INFORMATION RATES IN REMOTED RADAR SYSTEMS

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Abstract.

Air traffic information collected by long range radars is available to the CAA at the radar sites. This information will be remoted to the air route traffic control center. A theoretical study is made here of resolving power and the information rate inherent in the air traffic, radar video signals, displays, and various transmission techniques. Air traffic provides the basic information and radar video establishes the maximum information rate for the system. On the other hand, a display can show only a limited amount of this information. But if the display magnifies a small area, it can show all the information the radar collects. Between the radar and the presentation, the information may be transmitted by a wide band communication channel that transmits all the radar video information or it may be compressed by analog, digital or manual methods so that it can be transmitted over a much narrower communication channel. The final choice of system components will be decided by the requirements of the basic problem for resolution, off-centered displays and the needs of the traffic controller.

A. Introduction

A theoretical study is made here of the information rate inherent in the air traffic, radar video signals, displays, and various transmission techniques. Air traffic provides the basic information and radar video establishes the maximum rate for the system. On the other hand, a display can show only a limited amount of this information. But if the display magnifies a small area, it can show all the information the radar collects. Between the radar and the presentation, the information may be transmitted by a wide band communication channel that transmits all the radar video information or it may be compressed by analog, digital or manual methods so that it can be transmitted over a much narrower communications channel. The final choice of system components will be decided by the requirements of the basic problem for resolution, off-centered displays, etc. The basic problem is to remote information from various radars such as the ASR's at airports and the long range radars at other sites to a traffic control center such as AOEC. Previous studies indicate that the ASR's will be used to cover a circle of 30 miles radius up to 10,000 feet.

The long range radars will provide low altitude coverage out to 30 miles radius and high altitude coverage out to 100 miles range. Figure 1 shows a suggested PPI coverage pattern for a long range radar in a typical enroute area.

B. Air Traffic - The Data Source

The source of the data for air traffic control is the traffic itself. The number of aircraft within the control area determines the maximum information content of the system. Various studies have been made of traffic density in busy areas. Predictions of future traffic densities are also available. Since this subject has been treated elsewhere, we will not treat it here. However, we will quote two estimates for the New York City area to provide an order of magnitude. In VFR weather peak hour aircraft movements are between 107 and 163 per hour. In 1960 the New York Port Authority estimates there will be 240

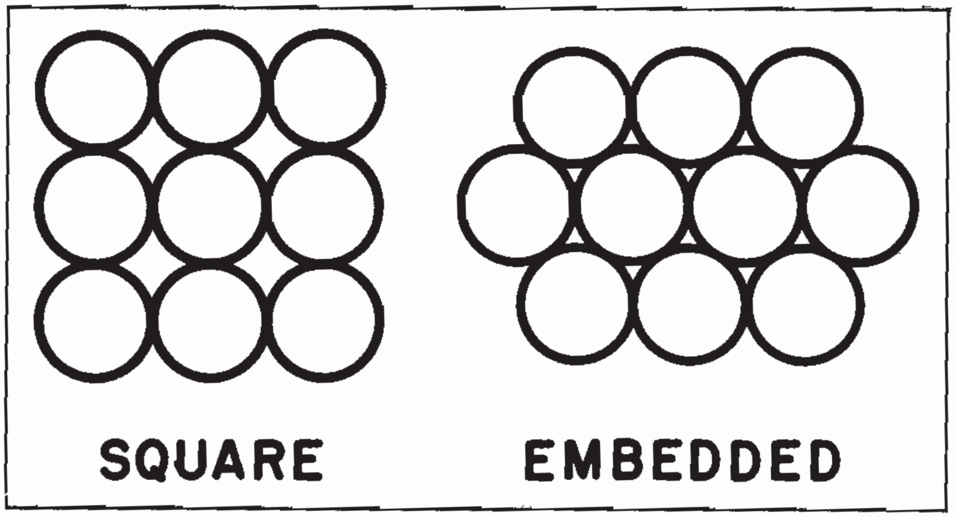

Fig. 1 - Suggested PPI coverage pattern for a long range radar.

movements in the peak hour in the New York area[1]. Assuming a radar with a 100 nautical mile range and an average aircraft speed of 200 knots, an average of 120 aircraft will be visible at any one moment.

C. Radar - The Data Collector

The radar set gathers the data for the system. With the present air traffic densities, targets are seldom close enough so that the radar imposes a limitation on the information available. The exception occurs when aircraft are at or near the same slant range and same azimuth but different altitudes. The method of collecting the data is fixed. Radars locate targets by the polar coordinates of range and azimuth. The characteristics of the set determine the target resolution and information rate and affect the design and use of the other components of the system (Table I).

The target resolution in range and azimuth and the maximum number of targets the radar can acquire can be determined from these characteristics. The range resolution is determined by the pulse width since Range Resolution (nautical miles)

$$= \frac{\text{Pulse width (microsec.)}}{12.2}.$$

Pulse width also determines the information rate of the radar set. The information rate of target reflections is the reciprocal of the pulse width.

The azimuth resolution of the radar is determined by the antenna beamwidth. This does not affect the minimum bandwidth for the system but it does affect the number of composite targets acquired per unit time. It also influences the design of narrow band systems and their bandwidths.

The size of the radar reflection is a function of the physical size of the target and the characteristics of the radar set. In general, aircraft dimensions are small enough when compared with pulse width and beamwidth to be considered point sources for reflections. Since the duration of a reflection determines its range dimension, a point target will have a minimum length equal to the pulse width. The maximum number of targets along any range sweep is the selected range divided by the pulse width.

This same point target reflects as long as it is in the rotating beam. Thus the azimuth dimension of the average radar target will be about one beamwidth wide. The maximum number of targets at the same range is 360° divided by the beamwidth.

The total number of radar targets that can be resolved in a circle of given range is: Maximum No. Targets =

$$\frac{360^\circ \text{ x Range(nautical miles)}}{\text{beamwidth x pulse width(nautical miles)}}.$$

For the two radar sets being considered, the number of resolvable point targets and the maximum information rate in targets per second are listed in Table II.

While resolution is important, the accuracy with which a target is located is also important to the traffic controller. For radar sets in

Table I

RADAR CHARACTERISTICS

Characteristic	Short Range	Long Range Radar
Pulse length, microseconds	0.83	1.0
Range resolution, nautical miles	0.07	0.08
Minimum bandwidth, cps	1.2×10^6	10^6
Antenna rotation rate, deg. per second	to 180	36
Azimuth beamwidth, degrees	3	1
Maximum range considered, nautical miles	30	100
PRF in pulses per second	1200	350

Table II

MAXIMUM RESOLVABLE NUMBER OF RADAR TARGETS

		Maximum Resolvable Number of Point Targets			
Radar Set	Selected Range (nautical miles)	Range	Azimuth	Total per Rotation	Total per sec.
Long Range Radar	100	1220	360	440,000	44,000
	30	366	360	132,000	13,200
ASR	30	440	120	52,800	26,450

general the relative positions of targets can be located to at least one third of the resolution in both range and azimuth. The absolute accuracy of a target's location depends on the circuit and components of the radar set and the calibration of the whole system. This additional detail available from the radar information is an aid to the controller in vectoring aircraft and maintaining radar separations.

D. Displays

The way in which the radar information is displayed determines the information rate which is required for the narrow band systems.

A rule of thumb states that 150 spots can be resolved on the radius of a PPI display on a cathode ray tube[2]. With increasing tube size the spot size also increases and resolution stays about the same. However, with more modern gun construction[3,4] additional resolution between 300 and 400 spots/radius can be expected. If the long range radar set has a resolution of .08 nautical mile and the scale chosen for a centered display on a 30" tube is 2 nautical miles per inch, then the maximum size desired for a resolvable spot is 1/25 inch and the maximum number of spots per radius is 390. Since an ASR radar has a pulse length of .83 microseconds, its resolution is .07 nautical miles. A resolution of 430 spots per radius is required from the 30" display to use the maximum range resolution of the radar set. This spot size is 1/29 inch in diameter. When off-centered displays are used, the range resolution of the display does not change if the range scale is not changed.

Azimuth resolution for a PPI display varies directly with the radial distance from the center of the tube. On the basis of 150 spots per radius, there are 942 resolvable spots around the periphery. So at the periphery of the scope the azimuth resolution is .38°. On a scope having a resolution of 400 spots per radius, the resolution at the periphery is .14°. These resolutions are better than one beamwidth for both the short and long range radars. As mentioned in section C, the azimuth accuracy of a search radar set is generally accepted to be 1/3 of the beamwidth of the antenna pattern. Whether the resolution of the system should be good enough to present this accuracy needs to be determined for short range targets. In general it is better than this for long range targets. The accuracy with which a target must be located probably will need to be decided by operational experience.

The azimuth resolution must be considered when using off-centered displays. Then the azimuth scale is magnified. A display 60 miles in diameter with the center offset 60 miles subtends an angle of approximately 53°. A scope having a resolution of 400 spots per diameter has a resolution of 7.5 spots per degree or 0.14 degree between adjacent spots at the center of the scope. Thus the limit on azimuth resolution is not the off-centered display, but rather the azimuth accuracy of the radar.

There is a circle between the origin of the display and the periphery that has a circumference such that each resolvable spot on the circumference is equivalent to a beamwidth. We can call this the minimum circle of resolution. Within this circle, sweeps one spot diameter wide overlap. The overlap is 100% at the origin and zero at the circumference of the minimum circle of resolution. The redundancy within this circle can be computed as follows: The number of elements or resolvable spots on the circumference of the circle is defined as $= 360°/\theta$ where θ is the beamwidth of a scan. Elements/radius $= 360/\theta \times 2\pi$. The number of resolvable elements covering the area within a circle of this radius

$$= \pi R^2 = \pi\left(\frac{360}{\theta \times 2\pi}\right)^2 = \left(\frac{360}{\theta}\right)^2 \times \frac{1}{4\pi}$$

The number of elements "painted" in this area = (No. sweeps) (Elements per radius)

$$= \frac{360}{\theta} \times \frac{360}{\theta \times 2\pi} = \left(\frac{360}{\theta}\right)^2 \times \frac{1}{2\pi}$$

The redundancy =

$$\frac{\text{"Painted" Spots} - \text{Resolvable Spots}}{\text{"Painted" Spots}}$$

$$= \frac{\left(\frac{360}{\theta}\right)^2 \times \frac{1}{2\pi} - \left(\frac{360}{\theta}\right)^2 \frac{1}{4\pi}}{\left(\frac{360}{\theta}\right)^2 \times \frac{1}{2\pi}}$$

$$= \frac{\frac{1}{2} - \frac{1}{4}}{\frac{1}{2}} = \frac{1}{2} \text{ or } 50\%$$

The display paints twice as many spots as are actually needed. This redundancy is inherent in the way the radar set gathers information. Thus there is no need to eliminate it in a normal PPI presentation of radar returns. However, the bandwidth required for narrow band relay systems can be reduced if this redundancy is eliminated. How much reduction depends on the particular scanning system used, such as TV or spiral to form either an embedded or a square pattern of spots, Figure 1. Redundancy in the scanning pattern is considered further in section F.

E. Wide Band Relay For Data Transmission[5]

To transmit the radar video or raw beacon video information without distortion of the signals requires a very wide video bandwidth. This bandwidth should transmit at least the fundamental frequency corresponding to the reciprocal of the pulse width. Thus the minimum bandwidth required is 1.2 MC for the ASR radar or 1.0 MC for the long range radar. Beacon pulses are only 0.35 microseconds wide and require a minimum video bandwidth of 2.86 MC.

In addition to the video information, the relay link must provide channels to transmit radar and beacon trigger pulses, radar range marks and azimuth information. By using a microwave relay system, all the information inherent in the radar and beacon signals is transmitted to the air traffic control center. No information is lost through encoding and decoding systems for the compression of the data. This allows radar data to be shown on magnified displays such as off-centered PPI scopes without any loss in range or azimuth resolution over the original radar picture. It also allows the beacon returns to be decoded most conveniently at the traffic control center.

Where coding is by aircraft altitude, for example, decoding must be done at the center unless complicated switching systems, multiple decoders at the receiver, and multiple narrow band relay links are furnished. This decoding requirement is the most important reason for using a wide band microwave relay system.

F. Narrow Band Systems For Data Transmission

A narrow band system is predicated on the basis that the radar picture contains less information than the radar video signal and possibly more information than the user needs. There are two general types of narrow band systems: namely, analog and digital. One such as the Rayfax is an analog system. Here a scanning system reads the composite radar picture rather than the individual pulses and transmits this information to the remote location where it is presented in time synchronism with the scanning system. The other is a digital system which locates a target on a coordinate system by its numerical coordinates, transmits these numbers to the remote location, and locates the target on a similar coordinate system. The requirements for a digital system will be discussed in the next section.

Rayfax System

The Rayfax system manufactured by Haller, Raymond & Brown, State College, Pa. is discussed below. A detailed description of the Rayfax system will be found in references 6, 7, 8 and 9. The Rayfax system limits the range and azimuth resolution as follows. Range resolution is determined by the diameter of the circular trace on an intensity modulated J-scope and the width of the scanning slot. The minimum slot size is determined by the light gathering qualities of the optical system. While a slot size small enough to provide a range resolution of 150 spots per range sweep has been built, production models use a range resolution of only 100 spots per radius. This is more satisfactory and trouble free. These resolutions are obtained with a cathode ray tube which is 3" in diameter and on which the circular display is 2" in diameter. Azimuth resolution is limited by the scanning rate of the optical system which reads the J-scope. The maximum speed at which the present scanning head can rotate is limited to 3600 RPM or 60 RPS by the large bearing used. Thus the maximum information rate of production Rayfax units is 60 x 100 or 6000 bits per second. Other Rayfax units having a slower scanning rate as low as 1.2 x 10^3 bits per second.

Haller, Raymond & Brown advise that some simple modifications would allow the resolution and picture stability to be increased. A new bearing arrangement was designed for the scanning head which would allow it to rotate at speeds up to 167 revolutions per second with increased reliability and azimuth resolution. The ultimate degree of azimuth resolution would allow the Rayfax presentation to match the accuracy of the radar. For search radars this is about 1/3 beamwidth. Table III shows the characteristics of the radar which are used to compute the scanning rates needed to provide this ultimate resolution for the Rayfax.

The tabulation also shows that the number of radar pulses per optical scane is 7 for the ASR radar and only 3 for the long range radar. At once the question arises as to how many hits are required on a target to provide a sufficient signal for the optical system. Haller, Raymond & Brown made some tests using a signal generator. Results showed that a single hit equivalent to a radar return from an aircraft at about 50 miles range would provide a signal output. Since multiple returns are integrated, three hits were believed to be adequate and ten hits would be a good margin of safety to provide a Rayfax signal. The resolution and scanning speed necessary to provide 10 pulses per optical scan are shown below.

	Radar	
Characteristic	ASR	Long Range
Scanning Speed	120 RPS	35 RPS
Azimuth Resolution	1.5°	1°

Table III

RADAR CHARACTERISTICS NOTED IN RAYFAX DESIGN

	Radar Set	
Characteristic	ASR	Long Range
Rotation rate in deg. per sec.	180	36
1/3 beamwidth in deg.	1	1/3
Matching scanning rate in rev. per sec.	180	108
Pulse repetition rate, in pulses per sec.	1200	350
Pulses per optical scan	about 7	about 3

Theoretically it seems that maximum scanning rates provided by Rayfax designs may be adequate but this must be confirmed by experimental tests.

When a scanning rate is chosen, several other design parameters must be matched to it. The antenna rotation rate, beamwidth, persistence of the phosphor and pulse repetition rate are all related to the optical scanning rate. The scanning time can be as long as the storage time of the phosphor. If it is shorter than this, targets will be smeared in the direction of rotation. Conversely the longest scanning rotation time should be no longer than the target illumination time so that no targets are missed. This includes the time required for the radar antenna to rotate one beamwidth plus the phosphor decay time. Greater range resolution can be obtained by increasing the diameter of the J-scope display while the slot size in the scanning head remains the same. The increased range resolution must be obtained by increasing the length of the display rather than decreasing the width of the slot because the minimum width is limited by the amount of light required by the optical system. By increasing the size of the J-scope to a 6" display on a 7" cathode ray tube, the range resolution could be increased 3 times. This would allow 3 x 100 or 300 spots to be resolved in range. On presently available 30" cathode ray tubes this is comparable to the maximum resolution obtainable on a centered PPI display and is about one-half the resolution obtainable on a display off-centered by one radius. If more resolution is desired for displays off-centered more than one radius, a delayed sweep might be designed so that the delay corresponded to the additional off-centering. Thus the displayed portion of the sweep would still have about one-half the resolution of the cathode ray tube.

The maximum information rate for the modified system can be calculated. If the sweep speed is 120 sweeps per second and the range resolution is 300 spots per radius, the information rate is 36×10^3 bits/sec.

While the present mechanical scanning approach is simple, direct and practical, future designs might employ an electronic scanning system. A tube with separate reading and writing guns could perform the same functions now performed mechanically. Moreover, scanning speed and range resolution would not be limited by the mechanical design. Electronic reading speed could be as high as the writing speed, and the range resolution need be limited only by spot size. Future requirements will have to determine the need for such a design.

In the final analysis, the way in which the Rayfax information is used and displayed will determine the bandwidth requirements for the system. For example, the amount of range information required from the Rayfax to present a centered display is only half that required for an equivalent display off-set by one radius and only one-third that for one off-set by one diameter provided range delay is not used. Azimuth resolution on the other hand is about the same as that of the radar and is not as likely to be influenced by the magnification of the sector displayed. It depends on the rotation rate and antenna beamwidth of the radar, where azimuth read-out rate = $\frac{\text{Rotation rate}}{\text{Beamwidth}}$. For the ASR, the azimuth rate is 60 beamwidths per second, while for the long range radar the rate is only 36.

Not all the range and azimuth information from the radar set may be required in the display. Just how much detail is required to follow an aircraft or to resolve nearby aircraft from each other must be determined by operational tests. However, if a fixed bandwidth is available for transmitting the Rayfax signal, there may be an optimum compromise between range and azimuth information. The total information content is the product of these two items; again any compromise should be determined operationally.

When decoded beacon returns are transmitted over a Rayfax system, three codes may be required. They are the single blip, the double blip, and the bloomer. If the distance between the two spots in the double blip reply can be adjusted easily, the setting where the Rayfax encoder will resolve these spots can be determined. The spot size required to transmit a bloomer can also be determined. Whether or not these spacings and sizes are suitable for the controller can then be determined by operational test. Where multiple beacon interrogations occur, it may be possible to eliminate the "fruit" by the proper setting of the Rayfax encoder. Where only the strong beacon returns are displayed there may be considerable latitude in the adjustment. If mixed radar and beacon returns are displayed, some method of setting the level must be devised so that weak radar targets are not eliminated. Separate encoders for radar returns and beacon returns may be the required solution. These two signals could then be mixed and transmitted as a single signal. If synchronizing problems occur in the mechanical system, an electronic scanning system might solve the problems.

One trouble encountered in the Rayfax system is the stability of the picture. Synchronization is established mechanically at north on every rotation. This tends to allow the presentation to shift a few degrees in azimuth. By eliminating this mechanical sync and depending on the electrical sync, the shift should be eliminated after the initial registration of the picture. A north strobe would still be provided to check registration.

The transmission of raw beacon returns will require different techniques. This problem will not be dealt with here.

A Digital System For Narrow Band Transmission

The basic design of a digital system depends on the coordinate system used. Various co-

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