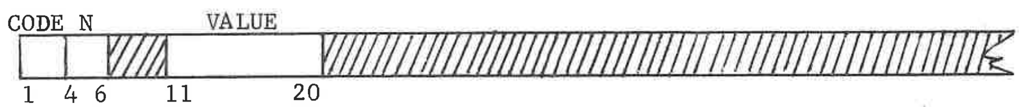
The following logic tree shows the valid combinations:



CODE (Col. 1-3)	OPERATION
SPG	The specific gravity of the glass type being used is specified by a card with SPG in columns 1-3.
PRC	The price per pound of the glass type being used is specified by a card with PRC in columns 1-3.

First Surface Mirrors

There is no representation of the substrate in the optical data and, in the absence of additional data, no weight is calculated for the substrate. To calculate substrate weight requires the additional items of thickness, specific gravity and back curve. Specific gravity and price per pound are entered by two cards of the form described above. Thickness and back curve are entered as follows:



CODE (Col. 1-3)		ENTRY
THM	n	Thickness of substrate for first surface mirror at surface n is entered in VALUE.
CUM	n	Back curve of substrate for first surface mirror at surface n is entered in VALUE.

Function:

The mounting edges and chamfers determined from the clear apertures are combined with the radii and thickness of each element to provide the data necessary to calculate the volume and center of mass. From the specific gravity of the material, the weight of the element is computed. Finally, cost is calculated from the prices entered or stored in the glass catalog.

The handling of outside diameters, edges and chamfers is identical to LAYOUT option used in the same manner. Therefore this analysis is for elements as drawn in that option.

Simplified formulas are used. Elements are assumed to be rotationally symmetric with spherical surfaces. Aspherics and other unusual surfaces are therefore not accurately represented.

Output:

A. Blocking Factor

Generates a table of curvature, thickness, clear aperture, sin B' and number on a blocker, for each surface. For plane surfaces, the number on a blocker is given as 99999.

B. Price

Generates a table of price per element and price per block from which the element can be made. Cost of material, when included from the data stored on disc, is for Grade B slab.

Error Conditions:

None.

SYSTEMS ANALYSIS

SPECTRAL ANALYSIS

Purpose

To combine all desired spectral response curves, plot them if desired, and calculate weights and/or wavelengths to be used in optical design computations.

Input Data

This option can be executed as either a separate analysis, not related to a specific lens, or as part of an optical job stream to define weights to be used in later analyses.

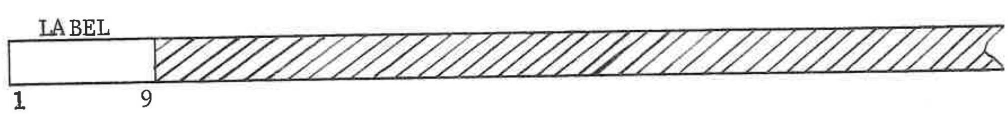
At least one response curve must be specified, using pre-stored values, or by specifying the data for one curve which is not pre-stored. In addition, control cards can be used to indicate the form of output (PLOT), the choice of wavelengths or weights, or whether the optical system wavelengths or weights are to be replaced with the calculated values. In detail, the input is as follows:

I. Response Curves

All requested response curves are cascaded together (multiplied together for each given wavelength) before the performance of the functions described later. These response curves are either a set of pre-stored curves, the curve for a blackbody source at a given color temperature, or curves fed in by the user. At least one must be provided (there is no point, otherwise, in running the program).

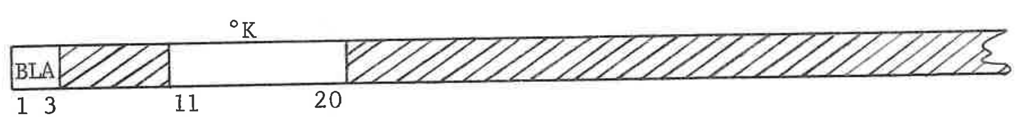
A. Pre-stored Responses

The pre-stored curves are shown graphically at the end of this section and are activated by listing the name printed out on the plot for each one desired. The requests are entered, one per card, using up to nine characters in the format:



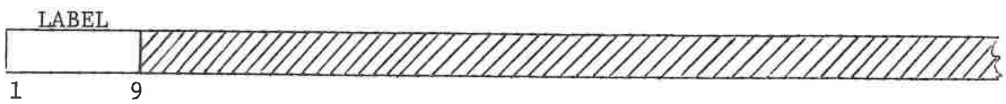
B. Blackbody Curves

For blackbody curves, the color temperature in °K is input using the following card:

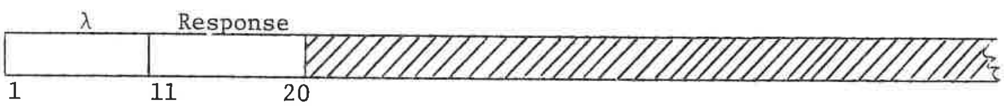


C. User Entered Responses

For user entered response curves (up to 10), the first card is a label which will be attached to the subsequent data. This name, consisting of nine characters (the first three of which - such as FILTER - cannot be the same as one of the CODE V option names, and the first of which must be a letter), is entered using the same format as for the pre-stored requests:



This is followed by up to 45 cards, each containing a pair of values; these are the wavelength in nanometers, and the response at that wavelength:

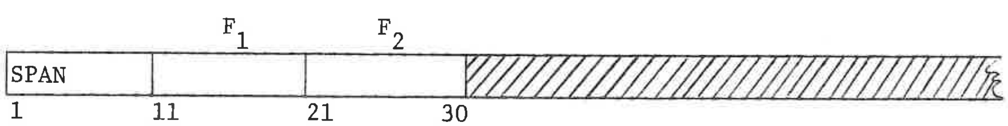


It is best to include wavelengths which will at least span the band which will be represented in the combined curve. Response values need not be normalized; the program will do this whenever necessary.

II. Computation Controls

A. Wavelength Cutoff

All curves are cascaded together using interpolation procedures, where necessary, to match wavelengths. Unless otherwise changed, the end points of any curve will be designated by a relative response of less than .01 or the wavelengths 300 nm and 1000 nm, whichever is the shorter span. If, however, this assumption is to be altered, use the card format:



If F_1 and F_2 are less than 1.0, the entries are assumed to be relative responses at the long and short wavelength ends respectively. If F_1 and F_2 are greater than 1.0, the entries are assumed to be wavelengths (nm) over which calculations are to be performed; the order is immaterial.

B. Wavelength Selection

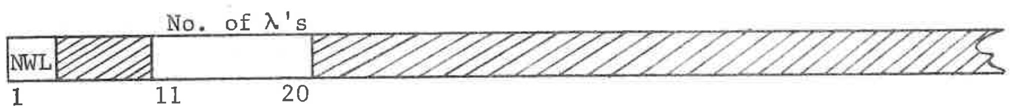
If no additional input is provided, the program will break up the span of the spectral region into 5 equal bands. The area under the combined curve for each band will be calculated; then the wavelength within each band which divides this area in half is chosen to represent the band. Finally, the areas for the bands are normalized and assigned as the weight for each wavelength. Computing

MTF's with discrete wavelengths is equivalent to having a spectral curve composed of spikes rather than a continuous curve. The above process has been chosen because it appears to provide the most accurate representation for MTF with a full spectral curve.

To alter the assumptions in this section, the following entries may be made:

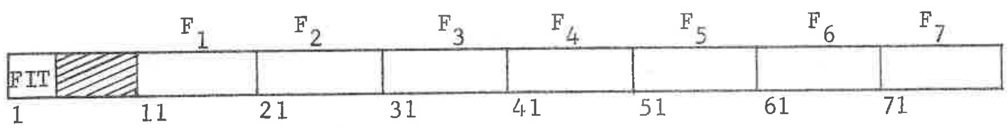
1. Number of Wavelengths

To alter the default value of 5 wavelengths, use an integer of 1 to 7 in the card format:



2. Fit to Specified Wavelengths

To override the automatic wavelength selection, use the card:

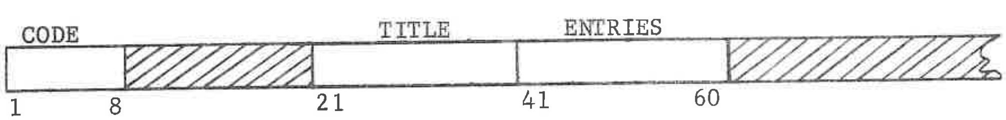


If F_1 to F_7 are blank, pre-existing wavelengths from the optical system data are used. Otherwise, enter the desired wavelengths (from 1 to 7) in F_1 to F_7. This data card will automatically supply the equivalent of the NWL data card.

When FIT is requested, the mid-points between adjacent wavelengths determine the bands. The weights are then the area under the curve within each band.

III. Optional Functions

After computation and printed output, several operations can be performed. Entries for these are requested using the card format:



CODE (Col. 1-3)	Function
PLOT PLOT ALL	Used to request that the curves be plotted. If several curves are cascaded, only the combined curve is plotted. If it is desired to have all of the curves plotted, (as well as the combined curve) the word ALL in columns 6-8 should follow the word PLOT.

<u>TITLE</u>	The contents of Columns 21-40, 41-60 replace any previous title on plots and printouts in this option.
<u>RWL</u>	The program will replace the lens system wavelengths with the wavelengths found by the program or designated in the FIT operation.
<u>RWT</u>	The program will perform the function of RWL plus entering the calculated weights for use by later performance analysis options. These weights are normalized to a maximum of 99.

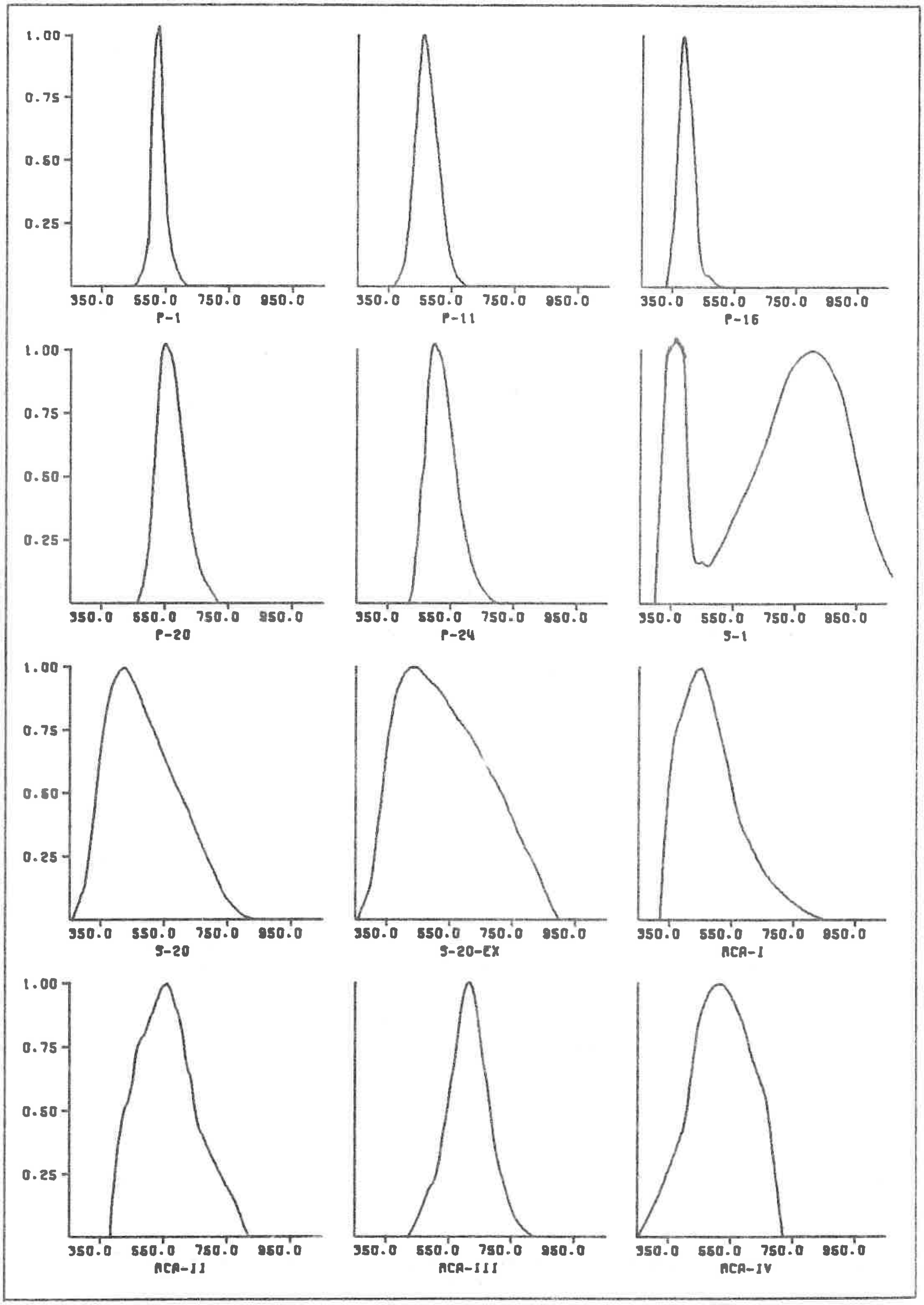
Output

The prime output consists of a table of wavelengths and their weights calculated as described under IIB. Wavelength Selection. In addition, for use in AUTOMATIC DESIGN, two tables for three wavelengths are printed out. The first of these gives the wavelengths and weights to be used if the wavelengths are to correspond to the .5, 1.0, .5 response values. The second table gives the wavelengths to be used with design weights of 121.

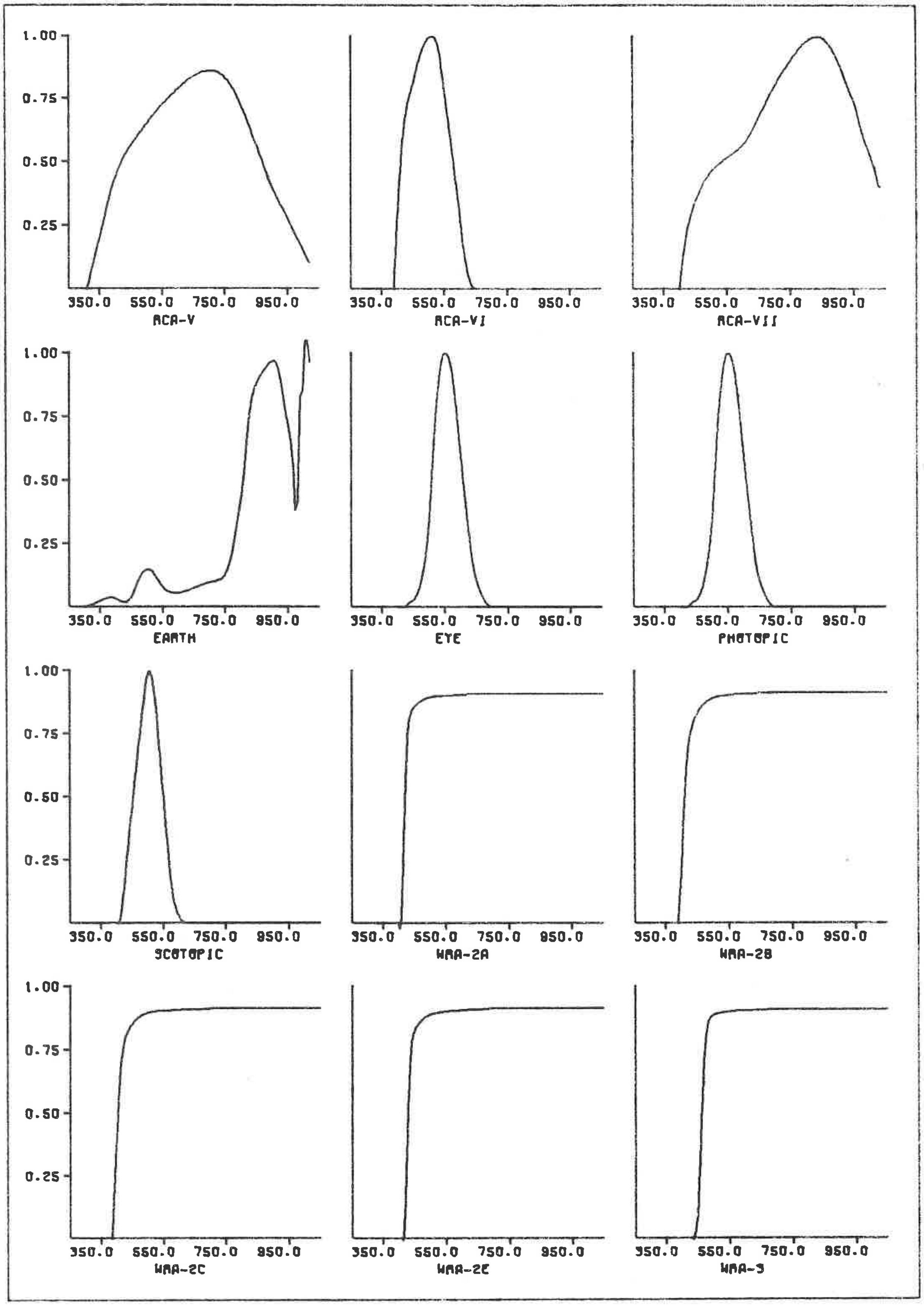
If FIT has been used a fourth table analagous to the first will be printed for the altered wavelengths. Graphical output will result from the use of PLOT, or PLOT ALL. Examples of each are given at the end of this option description.

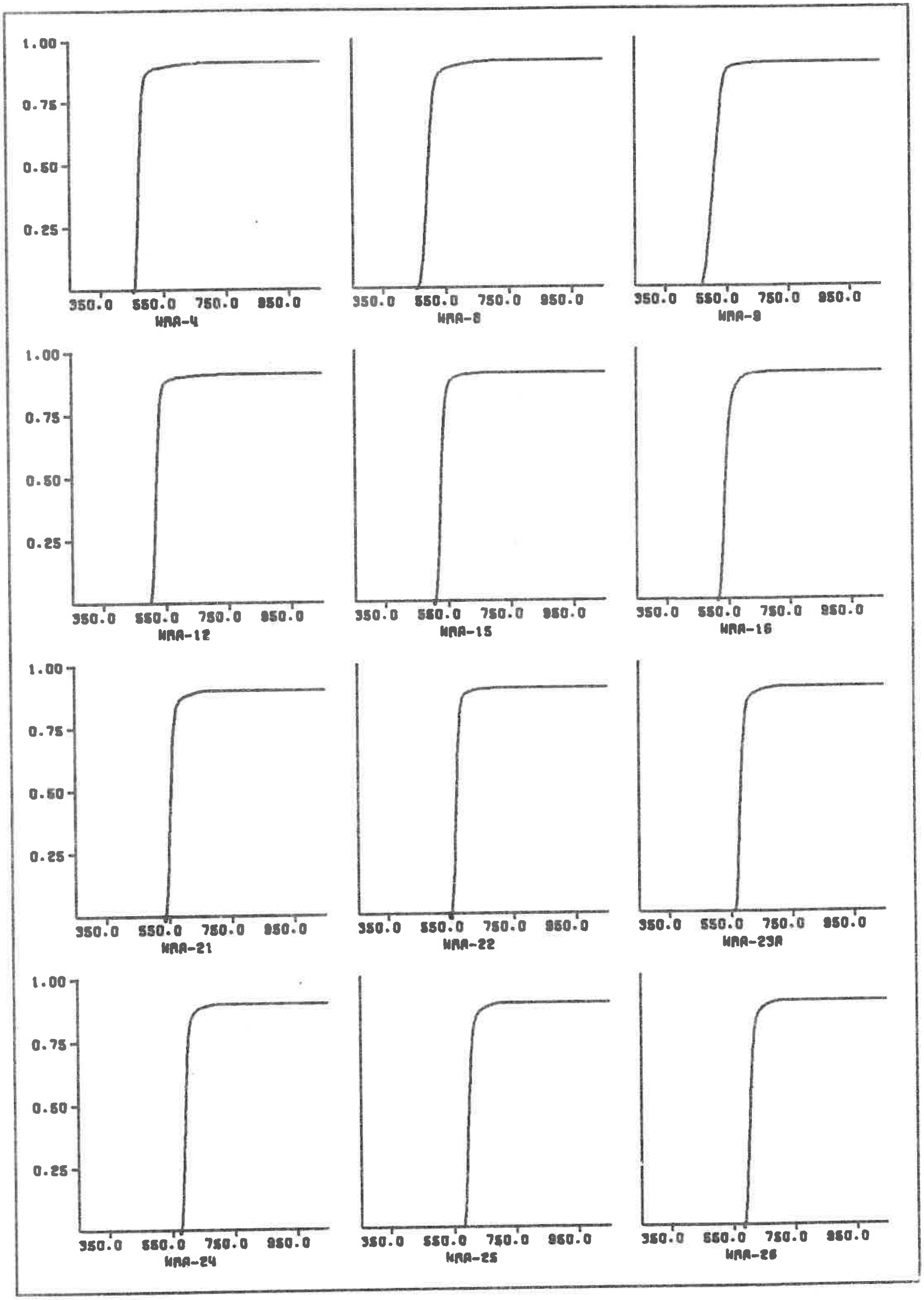
Error Conditions

If no response curves are input, the program will print an error message and exit.

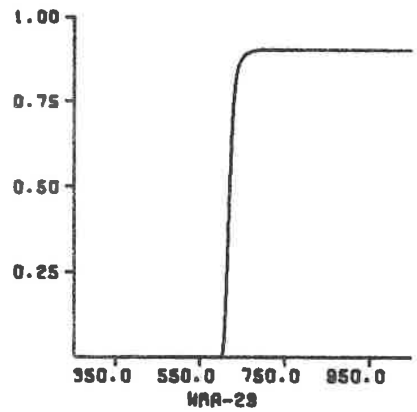

1.00
0.75
0.50
0.25
350.0
550.0
750.0
950.0
P-1
P-11
P-16
P-20
P-24
S-1
S-20
S-20-EX
RCA-I
RCA-II
RCA-III
RCA-IV

SPEC- 5

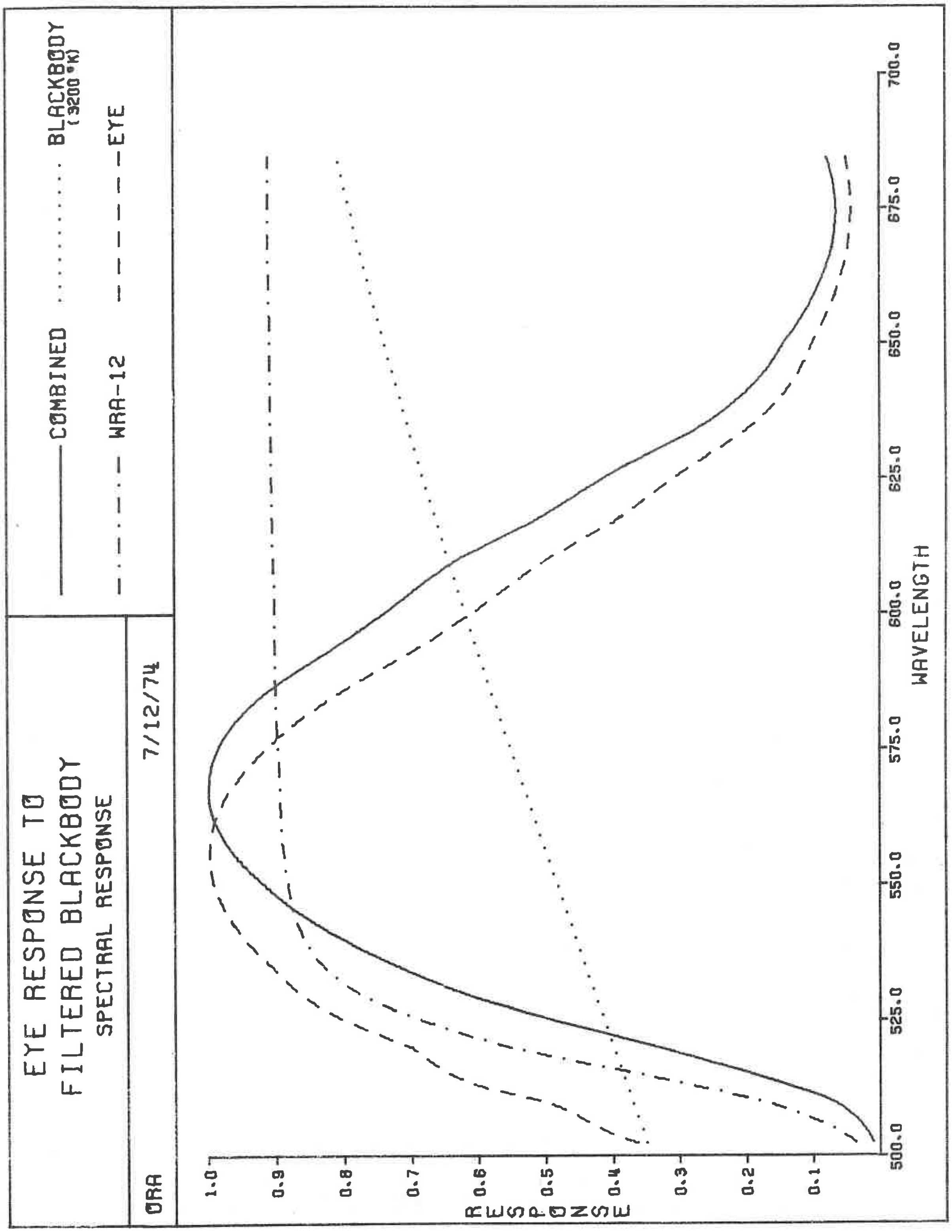

1.00
0.75
0.50
0.25
350.0 550.0 750.0 950.0
RCA-V
RCA-VI
RCA-VII
EARTH
EYE
PHOTOPIC
SCOTOPIC
WRA-2A
WRA-2B
WRA-2C
WRA-2E
WRA-3


1.00
0.75
0.50
0.25
350.0 550.0 750.0 950.0
WRA-4
WRA-6
WRA-9
WRA-12
WRA-15
WRA-16
WRA-21
WRA-22
WRA-23A
WRA-24
WRA-25
WRA-26

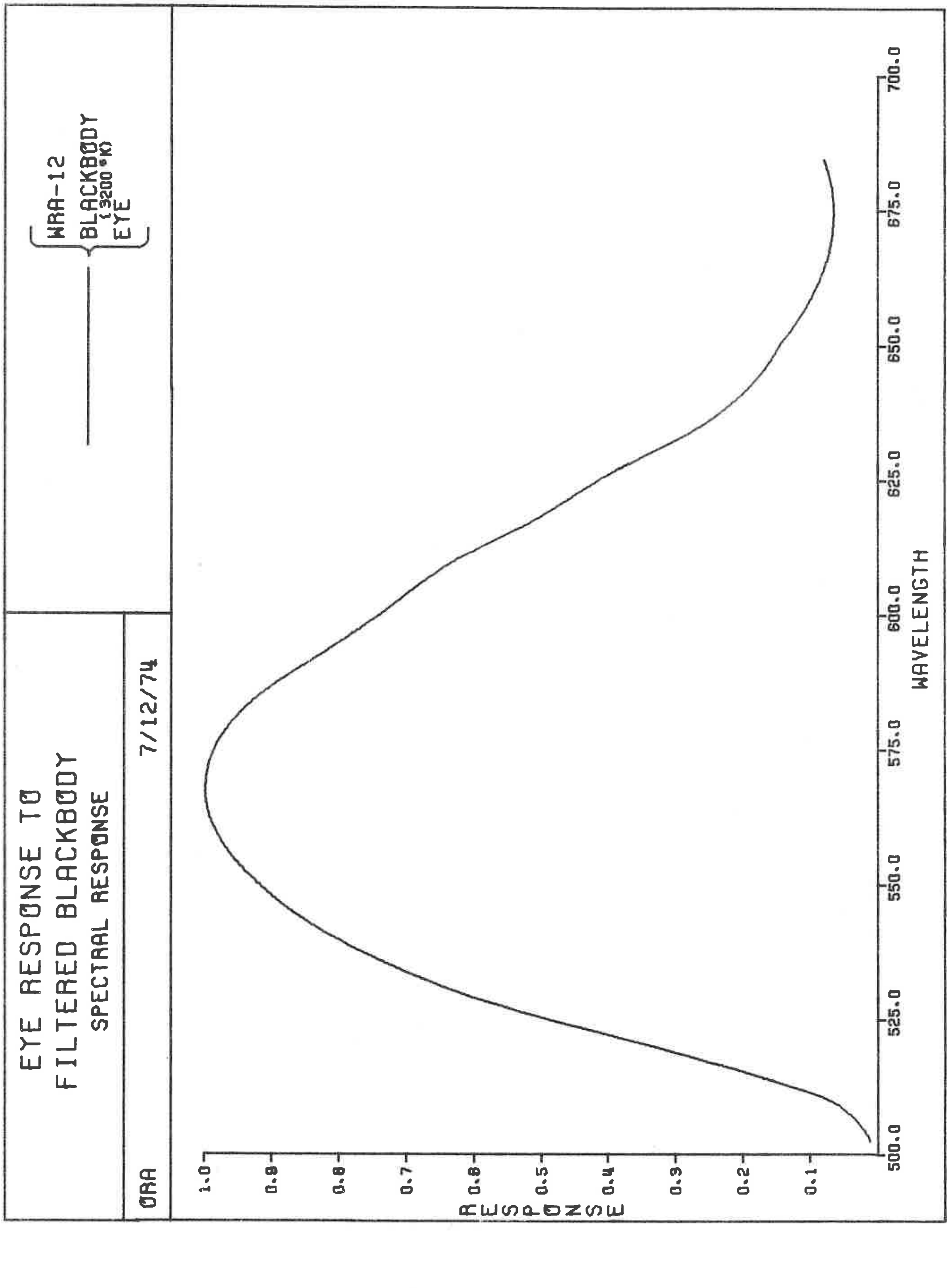
SPEC- 7



SPEC- 8


EYE RESPØNSE TØ
FILTERED BLACKBØDY
SPECTRAL RESPØNSE
7/12/74
ØRA
COMBINED
BLACKBØDY (3200°K)
WRA-12
EYE
RESPØNSE
WAVELENGTH
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
500.0
525.0
550.0
575.0
600.0
625.0
650.0
675.0
700.0

SPEC- 9



EYE RESPONSE TO
FILTERED BLACKBODY
SPECTRAL RESPONSE
ØRA
7/12/74
WRA-12
BLACKBODY
(3200°K)
EYE
RESPONSE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
500.0
525.0
550.0
575.0
600.0
625.0
650.0
675.0
700.0
WAVELENGTH

SPEC-10

ILLUMINATION SYSTEMS

Purpose:

To aid in the design of illuminating systems, assuming Kohler illumination (source not imaged on screen).

Input:

Illuminating systems are required to take the non-uniform distribution from a source and illuminate some receiving surface. The source can be an arc or tungsten filament, etc.; intermediate optics can be a deep dish reflector, or condenser lenses, etc.; the system can have a projection lens in it as well; and finally, the receiving surface can be a screen with directional characteristics.

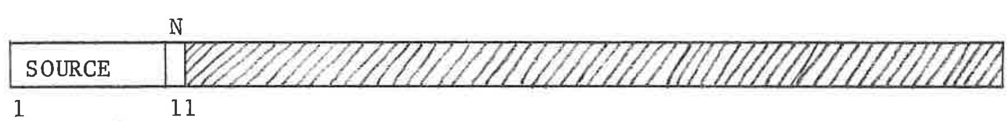
Because of the unusual requirements of each source, optical system and screen, this program has developed for it a series of modules which can be put together in various combinations to make up the system. As new modules are needed these will be added to those listed here.

The input data falls into two categories. These are source description and analyses to be carried out.

I. Sources

Each source configuration includes those components which generate and redirect rays so that they can be received by the optical system defined in the DATA FOR SYSTEM. In particular, optical elements of unusual form can be considered as part of the source.

The type of source is designated by a SOURCE card:



N (Col. 11) — The integer code of the source type described below.

A. SOURCE 1

- Source defined in X, Z plane with rotational symmetry about the optical axis, in a deep dish reflector. See Figure 1a.

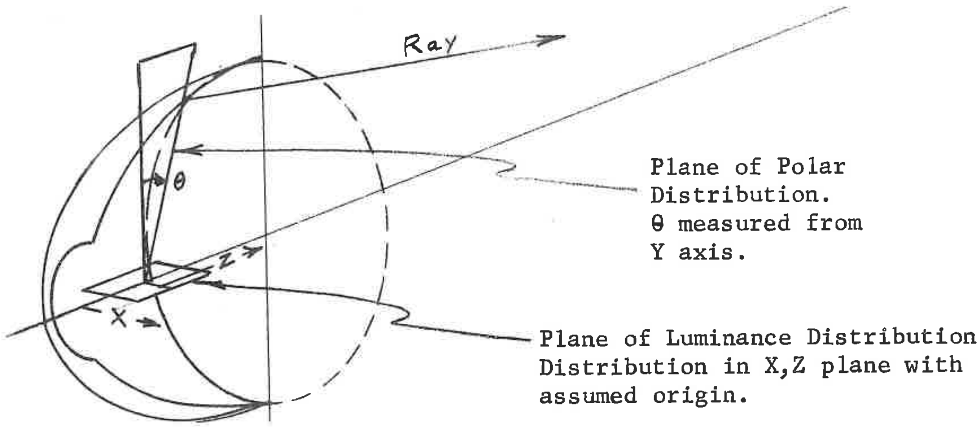


Figure 1a

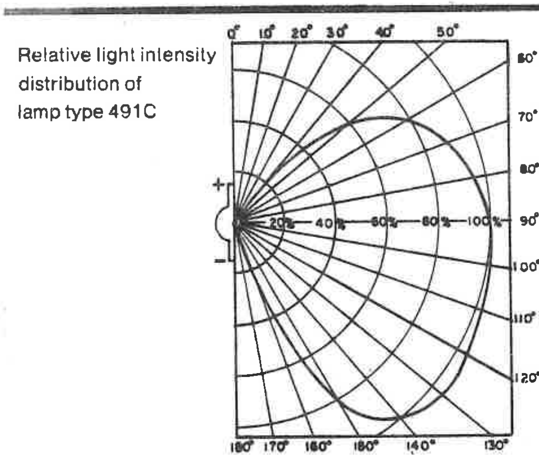


Figure 1b

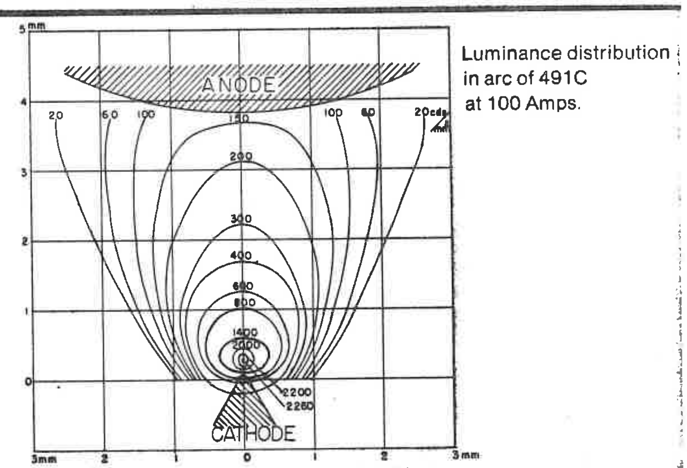


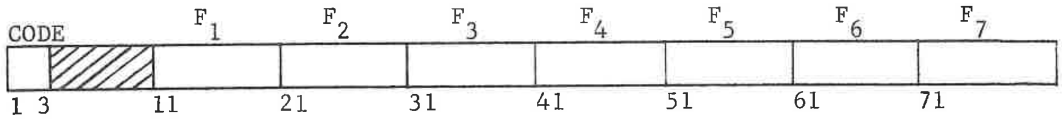
Figure 1c

1. Source Description

The source itself, such as a Xenon arc lamp with its

ILLU- 2

long axis coinciding with the optical axis, is defined by luminance data of two types, both using the format:



CODE (Col. 1-10) Mnemonic code, which is ANG, X, Z, or WT.

F_1 (Col. 11-20) Data fields are entered in sequence.

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F_7 (Col. 71-80)

The two types of distributions are:

a. Polar Distribution

This requires relative light intensity as a function of angle of view from the line (Y axis) perpendicular to the axis of the lamp (Z axis). An example of this data, typically available from the lamp manufacturer, is shown in Figure 1b. Pairs of cards are used to input this data; the codes are:

Card	CODE	Entries (F_1 to F_7)
1	ANG	Polar angle values in degrees; up to 35 entries may be made on as many cards as desired and should be in sequence from one extreme angle to the other; intervals do not need to be equal. Cards need not be filled out completely; a blank field will skip the remaining entries on the card and cause the corresponding entries on the WT card to be ignored. Include at each extreme angle, an angle that can be given a zero weight. Measure θ from the Y axis positive in the direction of the positive optical axis (Z axis).
2	WT	Weights in columns corresponding to the angles given in the preceding card. Any scale of weightings may be used; the

illumination values will incorporate the chosen scalings.

Example: Polar distribution of Figure 1b with anode in + Z direction:

ANG	50.	40.	30.	20.	10.	0.0	-10.
WT	0.0	59.	78.	88.	94.	100.	102.
ANG	-20.	-30.	-40.	-50.	-60.	-70.	
WT	103.	104.	105.	99.	80.	0.0	

b. Luminance Distribution

A typical luminance distribution is given in Figure 1c. The data points should extend over the area of the important parts of the arc and include points around the edge that can be weighted to zero. This distribution is considered to lie in the X, Z plane (X is the skew direction, Z is the optical axis or axis of rotational symmetry). Due to the assumption of rotational symmetry, the arc is assumed to be generated by rotating this plane figure about the Z axis.

In choosing the data points, only one half of the figure needs to be represented in the X direction, because of symmetry. The points can be a grid, but this is merely a convenience; the points can be unequally spaced in both X and Z.

Triplets of cards are used to enter this data; the codes are:

Card	CODE	Entries (F_1 to F_7)
1	X	X coordinate of data point relative to the optical axis. Up to 35 data points may be entered on as many cards as desired; intervals need not be equally spaced. Cards do not need to be filled out completely; a blank field will skip the remaining entries on the card and cause the corresponding entries on the Z and WT cards to be ignored. Include points at the edge that can be given zero values of WT. Have at least 19 data points.
2	Z	Z coordinate of the data points given on the preceding X card.
3	WT	Weights in columns corresponding to the data points specified by the X and Z

cards. Any scale of weightings may be used; the illumination values will incorporate the chosen scalings.

Example: Luminance distribution of Figure 1c (for a system described in millimeters):

X	0.0	.25	.5	.75
Z	-.5	-.5	-.5	-.5
WT	0.0	0.0	0.0	0.0
X	0.0	.5	1.0	1.5
Z	.25	.25	.25	.25
WT	2200.	600.	100.	0.0
X	0.0	.5	1.0	1.5
Z	1.0	1.0	1.0	1.0
WT	800.	550.	230.	0.0
X	0.0	.5	1.0	2.0
Z	2.0	2.0	2.0	2.0
WT	330.	290.	200.	0.0
X	0.0	1.0	2.0	2.5
Z	3.0	3.0	3.0	3.0
WT	210.	155.	55.	0.0
X	0.0	1.0	2.0	2.5
Z	4.0	4.0	4.0	4.0
WT	0.0	0.0	0.0	0.0

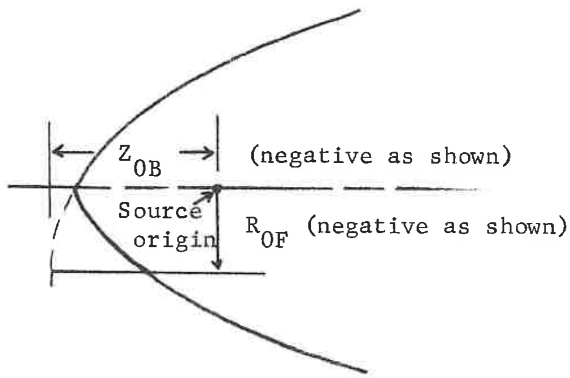
2. Reflector Description

The reflector is generated from a standard polynomial description of an aspheric contour:

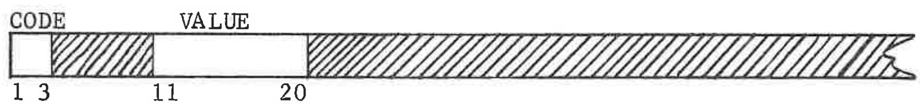
$$Z = \frac{c\,y^2}{1 + \left[1 - (1+K)\,c^2y^2\right]^{1/2}} + Ay^4 + By^6 + Cy^8 + + Dy^{10}$$

with the usual meanings of c, K, A, B, C, D. However, this curve can be displaced from the optical axis a distance R_{0F}. The reflector is then assumed to be generated by rotating this displaced aspheric curve about the optical axis.

In addition, the reflector is positioned a distance Z_{0B} from the origin established by the Z=0 point in the source distribution. This distance is measured from the origin in the source to the plane tangent to the aspheric curve at its local center-line; Z_{0B} is thus usually negative.



The data is provided on cards with the format:



CODE (Col. 1-3)	Value (Col. 11-20)
CUR	Curvature of aspheric
K	Conic constant
A	4th order coefficient
B	6th order coefficient
C	8th order coefficient
D	10th order coefficient
ROF	Radius of offset measured from the optical axis to the local axis of aspheric definition.
ZOB	Displacement of reflector tangent plane from source origin.

The values may be entered in standard decimal notation or in floating point notation but must fit into the 10 column space.

In addition, there may be a circular hole in the reflector, centered about the optical axis which will not reflect light contributions to the image patch. This "obscuration" is specified, if desired, by:

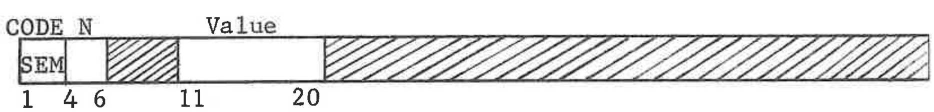
CODE	Value
HOL	Radius of non-reflecting hole.

3. Optical System Description

The reflector and source data previously described permit the program to generate the necessary ray coordinates, trace them through the one reflection and carry them up to a reference plane after which they can be passed through an optical system of any desired complexity. The reference plane is a plane perpendicular to the optical axis at the source origin (Z=0 in source coordinates). Any optical system which has been entered in a previous DATA option is placed with its first surface at this reference plane. The intensity will be calculated on the focal plane specified in this system. It is therefore important to freeze this focal plane or target plane at the right distance.

Thus, in setting up the optical system data, surface 1 coincides with the source origin and the last surface coincides with the screen or illuminated surface. All of the rules for entering systems in DATA must be observed. Thus a surface for the object is included even though this option ignores it. An aperture must be entered even though it is ignored. At least one wavelength must be entered but illumination calculations will only be run in ther reference wavelength. And, again, the image distance must be frozen to prevent the first order value from being substituted.

In addition, it may be desirable to limit some apertures to a given diameter, so that the illumination will be clipped. This can be done with additional data cards using the format:



Entry	Meaning
SEM (Col. 1-3)	Mnemonic code for SEMi-diameter.
N (Col. 4-6)	A number identifying the surface number to which the semi-diameter limit applies.
Value (Col. 11-20)	Value of the semi-diameter.

Up to 5 of these entries can be made with present program limits.

4. Source Functions

There are three operations on the source system which are designed to allow manipulation and analysis of the reflector.

These are:

a. FIND

- Solves CUR, K, A, B, C, D, ROF, ZOB in a least squares sense to satisfy six reflection angles and two intersection heights on the reflector resulting from six ray incident angles. Two cards are required using the format:

CODE	I_1	H_1	R_1	I_2	H_2	R_2	
FIND							//////////
1	11	21	31	41	51	61 70	

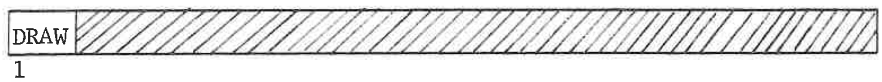
I_3	R_3	I_4	R_4	I_5	R_5	I_6	R_6
1	11	21	31	41	51	61	71 80

Entry	Meaning
I_1	First ray angle of incidence in degrees, using the source origin as the starting point. Angles are expressed with respect to the same coordinates as the polar distribution.
H_1	First ray height on reflector to be solved for.
R_1	First ray angle of mirror reflection, to be solved for - expressed in degrees.
I_2, H_2, R_2	Analogous values for the second ray.
I_i, R_i	Designated angle of incidence and requested angle of reflection for ith ray.

Values specified should be reasonably close to physically realizable values. Since the program will not usually be able to satisfy all of the requirements precisely with a smooth curve, the departures from requested angles (expressed as the sine) and heights are printed out. These are expressed as the excess of the target over the actual value. In addition, the new values of CUR, K, A, B, C, D, ROF, and ZOB are printed out.

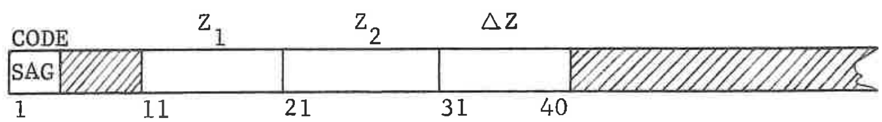
b. DRAW

- Draws on the plotter the contour of the reflector and adds the date and contents of the title card. One card is required using:



c. SAG

- Calculates a table of sags for the reflector contour. One data card is required using:

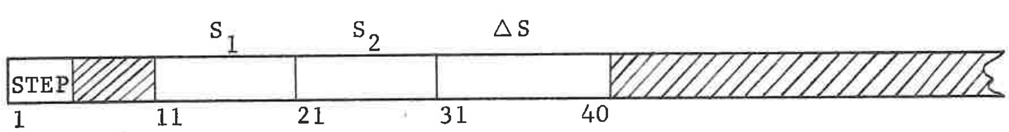


The form of the table is to present the y value as a dependent variable of the axial slice in Z as the independent variable. Entries are:

Z_1 (Col. 11-20)	First axial slice, measured from the pole of the surface as Z_1=0.0
Z_2 (Col. 21-30)	Last axial slice.
ΔZ (Col. 31-40)	Increment of slices.

II. Analysis

Illumination analysis is initiated by requesting a scan of the illuminated target plane or screen. One card is required, of the format:



The entries are as follows:

S_1	Start of scan.
S_2	End of scan.
ΔS	Scan increment.

These values are expressed as radial distances on the target plane. The sign conventions assume that the upper half of the source system is used in the calculation. If this illuminates the upper half of the screen, use positive values for S_1 and S_2; if the upper half of the source system illuminates the bottom half of the screen, use negative values of S_1 and S_2. In either case,

$$\Delta S = \frac{S_2 - S_1}{N}$$

where N is the number of desired increments.

The output of this analysis is a table listing the following items:

Radius	The value of S at the scan point.
Intensity	The resulting value of intensity. These are not scaled and bear a direct relationship to the scalings chosen for input distribution and the efficiency of the optical system.
Control Angle	The angle from the source which illuminates the scan point.
Maximum Angle	The largest angle from any part of the source, which reaches the scan point.
Minimum Angle	The smallest angle from any part of the source, which reaches the scan point.

Function:

The polar and luminance distributions of the source are fitted to polynomials for interpolation purposes. These two sets of polynomial coefficients are printed out as the first output but rarely are needed. Only if they display values approaching the largest possible size (10^{30} or more) is there any need for concern; such sizes indicate some unusual feature of the distribution such as lack of X values, non-zero end points, or sharp corners, for example.

If FIND has been requested, this function is carried out next and the new values of source parameters are printed out.

Finally, the scan points as a function of source input angle are fitted to a polynomial whose coefficeints are printed out. Again, if any of these approach the largest permissable size, the calculation will fail; this is an indication that the optical system allows a focusing of the source directly on the screen for some zone of the system. This is contrary to the basic assumption in the program (Kohler illumination) and is not allowed.

If STEP has been requested, it is carried out next and results are printed.

If SAG has been requested, the table is then printed out, followed by a table of clear apertures on all optical surfaces required to pass the bundles developed in STEP.

If DRAW has been requested, the appropriate drawing is made on the plotter.

Error Conditions:

1. " INVALID CODE (   )" - the contents of the bracket indicates an unacceptable card. Correct and re-run.

2. "NO SCAN STEP REQUESTED" - Warning.

3. "LESS THAN TWO ANGLES DEFINED" - Insufficient polar distribution data. Operation terminated.

4. "LESS THAN 19 SOURCE DATA POINTS DEFINED" - Insufficient luminance distribution data. Operation terminated.

5. "NO REFLECTOR DATA DEFINED" - For SOURCE 1, no values for any of the 8 reflector parameters have been entered. Operation terminated.

6. "LESS THAN TWO ANGLES TRACEABLE" - At least two of the polar distribution angles must be traceable through the system. This indicates that this condition is not met; alter data and re-run.

7. "STARTING SYSTEM NOT TRACEABLE AT REQUESTED ANGLE SOLVES" - The FIND option requires that the starting system at least be able to trace the 6 rays through the source configuration. Alter data to provide a feasible starting system and re-run.

8. "RAY TO REFLECTOR DID NOT CONVERGE" - For SOURCE 1, reflector form did not meet requirements for iterative convergence. This is a warning - recovery procedures for many cases are built in. However, illumination values on next line may be unreliable. To avoid, use a less extreme reflector.

Technical Notes:

Use of this program requires the designer to be cautious in not asking for too much on any given run. Problems are best approached by achieving success on runs which may not use the largest possible collection angle and then expanding the angle in later runs. This same conservative approach should be used in restricting the requests in the FIND operation. Since there are inherent limits on illuminating systems imposed by the laws of thermodynamics and expressed in the Lagrange invariant, approaching these limits will be manifested by increasing difficulty in departing from previous good solutions.

The illumination calculations do not include transmission or surface reflection losses. These will have to be incorporated by computing or estimating them separately and modifying results accordingly. Choices in convergence constants have been chosen so that for most cases, numerical consistency should be within 1%.

Re-distribution of illumination from the pattern found in the starting system can usually be accomplished by altering the target angles of the FIND operation. Causing more convergence at one zone in the system will tend to enhance the illumination at some scan point associated with that zone. However, care must be exercised to avoid asking for so much convergence that focusing the source on the target surface occurs.

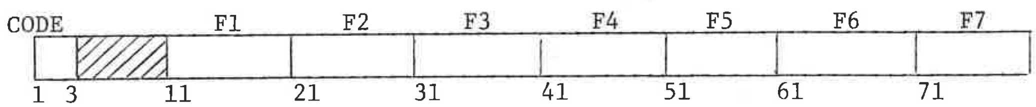
MULTILAYER COATING DESIGN

Purpose:

To analyse the transmission of a stack of non-absorbing, non-dispersive thin film coatings and to optimize it utilizing the coating thicknesses as variables.

Input Data:

A title card should be placed immediately following the MULTILAYER Option card. Additional data cards are used following the title card to describe the initial coating stack and various optimization controls. These cards are punched in the following format:



CODE (Col. 1-3) — Mnemonic code used to identify the data on the card; a list of CODES is given later.

F1 (Col. 11-20) — Data fields F1-F7 used to enter values specified in the CODE.

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F7 (Col. 71-80)

The following list gives the CODES and their associated data entries.

Coating Description:

COAT — This card is used to describe one coating layer; up to 50 layers may be entered. The data entered on each COAT card is the following:

Thickness (F1, Col. 11-20); the coating thickness is entered in reference wavelength units: ex. .25 for a 1/4 wave coating.

Thickness control (F2, Col. 21-30). An integer which is used to set up the thickness variables. A 100 is entered to freeze the coating thickness; a blank or zero entry will allow the coating thickness to independently vary during optimization, identical integers entered on more than one surface will cause those thicknesses to be coupled.

Index (F3, Col. 31-40); the coating index of refraction is entered in data field F3.

INC	The index of refraction of the incident medium is entered in data field F3 (Col. 31-40). If this card is omitted air is assumed
SUBSTRATE	The index of refraction of the substrate is entered in data field F3 (Col. 31-40). This card should be entered after the COAT cards have been entered.
WL	Wavelengths; the wavelengths in nanometers at which the transmission is computed and optimized are entered in data fields F1 - F7. More than one WL card may be entered until up to 20 wavelengths have been entered.
REFW	Reference wavelength; a wavelength in nanometers is entered in data field F1 which is used as the reference for converting thicknesses from wavelength units to absolute thicknesses. If REFW is omitted, the central wavelength (or left of center if an even number) of the above WL wavelengths is chosen as the reference.
ANGLES	Angles; up to 5 angles may be specified in data fields F1-F5 at which the transmission analysis and optimization will be performed.

If only an analysis is wanted, no additional input is required. The program will proceed with the analysis.

Optimization:

If optimization is desired, it is initiated by the OPT request:

OPT	Requests that optimization be done.

Additional data must be supplied to convey the results desired by optimization. The targets for reflectance of either or both of the polarizations, S or P, may be specified at each wavelength. And/or the transmittance of both polarizations combined may be specified. The relative importance of the targets at each wavelength must be supplied; this is done by weighting. The RST, RPT, or TRT cards supply the targets and match in order and number the WL values given above. Following each RST, (RPT or TRT) groups of cards the weights are supplied with WTW cards. Thus, for 10 wavelengths and optimization on S reflectance and total transmission, the requests would be:

```
RST - - - - - - -
RST - - -
WTW - - - - - - -
WTW - - -
TRT - - - - - - -
TRT - - -
WTW - - - - - - -
WTW - - -
```

RST RPT TRT	Targets for optimization; a target may be entered for each wavelength. The targets must be entered in the order corresponding to the order of wavelengths. The departure from these targets is minimized during the optimization. RST and RPT specify the reflectance of the S and P polarizations, respectively. TRT specifies the combined transmittance. Values supplied lie in the range of 0.0 to 1.0. If any entry is omitted, zero is supplied for that entry if the request is RST or RPT; 1.0 is supplied if the request is for TRT. If none of these is supplied, TRT is assumed with values of 1.0 at each wavelength.
WTW	Weight on wavelength; a relative weight to be used during optimization may be assigned to each wavelength. The weights, entered in data fields F1-F7, should be in the same order as the wavelengths. The default weight is 1.0 for each wavelength.
WTAN	Weight on angle; a relative weight to be used during optimization may be entered in data fields F1-F5 for each angle. The default weight is 1.0 for each angle.
MNT	Minimum thickness; the minimum allowable coating thickness for any variable coating is entered in data field F1. The default is 0.0, a value which, if reached, removes the effect of the coating.
MXT	Maximum thickness; the maximum allowable coating thickness for any variable coating is entered in data field F1. The default is 0.5 (1/2 wave).
MNC	Minimum number of cycles permitted; entered in data field F1. The default value is 0.
MXC	Maximum number of cycles permitted; entered in data field F1. The default is 25.
IMPR	Improvement Percentage; entered as a decimal fraction in data field F1. This number is used as an exit criterion, allowing approximately three cycles which have error function improvements less than the IMPR percentage before exit occurs. The default value is .05.

Function:

The reflectance (S and P) and transmission of the multilayer stack are computed at the wavelengths and angles specified. For optimization the differences between these values and the target values are summed into a number called the error function. Then, using a damped least squares method, this error function is reduced to the lowest possible value.

Throughout the improvement cycles, the constraints are brought under control when they are found to be violated, held under control for two cycles and until the program indicates that on release they will move in a direction away from the boundary.

As long as the machine is making good progress the optimization process continues; however, if improvements of less than IMPR (5% unless changed) are made the computer will be increasingly cautious of continuing. After a few such cycles, exit will occur unless the rate of improvement increases.

Output:

The output is a tabulation of the data followed by a printout of the reflectance (S and P) transmission of the input stack. If optimization has been requested, this is followed by the total number of variables and then for each optimization cycle:

1. Cycles number
2. Error function
3. Tabulation of the data as modified
4. Transmission analysis
5. Listing of Controlled Constraints

Error Conditions:

The following error conditions can occur:

1. "MORE THAN 20 WAVELENGTHS" - More than 20 wavelengths have been entered on WL cards.

2. "MORE THAN 50 COATINGS" - More than 50 coating cards have been entered.

3. "MORE THAN 5 ANGLES" - More than 5 angles have been entered on the ANG card.

4. "INDEX DATA ERROR ON COATING NUMBER N" - The index of refraction on coating number n is less than or equal to zero.

IMAGE SIMULATION PROGRAM:

IMSIM

This program, simulating image forming systems, is a powerful tool for analysis of system potential and limitations prior to starting a design. It is also useful for evaluating a finished lens design when combined with its system components.

The original form of the program was developed by Dieter P. Paris of IBM. It has been modified and adapted by ORA to be compatible with CODE V. The input format of the original program has been retained and the applicable sections of the program description are included here as the operating instructions.

The program facilitates the simulation of one-dimensional images in an incoherent photo-optical image-forming system. The single or multiple stage image-forming system may consist of a sequence of linear and non-linear components such as lenses, emulsions, and components that are described by their spread function or optical transfer function. Emphasis in developing the program was on:

1. Simplicity of the statements in which the user specifies the system configuration to the program;

2. Capability of requesting intermediate output at any point in the sequence of system components;

3. Capability of providing repeat runs with varied input or component parameters.

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Note: The following differences from the IMSIM manual should be noted:

(1) Columns 16-40 of the JOB card (see P. 25) will be included as a label on any requested plotted output, rather than ignored as indicated.

(2) Do not include the $DATA card of Table 6 (p. 26).

(3) The END and PRINT requests under IMSIM should be preceded by one or more blanks to distinguish them from CODE V options. Any CODE V option will immediately terminate IMSIM processing. Indenting all IMSIM input is a good general practice.

SECTION I

INTRODUCTION

When designing a photo-optical image-forming system, one would like to optimize the components (lenses, emulsions) for function and cost. To find the optimum parameters for each component used in the system, it is desirable to analyze the system and the components of the system by means of a digital computer program that will allow the user to process a typical input (object) through a simulated system and to evaluate the effect of each component upon the output (image) provided by the system. The parameters affecting component performance may then be varied to find the optimum design.

To calculate the output (image) of a photo-optical image-forming system for a given input (object), we use the optical transfer theory†, which requires that the components of the image-forming system be linear and space-invariant. However, in every real image-forming system, one or more components, such as photographic emulsions, are nonlinear. Thus, superposition does not hold for the total system, and we have to calculate the image for each new object separately. Such calculation makes the use of a digital computer very practical.

In the remainder of this section, we will discuss the requirements of a digital computer program for the simulation of a photo-optical image-forming system based upon the above considerations. In section II, we discuss the realization of these requirements in IMSIM/1. In section III, we provide a more detailed development of the simulation program. Readers who are primarily interested in the use of the program may omit Section III and proceed directly to the "User's Manual," Section IV. In section V, we present a number of examples illustrating the use of IMSIM/1. We recommend that any reader intending to use the simulation program study these examples carefully.

It will suffice if the computer program simulates objects that vary only in one dimension. This is justified in cases of systems with a rotationally symmetric point-spread function. This is also justified

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†The first book published about this subject by P. M. Duffieux[1] is difficult to obtain. Two recent books[2] (by E. L. O'Neill and by E. H. Linfoot) provide a comprehensive introduction to optical transfer theory. Tutorial papers by F. H. Perrin[3] and H. H. Hopkins[4] are also recommended.

for systems with a nonrotationally symmetric point-spread function (caused, for example, by coma or astigmatism) since it is a generally accepted practice to study the system by use of two one-dimensionally varying objects, one object varying tangentially and the other varying radially.

Also, it will suffice if the computer program simulates only space-invariant image formation since, when studying the performance of a lens or lens system, the objects in which one is interested will normally be small compared to an isoplanatic patch.+

The simulation program is designed so that the user will be able to describe the sequence of system components by a simple, special purpose programing language, IMSIM/1. Programs written in this language will consist of a sequence of statements. The first statement shall describe the desired input (object). Each of the following statements will contain a description of one component and numerical parameters representative of that component. Examples of possible components are: perfect lens (with defocusing and longitudinal vibration), photographic emulsion, linear and random image motion, and transverse vibration. If the user wants to provide the component characteristic in tabulated form (for example a line-spread function, a transfer function, or an H & D curve) means are available to do so. IMSIM/1 is a procedural language; that is, the sequence of the statements indicates the sequence of the components. The execution of a set of IMSIM statements results in calculating the image produced by the specified one-dimensional object. The user can request printing or plotting of intermediate images produced by any one of the components; he can thus discover the weakest link in the chain of system components.

The user can study the influence of one component or of several particular components on the performance of the total system; IMSIM/1 provides means for supplying several sets of parameters for each component instead of only one set of parameters. This feature has important application in the study of the performance of a lens system across its field; it is also useful for studying the off-axis field of a lens system for radially or tangentially varying objects, or for objects varying in any intermediate direction. The resolution of an image-forming system can be obtained by using periodic input functions

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+An isoplanatic patch[5,6] is an area in the object plane of a lens such that the spread function does not change its shape significantly if the point source (or line source) explores this area. In other words, within this patch the lens is space-invariant.

having various frequencies. Tolerances for depth of focus can also be determined easily by use of different sets of parameters representing various amounts of defocusing.

II. THE SIMULATION

For the purposes of this report, it is practical to assume that the simulated image-forming system consists of a sequence of blocks. Five types of blocks are discussed: input blocks, output blocks, intermediate storage blocks, linear-component blocks, and nonlinear-component blocks. Each block corresponds to one statement in IMSIM/1. The input, output, and intermediate storage blocks serve the purposes of communication between the simulation program and the program user. The linear-component and nonlinear-component blocks represent linear and nonlinear components of the image-forming system. Included in the nonlinear blocks are two nonlinear-conversion blocks, which do not actually represent a component of the system. However, they behave exactly the same way that nonlinear components do.

The output of one of the component blocks serves as the input to the next. The inputs and outputs of component blocks represent one-dimensional distributions of light intensity, transmittance, or photographic density, depending upon the type of component. To achieve the actual simulation, each block must be described by a statement in IMSIM/1. The formats of these statements are discussed in section IV.

2.1 INPUT BLOCKS

The first block in each simulation must be an input block. This block describes the desired input (object) to the simulation. Nine different inputs are provided in IMSIM/1, as shown in table 1. Input blocks 1 through 5 represent aperiodic inputs; input blocks 6 through 9 represent aperiodic inputs.

2.2 LINEAR-COMPONENT BLOCKS

For linear components, the law of superposition holds. If the linear components are also space-invariant, each can be characterized by either its line-spread function A(x) or its optical transfer function D(R). Because we want to simulate incoherent image formation, A(x) represents intensities and thus must be nonnegative. The optical transfer function D(R) defined as the Fourier transform of the line-spread function, will generally be complex:

$$D(R) = M(R)\, e^{i\theta(R)} = \int_{-\infty}^{+\infty} A(x)\, e^{-2\pi i x R}\, dx$$

Table 1. Input Blocks

INPUT (OBJECT)	u(x)
Periodic Inputs	
1. Sine	$\bar{u}\ [1 + m \sin(2\pi R_o x)]$
2. Cosine	$\bar{u}\ [1 + m \cos(2\pi R_o x)]$
3. Crenelate (square wave)	$\bar{u}\left[1 + \frac{4m}{\pi}\sum_{\nu=1}^{\infty}\frac{\sin\left(\pi\nu\frac{r}{r+1}\right)}{\nu\left(1+m\frac{r-1}{r+1}\right)}\cos(2\pi\nu R_o x)\right]$
4. Dirac Comb	$B + E\sum_{\nu=-\infty}^{\infty}\delta\left(x - \frac{\nu}{R_o}\right)$
5. Periodic Table	(specified by user in table form)
Aperiodic Inputs	
6. Line Source	$B + E\ \delta(x)$
7. Slit	$\begin{cases} B & \text{for } \lvert x\rvert > W/2 \\ (B+C)/2 & \text{for } \lvert x\rvert = W/2 \\ C & \text{for } \lvert x\rvert < W/2 \end{cases}$
8. Gaussian	$B + (C-B)e^{-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2}$
9. Aperiodic Table	(specified by user in table form)

PARAMETERS

$\bar{u}$ = mean	$\delta(x)$ = Dirac δ-function
m = modulation $\frac{u_{max}-u_{min}}{u_{max}+u_{min}}$	E = power contained in δ-function
R_o = special frequency	C = ordinate at center (x = 0)
r = $\frac{\text{(space width)}}{\text{(bar width)}}$	W = slit width
B = background	σ = standard deviation

M(R) is the modulation transfer function and $\Theta(R)$ the phase transfer function. $\Theta(R)$ is equal to zero if, and only if, the line-spread function A(x) is even, i.e., if A(x) is symmetric and centered at x = 0.

Let u(x) and v(x) be input and output of a linear component. The process of transfer from input to output can then be described in the space domain by a convolution†:

$$v(x) = \int_{-\infty}^{+\infty} u(x')\ A(x - x')\ dx'$$

Applying a Fourier transformation to each side of this equation we obtain the equivalent relation in the spatial frequency domain:

$$\tilde{v}(R) = \tilde{u}(R)\ D(R)$$

Here $\tilde{u}(R)$ and $\tilde{v}(R)$ are the Fourier transform of u(x) and v(x), and are, respectively:

$$\tilde{u}(R) = \int_{-\infty}^{+\infty} u(x)e^{-2\pi ixR}\ dx$$

$$\tilde{v}(R) = \int_{-\infty}^{+\infty} v(x)e^{-2\pi ixR}\ dx$$

If we have a sequence of N linear blocks, with each described by its transfer function $D_i(R)$, it follows that the final output is related to the input by

$$\tilde{v}(R) = \tilde{u}(R)\ D_1(R)\ D_2(R)\ .\ .\ .\ D_N(R)$$

The simplicity of this multiplicative relation describing the transfer from input to output for a sequence of linear blocks in the frequency domain is one reason for performing the transfer in the

†The fact that the convolution integral extends from $-\infty$ to $+\infty$ rather than from $-\infty$ to x, as in the case of dynamic systems, prohibits the use of conventional digital computer simulation techniques, as for instance, MIDAS, JANIS ("A Survey of Digital Simulation: Digital Analog Simulator Programs," R. D. Brennan and R. N. Linebarger, SIMULATION, December, 1964), or DSL/90 (IBM San Jose TR 02.355, W. M. Syn and D. C. Wyman). This fact can also be expressed as lack of directionality in the space domain as opposed to the existence of directionality in the time domain.

frequency domain. Another reason is that ordinarily the width of the frequency domain will become smaller as the simulation proceeds, because of the encounter of definite frequency cutoffs. For the numerical representation in the computer, performing the transfer in the frequency domain is more practical than performing the transfer in the space domain by the use of convolutions, because the width of the space domain would increase with every convolution encountered.

Table 2 shows all linear blocks implemented in IMSIM/1. Blocks 1 through 7 need no explanation. Block 8 (SCANNING) permits the user to simulate scanning of a one-dimensional object by a slit, for instance, with a microdensitometer. Block 11 (MAGNIFICATION), which serves to introduce any applicable magnification, is required because, traditionally, the transfer function of a PERFECT LENS (block 7) assumes imaging with a one-to-one magnification. Blocks 9 and 10 (OPTICAL TRANSFER FUNCTION TABLES and SPREAD FUNCTION TABLE) allow the user to introduce data, which may have been determined experimentally in the form of tables. OPTICAL TRANSFER FUNCTION TABLE allows the tables to be specified for both modulation transfer function and phase transfer function.

2.3 NONLINEAR-COMPONENT BLOCKS

When a nonlinear-component block is encountered in the simulation, its input must be transformed from the frequency domain to the space domain, and its output must be transformed from the space domain, as illustrated in figure 1. Thus, the computer program must

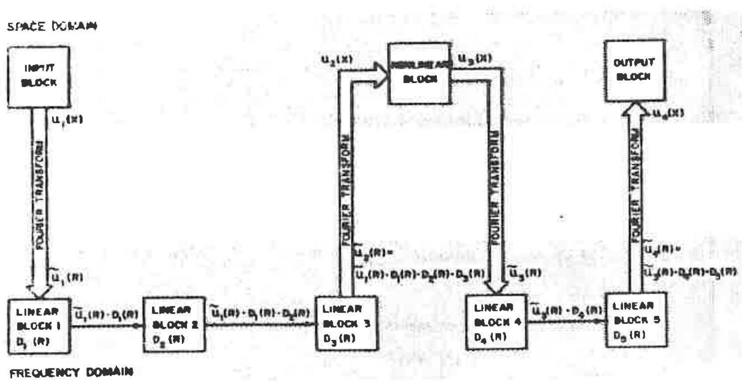


Figure 1. Sequence Illustrating Fourier Transformations Required for Nonlinear-Component Blocks

Table 2. Linear-Component Blocks

LINEAR COMPONENT	D(R)	REF.
1. Linear Image Motion	sinc (πdR)	7, 8
2. Vibration Transverse	$J_o(\pi\epsilon R)$	7, 8
3. Random Image Motion	$e^{-2(\pi\sigma R)^2}$	8
Gaussian Transfer Function	$e^{-\frac{1}{2}\left(\frac{R}{\sigma_F}\right)^2}$	
5. Focal Plane Shutter	$\begin{cases} 1 - \frac{\lvert R\rvert}{R_A} & \text{for } \lvert R\rvert \le R_A \\ 0 & \text{for } \lvert R\rvert \ge R_A \end{cases}$	9
6. Emulsion Light Diffusion	$\frac{1}{1 + (R/R_{0.5})^2}$	10, 11
7. Perfect Lens		
a. without defocusing and longitudinal vibration	$\frac{2}{\pi}\left[\cos^{-1}\left(\frac{R}{R_A}\right) - \frac{\lvert R\rvert}{R_A}\sqrt{1-\left(\frac{R}{R_A}\right)^2}\right]$	12
b. with defocusing and longitudinal vibration	$\frac{4}{\pi}\int_0^{1-\lvert R\rvert/R_A} J_o\left(\frac{\pi z_1 R}{\epsilon}x\right)\sqrt{1-\left(x-\frac{\lvert R\rvert}{R_A}\right)^2}\cos\left(\frac{\pi z_o R}{\epsilon}x\right)dx$	13
8. Scanning	sinc (πsR)	14
9. Optical Transfer Function Tables	$M(R)e^{i\theta(R)}$ (Specified by user in table form)	
10. Spread Function Table	$\frac{\int_{-W/2}^{+W/2} A(x)e^{-2\pi iRx}dx}{\int_{-W/2}^{+W/2} A(x)\,dx}$ where $A(x)$ is specified by user in table form	
11. Magnification		

PARAMETERS

d = displacement
ϵ = total excursion
σ = standard deviation of random motion
σ_F = standard deviation of transfer function
R_A = cutoff frequency
$R_{0.5}$ = halfwidth frequency
$\epsilon = \frac{0.5}{\text{(numerical aperture)}}$
J_o = Bessel function of first kind and zero order
z_o = static defocusing
z_1 = amplitude of longitudinal vibration
s = slit width
$\text{sinc}(x) = \frac{\sin(x)}{x}$

contain provisions for the execution of a Fouri :r transformation, which is calculated according to the relation

$$\tilde{U}(R) = \int_{-\infty}^{+\infty} u(x)\, e^{-2\pi i x R}\, dx$$

Generally, $\tilde{U}(R)$ is a complex function. Hence, both its real and imaginary parts must be determined. Because $u(x)$ is real (it represents intensity, transmittance, or density),

$$\tilde{U}(-R) = \tilde{U}^*(R)$$

where the asterisk (*) denotes the complex conjugate. Hence it suffices to calculate $\tilde{U}(R)$ only for non-negative spatial frequencies R. The complex Fourier transform $\tilde{U}(R)$ is related to the cosine and sine transform of $u(x)$ by:

$$\mathrm{Re}\{\tilde{U}(R)\} = \int_{-\infty}^{+\infty} u(x) \cos 2\pi R x\, dx$$

$$\mathrm{Im}\{\tilde{U}(R)\} = \int_{-\infty}^{+\infty} u(x) \sin 2\pi R x\, dx$$

Table 3 shows the nonlinear blocks provided in IMSIM/1. Block 1 represents a point-to-point nonlinearity $v = F(u)$. Block 2 represents the most common type of nonlinear component in a photo-optical system, the characteristic curve (H & D curve). The user has the option to let u_m be equal to the maximum of $u(x)$, equal to the minimum of $u(x)$ or equal to one. Thus he can expose either the maximum of $u(x)$, the minimum of $u(x)$ or the point $u(x) = 1$ at the working point u_o. Both block 1 and block 2 are specified by the user in table form. Block 3, which provides conversion from photographic density to transmittance, permits the user to simulate multiple-stage image-forming systems. Transparancies obtained as an output of an H & D curve represent densities. Block 3 converts these densities to transmittances so that they can be used as an input to the next block in the simulation. For completeness, the inverse operation (transmittance-to-density conversion) is included as block 4.

Table 3 - Nonlinear Blocks

NONLINEAR COMPONENT OR CONVERSION	v
Image-Forming System Component	
1. Nonlinear Function	$F(u)$
2. Characteristic Curve (H & D Curve)	$F\left[u_o + \log_{10} \frac{u}{u_m}\right]$
Conversion	
3. Density-to-Transmittance Conversion	10^{-u}
4. Transmittance-to-Density Conversion	$-\log_{10} u$

2.4 INTERMEDIATE STORAGE BLOCKS

Two intermediate storage blocks are provided in IMSIM/1: the SAVE block and the PICKUP block. The SAVE block permits storage of the momentary state of the simulation at an intermediate point following any of the component blocks. The PICKUP block allows resumption of the simulation at this intermediate point. The user can thus "look" at an image produced, for example, by scanning an intermediate transparency, obtain the output of the scan, and then resume the simulation from the point at which it was saved before the scanning operation took place.

2.5 OUTPUT BLOCKS

The output blocks are used to request an intermediate or a final output from the simulation program. Any number of them can be inserted between any two component blocks or added at the end of the sequence of component statements. Two Print Output blocks and four Plot Output blocks are provided in IMSIM/1, as shown in table 4.

The Print Output blocks initiate numerical printing of the space domain $u(x)$ or the complex frequency domain $\tilde{U}(R)$. For the latter, modulus and phase as well as real and imaginary parts are printed. The Space Domain and the two Frequency Domain Plot Output blocks provide plotting of the space domain, the complex frequency domain in the form of modulus and phase, and the complex frequency domain in the form of real and imaginary parts. The Component Plot Output block initiates plotting of the characteristic function of that linear or nonlinear component that immediately precedes this component plot block. If this preceding component is linear, its optical transfer function will be plotted; if it is nonlinear, the nonlinear function F(u) is plotted.

Table 4 -- Output Blocks

Print Output Blocks
Space Domain
Frequency Domain
Plot Output Blocks
Space Domain
Frequency Domain (Modulus and Phase)
Frequency Domain (Real and Imaginary Parts)
Component

2.6 PROGRAM BRANCHING FOR REPEAT RUNS

IMSIM/1 allows the user to obtain repeat runs of the simulation for different sets of parameters for components and inputs, instead of obtaining one run for only one set of parameters. Figure 2 illustrates the two ways of branching, showing a sequence of five blocks of a simulation run. Blocks 3 and 4 each provide 3-way branches and block 5 provides a 2-way branch.

Figure 2a illustrates the most straightforward branching arrangement, fan branching. Each set of parameters provided for a particular block is included in a sequence that also includes each parameter set provided for the other blocks. That is, there is a repeat run for every possible combination of parameter sets.

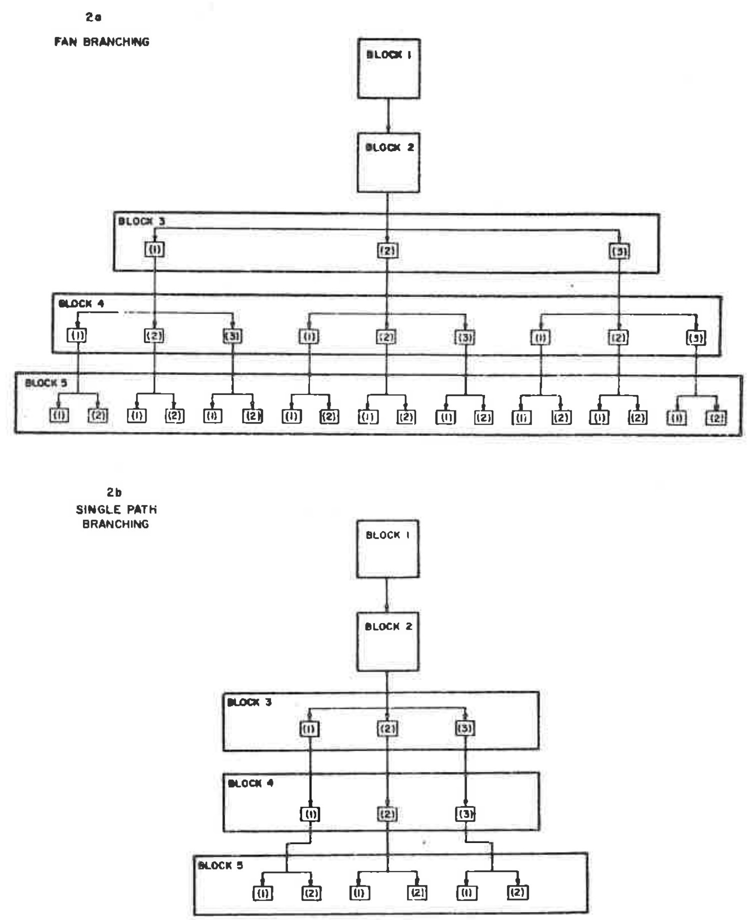


Figure 2.

Figure 2b illustrates single-path branching for block 4. A particular set of parameters of block 4 is included only in the sequence that uses the corresponding set of parameters of block 3. For example, set 2 of block 4 is evaluated only with set 2 of block 3, and not with sets 1 and 3 of block 3.

The user indicates branching in IMSIM/1 simply by supplying several sets of parameters instead of one set only. The user must indicate single path branching by use of a code together with the statement for block 4. Omission of the code will result in fan branching, as illustrated in figure 2a.

SECTION IV

USER'S MANUAL FOR IMSIM/1

This section provides information on formatting the block description of the simulation as a sequence of statements in IMSIM/1. Conditions that must be met by the statements are indicated. An encircled number, such as (13), refers to the particular error message that will be printed if the stated condition is violated. The error messages are described in paragraph 4.7.

4.1 GENERAL REMARKS

The user must decide in which units he wants to express the physical quantities that are used by the simulation program. The computer program accepts only pure numbers. It is the user's responsibility to express all parameters in compatible units. If, for example, the user specifies the spatial frequency 200 cycles/mm by the number 200, then he must express within the same job all other parameters representing spatial frequencies in cycles/mm, and all parameters representing a length in mm. The program prints or plots "CYCLES/L.U." for spatial frequency units and "L.U." for length units.

The user must also be aware of the units in which the ordinates of the space domain are momentarily represented. For instance, before the program executes a linear-component block, the space domain must be represented by intensities, or by some quantity proportional to intensities, such as transmittances. No program check exists to verify this condition. If a nonlinear transformation from density to density is to be executed by the NONLINEAR FUNCTION block, the user must ensure that the space domain is converted into densities before executing this block. In any output print or plot, ordinates will always appear in "REL. UNITS."

The user supplies the description of the image-forming system to the program in the form of statements punched on cards. These cards are considered data cards. Thus, the first must be a monitor control card. For the IBM Monitor IBSYS, this card requires $DATA in columns 1-5. All subsequent cards may be punched by the user in free format. That is, the program ignores blanks. All 80 columns of the card may be used.

4.2 DECK SET-UP

The user may stack as many simulation jobs as he wants. Each job must be introduced by a JOB card (16). Termination of a job by an

END card is optional, with the exception of the last job in the deck, which must be terminated by an END card (17), or else the last job will not be executed. The next card after a JOB card must be an INPUT card (1). There must be at least one additional block (2) but not more than thirty blocks (3) following the INPUT card. The sequence of the cards determines the sequence of the simulation.

Certain types of blocks require that numerical tables be supplied to the program. These are introduced by TABLE cards, which follow the set of block cards. A typical user's deck may look as shown in table 6.

4.3 JOB CARD AND END CARD

The words JOB or END must be the first three (non-blank) characters on the card. The word JOB may be followed by a job number, which must be an unsigned integer smaller than 10^6. Only a sign error will be indicated by an error message (7). If the number is greater than or equal to 10^6, it is truncated by the program and only 6 decimal places are retained. The job number will be printed with each heading of printed output and will appear at the beginning of each output plot. If the job number is omitted, it is implied to be 0. Information placed on the card to the right of the job number is ignored. On the END card, information to the right of the word END is ignored. Space after the job number on the JOB card or after the word END on the END card may be used for comments.

4.4 BLOCK CARDS

The block cards establish the input to the simulation, describe the image-forming system, select intermediate storage, and control output. The block cards follow the JOB card in the card deck. The first block card must contain an INPUT statement, after which up to 30 additional component statements, each punched on one card, may be used.

Statements on all block cards have the same general format (blanks ignored):

NAME... $(A_1, \ldots, A_n)$ where $n = 0, \ldots, 4$ (9)(24)

For OUTPUT statements, the first seven letters of the NAME are significant and subsequent characters are ignored until either a left parenthesis or the end of the card is encountered. For all other block

Table 6. Typical User's Deck Set-up

```
$DATA
JOB card
BLOCK cards:
    INPUT statement
    {LINEAR COMPONENT statements          }
    {NONLINEAR COMPONENT statements       }  as determined
    {INTERMEDIATE STORAGE statements      }  by user
    {OUTPUT statements                    }
TABLE cards (as required)
END card (optional)

JOB card
BLOCK cards:
    INPUT statement
    {LINEAR COMPONENT statements          }
    {NONLINEAR COMPONENT statements       }  as determined
    {INTERMEDIATE STORAGE statements      }  by user
    {OUTPUT statements                    }
TABLE cards (as required)
END card
```

statements, the first four letters of the NAME are significant, and subsequent characters are ignored until either a left parenthesis or the end of the card is encountered. The significant portions of the names must be as described in the following paragraphs, under "Permitted Formats."

Parameter sets are provided in parentheses. Within the parentheses, the parameter values A_i must be separated by commas. A_i must be written as a signed or unsigned integer or as a decimal fraction. Other symbols within the parenthesis are not permitted (10).

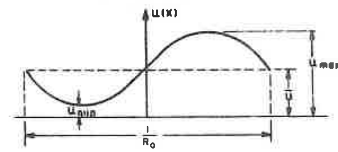
When there is nothing written between two commas or between comma and parenthesis, A_i is implied to be 0. Each parameter set must be terminated by a right parenthesis (6) (10). As many as 11 parameter sets may be included on some component cards.

With the exception of the word EVEN (see paragraphs 4.4.1.5 and 4.4.1.9) there is no further information allowed in an INPUT statement (5). In certain other block statements (see paragraphs 4. 4. 2, 4. 4. 3, and 4. 4. 5) the terms SP or FAN (see paragraph 4. 6) are permitted. No other information is allowed after the parameter sets on any block card (5).

The statements for each of the blocks are described in the following paragraphs. Each paragraph describes one block. For each statement, one and only one card must be used.

4. 4. 1 INPUT STATEMENTS

4. 4. 1. 1 SINE



$$u(x) = \bar{u} \; [1 + m \sin 2\pi R_o x]$$

Permitted Formats: (9) (24)

SINE (A_1, A_2, A_3)

SINE (A_1, A_2) where $A_3 = 1$, by implication

SINE (A_1) where $A_2 = A_3 = 1$, by implication

Parameters:

A_1 = spatial frequency R_o

A_2 = modulation $m = \frac{u_{max} - u_{min}}{u_{max} + u_{min}}$

A_3 = mean $\bar{u}$ over one period

Conditions: (7)

$A_1 > 0$

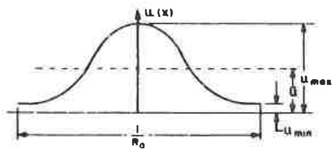
$|A_2| \leq 1$

$A_3 > 0$

Action:

The frequency domain is filled with the Fourier coefficients of the Fourier series expansion of u(x).

4.4.1.2 COSINE



$u(x) = \bar{u}\,[1 + m \cos 2\pi R_o x]$

Permitted Formats: (9)(24)

- COSI (A_1, A_2, A_3)
- COSI (A_1, A_2) where $A_3 = 1$, by implication
- COSI (A_1) where $A_2 = A_3 = 1$, by implication

Parameters:

A_1 = spatial frequency R_o

A_2 = modulation $m = \frac{u_{max} - u_{min}}{u_{max} + u_{min}}$

A_3 = mean $\bar{u}$ over one period

Conditions: (7)

$A_1 > 0$

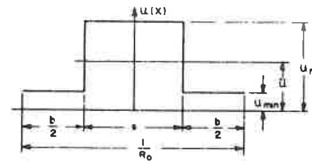
$|A_2| \leq 1$

$A_3 > 0$

Action:

The frequency domain is filled with the Fourier coefficients of the Fourier series expansion of u(x).

4.4.1.3 CRENELATE



$$u(x) = \bar{u}\left\{1 + \frac{4}{\pi} m \sum_{\nu=1}^{\infty} \frac{\sin\left(\pi\nu \frac{r}{r+1}\right)}{\nu\left(1 + m\,\frac{r-1}{r+1}\right)} \cos\,(2\pi\nu R_o x)\right\}$$

Permitted Formats: (9)(24)

- CREN (A_1, A_2, A_3, A_4)
- CREN (A_1, A_2, A_3) where $A_4 = 1$, by implication
- CREN (A_1, A_2) where $A_3 = A_4 = 1$, by implication
- CREN (A_1) where $A_2 = A_3 = A_3 = 1$, by implication

Parameters:

A_1 = spatial frequency R_o

A_2 = modulation $m = \frac{u_{max} - u_{min}}{u_{max} + u_{min}}$

A_3 = mean $\bar{u}$ over one period

$A_4 = \frac{(space)}{(bar)} = \frac{a}{b} = r$

Conditions: (7)

$A_1 > 0$

$|A_2| \leq 1$

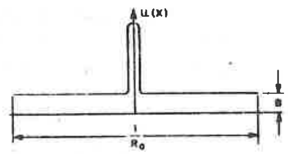
$A_3 > 0$

$A_4 > 0$

Action:

The space domain is filled with u(x).
The frequency domain is filled with the Fourier coefficients of the Fourier series expansion of u(x).

4.4.1.4 DIRAC COMB



$$u(x) = B + E \sum_{\nu=-\infty}^{+\infty} \delta\left(x - \frac{\nu}{R_o}\right)$$

Permitted Formats: (9)(24)

DIRA (A_1, A_2, A_3)

DIRA (A_1, A_2) where $A_3 = 0$, by implication

DIRA (A_1) where $A_2 = 1$ and $A_3 = 0$, by implication

Parameters:

A_1 = spatial frequency R_o

A_2 = power E, contained in each δ-function

A_3 = background B

Conditions: (7)

$A_1 > 0$

$A_2 > 0$

$A_3 \geq 0$

Action:

The frequency domain is filled with the Fourier coefficient of the Fourier series expansion of $u(x)$.

4.4.1.5 PERIODIC TABLE

Permitted Formats: (9)(24)

PERI (A_1, A_2)

PERI (A_1, A_2) EVEN

Note: To take advantage of the faster execution in case of an even tabulated input function, the word EVEN must follow the right parenthesis of the parameter set. If more than one parameter set is provided, EVEN must follow the last parameter set. All table numbers referenced in the PERIODIC TABLE statement are then treated as referring to even functions. The table must still specify the total tabulated input function.

Parameters:

A_1 = table number

A_2 = spatial frequency R_o

Conditions: (7)

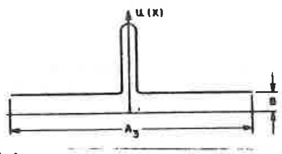
$A_1 = 1, \ldots, 10$ where only the integer portion of A_1 is used if A_1 is specified as a noninteger.

$A_2 > 0$

Action:

The space domain is filled with the tal ulated function.

4.4.1.6 LINE SOURCE



$u(x) = B + E\,\delta(x)$

Permitted Formats: (9)

LINE (A_1, A_2, A_3)	
LINE (A_1, A_2)	where $A_3 = 0$, by implication
LINE (A_1)	where $A_2 = A_3 = 0$, by implication
LINE	where $A_1 = 1$ and $A_3 = A_2 = 0$, by implication

Parameters:

A_1 = power E contained in δ-function

A_2 = background B

A_3 = initial width of space domain

Conditions: (7)

$A_1 > 0$

$A_2 \geq 0$

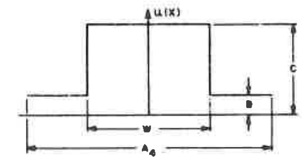
$A_3 \geq 0$

Action:

The frequency domain is filled with the Fourier transform of u(x). If $A_3 = 0$, the program determines the initial width of the space domain essentially by adding the widths of all subsequent line-spread functions. If $A_3 \neq 0$, its value is taken as the initial width of the space domain.

Note that the cutoff of a subsequent frequency domain output is given by 100/(width of space domain).

4.4.1.7 SLIT



$$u(x) = \begin{cases} B & \text{for } |x| > W/2 \\ (B+C)/2 & \text{for } |x| = W/2 \\ C & \text{for } |x| < W/2 \end{cases}$$

Permitted Formats: (9) (24)

SLIT (A_1, A_2, A_3, A_4)	
SLIT (A_1, A_2, A_3)	where $A_4 = 0$, by implication
SLIT (A_1, A_2)	where $A_3 = A_4 = 0$, by implication
SLIT (A_1)	where $A_2 = 1$ and $A_3 = A_4 = 0$, by implication

Parameters:

A_1 = slit width W

A_2 = center ordinate C

A_3 = background B

A_4 = initial width of space domain

Conditions: (7)

$A_1 > 0$

$A_2 \geq 0$

$A_3 \geq 0$

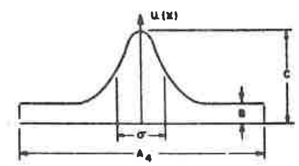
$A_4 \geq 0$

Action:

The space domain is filled with the function u(x). The frequency domain is filled with the Fourier transform of u(x). If $A_4 = 0$, the program determines the initial width of the space domain essentially by adding the widths of all subsequent line-spread functions to A_1. If $A_4 \neq 0$, its value is taken as the initial width of the space domain.

Note that the cutoff of a subsequent frequency domain output is given by 100/ (width of space domain).

4.4.1.8 GAUSSIAN



$$u(x) = B + (C-B)e^{-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2}$$

Permitted Formats: (9)(24)

GAUS (A_1, A_2, A_3, A_4)	
GAUS (A_1, A_2, A_3)	where $A_4 = 0$, by implication
GAUS (A_1, A_2)	where $A_3 = A_4 = 0$, by implication.
GAUS (A_1)	where $A_2 = 1$ and $A_3 = A_4 = 0$, by implication

Parameters:

A_1 = standard deviation σ

A_2 = center ordinate C

A_3 = background B

A_4 = initial width of space domain

Conditions: (7)

$A_1 > 0$

$A_2 \geq 0$

$A_3 \geq 0$

$A_4 \geq 0$

Action:

The space domain is filled with the function u(x). The frequency domain is filled with the Fourier transform of u(x). If $A_4 = 0$, the program determines the initial width of the space domain essentially by adding the widths of all subsequent line-spread functions to $7A_1$. If $A_4 \neq 0$, its value is taken as the initial width of the space domain.

Note that the cutoff of a subsequent frequency domain output is given by 100/ (width of space domain).

4.4.1.9 APERIODIC TABLE

Permitted Formats: (9) (24)

APER (A_1, A_2, A_3, A_4)

APER (A_1, A_2, A_3, A_4)EVEN

APER (A_1, A_2, A_3) }
APER (A_1, A_2, A_3) EVEN } where $A_4 = 0$, by implication

APER (A_1, A_2) }
APER (A_1, A_2) EVEN } where $A_3 = A_4 = 0$, by implication

Note: If the user wants to take advantage of faster execution in case of an even tabulated input function, the word EVEN must follow the right parenthesis of the parameter set. If more than one parameter set is provided, EVEN must follow the last set. All tables referenced in the APERIODIC TABLE statement are then treated as referring to even functions. The table must still specify the total tabulated input function.

Parameters:

A_1 = table number

A_2 = width of table

A_3 = background

A_4 = initial width of space domain

Note: The ordinates that the user provides in the referenced table are interpreted by the program to be above the background.

Conditions: (7)

$A_1 = 1, 2, \ldots, 10$ where only the integer portion of A_1 is used if A_1 is specified as a noninteger

$A_2 > 0$

$A_3 \geq 0$

$A_4 \geq 0$

Action:

The space domain is filled with the sum of the tabulated function and the background A_3. If $A_4 = 0$, the program determines the initial width of the space domain essentially by adding the widths of all subsequent line-spread functions to A_2. If $A_4 \neq 0$, its value is taken as the initial width of the space domain.

Note that the cutoff of a subsequent frequency domain output is given by 100/ (width of space domain).

4.4.2 LINEAR COMPONENT STATEMENTS

4.4.2.1 LINEAR IMAGE MOTION

Transfer Function:

$$D(R) = \text{sinc}\ (\pi dR)$$

Permitted Format: (9)(24)

LINE (A_1)

Parameters:

A_1 = displacement d (amount of motion)

Conditions: (7)

$A_1 \geq 0$

Action:

The frequency domain is multiplied by D(R).

4.4.2.2 VIBRATION TRANSVERSE

Transfer Function:

$$D(R) = J_o(\pi \epsilon R)$$

Permitted Format: (9)(24)

VIBR (A_1)

Parameters:

A_1 = total excursion ϵ (peak-to-peak distance)

Conditions: (7)

$A_1 \geq 0$

Action:

The frequency domain is multiplied by D(R).

4.4.2.3 RANDOM IMAGE MOTION

Transfer Function:

$$D(R) = e^{-2(\pi \sigma R)^2}$$

Permitted Format: (9)(24)

RAND (A_1)

Parameters:

A_1 = standard deviation of random motion, σ

Conditions: (7)

$A_1 \geq 0$

Action:

The frequency domain is multiplied by D(R).

4.4.2.4 GAUSSIAN TRANSFER FUNCTION

Transfer Function:

$$D(R) = e^{-\frac{1}{2}\left(\frac{R}{\sigma_F}\right)}$$

Permitted Format: (9) (24)

GAUS (A_1)

Parameters:

A_1 = standard deviation of Gaussian modulation transfer function, σ_F

Conditions: (7)

$A_1 > 0$

Action:

The frequency domain is multiplied by D(R).

4.4.2.5 FOCAL PLANE SHUTTER

Transfer Function:

$$D(R) = \begin{cases} 1 - |R|/R_A & \text{for } |R| \leq R_A \\ 0 & \text{for } |R| \geq R_A \end{cases}$$

Permitted Format: (9) (24)

FOCA (A_1)

Parameters:

A_1 = cutoff frequency R_A

Conditions: (7)

$A_1 > 0$

Action:

The frequency domain is multiplied by D(R).

4.4.2.6 EMULSION LIGHT DIFFUSION

Transfer Function:

$$D(R) = \frac{1}{1 + \left(\frac{R}{R_{0.5}}\right)^2}$$

Permitted Format: (9) (24)

EMUL (A_1)

Parameters:

A_1 = half-width frequency $R_{0.5}$

Conditions: (7)

$A_1 > 0$

Action:

The frequency domain is multiplied by $D(R)$.

4.4.2.7 PERFECT LENS

Transfer Function:

$D(R) =$

$$\begin{cases} \frac{2}{\pi}\left[\cos^{-1}\frac{R}{R_A} - \frac{|R|}{R_A}\sqrt{1 - \left(\frac{R}{R_A}\right)^2}\right] & \text{if } A_2 = A_3 = 0 \\ \frac{4}{\pi}\int_0^{1 - \frac{|R|}{R_A}} J_o\left(\frac{\pi z_1 R}{\kappa} x\right)\sqrt{1 - \left(x - \frac{|R|}{R_A}\right)^2}\cos\left(\frac{\pi z_o R}{\kappa} x\right) dx & \end{cases}$$

Permitted Formats: (9) (24)

PERF (A_1, A_2, A_3)

PERF (A_1, A_2) where $A_3 = 0$, by implication

PERF (A_1) where $A_2 = A_3 = 0$, by implication

Parameters:

A_1 = cutoff frequency R_A

$A_2 = \frac{z_o}{\kappa}$, $A_3 = \frac{z_1}{\kappa}$ where z_o = defocusing

z_1 = amplitude of longitudinal vibration

$$\kappa = \frac{0.5}{(\text{numerical aperture})}$$

Conditions: (7)

$A_1 > 0$

$A_3 \geq 0$

Note: If either defocusing or longitudinal vibrations are present ($A_2 \neq 0$ or $A_3 \neq 0$, or both), the user must insure that one of the ten tables available to the program is left unused (21). If, within one job, identical values for A_2 and A_3 appear repeatedly in the same or another PERFECT LENS statement, only one table must be left unused. The table will be used by the program to store the corresponding modulation transfer function.

Action:

The frequency domain is multiplied by D(R).

4.4.2.8 SCANNING

Transfer Function:

$$D(R) = s.nc\ (\pi s R)$$

Permitted Format: (9)(24)

SCAN (A_1)

Parameters:

A_1 = slit width s

Conditions: (7)

$A_1 \geqq 0$

Action:

The frequency domain is multiplied by D(R).

4.4.2.9 OPTICAL TRANSFER FUNCTION TABLES

Transfer Function:

$$D(R) = M(R)\,e^{i\theta(R)}$$

Permitted Formats: (9) (24)

OPTI (A_1, A_2, A_3)

OPTI (A_1, A_2) where $A_3 = 0$, by implication

Parameters:

A_1 = cutoff frequency

A_2 = table number for modulation transfer function table $M(R)$

A_3 = table number for phase transfer function table $\theta(R)$

$A_2 = 0$ means there is no modulation transfer function table

$A_3 = 0$ means there is no phase transfer function table

Conditions: (7)

$A_1 > 0$

$A_2 = 0, 1, \ldots, 10$
$A_3 = 0, 1, \ldots, 10$ } where only the integer portions of A_2, A_3 are used if they are specified as nonintegers.

At least one of the table numbers A_1, A_2 must be unequal to 0 (23).

Action:

The complex representation of the frequency domain is multiplied by $M(R)\,e^{i\theta(R)}$.

4.4.2.10 SPREAD FUNCTION TABLE

Transfer Function:

$$D(R) = \frac{\int_{-\frac{W}{2}}^{+\frac{W}{2}} A(x)\,e^{-2\pi iRx}\,dx}{\int_{-\frac{W}{2}}^{+\frac{W}{2}} A(x)\,dx}$$

Permitted Format: (9) (24)

SPRE (A_1, A_2)

Parameters:

A_1 = table number for line spread function table $A(x)$

A_2 = width of spread function W

Conditions: (7)

$A_1 = 1, 2, \ldots, 10$ where only the integer portion of A_1 is used if A_1 is specified as a noninteger.

$A_2 > 0$

Note: If $A(x)$ is not an even function, the user must insure that one of the ten tables available to the program is left unused and is available for storage of the imaginary part of $D(R)$. If, within one job, identical values for A_1 (i.e., identical table numbers) appear repeatedly as parameters of the spread function table, referring to the same noneven spread function table, it suffices if one table is left unused.

Action:

The complex representation of the frequency domain is multiplied by D(R).

Note that the cutoff of D(R) is given by $20/A_2$.

4.4.2.11 MAGNIFICATION

Permitted Format: (9) (24)

MAGN (A_1)

Parameters:

$$A_1 = \frac{\text{(image size)}}{\text{(object size)}}$$

Conditions: (7)

$A_1 > 0$

Action:

For periodic inputs, the fundamental frequency F is divided by A_1. For aperiodic inputs, the width of the space domain is multiplied by A_1. If the user has not executed the option of specifying the width of the space domain in the input statement, the new width is adjusted to the next higher value in the set

$$\{10^k,\ 2 \times 10^k,\ 5 \times 10^k\},$$

where k is an integer. Then, the space domain is again filled according to the new adjusted width.

4.4.3 NONLINEAR COMPONENT STATEMENTS

4.4.3.1 NONLINEAR FUNCTION

Permitted Format: (9) (24)

NONL (A_1)

Parameters:

A_1 = table number of table specifying F(u)

Conditions: (7)

$A_1 = 1, \ldots, 10$ where only the integer portion of A_1 is used if A_1 is specified as a noninteger

Action:

The space domain is transformed according to F(U), with the use of interpolation and extrapolation. The function F(u), which the user can specify only within a finite abscissa range, is continued outside of this range and is assumed to be constant there. For arguments smaller than the specified range, F(u) is assumed to be equal to the left-most ordinate. For arguments greater than the specified range, F(u) is assumed to be equal to the right-most ordinate. Within the range of the table, linear or third order polynomial interpolation is applied, depending upon the interpolation code included on the referenced TABLE card. Third order interpolation is applied only to inner intervals. The intervals between the first and the second table points and between the next-to-last and the last table points are always interpolated linearly.

4.4.3.2 CHARACTERISTIC CURVE (H&D CURVE)

Permitted Formats: (9) (24)

CHAR (A_1, A_2, A_3)

CHAR (A_1, A_2) where $A_3 = 0$, by implication

CHAR (A_1) where $A_2 = A_3 = 0$, by implication

Parameters:

A_1 = table number of table specifying F(u)

A_2 = working point u_o

A_3 = code

Conditions: (7)

$A_1 = 1, \ldots, 10$ where only the integer part of A_1 is used if A_1 is specified as a noninteger.

Action:

The space domain is transformed according to

$$F\left(u_o + \log_{10}\frac{u(x)}{u_m}\right)$$

where

$$u_m = \begin{cases} 1 \text{ if } A_3 = 0 \\ \max\{u(x)\} \text{ if } A_3 > 0 \\ \min\{u(x)\} \text{ if } A_3 < 0 \\ 1 \text{ if } A_3 < 0 \text{ and } \min\{u(x)\} = 0 \end{cases}$$

If the program finds negative values of u(x), the absolute value |u(x)| is taken. If u(x) is found zero, $\log_{10}(u(x)/u_m)$ is taken to be -100. In each case, a warning is printed and the program proceeds.

If $A_3 < 0$, the user must be aware that u_m may be set equal to a very small number, which shifts the exposure of the interesting part of the space domain so far to the right that it may fall outside the range of the specified characteristic curve.

The function $F(u)$, which the user can specify only within a finite abscissa range, is continued outside of this range and is assumed to be constant there. For arguments smaller than the specified range, $F(u)$ is assumed to be equal to the left-most ordinate. For arguments greater than the specified range, $F(u)$ is assumed to be equal to the right-most ordinate. Within the range of the table, linear or third order polynomial interpolation is applied, depending upon the interpolation code included on the referenced TABLE card. Third order interpolation is applied only to inner intervals. The intervals between the first and the second table points and between the next-to-last and the last table points are always interpolated linearly.

4.4.3.3 DENSITY-TO-TRANSMITTANCE CONVERSION

Permitted Format: (5)

DENS

Action:

The space domain is transformed according to $10^{-u(x)}$.

4.4.3.4 TRANSMITTANCE-TO-DENSITY CONVERSION

Permitted Format: (5)

TRAN

Action:

The space domain $u(x)$ is transformed according to $-\log_{10} u(x)$. If negative values of $u(x)$ are found, $|u(x)|$ is taken. If $u(x)$ is found to be 0, $\log_{10} u(x)$ is taken to be -100. In either case, a warning is printed and the program proceeds.

4.4.4 INTERMEDIATE STORAGE STATEMENTS

4.4.4.1 SAVE

Permitted Format: (5)

SAVE

Action:

The present state of the simulation is saved. No nesting is allowed: thus, the next SAVE statement cannot be used before a PICKUP statement has been encountered.

4.4.4.2 PICKUP

Permitted Format: (5)

PICK

Action:

Program restarts simulation from the state saved by the most recent SAVE statement. The user must ensure that PICKUP has been preceded by a SAVE statement: there is no program check on this condition. The PICKUP statement may be applied repeatedly. It will always initiate restarting the simulation from the state saved by the most recent SAVE statement.

4.4.5 OUTPUT STATEMENTS

4.4.5.1 PRINT SPACE

Permitted Formats: (9)

PRINTSP (A_1)

PRINTSP where $A_1 = 0$, by implication

Parameters:

A_1 = print number, truncated by program to a 6-digit integer.

Conditions: (7)

$A_1 \geq 0$

Action:

For periodic inputs, the numerical values of 200 equi-distant points (abscissa and ordinates) of the momentary state of the space domain, extending over one period, are printed. For aperiodic inputs, the same action is taken over one of the artificially created periods. (See paragraph 3.2.)

4.4.5.2 PRINT FREQUENCY

Permitted Formats: (9)

PRINTFR (A_1)
PRINTFR where $A_1=0$, by implication

Parameters:

A_1 = print number, truncated by program to 6-digit integer.

Conditions: (7)

$A_1 \geq 0$

Action:

For periodic inputs, both the modulus and phase and the real and imaginary parts of up to 100 of the complex coefficients a_ν of the Fourier series expansion of the space domain u(x) are printed

$$u(x) = \bar{u}\left\{\sum_{\nu=-\infty}^{+\infty} a_\nu e^{-2\pi i \nu F x}\right\} \quad \text{with } a_o = 1$$

F is the present fundamental frequency in the space domain. For aperiodic inputs, both modulus and phase and real and imaginary parts of up to 100 equidistant sampling points of the complex Fourier transform a(R) of the space domain u(x) are printed. The spacing of the sampling points is equal to 1/ (present width of space domain). Note that the background B is separated from u(x) before a(R) is calculated:

$$u(x) = B + \bar{u}\int_{-\infty}^{+\infty} a(R)e^{2\pi i R x}\, dR \quad \text{with } a(0) = 1$$

where $\bar{u}$ is the mean above the background. The background B is calculated as the arithmetic mean of the ordinates at both ends of the space domain.

For both periodic and aperiodic inputs, the printing is terminated if the modulus is consistently smaller than 10^{-4}. If the space domain is represented by an even function, printing of phase and imaginary part is suppressed.

4.4.5.3 PLOT SPACE

Permitted Formats: (9)

PLOTSPA (A_1)
PLOTSPA where $A_1 = 0$, by implication

Parameters:

A_1 = plot number, truncated by program to 6-digit integer

Conditions: (7)

$A_1 \geq 0$

Action:

The plotting action corresponds to the action taken by the PRINT SPACE statement. If $A_1 = 0$, no plot number is plotted.

4.4.5.4 PLOT FREQUENCY

Permitted Formats: (9)

PLOTFRE (A_1)
PLOTFRE where $A_1 = 0$, by implication

Parameters:

A_1 = plot number, truncated by program to 6-digit integer

Conditions: (7)

$A_1 \geq 0$

Action:

For periodic inputs, the modulus and phase of the first 50 complex coefficients a_ν of the Fourier series expansion of the space domain u(x) are plotted. Rather than connecting the ordinate by a continuous line, individual values of the Fourier coefficients are plotted as spikes over the spatial frequency axis. For aperiodic inputs, the modulus and phase of 100 equidistant sampling points of the complex Fourier transform a(R) of the space domain u(x) are plotted. The spacing of the sampling points is equal to 1/(present width of space domain). Note that the constant background is subtracted from the space domain before the Fourier transform is determined (see PRINT FREQUENCY statement). For either periodic or aperiodic inputs, if the space domain is represented by an even function, plotting the phase is suppressed. If $A_1 = 0$, no plot number is plotted.

4.4.5.5 PLOT REAL FREQUENCY

Permitted Formats: (9)

PLOTREA (A_1)
PLOTREA where $A_1 = 0$, by implication

Parameters:

A_1 = plot number, truncated by program to 6-digit integer.

Conditions: (7)

$A_1 \geq 0$

Action:

For periodic inputs, real and imaginary parts of the first 50 complex coefficients a_ν of the Fourier series expansion of the space domain u(x) are plotted. Rather than connecting the ordinates by a continuous line, individual values of the Fourier coefficients are plotted as spikes over the spatial frequency axis. For aperiodic inputs, real and imaginary parts of 100 equidistant sampling points of the complex Fourier transform a(R) of the space domain u(x) are plotted. Note that the constant background is subtracted from the space domain before the Fourier transform is determined (see PRINT FREQUENCY statement). For either periodic or aperiodic inputs, if the space domain is represented by an even function, plotting of the imaginary part is suppressed. If $A_1 = 0$, no plot number is plotted.

The spacing of the sampling points is equal to 1/ (present width of space domain).

4.4.5.6 PLOT COMPONENT

Permitted Formats: (9)

PLOTCOM (A_1)
PLOTCOM where $A_1 = 0$, by implication

Parameters.

A_1 = plot number, truncated by program to a 6-digit integer

Conditions:

$A_1 \geq 0$

Action:

The most recent component characteristic is plotted. If this component is linear, its optical transfer function is plotted. If this component is either a NONLINEAR FUNCTION or a CHARACTERISTIC CURVE, F(u) is plotted. MAGNIFICATION, DENSITY-TO-TRANSMITTANCE CONVERSION, and TRANSMITTANCE-TO-DENSITY CONVERSION as well as all intermediate storage and output blocks are ignored during the search for the most recent component.

4.5 TABLE CARDS

TABLE cards must be used to provide tabulated functions to the simulation program. They follow the block cards and precede the END card or the next JOB card. (See paragraph 4.2.) There is space available for 10 tables, numbered 1 through 10. The table numbers link the tables to the INPUT statement or the COMPONENT statements using the tables. If several tables are present, they may appear in any sequence. No table number may appear more than once (8). Each table called by an INPUT or a COMPONENT statement must be present (4); each present table must be called for at least once (8).

Each table consists of one or several cards. Ignoring blanks, the first card must begin with:

TABLE (A_1, A_2)

where A_1 = table number

$$A_2 = \begin{cases} 1 \text{ if linear} \\ 3 \text{ if third order} \end{cases} \text{ interpolation is requested for this table (13)}$$

If A_1 is a noninteger, it is truncated, and only the integer portion is retained by the program as A_1. A_1 must be 1, 2, . . . , 9, 10 (8). The abscissa and ordinate values of the table are provided in form of couples (9)

(x_i, y_i)

where x_i is the abscissa and y_i is the corresponding ordinate. The A_1, A_2, x_i and y_i are signed or unsigned decimal numbers or integers. They must be separated by a comma and enclosed in parentheses (6) (10). Other symbols within the parentheses are not permitted (10).

The set of couples must appear in sequence of nondecreasing x_i. They may start on the TABLE card following (A_1, A_2), or they may start on the next card. As many cards as required may be used for each table. One individual couple must not be split by the end of one card. There must be at least two and not more than 51 couples per table (12). There are a number of restrictions on the values of the couples. The restrictions are stated below in relation to the calling INPUT or COMPONENT statement. It is assumed that N couples are supplied by the user, where $2 \leq N \leq 51$.

4.5.1 PERIODIC INPUT TABLE

Called by:

PERIODIC TABLE input block

Conditions:

$x_N - x_1 = 1$	(14)	(The actual value of the width of the period is provided as a parameter of the calling statement.)
$x_1 < x_2$	(14)	
$x_{N-1} < x_N$	(14)	
$x_i \leq x_{i+1}$	(14)	for i = 2, . . . , (N-2). However, no more than two successive couples may have the same abscissa (14). Permission of equal abscissas for two consecutive couples allows specification of functions exhibiting a finite jump.
$y_i \geq 0$	(15)	for i = 1, . . . , N.

4.5.2 APERIODIC INPUT TABLE

Called by:

APERIODIC TABLE input block

Conditions:

$x_N - x_1 = 1$ (14) (The actual value of the width of the input function is provided as a parameter of the calling statement).

$x_i \leq x_{i+1}$ (14) for i = 1, . . . , (N-1). However, no more than two successive couples may have the same abscissa (14). Permission of equal abscissas for two consecutive couples allows specification of function, exhibiting a finite jump.

$y_1 = y_N = 0$ (15)

4.5.3 OPTICAL TRANSFER FUNCTION TABLES

Called by:

OPTICAL TRANSFER FUNCTION TABLE
linear-component block

Conditions:

$x_N - x_1 = 1$ (14) (The actual frequency range of the table is provided as a parameter of the calling statement.)

$x_1 = 0$ (14)

$x_i \leq x_{i+1}$ for i = 1, . . . , (N-1). However, no more than two successive couples may have the same abscissa (14). Permission of equal abscissas for two consecutive couples allows specification of functions exhibiting a finite jump.

Note: If the table represents a phase transfer function, ordinates must represent the phase values in radians.

4.5.4 LINE SPREAD FUNCTION TABLE

Called by:

SPREAD FUNCTION TABLE linear-component block

Conditions:

$x_N - x_1 = 1$	(14)	(The actual width of the spread function is provided as a parameter of the calling statement.)
$x_i \leq x_{i+1}$		for i = 1, . . . , (N-1). However, no more than two successive couples may have the same abscissa (14). Permission of equal abscissas for two consecutive couples allows specification of functions exhibiting a finite jump.
$y_1 = y_N = 0$	(15)	
$y_i \geq 0$	(15)	for i = 2, . . . , (N-1).

Note: It is the user's responsibility to ensure that there is one unused table available to the program for each SPREAD FUNCTION TABLE, which represents a non-even line-spread function (21). The program needs this unused table to store the imaginary part of the associated transfer function.

4.5.5 NONLINEAR FUNCTION

Called by:

NONLINEAR FUNCTION nonlinear-component block

Conditions:

$x_i < x_{i+1}$	(14)	for i = 1, . . . , (N-1).

4.5.6 CHARACTERISTIC CURVE (H & D CURVE)

Called by:

CHARACTERISTIC CURVE nonlinear-component block

Conditions:

$x_i < x_{i+1}$	(14)	for i = 1, . . . , (N-1).
$y_i \geq 0$	(15)	for i = 1, . . . , N.

4.6 REPEAT RUNS WITH VARIED PARAMETERS

As described in paragraph 2.6, the design of the program allows the simulation to be repeated completely or in part, while some parameters are varied. It is possible to specify up to 11 sets of parameters for one block (18). Each set is enclosed in parentheses, and all sets applicable to one block must be punched on that particular block card. The parameter sets must follow the rules and restrictions stated in paragraph 4.4. The input block and an additional 10 blocks may be used with varied parameters (19).

In order to indicate single-path branching (see paragraph 2.6), the letters SP must follow the last set of parameters on the applicable block card. If SP branching is specified on a block card, the branch at the input to this block occurs in parallel with the first branch of the job (which may be on the input card). Within one job, all component cards with SP branching must have the same number of branches as the first branch point (22). Fan branching (paragraph 2.6) may be indicated by the letters FAN. Omission of any code on a block card with several parameter sets implies fan branching. Only 5 fan branch points are permitted in each job (20).

4.7 ERROR MESSAGES

If the user supplies invalid information or parameter values to the simulation program, one or more error messages may be printed. All error messages suppress execution of the actual simulation; however, the error scan continues unless the error message specifically states otherwise. Encircled numbers have been used in paragraphs 4.2 through 4.6 to indicate which error messages will be printed if a stated condition is not met. The messages are as follows:

(1) ILLEGAL INPUT DESCRIPTION

(2) NO COMPONENT

(3) TOO MANY COMPONENTS
ERROR SCAN STOPS

(4) TABLE NUMBER XX MISSING

(5) ILLEGAL SYMBOL ON CARD

(6) NO CLOSING PARENTHESIS

(7) ILLEGAL PARAMETER VALUE

(8) ILLEGAL TABLE NUMBER

(9) ILLEGAL NUMBER OF PARAMETERS

(10) ILLEGAL SYMBOL IN PARAMETER FIELD OR NO CLOSING PARENTHESIS

(11) ILLEGAL COMPONENT DESCRIPTION

(12) ILLEGAL NUMBER OF TABLE POINTS IN TABLE NUMBER XX
ERROR SCAN STOPS

(13) ILLEGAL INTERPOLATION CODE IN TABLE NUMBER XX

(14) ILLEGAL ABSCISSA IN TABLE NUMBER XX

(15) ILLEGAL ORDINATE IN TABLE NUMBER XX

(16) NO JOB CARD

(17) NO TABLE CARD OR NO END CARD OR NO JOB CARD

(18) TOO MANY BRANCHES

(19) TOO MANY BRANCH POINTS
ERROR SCAN STOPS

(20) TOO MANY FAN BRANCH POINTS

(21) NUMBER OF TABLES USED EXCEEDS AVAILABLE LIMIT

(22) NOT ENOUGH PARAMETER SETS FOR SINGLE PATH BRANCH

(23) ONE TABLE NUMBER MUST BE UNEQUAL TO ZERO

(24) REQUIRED PARAMETER(S) MISSING

SECTION V

EXAMPLES

5.1 GENERAL FEATURES

The simple example of a camera (figure 4) was chosen to show some of the features of IMSIM/1. Assume that we want to simulate a

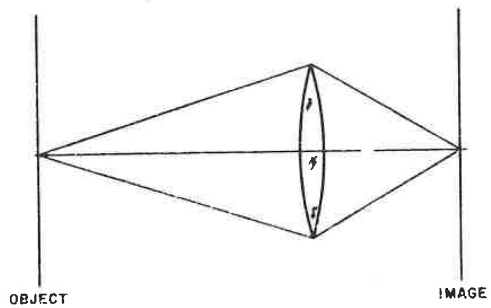


Figure 4.

camera system using, as an object (input), a 3-bar target having a background density of 1.5 and a density of .1 for the transparent lines. We want to know what the image looks like for the following values of the line frequency: 5, 10, and 20 lines/mm. The lens ($F_{\#}$ = 8) which images the target with a reduction of 10:1 onto a photographic emulsion, is assumed to be diffraction limited. For the light spread within the emulsion, a modulation transfer function as suggested by Frieser[10], with a half-width frequency of 100 cycles/mm, is used. The characteristic curve (H & D curve) is shown in figure 5. The exposure is set so that the background density of the image is always equal to .1 (arrow in figure 5).

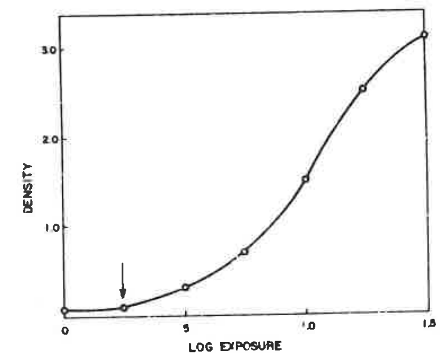


Figure 5.

The set of IMSIM statements describing the desired simulation is shown in figure 6.

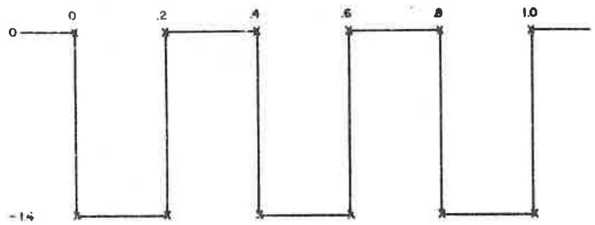
```
   JOB 1     CAMERA EXAMPLE (RESOLUTION OF 3-BAR TARGET)


APERIODIC TABLE  (1,.5,1.5) (1,.25,1.5) (1,.125,1.5)  EVEN
   PLOT SPACE (1) (2) (3)  SP
DENSITY TRANSMITTANCE CONVERSION
MAGNIFICATION  (.1)
PERFECT LENS  (250)
EMULSION SPREAD  (100)
CHARACTERISTIC CURVE (2,.25,-1)
   PLOT SPACE (12) (22) (32)  S P
TABLE (1,1)  (0,0) (0,-1.4) (.2,-1.4) (.2,0) (.4,0) (.4,-1.4)
             (.6,-1.4) (.6,0) (.8,0) (.8,-1.4) (1,-1.4) (1,0)
TABLE (2,3)  (0,.08) (.25,.1) (.5,.27) (.75,.69) (1,1.47)
             (1.25,2.5) (1.5,3.14)
END
```

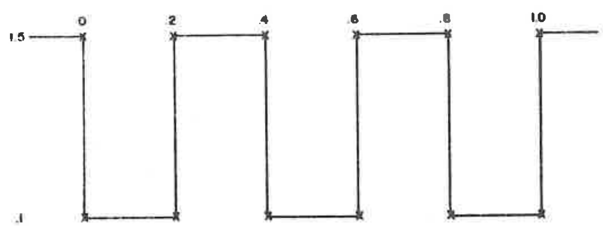
Figure 6.

With the APERIODIC TABLE statement, we request a tabulated aperiodic function as input. The first value of each parameter set indicates that the input function is tabulated in TABLE 1. The second and third parameter values represent table width and background.

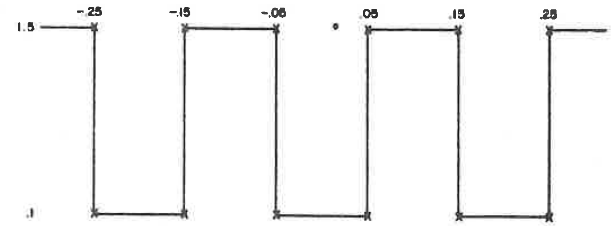
Referring to the TABLE card, we see that TABLE 1 is linearly interpolated, as determined by the interpolation code 1, which is the second parameter value in the parenthesis immediately following the word TABLE. The input function is of the form:



The abscissa range for the table must be equal to 1. We arbitrarily chose the range from 0 to 1, so that the center is at x = 0.5. The following set of data couples for TABLE 1 would have had the exact same result for the simulation: (-.5, 0) (-.5, -1.4) (-.3, -1.4) (-.3, 0) (-.1, 0) (-.1, -1.4) (.1, -1.4) (.1, 0) (.3, 0) (.3, -1.4) (.5, -1.4) (.5, 0). The APERIODIC TABLE statement specifies a background of 1.5, which must be added to the values provided by TABLE 1 so that we now have:



The second parameter of the APERIODIC TABLE statement specifies a width of .5 for the table. This width, combined with the data provided by TABLE 1, produces an input function which has the following final form:



This function represents a 3-bar target centered at x = 0 with background density 1.5 and a density at the transparent line of .1. The line frequency is 5 lines/mm. (Note that we use 1 mm as length unit, which we now must apply to all following statements within this job.) The three sets of parameters will give rise to three simulation runs. The word EVEN in the APERIODIC TABLE statement indicates that TABLE 1 represents an even function and thus reduces execution time.

After establishing the input, we request plotting of the input target by the PLOT SPACE statement, using the single path branch feature with the code SP. Each of the three output plots (resulting from the three simulation runs initiated by the three input parameter sets) will be numbered differently. If we have omitted the plot numbers and the code SP in the PLOT SPACE statement, we would have obtained the same three plots, but without any plot numbers. Omission of the code SP alone would have been disastrous. The branch would have been executed as a fan branch and, for each of the three simulation runs, we would have obtained three space domain plots, which would have differed only in their plot numbers.

According to figure 4, the component statement following PLOT SPACE should be PERFECT LENS, which designates a linear-component block. The target used in this example is represented by photographic densities. Hence, the densities must be changed into transmittances before use of a linear component is permitted. Therefore, we must first apply the block DENSITY-TRANSMITTANCE CONVERSION.

A diffraction limited lens with $F_{\#} = 8$, assuming 0.5×10^{-3} mm for the wavelength of the light, has a cutoff frequency equal to 250 lines/mm for imaging into the focal plane. A reduction of 10:1 means that the image plane is fairly close to the focal plane. Hence, PERFECT LENS statement gets the parameter value 250. However, we must first apply the component MAGNIFICATION (.1), which reduces the size of the input target into the size applicable in the image plane of the lens.

Exchanging the sequence of the two statements, MAGNIFICATION and PERFECT LENS, and substituting 25 for 250 as cutoff frequency of the latter, would result in the same simulation. MAGNIFICATION can also be moved further towards the top of the set of statements, and can even be omitted entirely if the width parameters of the tabulated functions are adjusted accordingly. We list the five alternatives, all resulting essentially in the same simulation:

```
(a)   APERIODIC TABLE (1, .5, 1.5)...
      PLOT SPACE (1)...
      DENSITY TRANSMITTANCE CONVERSION
      MAGNIFICATION (.1)
      PERFECT LENS (250)
        :

(b)   APERIODIC TABLE (1, .5, 1.5)...
      PLOT SPACE (1)...
      DENSITY TRANSMITTANCE CONVERSION
      PERFECT LENS (25)
      MAGNIFICATION (.1)
        :

(c)   APERIODIC TABLE (1, .5, 1.5)...
      PLOT SPACE (1)...
      MAGNIFICATION (.1)
      DENSITY TRANSMITTANCE CONVERSION
      PERFECT LENS (250)
        :

(d)   APERIODIC TABLE (1, .5, 1.5)...
      MAGNIFICATION (.1)
      PLOT SPACE (1)
      DENSITY TRANSMITTANCE CONVERSION
      PERFECT LENS (250)
        :
```



```
(e)   APERIODIC TABLE (1, .05, 1.5)...
      PLOT SPACE (1)
      DENSITY TRANSMITTANCE CONVERSION
      PERFECT LENS (250)
        :
```

The two statements following PERFECT LENS describe the photographic emulsion. The first, EMULSION SPREAD, approximates the modulation transfer function of the light diffusion in the emulsion by the expression

$$1/(1 + (R/R_{0.5})^2)$$

where $R_{0.5}$ = 100 cycles/mm. Then, CHARACTERISTIC CURVE (H & D curve) accomplishes conversion of the actual exposure into photographic density. The H & D curve is tabulated in TABLE 2. The data couples of this table represent pairs of log exposure and density. The interpolation code 3 signifies third order polynomial interpolation when this table is used by the program. The negative value of the third parameter in the CHARACTERISTIC CURVE statement (its magnitude is irrelevant) indicates that we want the actual exposure adjusted so that its minimum falls at the working point (second parameter). The minimum in our example will be the background. Thus, we achieve the desired background density of .1 for the image.

Finally, we request plotting of the image by PLOT SPACE, again using the single path feature.

Figure 7 shows the sequence of output plots resulting from the statements in figure 6. The execution time was 27 seconds. The ordinates in all plots represent photographic densities. The length unit L.U. is equal to 1 mm. The background of the image is equal to 0.1, as we requested. Note that the plots of the input targets are not exactly vertical at the borders of the lines, as was requested in TABLE 1. The reason for this is a practical one. Because ultimately we want to perform Fourier transformations, the program assumes the arithmetic mean at points of discontinuities of this kind in the space domain. This is reasonable, because it is exactly the way in which such discontinuities are represented by the Fourier transform.

If the space domain here were not taken from the aperiodic table representation, but were calculated from its necessarily truncated Fourier representation, the well-known Gibbs phenomenon would

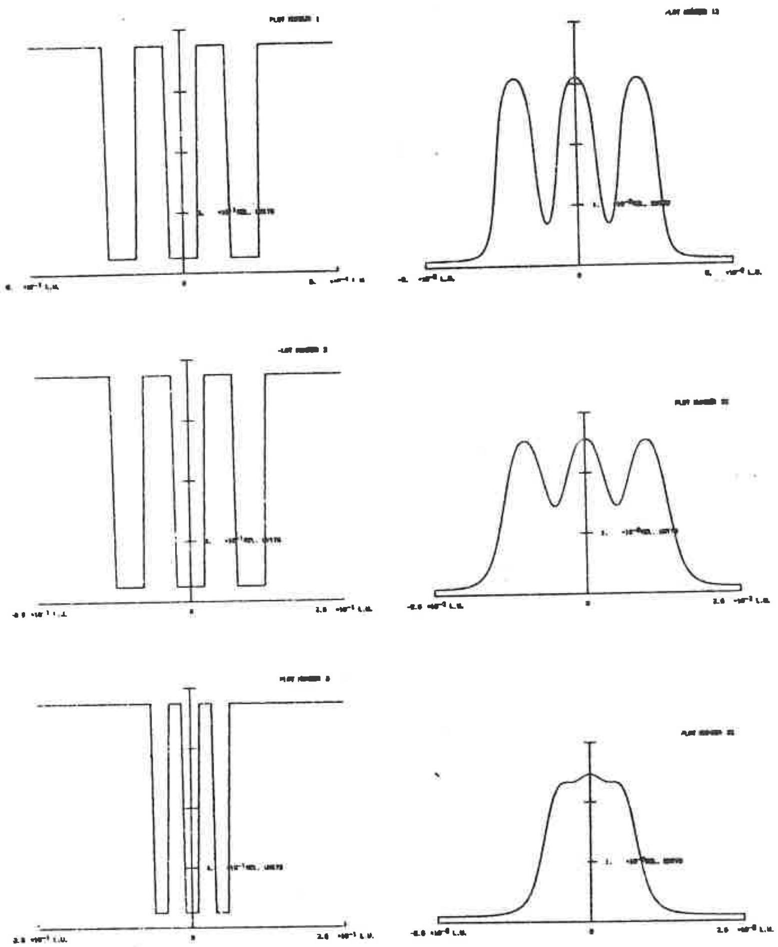


Figure 7.

appear. In order to suppress it, the method of Lanczos' σ-factors[15] is employed (see paragraph 5.7).

Figure 7 shows that the target with a line frequency of 20 lines/mm is not resolved by the system. To determine whether this failure of resolution is caused by the lens or the photographic emulsion, we add a PLOT SPACE statement between PERFECT LENS and EMULSION SPREAD. Also, since we would like to see all three runs using the same width of the space domain, we make use of the fourth parameter of APERIODIC TABLE. In the previous run this parameter was omitted. It was implied to be zero, and the program calculated separately the applicable initial width of the space domain for each input parameter set. Now we choose the largest of these three values, 1 mm, and apply it as fourth parameter to each of the inputs. Figure 8 shows the new set of statements, which produces the sequence of output plots shown in figure 9. All plots of the space domain have the desired width of 1 mm for the input and .1 mm for the intermediate and final images. It becomes apparent that, for the case of the 20 lines/mm target, the degradation caused by the lens alone is considerable, but that the emulsion is the component that destroys the resolution entirely.

```
    JOB 10   CAMERA EXAMPLE (RESOLUTION OF 3-BAR TARGET)

APERIODIC TABLE (1,.5,1.5,1)  (1,.25,1.5,1)  (1,.125,1.5,1)   EVEN
   PLOT SPACE (1) (2) (3)  SP
DENSITY TRANSMITTANCE CONVERSION
MAGNIFICATION  (.1)
PERFECT LENS  (250)
   PLOT SPACE (11) (21) (31)  S P
EMULSION SPREAD   100)
CHARACTERISTIC CURVE (2,.25,-1)
   PLOT SPACE (12) (22) (32)  S P
TABLE (1,1)  (0,0) (0,-1.4) (.2,-1.4) (.2,0) (.4,0) (.4,-1.4)
             (.6,-1.4) (.6,0) (.8,0) (.8,-1.4) (1,-1.4) (1,0)
TABLE (2,3)  (0,.08) (.25,.1) (.5,.27) (.75,.69) (1,1.47)
             (1.25,2.5) (1.5,3.14)
END
```

Figure 8.

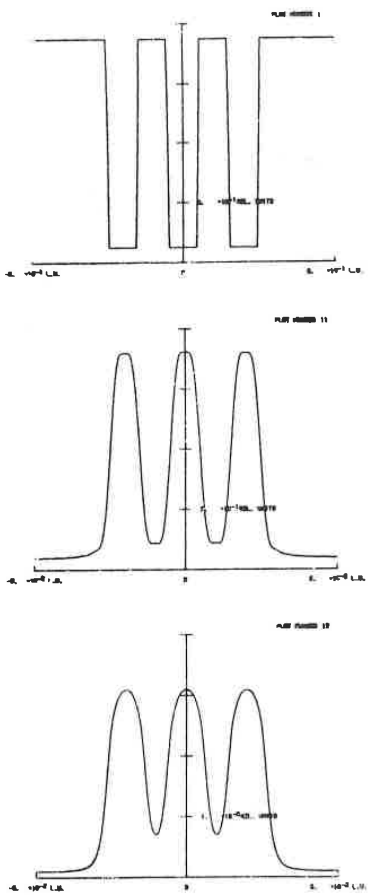


Figure 9a.

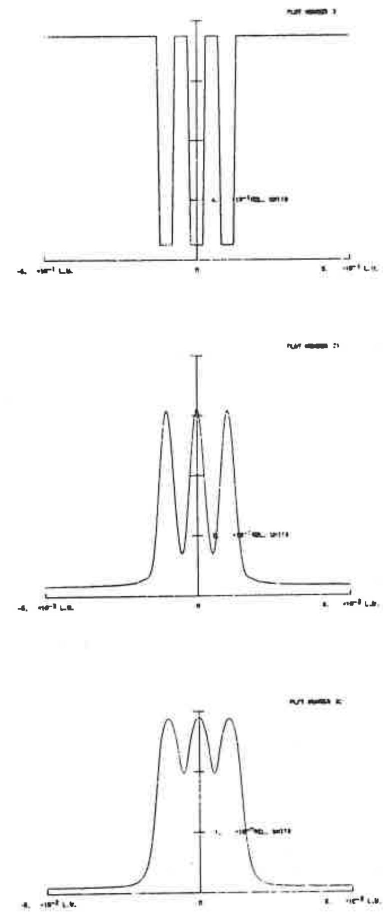


Figure 9b.

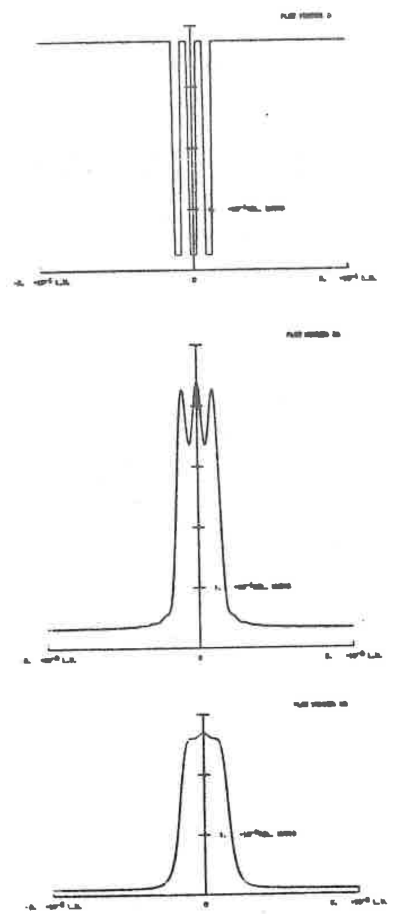


Figure 9c.

5.2 LINEAR IMAGE MOTION

In this example we want to demonstrate how accurately the simulation program calculates the space domain representation from its Fourier transform. We will also illustrate the use of the component LINEAR IMAGE MOTION. We request as input a slit, having a width of 1.5 and representing an intensity of 1 above the background of .2 relative units. After plotting this slit, we apply LINEAR IMAGE MOTION followed by another PLOT SPACE statement. We choose the amount of motion equal to the width of the slit.

Figure 10 shows the set of statements and figure 11 shows the sequence of output plots. The result of the image motion must be a

```
JOB 2     DEMONSTRATION OF LINEAR IMAGE MOTION


SLIT  (1.5,1.2,.2)
   PLOT SPACE
LINEAR IMAGE MOTION  (1.5)
PLCT SPACE
E N D
```

Figure 10.

triangle with base 3 and maximum ordinate 1 above background. Note that this triangle is created from its Fourier transform because, according to the design of the simulation program, the LINEAR IMAGE MOTION statement initiates multiplication of the Fourier transform of the input (slit) with the appropriate transfer function [here sinc (πdR)], thus destroying the original representation of the space domain. The space domain is recreated from its Fourier transform when PLOT SPACE is requested after execution of the motion.

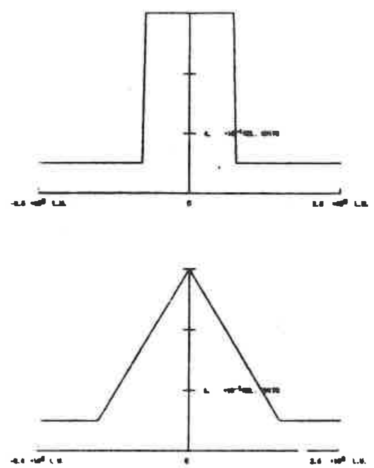


Figure 11.

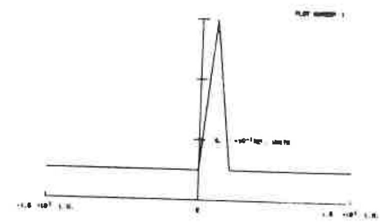
5.3 FOURIER TRANSFORMATION

Assume that we ask for the Fourier transform of the triangle produced as the result of the previous example. Figure 12 shows the statements required as well as the output plots produced. The triangle had a base of 3, was centered at $x = 0$, and its maximum was 1 relative unit above the background of 0.2 relative units. When asking for the Fourier transform, however, we do not want the triangle centered, but want it shifted to the right so that its left corner is located at $x = 0$. To represent this input, we use APERIODIC TABLE. In the data couples of TABLE 1 we recognize the triangle, shifted off center.

To obtain the desired base length of 3, the total width of the table (second parameter value of input statement) must be set equal to 6. To represent the total input, the table ordinates are added to the background of 0.2 (third parameter). Finally, the fourth parameter indicates that we want the space domain to have a width of 30. We use the option of specifying the width of the space domain in order to have control over the cutoff frequency in the frequency domain. Remember,


```
JOB 3  FOURIER TRANSFORM OF TRIANGLE (OFF CENTER)

APERIODIC TABLE (1,6,.2,30)
   PLOT SPACE (1)
   PLOT FREQUENCY (2)
   PRINT FREQUENCY
TABLE (1,1)  (0,0) (.5,0) (.75,1) (1,0)
E N D
```



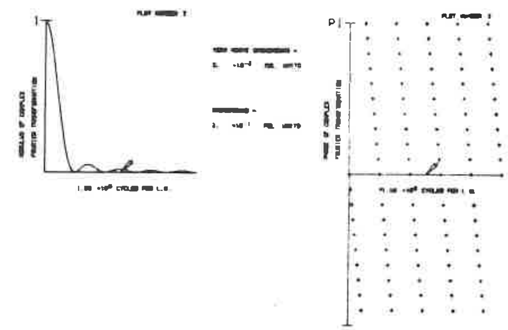


Figure 12.

the simulation program is designed so that a Fourier transformation is always taken such that the cutoff frequency is equal to 100 times the reciprocal of the space domain. We recognize that, for a triangle with base b, the modulus of the Fourier transform is equal to

$$\text{sinc}^2\left(\frac{\pi b R}{2}\right).$$

It should be noted that, for aperiodic input functions such as is the case here, the represented Fourier transform is taken only from the function above the background. The value of the background is indicated separately. Also, the Fourier transform is normalized such that it is equal to 1 for zero frequency. Hence, if one wants to obtain the space function from the frequency representation, the following procedure is necessary:

(a) Calculate Fourier transform from the frequency domain representation.

(b) Multiply the so obtained space function by the value "MEAN ABOVE BACKGROUND."

(c) Add the value "BACKGROUND" to the product obtained in step (b).

This procedure also holds for the numerical output print of the frequency domain which is shown in figure 13.

The shift of the triangle off center by the amount b/2 gives rise to the appearance of a linear phase function equal to $-\pi bR$. Notice that these results have been obtained using a numerical procedure. When plotting a phase function, individual sampling points are plotted rather than a continuous line. Thus, we avoid ambiguity which would arise if two sequential points, separated by essentially a phase jump of 2π, would be connected by a continuous line.

In order to demonstrate again the precision with which the employed numerical procedures operate, we want to shift the triangle back into the center of the space domain. We use the OPTICAL TRANSFER FUNCTION TABLE statement (figure 14). By setting the second parameter equal to zero, and the third equal to 2, we request TABLE 2 to be a phase transfer function. As we see from the previous plot, the cutoff in the frequency domain is 3.33 cycles/L. U. Hence, we use this value as first parameter. To achieve the desired shift, we use the fact that a linear phase function $2\pi sR$ gives rise to a shift by the amount s to the left. Here, we want s to be equal to 1.5.

JOB 1

FREQUENCY DOMAIN

PRINT NO. 0

NORMALIZED FOURIER INTEGRAL OF SPACE DOMAIN ABOVE BACKGROUND

BACKGROUND = 0.200E-00 REL. UNITS   MEAN ABOVE BACKGROUND = 0.500E-01 REL. UNITS

SPAT. FREQ. (CYCLES/L.U.)	MODULUS	PHASE (RADIANS)	PHASE (DEGREES)	REAL PART	IMAGINARY PART
0.	1.0000	-0.	-0.	1.0000	-0.
0.0333	0.9919	-0.3142	-18.0001	0.9433	-0.3065
0.0667	0.9679	-0.6283	-36.0001	0.7830	-0.5689
0.1000	0.9288	-0.9425	-54.0001	0.5459	-0.7514
0.1333	0.8763	-1.2566	-72.0002	0.2708	-0.8334
0.1667	0.8122	-1.5708	-90.0002	-0.0000	-0.8122
0.2000	0.7390	-1.8850	-108.0002	-0.2284	-0.7029
0.2333	0.6593	-2.1991	-126.0003	-0.3875	-0.5334
0.2667	0.5758	-2.5133	-144.0003	-0.4658	-0.3385
0.3000	0.4914	-2.8274	-162.0003	-0.4673	-0.1518
0.3333	0.4086	3.14	179.9996	-0.4086	0.0000
0.3667	0.3300	2.82	161.9996	-0.3139	0.1020
0.4000	0.2576	2.5133	143.9996	-0.2084	0.1514
0.4333	0.1931	2.1991	125.9996	-0.1135	0.1562
0.4667	0.1375	1.8849	107.9996	-0.0425	0.1308
0.5000	0.0917	1.5708	89.9996	0.0000	0.0917
0.5333	0.0559	1.2566	71.9996	0.0173	0.0531
0.5667	0.0296	0.9425	53.9996	0.0174	0.0239
0.6000	0.0123	0.6283	36.0000	0.0099	0.0072
0.6333	0.0028	0.3142	18.0002	0.0027	0.0009
0.6667	0.0000	INDETERMINED		0.0000	0.0000
0.7000	0.0023	-0.3142	-18.0017	0.0022	-0.0007
0.7333	0.0083	-0.6283	-36.0017	0.0067	-0.0049
0.7667	0.0165	-0.9425	-54.0012	0.0097	-0.0133
0.8000	0.0255	-1.2567	-72.0012	0.0079	-0.0242
0.8333	0.0341	-1.5708	-90.0010	-0.0000	-0.0341
0.8667	0.0415	-1.8850	-108.0011	-0.0128	-0.0395
0.9000	0.0469	-2.1991	-126.0010	-0.0276	-0.0379
0.9333	0.0499	-2.5133	-144.0010	-0.0404	-0.0293
0.9667	0.0504	-2.8275	-162.0010	-0.0479	-0.0156
1.0000	0.0485	3.1416	179.9991	-0.0485	0.0000
1.0333	0.0446	2.8274	161.9991	-0.0424	0.0138
1.0667	0.0390	2.5133	143.9992	-0.0315	0.0229
1.1000	0.0323	2.1991	125.9992	-0.0190	0.0262
1.1333	0.0253	1.8849	107.9992	-0.0078	0.0240
1.1667	0.0183	1.5708	89.9996	0.0000	0.0183
1.2000	0.0120	1.2566	71.9998	0.0037	0.0114
1.2333	0.0068	0.9425	54.0000	0.0040	0.0055
1.2667	0.0030	0.6283	36.0017	0.0024	0.0018
1.3000	0.0007	0.3142	18.0043	0.0007	0.0002
1.3333	0.0000	INDETERMINED		0.0000	0.0000
1.3667	0.0007	-0.3143	-18.0063	0.0006	-0.0002
1.4000	0.0025	-0.6284	-36.0044	0.0021	-0.0015
1.4333	0.0053	-0.9425	-54.0021	0.0031	-0.0043
1.4667	0.0085	-1.2567	-72.0034	0.0026	-0.0081
1.5000	0.0119	-1.5708	-90.0013	-0.0000	-0.0119
1.5333	0.0150	-1.8850	-108.0017	-0.0046	-0.0142
1.5667	0.0175	-2.1991	-126.0015	-0.0103	-0.0142
1.6000	0.0193	-2.5131	-144.0013	-0.0156	-0.0113
1.6333	0.0201	-2.8275	-162.0012	-0.0192	-0.0062
1.6667	0.0200	3.1416	179.9989	-0.0200	0.0000
1.7000	0.0189	2.8274	161.9990	-0.0180	0.0058
1.7333	0.0170	2.5133	143.9993	-0.0138	0.0100
1.7667	0.0145	2.1991	125.9995	-0.0085	0.0117
1.8000	0.0116	1.8850	107.9999	-0.0036	0.0111
1.8333	0.0086	1.5708	89.9991	0.0000	0.0086
1.8667	0.0059	1.2566	72.0003	0.0018	0.0055
1.9000	0.0034	0.9425	54.0022	0.0020	0.0027
1.9333	0.0015	0.6284	36.0044	0.0012	0.0009
1.9667	0.0004	0.3143	18.0056	0.0004	0.0001
2.0000	0.0000	INDETERMINED		0.0000	0.0000
2.0333	0.0004	-0.3142	-18.0036	0.0003	0.0001
2.0667	0.0014	-0.6283	-36.0007	0.0011	-0.0008
2.1000	0.0030	-0.9426	-54.0063	0.0017	-0.0024
2.1333	0.0048	-1.2567	-72.0021	0.0015	-0.0046
2.1667	0.0069	-1.5708	-90.0017	-0.0000	-0.0069
2.2000	0.0088	-1.8850	-108.0024	-0.0027	-0.0084
2.2333	0.0105	-2.1991	-126.0018	-0.0062	-0.0085
2.2667	0.0119	-2.5133	-144.0012	-0.0095	-0.0069
2.3000	0.0125	-2.8275	-162.0011	-0.0119	-0.0039
2.3333	0.0126	3.1416	179.9991	-0.0126	0.0000
2.3667	0.0121	2.8274	161.9992	-0.0115	0.0037
2.4000	0.0110	2.5133	143.9995	-0.0089	0.0065
2.4333	0.0095	2.1991	126.0033	-0.0056	0.0077
2.4667	0.0078	1.8850	108.0028	-0.0024	0.0074
2.5000	0.0059	1.5708	90.0037	-0.0000	0.0059
2.5333	0.0040	1.2567	72.0043	0.0012	0.0038
2.5667	0.0024	0.9425	53.9998	0.0014	0.0019
2.6000	0.0011	0.6285	36.0092	0.0009	0.0006
2.6333	0.0003	0.3145	18.0216	0.0003	0.0001

Figure 13.

```
JOB 30 FOURIER TRANSFORM CF TRIANGLE (OFF CENTER) AND SHIFT BY LINEAR PHASE

APERIODIC TABLE (1,6,.2,30)
   PLOT SPACE (1)
   PLOT FREQUENCY (2)
   PRINT FREQUENCY
OPTICAL TRANSF.F. TABLE  (3.333333,,2)
   PLOT COMPONENT (3)
   PLOT SPACE (4)
   PLOT FREQUENCY (5)
TABLE (1,1)  (0,0) (.5,0) (.75,1) (1,0)
TABLE (2,1)  (0,0) (1,+31.41593)
E N D
```

Figure 14.

Hence the ordinate of the table at the cutoff frequency becomes equal to 10π. The two points of TABLE 2 represent the desired function. In figure 15 we show the result of the simulation as obtained from the statements in figure 14. Clearly, after the shift, the triangle is centered at $x = 0$, and there is no phase function present any more.

Notice the results of the use of PLOT COMPONENT statement in figure 15. The requested phase transfer function is plotted; however, the program automatically reduces the ordinates, specified by the table, to the range from $-\pi$ to $+\pi$.

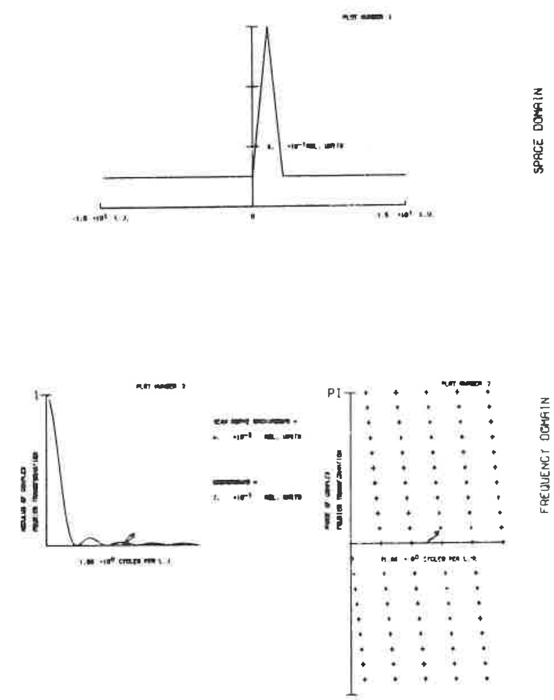


Figure 15a.

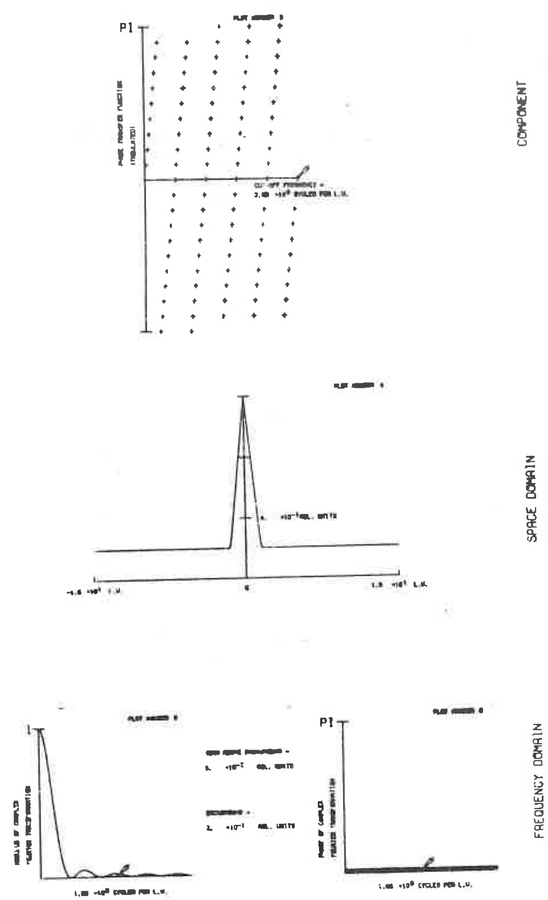


Figure 15b.

5.4 LINE SPREAD FUNCTION OF DIFFRATION LIMITED LENS WITH DEFOCUSING

It is a simple matter to use IMSIM/1 for obtaining plots of the various line-spread functions associated with the linear components of table 2. As an example, we want to show the line-spread function of a diffraction limited lens which is defocused by various amounts. We use the input statement LINE SOURCE, followed by the linear component PERFECT LENS. As in example 1, we chose $F_{\#} = 8$ and the cutoff frequency equal to 250 lines/mm. Assume defocusing to be .1 and .2 mm; hence, the defocusing parameters become equal to .0125 and .025 respectively. The two output statements PLOT COMPONENT and PLOT SPACE result in the graphs shown in figure 16. Each transfer function (COMPONENT) is followed by the corresponding line-spread function (SPACE DOMAIN). Use of single path branching provides convenient numbering of all plots.

Note that, according to the definition of a line-spread function, the ordinates of the space domain plots are such that the area under the line-spread function is always equal to one.

```
JOB 4    LINE SPREAD FUNCTION OF DIFFRACTION LIMITED LENS

LINE SOURCE
PERFECT LENS   (250) (25C,.0125) (250,.025)
   PLOT COMPONENT (1) (3) (5) SP
   PLOT SPACE (2) (4) (6)  SP
E N D
```

Figure 16a.

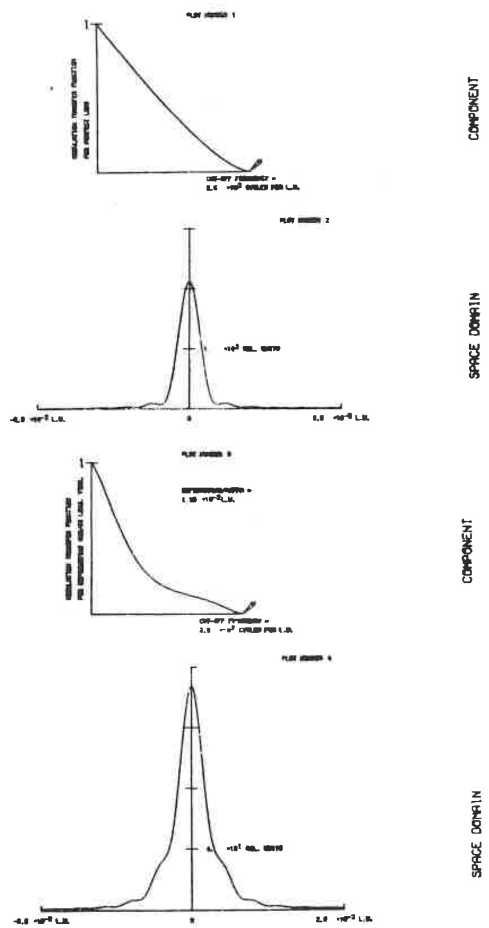


Figure 16b.

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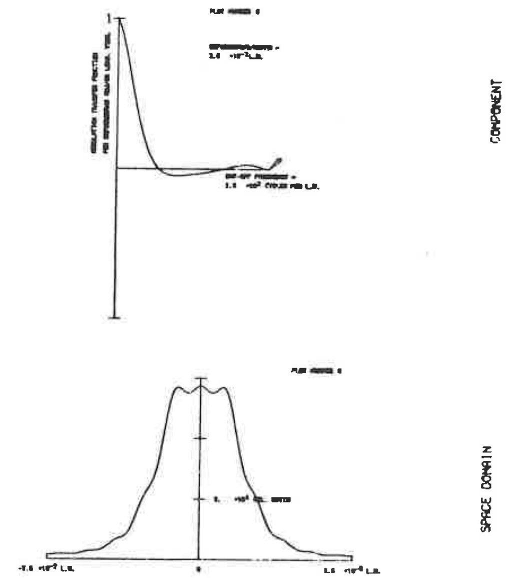

Figure 16c.

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5.5 TONE REPRODUCTION

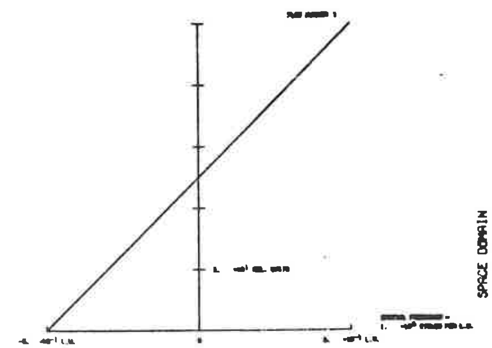
Suppose we want to know how the exposure range 0 to 100 (relative units) is reproduced by a two-generation photographic printing process. Figure 17 illustrates the sequence of IMSIM/1 statements that accomplish what we want.

```
JOB 5    DEMONSTRATION OF TONE REPRODUCTION


PERIODIC TABLE  (1,1)
   PLOT SPACE (1)
CHARACTERISTIC CURVE  (2,1,1)
   PLOT COMPONENT (2)
   PLOT SPACE (3)
DENSITY TRANSMITTANCE CONVERSION
   PLOT SPACE (4)
CHARACTERISTIC CURVE (3,-1,-1)
   PLOT COMPONENT (5)
   PLOT SPACE (6)
DENSITY TRANSMITTANCE CONVERSION
   PLOT SPACE (7)
TABLE (1,1)   (0,0) (1,100)
TABLE (2,3)   (-.25,.1)
              (0,.1) (.25,.2) (.5,.65) (.75,1.4) (1,1.8) (1.25,1.92)
              (1.5,1.96) (1.75,1.98)
TABLE (3,3)   (-1,.2) (-.75,.5) (-.5,1) (-.25,1.55) (0,1.9) (.25,2.05)
              (.5,2.1)
E N D
```

Figure 17.

We use PERIODIC TABLE as input, which assures that the full width of the space domain will be filled with the corresponding TABLE 1. This table consists of only 2 points and represents a straight line. The two H & D curves are given by TABLES 2 and 3 (plots #2 and 5 in figure 18). For the first emulsion, we request that the maximum be exposed at log exposure = 1, resulting in a density of 1.8 (see figure 18, plot #3). The next plot, #4, shows the space domain converted into transmittances. We request that, for the second emulsion, the minimum be exposed at log exposure = -1, resulting in a density of .2 (see figure 18, plot #6). Plot #7 finally shows the space domain again after the density has been converted into transmittance. Comparison of this plot with input plot #1 demonstrates the tone reproduction for the case of the particular H & D curves and exposures chosen.



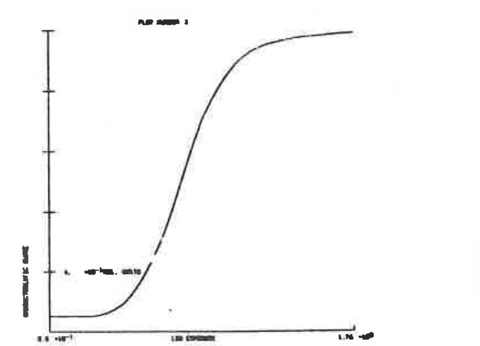


Figure 18a.

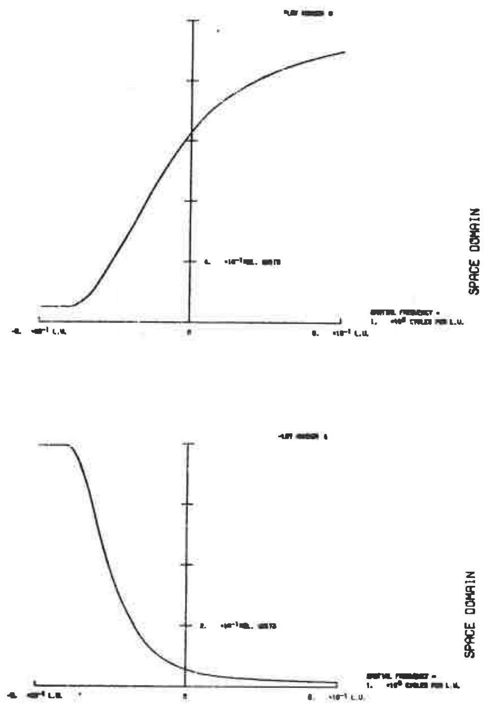
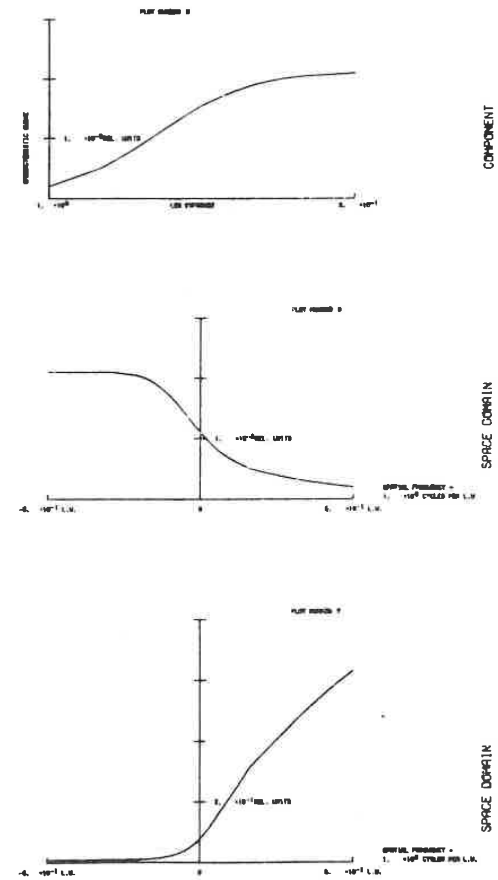


Figure 18b.



,Figure 18c.

5.6 DESCRIBING FUNCTION

This example demonstrates the use of IMSIM/1 for obtaining the describing function. We chose a simple quadratic function as the nonlinearity, for which the describing function can be calculated analytically, so that the results of the computer program could be checked.

The describing function is commonly defined as the first harmonic of the output of a nonlinear function, provided the input was a sinusoid. It depends on the frequency, modulation, and mean of the input sinusoid. In our example, we use the input (mean and frequency both equal to one),

$$u(x) = 1 + m \sin(2\pi x)$$

and we vary the modulation m. Figure 19 shows the IMSIM statements. TABLE 1 represents the second order polynomial by a set of points located on a parabola.

```
JOB  6    DESCRIBING FUNCTION

SINE  (1) (1,.8) (1,.6) (1,.4)
NONLINEAR FUNCTION (1)
   PRINT FREQUENCY (1) (2) (3) (4) SP
TABLE (1,3)  (-1,1) (0,0) (1,1) (2,4) (3,9)
     E  N  D
```

Figure 19.

The output of a second order nonlinearity with our selected input u(x) is given by

$$v(x) = [u(x)]^2 = \frac{2+m^2}{2}\left[1 + \frac{4m}{2+m^2}\sin(2\pi x) - \frac{m^2}{2+m^2}\cos(4\pi x)\right]$$

Here, the describing function (for given frequency and mean) becomes

$$d(m) = \frac{4m}{2+m^2}.$$

We evaluate the theoretical values of d(m) for the four values of m used in the SINE statement of figure 19.

m:	1	.8	.6	.4
d(m):	1.3333	1 2121	1.0169	.7407

The computer program calculates real and imaginary parts (or modulus and phase) of the coefficients of the complex Fourier series expansion of the space domain. In order to compare these numerical calculations with the theoretical values, we must rewrite v(x), substituting the exponential representations for the sine and cosine:

$$v(x) = \bar{v}\sum_{\nu=-2}^{2} a_\nu e^{2\pi i \nu x} \qquad \text{with } a_o = 1.$$

The mean is equal to

$$\bar{v} = \frac{2+m^2}{2}$$

and the coefficients are

$$a_1 = -\frac{2m}{2+m^2}i = -a_{-1}$$

$$a_2 = -\frac{m^2}{2(2+m^2)} = a_{-2}$$

Comparing these relations with the previously found formula for d(m), we recognize that the describing function is equal to twice the negative of the imaginary part of a_1:

$$d(m) = -2\,\mathrm{Im}\{a_1\}.$$

The values of a_1 are circled in figure 20. Taking into account the factor of -2, the agreement with the theoretical values is excellent.

Note that the set of table points on figure 19 extends one point further to the left and to the right than the abscissa range that is actually needed by the requested inputs. These points are added to avoid actual use of the two outside intervals because, for these, the program always interpolates linearly. The third order interpolation in the inner intervals will be automatically reduced to second order, because the specified table points fall exactly on a parabola.

JOB 6

FREQUENCY DOMAIN PRINT NO. 1

COMPLEX COEFFICIENTS OF NORMALIZED FOURIER SERIES EXPANSION
MEAN = 0.150E 01 REL. UNITS

SPAT. FREQ. (CYCLES/L.U.)	MODULUS	PHASE (RADIANS)	PHASE (DEGREES)	REAL PART	IMAGINARY PART
0.	1.0000	-0.	-0.	1.0000	-0.
1.0000	0.6667	-1.5708	-90.0000	0.0000	-0.6667
2.0000	0.1667	-3.1416	-179.9999	-0.1667	-0.0000

JOB 6

FREQUENCY DOMAIN PRINT NO. 2

COMPLEX COEFFICIENTS OF NORMALIZED FOURIER SERIES EXPANSION
MEAN = 0.132E 01 REL. UNITS

SPAT. FREQ. (CYCLES/L.U.)	MODULUS	PHASE (RADIANS)	PHASE (DEGREES)	REAL PART	IMAGINARY PART
0.	1.0000	-0.	-0.	1.0000	-0.
1.0000	0.6061	-1.5708	-90.0000	0.0000	-0.6061
2.0000	0.1212	-3.1416	-179.9999	-0.1212	-0.0000

JOB 6

FREQUENCY DOMAIN PRINT NO. 3

COMPLEX COEFFICIENTS OF NORMALIZED FOURIER SERIES EXPANSION
MEAN = 0.118E 01 REL. UNITS

SPAT. FREQ. (CYCLES/L.U.)	MODULUS	PHASE (RADIANS)	PHASE (DEGREES)	REAL PART	IMAGINARY PART
0.	1.0000	-0.	-0.	1.0000	-0.
1.0000	0.5085	-1.5708	-90.0000	0.0000	-0.5085
2.0000	0.0763	-3.1416	-179.9999	-0.0763	-0.0000

JOB 6

FREQUENCY DOMAIN PRINT NO. 4

COMPLEX COEFFICIENTS OF NORMALIZED FOURIER SERIES EXPANSION
MEAN = 0.108E 01 REL. UNITS

SPAT. FREQ. (CYCLES/L.U.)	MODULUS	PHASE (RADIANS)	PHASE (DEGREES)	REAL PART	IMAGINARY PART
0.	1.0000	-0.	-0.	1.0000	-0.
1.0000	0.3704	-1.5708	-90.0000	0.0000	-0.3704
2.0000	0.0370	-3.1416	-179.9999	-0.0370	-0.0000

Figure 20.

5.7 GIBBS PHENOMENON

This example serves to illustrate the effectiveness of the built-in suppression of the Gibbs phenomenon.

The Gibbs phenomenon is caused by the fact that an otherwise continuous function has, at one point, a finite ordinate jump and is then represented by a truncated Fourier series. Hence, this phenomenon would appear if we use a rectangle as input function and this rectangle is created from its Fourier transform. However, this does not happen in the program because, in all such cases (CRENELATE, SLIT, and possibly PERIODIC or APERIODIC TABLE), the space domain is directly filled by the program. We can, however, artificially destroy the space domain, for example, by applying the block LINEAR IMAGE MOTION (0). The parameter value of zero ensures that the associated transfer function is equal to 1 over the whole range of the frequency domain. Hence, the original representation of the frequency domain is not changed. If we now ask for PLOT SPACE, the rectangle in the space domain is recreated from its Fourier representation. Figure 21 shows the set of IMSIM/1 statements and the resulting output plots. The rectangle in the first plot does not exhibit any Gibbs phenomenon, because it was created directly according to the set of parameters we supplied. The rectangle in the second plot illustrates the effectiveness of the suppression. This rectangle is calculated from the truncated frequency representation with the Gibbs phenomenon suppressed. For comparison, figure 22 shows a rectangle for which the suppression was not applied.

The two plots in figure 21 illustrate also the automatic scaling of ordinates employed by the program. Ordinates of space domain and nonlinear function component plots are always scaled so that the maximum does not exceed 5 inches, but comes as close to 5 inches as is permitted by choice of reasonable scale factors. In the first plot, the maximum of 1 is made just equal to 5 inches, using the scale factor 5. In the second plot, where the rectangle exhibits a small amount of Gibbs overshoot, the use of the scale factor 5 would have exceeded the 5-inch limit. Here the ordinates are reduced by half. The appearance of a negative ordinate axis indicates that there also exists a slight undershoot of the ordinates into the negative.

The suppression of the Gibbs phenomenon works equally well if we request LINE SOURCE and then apply LINEAR IMAGE MOTION. The result of this procedure should be a rectangle: the line-spread function. Figure 23 shows the set of statements and the output. Another example is shown in figure 24, where VIBRATION TRANSVERSE has been used instead of LINEAR IMAGE MOTION. The plot in figure 24

```
JCB  7   GIBBS PHENOMENON

    SLIT (1,1,0,2)
       PLOT SPACE
    LINEAR IMAGE MOTION (0)
       PLOT SPACE
    END
```

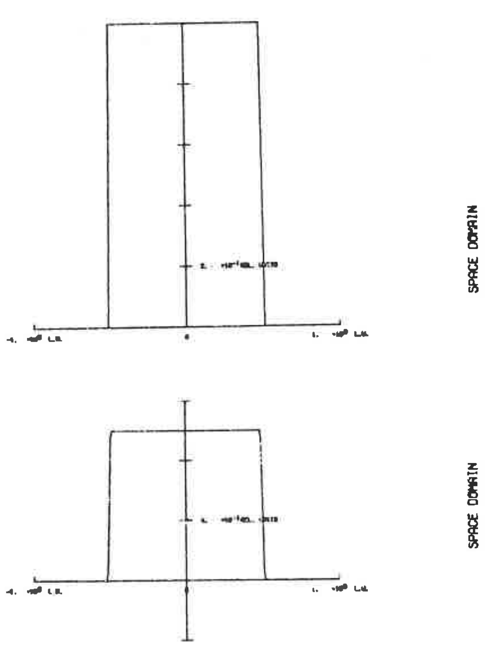


Figure 21.

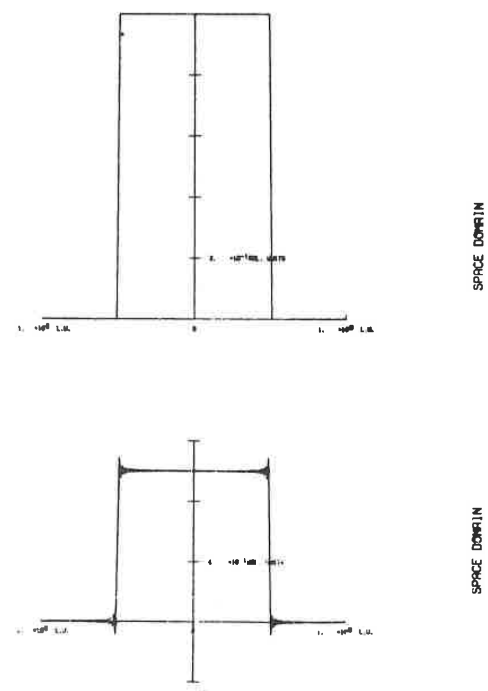


Figure 22.

```
JOB 70   GIBBS PHENCMENON

LINE SOURCE (1,0,2)
LINEAR IMAGE MOTION (1)
   PLOT SPACE
E N D
```

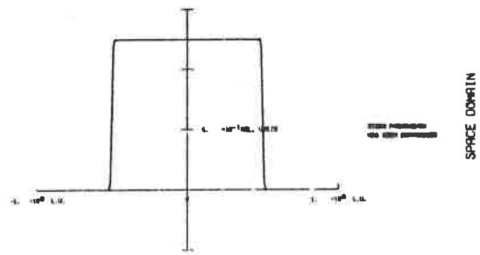


Figure 23.

depicts the line-spread function for transverse vibrations. Of course, this plot must necessarily be an approximation because the line-spread function should theoretically become equal to infinity at the edges. For comparison, we show the asymptotes as dotted lines. The approximation is satisfactory.

The suppression of the Gibbs phenomenon does not work satisfactorily when we request a rectangular line-spread function and apply it to a LINE SOURCE input, as shown in figure 25. The reason that the suppression is not as good in this case is that the calculation of the corresponding transfer function proceeds to only half the cutoff frequency usually employed by the program. It is advisable not to use the SPREAD FUNCTION TABLE block if one wants to represent a rectangular spread function; use of LINEAR IMAGE MOTION or SCANNING with the appropriate parameters accomplishes the same purpose with a much more efficient suppression of the Gibbs phenomenon.


```
JOB 71   GIBBS PHENCMENON

LINE SOURCE (1,0,2)
VIBRATICN TRANSVERSE (1)
   PLOT SPACE
E N D
```

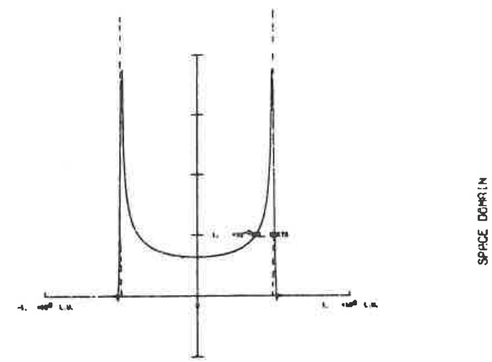


Figure 24.

```
JCB  72  GIBBS PHENOMENON

    LINE SOURCE (1,0,2)
    SPREAD FUNCTION TABLE (1,1)
        PLOT SPACE
    TABLE (1,1)  (0,C) (0,1) (1,1) (1,0)
    END
```

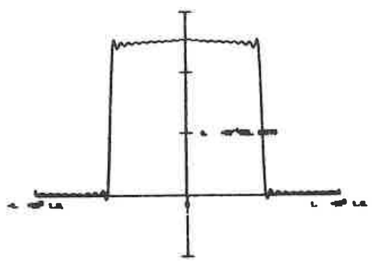


Figure 25.

SECTION VIII

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END

Purpose:

To act as a separator between options and to signal the end of the data deck.

Function:

Since many options can have a variable number of data cards following the option card, the end of these data cards is signalled by reading the next option card. For on-line operations, the designer may wish to insert a non-functional option card before proceeding to the next operation. He may use END as this non-functional option.

After the last desired option (and its data, if required), the user should always terminate his decks with an END option. This ensures completion of all options. For on-line operations, a bell is rung to signal the operator that the job has been completed.

EXIT

Purpose:

To exit to the operating system at the completion of a run. For some computers this is necessary to properly terminate runs.

Function:

Executes a CALL EXIT statement (FORTRAN).

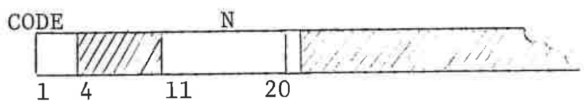
FILE

Purpose:

To provide entry of the installation name, initials, defaults and listing of the glass data stored on the disc.

Input Data:

One or more data cards required for this option punched in the following format:



CODE (Col. 1-3)	FUNCTION
GLIST	Lists N copies of the glass data from disk to line printer.
HEADER	The HEADER code causes the next two cards to be read and interpreted as follows: First card - the system flag for page eject is placed in column 11; a 1 causes eject flag to be on, blank or zero is off. On means a page eject will occur at the start of each option. Column 21 is used to enter the default dimensions; I should be entered for inches, M for millimeters, or C for centimeters. Second Card - All 80 columns of the card are saved as the MODEL DATA header. The MODEL DATA header allows each CODE V system installation to customize their output.

RELATIVE

This finds the partial dispersion for requested wavelengths. F1 contains the glass catalog names. If these columns are blank, then the Schott catalog is used. Fields F2 and F3 contain the first set of wavelengths; F4 and F5 the second set. If F4 is zero, then 486.133 is used. If F5 is zero, then 656.273 is used.

CPLOT

This will cause all of the stored spectral weight curves to be plotted.

TLIST

This causes all stored transmission data to be listed.

MLIST

This causes all stored glass data, other than the index data, or transmission data, to be listed.

LOAD
EXECUTE

Purpose:

Provides a means of loading a CODE V data deck (or typewriter input) on to a disc file and then executing the run. This eliminates the necessity of leaving the card reader on or, in the case of typewriter input, allows an input file to be created that can then be executed without further attention.

Input Data:

Any CODE V input data may follow the LOAD card; this string of data should be terminated with the EXECUTE option which transfers the CODE V input to the file that has been generated and execution begins.

Function:

A LOAD option simply causes all input to be read from the current input device (card reader or typewriter) and written out on a disc file. An EXECUTE option is the only input that will terminate the LOAD operation; in addition it transfers the input to the disc file for execution. If during execution, console switch 0 is depressed, the input will be returned to the card reader (or typewriter).

Output:

There is no output (except error messages) produced by these options; even the printout of the option LOAD and EXECUTE have been suppressed in the interest of saving paper and time.

Error Conditions:

1. "LOAD CARD OUT OF ORDER" - a LOAD option has been encountered while performing a loading operation; this process must be ended with an EXECUTE option.

EJECT

EON

EOFF

Purpose:

To allow the user a means of controlling the carriage control (top of form) on the print output (line printer or teleprinter).

Input Data:

No input data is required by these options.

Function:

CODE V can be configured to either eject to the top of form at the start of each CODE V option or not; this installation default is controlled by a flag on the initials card entered under the FILE option. These options allow temporary modification of this eject control flag independent of the installation default.

EJECT	Ejects the paper to the top of form; effective regardless of the setting of the eject flag.
EON	Sets the eject flag on; all options will eject to the top of form before any output is printed.
EOF	Sets the eject flag off; no paper ejects will occur except those specifically issued by EJECT, DATA, and LIBRARY-RESTORE options.

The DATA option always returns the eject flag to the installation default. Regardless of the setting of the eject flag, a paper eject is always performed on a DATA or a LIBRARY-RESTORE option.

Each lens stored with LIBRARY carries the present setting of the eject flag; restoring the lens will set the flag to the setting used when the lens was stored.

Output:

No output is produced.

O=TY

O=LP

O=NO

I=CR

I=TY

Purpose:

To provide a means of re-assigning the input-output devices during a CODE V run.

Input Data:

No input data is required by these options.

Function:

O=T The output is assigned to the console control device (teleprinter or CRT)

O=L The output is assigned to the line printer

O=N The output is eliminated for all succeeding CODE V options until an O=T or O=L is executed. Can be useful when rerunning a previous run to produce plots, for example.

I=C The input is assigned to the card reader.

I=T The input is assigned to the console control device (teleprinter or CRT)

Output:

These options produce no output; even the listing of the option card itself is omitted.

RJSTART
RJEND
/*EOF

Purpose:

To initiate and terminate execution of CODE V jobs submitted over remote job entry (RJE) terminals.

Introduction:

RJE capability has been implemented on Model 1-1A CODE V computer/software systems so that facilities which have IBM 2780 terminal emulators may submit CODE V jobs to the host CODE V computer; this permits sharing the CODE V computer resource remotely with other user sites.

A number of convenience features are included:

1. Receiving and transmitting of data can be done anytime, even when another CODE V task is being executed, with simple operator entries.

2. The execution of the remote CODE V job can be initiated in sequence with host site CODE V jobs simply by inserting the option RJSTART. Upon completion of the remote job execution, control is given back to the host CODE V job stream. The output of the remote job can then be transmitted back at the convenience of the operator.

Use:

A. At remote terminal
Deck consists of:

1. Terminal transmission header, if any, as supplied by terminal operator.

2. CODE V job deck supplied by designer, consisting of:

    a. LOAD option - if desired
    b. Normal CODE V decks
    c. RJEND option
    d. EXECUTE option - if LOAD was used
    e. /*EOF option

3. Terminal signoff trailer, if any, as supplied by terminal operator.

B. At CODE V host computer site

At the time the above deck is transmitted, the computer presumably will be busy on another CODE V job. The host site user brings the remote job in for execution by inserting the option card

RJSTART

in his CODE V deck. When this card is read, the transmitted deck is executed just as if it had been in the host site card deck at that point. Detailed host site operating instructions are supplied as part of the CODE V facility instructions.

C. Function of Codes

In the CODE V deck, item 2 above, LOAD and EXECUTE may be used if desired; they must be placed as shown. If used, they permit two actions:

1. As soon as the RJSTART is executed, the remote job is copied over to the LOAD-EXECUTE file. The remote job file is then free to receive another remote job even before computation on the first one is complete.

2. Telephone instructions to the host site operator can be given to use CTRL-S to skip the rest of the remote job, if the submitter of the remote job changes his mind about the run.

When RJEND is executed as part of the remote job, appropriate terminators and messages are written and control is switched back to the host site CODE V job stream which then continues. All of this permits the host site operator to schedule the remote computation at a convenient point, load the decks and leave the system unattended knowing his decks before and after the RJSTART card will also be processed.

The /*EOF option is only "seen" by the host site emulator as its "end of deck" label and is not used by CODE V.

File Space:

The input file is allocated to hold approximately 600 cards; the output file is allocated to hold approximately 100 pages of print. Amounts will vary depending upon fullness of lines.

RJSTART
RJEND
I=R
O=R

Purpose:

To initiate and terminate CODE V execution over a remote teleprinter.

Introduction:

On CODE V systems configured with a remote teleprinter, these options are designed to provide the capabilities of transferring input/output control to the teleprinter and returning control to the host computer. In addition, the remote user has the capability of directing either his input or his output separately back to the host system.

RJSTART - transferring control to the remote teleprinter:

At any point after CODE V has been initialized on the host computer and the remote teleprinter is "on-line" (the telephone communication line is established and active), the host operator may transfer CODE V input and output to the remote user by entering the option RJSTART. This will cause a message "CODE V RJE EXECUTING" to appear on the host console device and a "READY FOR CODE V INPUT" will be printed on the remote teleprinter followed by a question mark. CODE V options and input data may then be typed in.

RJEND - transferring control back to the host computer:

The entry of the CODE V option RJEND by the remote user will cause the input and output to be returned to the host computer. The input/output devices will be returned to those active when the RJSTART option was executed, typically the card reader for input and the line printer for output.

I=R and O=R - Individual input/output control:

At various times, the remote user may wish to change either the input or output units individually (typically the output) to a device at the host site. For example, he may wish to have his output for a particular run or part of a run be directed to the line printer. This can be done by executing the O=L option (described elsewhere in the CODE V manual); output may then be returned to his teleprinter by entering the O=R option. The remote user can also send messages to the host console device by assigning the output to it through the O=T option; when finished with the message the O=R command will return output to the teleprinter.

Re-assigning the input device can be done also by entering an I=C command, for example. This may be useful if the remote user has need of a particular deck (perhaps a test plate deck) that may be available at the host site. This deck would have to be terminated with the I=R card to return input control to the remote teleprinter.

APPENDEICES

DATA PREPARATION PROCEDURES

Standard Format

The input data to most of the CODE V options (with the notable exception of DATA) is entered in a common format. The format is:

CODE	N	L	F1	F2	F3	F4	F5	F6	F7
1	4	7	11	21	31	41	51	61	71

CODE (Col. 1-3)	Alphanumeric code designating a request (sub-option) and/or describing the data being entered.
N (Col. 4-6)	Integer field used most commonly for entering surface numbers or field position numbers.
L (Col. 7-10)	Label field used for entering a single character alphanumeric label or flag.
F1 (Col. 11-20) . . . . F7 (Col. 71-80)	Data fields F1-F7; used for entering integer, decimal, or alphanumeric data identified by the CODE. The data for a particular zoom position is entered in the data field corresponding to that zoom position. For example, the data for zoom position 3 would be entered in data field F3.

Integer and Decimal Fields

The CODE V designers manual designates some input fields as "integer". This means that internally the numbers are stored as integers and no fractional data will be retained. However, the presence of a decimal point on the input card will cause no problem. Also, the number does not have to be right justified but can be entered anywhere in the field.

All numeric data for CODE V (with the exception of fictitious glass data) may be entered with or without decimal point or in exponential format. For example, a wavelength card could be entered in any of the following forms:

```
WL     600.    500.    400.
WL     600     500     400
WL     6.E2    5.E2    4.E2
```

Surface Numbers

For convenience, some surface numbers may be referred to by a letter code rather than a number; the object surface is always referenced in this way. Specifically, the codes are:

O - object surface (letter "O")

S - stop surface

I - image surface

Also, an integer may be added or subtracted to these surfaces by simply placing the sign and the integer immediately after the surface letter code. The following examples show how this is used:

```
OAL       5.4
SUR       1         I

CT        .3
SUR       S+1

OAL       20.0
SUR       0         I-1

THI S+1   .1
```

Warning: S and I are immediately converted to their numerical equivalents. Results are indeterminate if those numbers have not yet been defined or are zoomed.

Standard Requests

The request POS and the data entry NO (or just N) are common to nearly all CODE V options.

1. POS - a request which enables the user to delete the calculation and/or output for a specific zoom position by placing a N (or NO) in the data field corresponding to that zoom position.

2. NO - an entry in a specific zoom position data field which reverses (or eliminates), for that zoom position, the request specified in the CODE.

   Examples of these for a 3 position zoom are:

```
DIFFRACTION MTF
POS                    NO     NO

LAYOUT
LABEL            NO           NO
RAYS             NO           NO
RETURN                        NO
```

3. SC - invokes use of APERTURE DATA

   The request SC is common to all CODE V options that use APERTURE data. It tells the program to use the APERTURE data for any surface on which it has been entered; the apertures on the other surfaces are determined by ray tracing the ray fans specified for the system in the SPECIFICATION DATA. If the SC card is omitted, all APERTURE data is ignored in that option.

Comma Input

Commas may be used to designate input fields as an alternative to entering the data in the established formats. This is particularly convenient for on-line typewriter entry of data but may be used for card entry also.

The following rules regarding comma input apply:

1. If commas are used to designate any data fields on a card, all data fields on that card must be designated with comas. An example of incorrect input would be:

```
WL        600.        500., 400.
```

This input would result in only the 400. being entered.

2. In the standard format referred to above no commas should separate items normally found in the first 10 card columns; thus, no commas should be entered to separate the CODE, N, and L fields. The CODE, N, and L fields should be separated by one or more blanks. Examples of this are:

```
CUY 16 MRY, -.125
THI 5, 2.3
GLA 8 P, SK16      (P is the power flag)
WTF 3, 1, .8, .8
Y   3,1.065
```

3. If the remaining data on an input record is blank, no additional commas are necessary. As an example, for surface data, the following would be typical input:

```
.02333,,.150,100
0.0,100,.500,0,BK7
```

4. If the remaining items on surface data are blank, except for the aperture flag or special surface type code, the intervening commas may be dropped and these flags set by using STO and TYP as follows:

```
.02333,,.150,100, STO
0.0,100,.500,0,BK7, TYP 2
```

If both STO and TYP are required on the same surface, STO comes first.

5. In cases where there are multiple single column entries, no commas are used to separate them. For example:

```
AUTOMATIC DESIGN
WTW, 121, 232            (2 position zoom system)
BFL, .50+, .00000011,
ANALYSIS
THIRD, NFN, NNF
```

Note that the control code (+) on BFL in AUTO is not separated with a comma; it is interpreted to be the last character in the field. If a blank control code is wanted, a blank must precede the comma.

Comment Cards

Any option request may be altered after the first three characters to carry comments or added information. In addition, any card with a colon (:) in the first column is printed as a comment but otherwise ignored. This allows the designer to annotate his runs.

[redacted]

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CODE V-CDC CYBERNET

March 15, 1979

CODE V™ - New Release on CDC CYBERNET* Computing Network

CODE V is actively under continuing development by ORA's technical staff with the objective of enhancing our user's success and efficiency, and extending the scope of coverage in optical calculations. As always, thorough testing by our own engineering staff precedes release to our user.

We serve three user communities: the CDC user, the user of our service centers in Pasadena and Mountain View, and those companies who have a dedicated CODE V facility of their own. Enhancements of CODE V may be principally aimed at one of these user communities but often turn into advantages for all.

The extension of CODE V availability through the CDC CYBERNET network has increased our attention to speeding up the processes of computation; this previously has not needed as high a priority. This announcement describes the first phase results of this activity as well as describing some new facilities and features beyond those described in the CODE V manual. An outstanding feature is the significant advance toward automatic tolerancing (TOR).

I. Performance Enhancement (Speed/Cost)

A. Overhead has been reduced in disc accesses between program sections. This reduces cost per run. For example, the time to do a DIFFRACTION MTF computation, already fast using convolution techniques, has been reduced to 72% of its former value (triplet test problem). All options benefit, cutting down the cost of each run.

B. Lens library storage is variable in length; storage charges will therefore be only for the used length. The minimum charge for the library file is approximately $1.00 per month.

C. AUTOMATIC DESIGN has been reorganized in its operations to reduce computing overhead, particularly on zoom or multi-mode lenses, and to prepare for later enhancements. So far, this has resulted in the following faster speeds:

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*CYBERNET is a registered trademark of Control Data Corporation. CODE V is a product of Optical Research Associates, and is offered and supported exclusively by ORA.

Problem Type	Speed Increase	Overall Cost Change
Double Gauss	17%	-19%
4 Position Zoom	39%	-28%

This speedup has had no effect on the result of a run and is thus completely transparent to the user.

This addresses only one of four potential types of AUTOMATIC DESIGN speed enhancements; the others will be applied in later releases.

II. PUNCH

This new option permits the user to punch out any system in the form of a DATA deck, which can be used for later input to another run. The DATA card thus produced has the date and time also punched in it as a way of correlating the deck and the run that generated it. In addition, the user may add an identifier label of 40 characters centered on the DATA card by adding the request:

	Col. 21-60
LABEL	XXXX---XXX

where XXXX---XXX is the desired 40 character label.

If the system contains zoom data that would overflow the card length, the deck is punched with reduced number of zoom positions plus a CHANGE option and entries which extends the data back up to the full zoom system. Trailing zeros are always dropped from the output; all formatting is chosen for maximum significance consistent with card layout.

III. AUTOMATIC DESIGN Derivative Increment

Experience has shown that a smaller sized set of derivatives covers a wider range of problems. Therefore, with this release, the defaults have been scaled down by a factor of 10. Users who have used the DER request will be able to repeat their runs by using a value 10 times as large. Users who have not used a DER request can repeat runs by entering a DER request with a value of 10; in general, there is no effective difference in convergence, but users will need to use DER requests less often with the new default. For zoom lenses, a change has been made to shift derivatives to a more suitable range, but old runs will not be exactly duplicatable.

Recommended limits on the value are 10 to .001; any smaller value will imbed the computations increasingly in numerical noise.

IV. Outside Diameter Control for LAYOUT

LAYOUT normally adds a small increment to the clear apertures of concave surfaces before generating the flat chamfer; this increment can be suppressed by using:

ID	Indicates that the APERTURE DATA specified in the system data are to be used as the surface diameter on the element. There is to be nothing added on for mechanical free aperture.

A larger increment based on good mounting practices is added to plano or convex surfaces to generate the edges (outside diameter). If the user wishes to supply his own values for outside diameters, use

OD n (z)	Outside diameter; the values in F1-F7 are the outer diameter of that element for each zoom position. If surface n is followed by glass, then the trailing surface (n+1) will have the same OD. If the system has elements which have multiple passes made through them, then only the first pass is drawn. An OD card placed on the surface representing the second pass will be ignored.

V. TOR Improvements

Several important advances have been made in TOR. These include an automatic tolerancing procedure, eight new parameters, an expanded input scheme, improved compensation, a tabular output of tolerances, and the inclusion of cross terms in the calculation of the probable change.

A. Speed Increase - Number of Rays

The default number of rays has been reduced from 320 to 205; this will give about a 30% increase in speed.

Studies have shown that even 100 rays can be used effectively for rough tolerancing for a further increase in speed, using the entry described in the CODE V manual. The default of 205 is suitably accurate for most cases.

B. Improved Solution for Compensators

The criterion used when solving for the compensators is the minimization of the change in MTF or RMS. Previously, this has been accomplished by minimizing the quadratic term. However, for parameters with large linear terms, this has not given optimum results. The program has been changed to include a minimization of the linear term along with the quadratic term. A weight is applied to the linear term which changes the emphasis compared to the quadratic term. The default value of the weight is 1.0; the prior program was equivalent to using a value of 0.0. Although use of the new default is strongly recommended, the value of this weight can be changed, using a WTS card with the desired value in columns 11-20 (the first field).

In many cases, this change of compensation technique is transparent to the user, but in some, substantial reductions in sensitivity for particular parameters has resulted.

C. Automatic Tolerancing

Automatic tolerancing requires, at a minimum, the following:

- Automatic generation of a default group of tolerances - see Section 1 below.
- A means of scaling these tolerances based on their inverse sensitivity (how large each tolerance value must be to generate a uniform degradation) - see Section 2 below.
- Upper and lower bounds to this scaling so that no tolerance is larger than the point where cost is not affected nor smaller than can practically be made - see Section 2 below.
- Rounding of resulting values to one or two significant figures - see Section 2 below.
- An exception report which highlights those tolerances which drive the performance degradation beyond acceptable limits - see Section 3 below.
- Output of toleranced lens data in a convenient form for both optical designer and mechanical designer with a performance summary to demonstrate the effects of the tolerance budget - see Section 4 below.

All of these have been implemented in this release with the INVerse option as a basis, which has become the default mode. To revert to the sensitivity analysis use the input request SNS.

1. Default Set of Tolerances

The default set of tolerances has been re-defined to give a meaningful dissection of the lens into its elements and components and to specify those parameters which would normally be toleranced:

Centered tolerances:

- For each optical surface: fringe (DLF), thickness (DLT) and irregularity (IRR).
- For each element, index (DLN).

Decentration errors:

- For each element: wedge or total indicator runout (TIR) on the surface of the element with the smallest clear aperture.
- For each component (element or cemented group bounded by air on both sides): a displacement (DIS) and tilt (BTI).
- For each cemented element except the first of a group: a roll (ROL) on the first surface of the element.

The default set of tolerances will automatically be defined if no tolerances are input, as described in the CODE V manual. However, it is now possible to insert the default set (not including compensators) by using a DEFAULT card. This is useful for defining the default set and then adding or changing a few. A SUR card may follow the DEF card to define a block of surfaces. Otherwise, the entire lens will be used. For example, to define the default set on surfaces 10 to 25 only, use the cards

```
DEF
SUR,10,25
```

2. Inverse Sensitivity

This mode, now the default, assumes that each tolerance will be scaled (non-linearly) to provide a change of .01 in MTF (or RMS) as the basic degradation target for each tolerance. If it is necessary to change this number, an INV card may be used with the desired value in the first numerical field. The change is always assumed to be negative for MTF and positive for RMS regardless of the sign on the entered data. It is also possible to input different changes for each field and zoom. The input is similar to the input for FREQ (see CODE V manual).

The INV mode now uses the one most sensitive field of all zoom positions to determine the scaling of the tolerance. In addition, the tolerance is restricted to lie between upper and lower bounds and is rounded to two significant figures or less. A table of tolerances is printed at the end of the run. Therefore, this is close to being an automatic procedure.

A typical default run for tolerancing a lens at a spatial frequency of 20 ℓ/mm would contain the following two cards:

```
TOR
FRE,20
```

The tabular output provided in this section is the result of this input. This run would define a default set of tolerances which includes decenters and tilts for elements and cemented groups (see new definition of default set). It would then either scale and round the tolerances to give an MTF drop of .01 or else set them at the default minimum or maximum bounds. The output would include the standard TOR output plus a table of tolerances and a performance summary.

The tolerance limits for any type of tolerance may be modified with a LIM card. The name of the tolerance (e.g., DLF DLT, etc.) goes in the label field (columns 5-10). The minimum, maximum and increment go in the first three numerical fields (columns 11-20, 21-30, 31-40). The increment is used to round the tolerance. If any of these three items is omitted, the default for that item will be used. For example, to change the minimum on irregularity to .25 fringes, use the following card:

```
LIM  IRR,.25
```

In some cases it may be desirable to freeze a particular tolerance and not allow it to be scaled or set at its limits. To accomplish this, the tolerance should be entered with a negative value. For example, if the default set of tolerances is desired, but the tolerance on the radius of surface 3 is to be set to .01, the following cards are needed:

```
DEF
DLR3,-.01
```

Note that any compensators which are required must be defined before the DEF card.

3. Edited Listing - Exception Report

Optical systems can easily have seven tolerances per surface; output can therefore be extensive. Edited output can be provided to ease the burden of searching for the dominant tolerances.

If the INV option is used, those tolerances which introduce a change in MTF (or RMS) of less than 5 times the designated change may be deleted from the output. This is accomplished by using a EDIT request. The factor 5 may be overridden by inserting a different factor in columns 11-20 of the card. This feature is useful for printing only those tolerances which were set at the minimum or user-defined and cause the MTF (or RMS) to change significantly.

4. Summary Table

A table may be printed which summarizes the tolerances and performance degradation. Three sections are printed, one for the centered tolerances (radius, fringe, irregularity, thickness, index, homogeneity), one for the decentered tolerances (wedge, tilt, roll, decenter), and one for the performance summary. The table is automatically printed if the INV option is being used. There are two other ways in which to execute this option:

TAB	Prints the table at the end of all calculations. It includes the effect of any scaling done in the INV option.
TBO	Table only. Prints the table after the data input but before any calculations are done and then exits. No calculations are done. This is useful for getting a table without rerunning the whole calculation. This cannot be used with the INV option.

A sample table output is included in this newsletter, on the next 3 pages.

CENTERED TOLERANCES

DOUBLE GAUSS EXAMPLE

SUR	RADIUS	RADIUS TOL	FRINGES POW/IRR	THICKNESS	THICKNESS TOL	GLASS	INDEX TOL	INHOMO-GENEITY
1	0.64141		12.0/ 3.00	0.08099	.00300	747.377	.00200	
2	2.40305		10.0/ 2.50	0.00300	.00200			
3	0.43459		12.0/ 3.00	0.20000	.00100	620.603	.00200	
4	INF		12.0/ 3.00	0.03800	.00100	755.276	.00200	
5	0.26548		10.0/ 2.50	0.05521	.00400			
6				0.17064	.00400			
7	-0.30151		12.0/ 3.00	0.03800	.00100	657.329	.00200	
8	INF		12.0/ 3.00	0.08110	.00100	744.448	.00200	
9	-0.45791		12.0/ 3.00	0.00300	.00300			
10	1.85997		12.0/ 3.00	0.08505	.00500	744.448	.00200	
11	-0.76242		12.0/ 3.00	0.54722				
12				-0.00076				

RADIUS, RADIUS TOLERANCE, THICKNESS AND THICKNESS TOLERANCE ARE GIVEN IN INCHES

FRINGES OF POWER AND IRREGULARITY ARE AT 546.1 NM. OVER THE CLEAR APERTURE

IRREGULARITY IS DEFINED AS FRINGES OF CYLINDER POWER IN TEST PLATE FIT

TOLERANCE LIMITS

	MINIMUM	MAXIMUM
* RADIUS	0.0010	
* SAG	0.0001	0.0020
** POWER	2.0	12.0
IRREGULARITY	0.50	3.00
THICKNESS	0.00100	0.02500
INDEX	0.00010	0.00200

* RADIUS TOLERANCE IS DETERMINED BY BOTH RADIUS AND SAG LIMITS
** POWER TOLERANCE IS 4 TIMES THE IRREGULARITY TOLERANCE

3/ 9/7*

POSITION 1

DECENTERED TOLERANCES

DOUBLE GAUSS EXAMPLE

ELEMENT NO.	FRONT RADIUS	BACK RADIUS	ELEMENT WEDGE TIR	ELEMENT WEDGE ARC MIN	ELEMENT TILT TIR	ELEMENT TILT ARC MIN	EL. TIR	DEC/ROLL(R) INCHES
1	0.64141	2.40305	0.0005	3.5	0.0002	1.7	0.0006	0.0010
2	0.43459	INF	0.0002	1.9				
2- 3	0.43459	0.26548			0.0002	1.7	0.0001	0.0010
3	INF	0.26548	0.0001	1.1			0.0011	0.0010 (R)
4	-0.30151	INF	0.0002	2.4				
4- 5	-0.30151	-0.45791			0.0007	8.6	0.0001	0.0010
5	INF	-0.45791	0.0002	1.9			0.0008	0.0010 (R)
6	1.85997	-0.76242	0.0005	3.9	0.0009	6.9	0.0008	0.0010

RADII ARE GIVEN IN UNITS OF INCHES

TIR IS MEASURED PARALLEL TO THE OPTICAL AXIS IN INCHES
AT THE SMALLER OF THE TWO CLEAR APERTURES FOR WEDGE AND TILT
AT THE INDIVIDUAL CLEAR APERTURES FOR DECENTER AND ROLL

DECENTER OR ROLL IS MEASURED PERPENDICULAR TO THE OPTICAL AXIS IN INCHES

TOLERANCE LIMITS

	MINIMUM	MAXIMUM
TIR	0.0001	0.0050
TILT	0.0003	0.0050
DECENTER	0.0010	0.0250
ROLL	0.0010	0.0250

DOUBLE GAUSS EXAMPLE

WAVELENGTH	WEIGHT
650.0 NM	10
550.0 NM	20
450.0 NM	10

P E R F O R M A N C E   S U M M A R Y

POLYCHROMATIC MODULATION TRANSFER FUNCTION

FIELD POS	FREQ L/MM	AZIM DEG	DESIGN	DESIGN PLUS TOLERANCES *	COMPENSATOR RANGE (+/-) * DLT 11
0.00	20.00	TAN	0.921	0.767	0.012190
0.71	20.00	TAN	0.907	0.751	0.012190
1.00	20.00	TAN	0.901	0.738	0.012190

* THE CHANGE IN MTF IS A MEAN PLUS 2 SIGMA VALUE (97.7 PERCENT) AND ASSUMES A UNIFORM DISTRIBUTION OF MANUFACTURING ERRORS OVER THE RANGE FOR ALL TOLERANCES EXCEPT DECENTRATION ERRORS WHICH HAVE A TRUNCATED GAUSSIAN DISTRIBUTION IN X AND Y
THE COMPENSATOR RANGE IS A MEAN PLUS 2 SIGMA VALUE

D. Boresight Compensation

It is now possible to correct the boresight error at the first field of the first zoom position by using the last compensator; the boresight compensation is applied to all remaining fields and zoom positions. Simultaneously the change in MTF is minimized over all fields and zoom positions using the remaining compensators. The option is selected by using a BOR card. The following conditions apply.

- The boresight calculation and compensation is in the y-direction only. The last compensator must be one which has the proper effect, e.g., DLY, DLA, BTY, DSY, RLY, STY.
- The first field will normally be the axial field.
- There must be at least one compensator.
- All compensators except the last will be used to compensate MTF.
- The DST option (Distortion) will be automatically executed.
- The boresight calculation is available only with MTF and not RMS.

E. Miscellaneous TOR Improvements

1. Roll and Tilt

Roll and tilt of an element or group may now be done about the last surface of the group. This is accomplished by reversing the surface numbers on the SUR card. This only applies to ROL, RLX, RLY, BTI, BTX, BTY.

2. New Parameters (and Revised Parameter Names)

Eight new parameters have been added:

CODE	Default In.	Default Cm.	Default Mm.	Description
HOM	-----	$\pm 5\text{x}10^{-6}$	-----	Non-refocusable inhomogeneity in the space following the surface.
AXG	-------	.001	-------	Axial linear index gradient in the space following the surface. Each of the two surfaces bounding the space is at a constant index and the iso-index contours lie proportionally between the surfaces.
RAG	-------	.001	-------	Radial quadratic index gradient to the clear aperture in the space following the surface.
TRX (n)	.001	.0025	.025	Alternate to DLB - Tolerance on the total indicator run-out in the x-direction at the edge of the clear aperture.
STX	.001	.001	.001	Tilt (in radians) in the x-z plane of each surface about its pole in group N1-N2 of the SUR card (shear tilt).
BTX	.001	.001	.001	Tilt (in radians) in the x-z plane of the group of surfaces N1-N2 about N1 specified in the SUR card.
DSX	.001	.0025	.025	Lateral displacement in x of the group of surfaces N1-N2 specified by the SUR card.
RLX	.001	.0025	.025	Roll of surfaces N1-N2 in the x-direction on the seat of N1 (N1 itself does not tilt), specified in the SUR card.

NOTE: An improvement in the calculation of the probable change in MTF (or RMS), which now includes cross-terms, makes it necessary that both components of tilt, decenter and irregularity be included so that modeling of the azimuthal variation can be properly done. Both components should have the same value. In order to make the input easier, a set of codes is available which will enter both components at the same time. The following table lists these codes. Note that the names have been changed for some of the previously available parameters. For example, DIS used to be a displacement in the y-direction. It now represents both the x and y components (the corresponding y component is DSY).

FUNCTION	x COMPONENT	y COMPONENT	BOTH COMPONENTS
Surface tilt	DLB	DLA	TIL
Surface decenter	DLX	DLY	DEC
Irregularity*	CYD	CYL	IRR
Total indicator runout	TRX	TRY	TIR
Barrel tilt	BTX	BTY	BTI
Group displacement	DSX	DSY	DIS
Roll	RLX	RLY	ROL
Shear Tilt	STX	STY	STI

*The components of cylinder are at 45° (CYD) and 0° (CYL).

As an example, in order to decenter surface 7 by .005, enter

DEC7,.005

This will generate the inputs

DLY7,.005
DLX7,.005

On all output, the two components will be printed.

NOTE: If both components are used as a compensator, two compensators must be specified on the CMP card even if only one card was used as input. If tilt of the image plane is used as a compensator, only the y-component is needed.

3. Improved Input

It is now possible to delete parameters from the list and also to input and delete a parameter for a block of surfaces with one card. If the code DEL is put in place of the tolerance value (field F1) the parameter will be deleted from the list. If a SUR card is used after a simple parameter, the parameter will be applied to (or deleted from) all the surfaces defined in the SUR card. The following examples define the ways in which this capability can be used.

DLR,.001 SUR,3,8	Add to the list a change of radius of .001 on each of the surfaces 3 through 8.
DLR5,DEL	Delete the radius change on surface 5 from the list.
BTI,DEL SUR,2,6	Delete the barrel tilt of the group of surfaces 2-6 from the list.
DLT,DEL SUR,5,10	Delete the thickness changes on 5 through 10.

NOTES:

- If a tolerance value is omitted, the default will be used.
- SUR is used in two different ways:
  1) to define a group for a group parameter
  2) to define a block for a simple parameter
- As before, if a simple parameter is added which is already in the list, the previous value will be updated.
- In a block input or the standard set of tolerances, dummy surfaces will be skipped, index changes in air will be skipped, and curvature, radius and sag changes will be skipped on plano surfaces.

It is possible to scale tolerance values as they are input. This may be used to avoid repunching the values on the input cards. It may also be used to scale the default set of tolerances. The scale factor is entered on a SF card with the desired value in columns 11-20 (the first field). A value of 1.0 is equivalent to no scaling. All of the tolerances following the SF card will be multiplied by the value on the SF card. Any number of SF cards may be used in the deck in order to change the scale factor or set it back to 1.0.

F. Technical Notes

1. The equation for MTF as a function of tolerance has been changed. It is now

$$MTF = AT^2 + BT + C$$

and no longer has the square root. Thus, the coefficients will also be different. This form tends to be more accurate for excessively large changes in MTF. For the small changes typically resulting in a tolerance analysis, there should be no significant changes.

2. Cross-terms are now included in the calculation of the probable change giving a more accurate answer. These are the terms which allow one parameter to partially compensate or add to the effect of another parameter.

3. The aberration introduced by CYL and CYD is represented by cylindrical power in one meridian, and thus includes average power as well as astigmatism. Thus, it is important to have a compensating parameter which just compensates focus when using these (this is not new, just a reminder); this has the benefit that the potential range of compensation will include a term for the cylinder which can, in fact, be needed.

4. The number of available tolerances is 350. The number of available compensators is 3.

5. More complete discussions of the mathematics used in TOR are contained in two papers by M. Rimmer and D. Koch, respectively, in Proc. of the SPIE, Vol. 147, August 1978.

APPENDIX

Statistical Models Used in TOR for Perturbations Having Arbitrary Orientation

In the statistical summary given in TOR, certain assumptions are made about the distribution of manufacturing errors. For one-dimensional tolerances (e.g., radius, thickness, index, homogeneity, etc.), it is assumed that the error is equally likely to be anywhere within the tolerance range. This is called a uniform model for the probability density function.

In the case of cylindrical irregularity, which may have arbitrary orientation, it is assumed that the manufacturing error can be anywhere with equal probability within a cylinder whose radius is equal to the magnitude of the input perturbation. It is convenient in this case to transform coordinates into a polar form in order to integrate out the angular dependence. When this is done the resulting probability density function for the radial coordinate is triangular as illustrated in Figure A. The implication of this form is that the errors tend to accumulate near their maximum magnitude, which is probably a reasonable model for irregularity.

For decentration errors (e.g., tilt, decenter, roll, etc.), it is assumed that each component has a truncated Gaussian probability density function. The resulting radial distribution has a truncated Rayleigh form. This is illustrated in Figure B. The maximum is halfway between the center and edge. This is a more reasonable model for decentration errors which do not tend to accumulate near the maximum value.

In order for these two-dimensional distributions to be used, both components of decentration and irregularity must be entered and each must have the same tolerance. For example, for a surface tilt enter both DLA and DLB (or use the TIL input as described earlier).

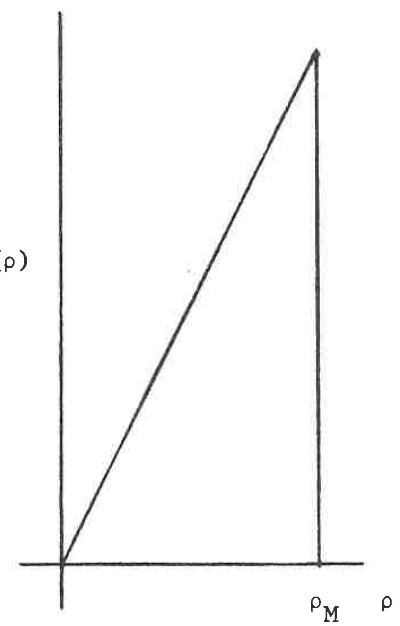

Fig. A. Triangular Density (radius magnitude density function for a uniform density in x and y).

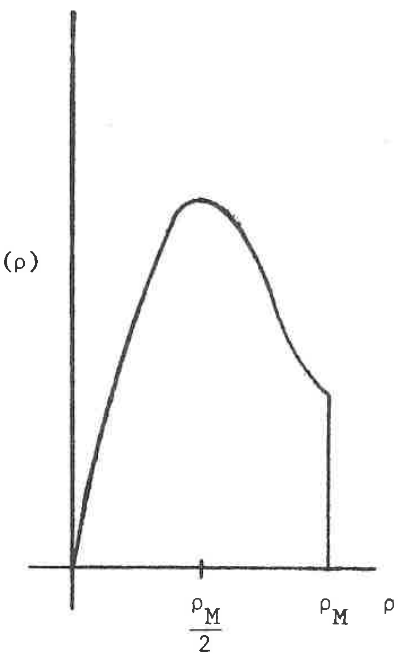

Fig. B. Truncated Rayleigh Density Peaked at $\rho_M/2$ (Gaussian density in x and y).

OPTICAL RESEARCH ASSOCIATES

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March 15, 1979

Subject: New Release of CODE V™ on the CDC CYBERNET* Computing Network

ORA has generated a new release of CODE V on the CDC CYBERNET computing network which is described in detail in the attached document.

The major advances made with this release are in speed enhancement (reduction in run costs), the addition of a PUNCH capability, and the extension of TOR toward the first commercially available automatic tolerancing program ever developed for optical systems. Specifically, the sections are:

I. Performance Enhancement (Speed/Cost)

Describes improvements in disc accessing that substantially reduce the cost of minimum runs and benefit all runs, reductions in computing time for AUTOMATIC DESIGN and TOR, and provision for a variable length lens library with small minimum monthly cost.

II. PUNCH

Provides the ability to punch a DATA deck for a lens modified by AUTOMATIC DESIGN, CHANGE, etc., that is suitable for re-entry for a later run.

III. AUTOMATIC DESIGN Derivative Increment

Initial increments have been altered to more suitable average values based on experience.

IV. Outside Diameter Control for LAYOUT

Provides for user override in establishing element edge configurations to conform to engineering requirements.

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*CYBERNET is a registered trademark of Control Data Corporation. CODE V is a product of Optical Research Associates, and is offered and supported exclusively by ORA.

V. TOR Improvements

Major advances substantially reduce the effort required to come up with a tolerance budget and a table of tolerances for inclusion in engineering drawings. Using ORA's powerful MTF (or RMS wave error) tolerancing program, one run with little input (1) dissects the lens into element and component tolerances, (2) assigns tolerances (within a default set of practical limits) based on their relative sensitivity, (3) prints an exception report highlighting those tight tolerances which act as drivers of performance degradation, and (4) prints a concise table of all system tolerances so generated and a summary table of effects. The user can selectively alter the tolerance limits and tolerances to complete his budgeting. The entire tolerancing process is much reduced in both computer and engineering cost; for example, the computer run for the double Gauss sample was $22.00. For visual or fire control systems, a boresight compensation capability has also been added so that assembly procedures which require a lateral re-alignment for boresight can be simulated.

Please contact Bob Cole or Darryl Gustafson, ORA, for access instructions for this new release.

Sincerely,

OPTICAL RESEARCH ASSOCIATES
Thomas I. Harris
President

TIH/lk

Attachment

OPTICAL RESEARCH ASSOCIATES

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September 26, 1978

To our CODE V Manual holders:

Your new CODE V manual and larger binder are enclosed. The larger binder was required to accommodate the documentation of the many new CODE V features as well as to allow room for future growth.

This update impacted such a large portion of the old manual that the costs of sending only update pages were comparable to that of replacing the entire manual. If you have an old manual, we suggest that you discard the contents and use the binder for CODE V related material.

This manual contains stripes on the borders to indicate manual and program changes. A short horizontal stripe at the top of the page indicates an all new option or section. Vertical stripes along the outside edge of the page denote new program features; stripes along the inside edge indicate manual changes only.

In addition to the manual, there is enclosed a summary of new CODE V features. This will give you a quick overview of the new CODE V capabilities.

If you change your address, please let us know so that future updates will reach you. Also, we would appreciate any comments or suggestions you have on the manual.

Sincerely,
OPTICAL RESEARCH ASSOCIATES

Darryl E. Gustafson

Darryl E. Gustafson
Executive Vice President

DEG:mjp

enclosures

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August 1978

Thank you for your interest in CODE V . . . . . .

CODE V is a new approach to filling your needs for optical computations. It is:

- A large (50,000 FORTRAN and Assembly Language Statements) integrated package of optical design programs.
- Under active continuing development by a unique group of optical designers, programmers and scientists, who use it daily for their own engineering and consulting.

It is available to you in the following forms:

- Through the CDC CYBERNET* computing network on teleprinter and plotter in your own office, or on large terminals in your own plant or local CDC offices.
- For the steady, higher volume user of optical design programs, ORA will lease a stand-alone computer hardware/software package which gives many more times the computing capacity for the money.
- For users in the Southern California or San Francisco area, usage at ORA local offices.

Your choice is dependent on usage rate and convenience.

CDC CYBERNET Computing Network

The CYBERNET service is a telecommunications network that ties together several major high speed Control Data Computer systems. In addition, Control Data offers remote batch access to this network in more than 100 major cities plus access by telephone from private customer terminals, either in batch or interactive mode.

The availability of CODE V on the CYBERNET network makes this powerful software accessible to any user of optical design programs. Regardless of your volume, you can now use CODE V and discover for yourself its power and unique capabilities. The graphics can be used to help you communicate the character and quality of your optical designs.

*CYBERNET is a registered trademark of Control Data Corporation.

When you use CODE V on the CDC CYBERNET network you will:

- Use a comprehensive program - It has features for optimization, evaluation, tolerancing, mechanical design support, system and coating design.

- Use a state-of-the-art program - It has MTF tolerancing, laser beam waist analysis, Narcissus analysis and optimization, and diffraction analyses of tilted and decentered systems.

- Use a tested program - It's the same one we use every day in our own engineering work and has been used for years by other designers at many different companies.

- Use a documented program - The CODE V user's manual is a current and comprehensive guide for the beginning and experienced user. It is updated in parallel with the program to provide a single integrated reference manual.

- Use a growing program - It is constantly being upgraded to incorporate new capabilities, improvements, and customer-suggested enhancements.

- Use a cost-effective computing service - the CDC CYBERNET computing network is well established as offering low cost per calculation for scientific computing.

Where can I access CODE V?

- CDC Service Center - CDC has dozens of computing centers around the country where users may submit jobs and receive output. Many of these have plotters, so the CODE V graphics can be generated there also.

- Your Company with Remote Batch Terminal - Many companies have installed UT200 RJE (remote job entry) terminals or a terminal that emulates the UT200. Any of these terminals can access the CDC CYBERNET computing network. In most cases plotters can be attached to these terminals also.

- Your Office with Teleprinter and Plotter - Most teletype compatible terminals combined with the appropriate modem and standard telephone line can be used to access CODE V. These terminals vary a great deal in specific capabilities and ORA can assist in recommending the most effective choice. A plotter can also be attached to provide the graphics output.

If you are interested in using or learning more about CODE V access on the CDC CYBERNET network contact ORA about:

- A CODE V User's Manual; please indicate your request on the enclosed reply card.
- Assistance in choosing and procuring terminal and plotting hardware.
- Access to the CYBERNET network through an ORA supplied charge number. NOTE: CDC cannot activate your access to the CODE V software; this and all other CODE V related services must be provided by ORA.
- An agreement for CODE V usage on the CYBERNET computing network.
- Monthly accounting services on CYBERNET computer usage.

Enclosed are the Table of Contents for the CODE V User's Manual and a reply postcard. We value your comments and questions - please return it.

Darryl E Gustafson

Darryl E. Gustafson
Executive Vice President

Optical Research Associates