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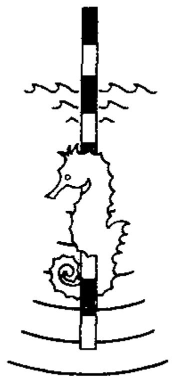

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A Rigorous and Integrated Approach to Hydrophone and Source Positioning during Multi-Streamer Offshore Seismic Exploration

V. Gikas*, P.A. Cross* and A. Asiama-Akuamoa**

Abstract
This paper describes a rigorous and integrated approach for positioning sources and hydrophones within a seismic spread that may contain multi-vessel and multi-streamer configurations. Any number of observations relating to any point(s) within the spread can be accommodated. Quantification and analysis of error propagation within the spread are provided. Test results based on the implementation of the algorithm on a UNIX platform are discussed.

Résumé
Cet article donne la description d'une approche rigoureuse et cohérente des sources de positionnement et des hydrophones dans un déploiement sismique que les configurations multi-vaisseaux et multi-streamer peuvent englober. On peut utiliser un nombre indifférent d'observations relatives à n'importe quel(s) points(s) compris dans le déploiement. La qualification et l'analyse de la propagation d'erreurs à l'intérieur du déploiement y est donnée et les résultats des tests basés sur l'exécution de l'algorythme sur une plataforme UNIX y sont discutés.

Resumen
Este artículo describe un enfoque riguroso y armonioso sobre las fuentes de posicionamiento e hidrófonos dentro de un despliegue sismico que las configuraciones multi-buque y multi-streamer peuden contener. Se puede usar cualquier número de observaciones referentes a un punto(s) cualquiera del interior del despliegue. El artículo proporciona la cuantificación y el análisis de la propagación de errores dentro del despliegue y discute los resultados de las pruebas, basados en la implementación del algoritmo en una plataforma UNIX.

1. Introduction

The basic configuration of an offshore seismic exploration survey is as follows. One or more vessels sail in approximately straight lines whilst towing a number of 'streamers' (typically up to 6 kilometres long) and 'seismic sources'. The streamers carry a number of hydrophones (typically 50-100 per kilometre) and are towed just below the surface of the water [*Morgan*, 1992]. At a specified distance interval (typically every 20-25 metres) one of the guns is fired resulting in seismic waves which travel through the water and penetrate the subsurface. The times of arrival of the reflected and/or refracted signals are then measured by the hydrophones. The surveying problem is to determine the position of the guns and hydrophones at the instants of firing and reception respectively. In principle the position of the vessel is of no interest – except, of course, for navigation.

In recent years the problem has become increasingly complex, mainly due to an expansion of the type and quantity of survey data collected. In a typical configuration, Fig. 1.10, measurements will include compass orientations at points along the streamer (typically 4-7 per kilometre), laser ranges from the vessel to a variety of floats (for instance those carrying the guns and those at the front of the streamer), underwater acoustic measurements (of the distance) between a number of points at the front and back of the system (referred to as the 'front-end' and 'rear-end' acoustic networks), the position of the tailbuoy and the position of the vessel (both typically, but not necessarily, by DGPS). More complicated systems may also include acoustics throughout the length of the streamer and additional navigation devices on the vessel. Moreover, in the case of several vessels operating simultaneously, between vessel measurements would also be made.

The most common approach currently applied to the positioning problem is to treat each epoch, and each measuring system, more or less independently. So both the laser and acoustic measurements are used to transfer the position of the vessel to the floats, while the front-end acoustics relate the floats to the guns and front-end of the streamer, and then the compasses determine the streamers shape. The rear-end acoustics and the tailbuoy positioning serve to provide some control of the orientation and stretch of the streamers. Typically the process will involve some sort of curve fitting operation for the compasses [*Ridyard*, 1989], and several independent 'network adjustments' for the acoustic and laser networks. It is possible that the process will involve 'iterating' several times through the various data types in order to 'best fit' (in some rather general sense) all of the measurements.

Although this approach is probably perfectly satisfactory from an accuracy point of view it suffers from two major disadvantages. Firstly it is highly 'case dependent', i.e. relatively small changes to the configuration or measurement set may lead to major changes in the processing software – something that is especially difficult in real-time (or quasi real-time) quality control. Secondly, and probably most importantly, it is extremely difficult to analyse the error

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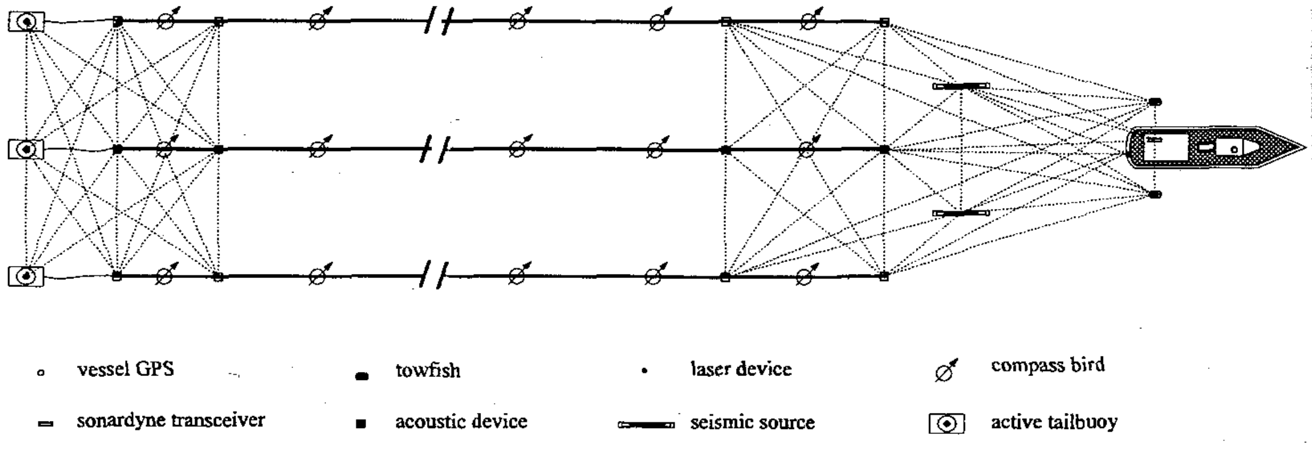

Fig. 1.10: Typical dual source triple streamer configuration

propagation through such a process – hence it is almost impossible to describe the precision and reliability of the final gun and hydrophone positions. This aspect is becoming increasingly important as clients require proof (often in real-time) that the survey specifications are being met.

There is hence a need to develop a completely general (for flexibility purposes) and rigorous (for error propagation purposes) approach to the positioning of guns and hydrophones during seismic exploration and this paper is an attempt to address that need. It describes the mathematical basis, implementation and testing of a Kalman filter that can in principle, handle any geometrical configuration (i.e. any number of vessels, streamers and guns) and any set of observations.

Kalman filters have, in the past, not proved popular with the offshore positioning community and most offshore operators currently prefer simple and independent 'epoch by epoch' least squares computations. For this reason a brief review of the advantages of using a Kalman filter is included before describing the models used in detail.

1.1. Kalman filtering versus simple least squares

Kalman filtering has the following specific advantages over simple 'epoch by epoch' least squares and it is in order to exploit these fully that Kalman filtering was selected as the basic stochastic process behind the unified solution presented in this paper.

1. Simple least squares treats each epoch independently. This means that it does not use knowledge of the motion of the system. Often, and especially in seismic work, it is possible to make a very accurate prediction of where the network will be at any epoch using just the previous position and the estimated configuration motion. Not using this 'knowledge of motion' is effectively discarding information and leads to poorer quality results than those obtainable from a properly tuned Kalman filter. In the past (and sometimes today) poorly tuned filters were used and in this case results might be worse – simply because the system motion may have not been well determined and/or not used properly in the estimation process. So simple least squares is a safe option – but it does not have the potential accuracy of Kalman filtering. The challenge, of course, is to tune the filter properly in real time – and the fact that some have failed to do this in the past has led to Kalman filtering gaining a poor reputation in some circles.
2. The use of a Kalman filter for a highly complex seismic configuration enables a rigorous computation of precision and reliability measures such as error ellipses and marginally detectable errors respectively [*Cross et al,* 1994]. If a step-by-step approach is adopted (such as curve fitting the compass data followed by fitting the results to the acoustics and then to the navigation data) it is almost impossible to compute these measures.
3. Due to its ability to predict the network, a Kalman filter is a far more powerful tool than simple least squares for quality control. Much smaller outliers and biases can be found by Kalman filtering than by simple least squares. It is, however, recommended that, where possible, simple least squares also be carried out at every epoch in order to identify (and correct or remove) the larger outliers. This is because Kalman filtering can be rather time-consuming from a computational point of view and any initial cleaning that can be done by other methods will increase its efficiency.
4. Kalman filtering is able to solve for small biases that will remain in the data if only epoch by epoch processing is used – such as drifts in gyros and (C-O)s in terrestrial (shore-based) ranging systems. These look like noise in simple least squares and can easily go undetected. A lot can be learnt by looking at the time variation of the data. Of course, in principle this could be done in simple lease squares by analysing time series of residuals but it would be hard to do this in real time – and hard to feed back any findings into the system.
5. Because it can determine and use the system motion, Kalman filtering is able to use observations that do not completely define the system – i.e. GPS data from just two satellites could be used to update a vessel position. Of course, long periods of such data would lead to a significantly degraded result.
6. A Kalman filter can accept data as and when it is measured. With simple least squares, data has to be

reduced to a specified epoch. Therefore, a Kalman filter can cope well with data arriving as a more or less continuous stream.

7. The Kalman filter regime is highly suited to the mixing of varied data types [*Celik and Cross,* 1994], when poor satellite geometry leads to poor positions in a DGPS-only solution, the introduction of data from a gyro carried by the vessel can make a major improvement. It would not be possible to combine these data types in simple least squares because, for an individual epoch the gyro does not give any positional information.

2. Streamer modelling

Since the compasses and other measuring devices are not co-located with the hydrophones it is necessary, in any approach, to have a mathematical model that describes the shape of each streamer. Moreover, because of the numerous hydrodynamic forces acting on the cable in the underwater environment, the cable shape is likely to be significantly distorted from a nominal straight line – so a simple linear model is very unlikely to be sufficient. To estimate this distorted shape two alternatives can be considered.

In the first approach a physical model of the hydrodynamic forces acting on the cable could be used to derive equations which describe the streamer shape. It is known that tension forces due to the vessel pull, and drag forces due to the resistance of the cable through the water, determine its three dimensional shape. Any change in the vessel's speed and any fluctuation in the sea waves, or those generated by the vessel, the wind load or the water currents, would mean changes in the towing tension and drag forces respectively. Such a model can only be applied when these external forces acting on the cable are known with a reasonable accuracy [*Krail and Brysk,* 1989]. It should be stressed, however, that, even if these quantities were known, a system of several streamers and floats would lead to models that would be too complicated and inflexible for the construction and implementation of a practically useful positioning algorithm. It is therefore unlikely that, although they have been used for vessel motion, [*Cross and Pritchett,* 1986], hydrodynamic models will be adopted for positioning purposes in the foreseeable future.

The other way to tackle this problem is to consider an 'empirical' numerical approach in which the solution to the problem is deduced by adopting a 'model curve' that best fits the observed data.

2.1 Curve-fitting procedures

Several numerical methods can be adopted to obtain the streamer shape. The simplest one is to consider the cable as a straight line which follows exactly the ship's track. Although this approach would be very simple in practice, significant differences from the final expected position may result, not only because of the angle between the ship's track and the cable's baseline, but also because of the 'deformed' shape of the cable.

A more efficient way to address this problem might be to use a mathematical function such as a cubic spline. However, even though a cubic spline gives a curve which is continuous and continuously differentiable, and one which is capable of fitting the data very closely, it is not the best solution of the problem. This is because its coefficients vary along the length of the cable (i.e. the streamer shape is not represented by a single function) and its incorporation into a single operational system, which is the aim of this study, is extremely difficult. Moreover, because the cubic spline is technically capable of representing faithfully each compass reading, it is hyper-sensitive to compass errors leading to the possibility of a completely unrealistic final curve.

Alternative curve fitting models include least squares polynomial approximation and the use of harmonic functions. This work concentrates on the former. Using least squares polynomials leads to a curve which describes the complete streamer's shape using only one set of coefficients, and furthermore the resultant curve is continuous and continuously differentiable at every point of the cable [*Douglas,* 1980 and *Owsley,* 1981]. As a result, this method can be incorporated much more easily in a unified recurrent process such as a Kalman filter.

Variations of the foregoing are also possible in practice for instance *Ridyard,* (1989), has suggested the use of a 'rolling quadratic' algorithm in which a series of individual quadratics are used to fit a small group of compasses. This algorithm is clearly very effective and this, and similar approaches have been widely adopted within the industry. Whilst they may be very powerful interpolation devices, and whilst they may be very effective in sorting out outliers and highlighting problems, they cannot be easily adopted in the unified approach presented here. This is because (as was the case of the cubic spline) the approach demands the use of a single function to describe the streamer shape.

Hence in this study a 'n-order' polynomial shape model has been utilised. Such 'single' polynomials are not popular in some sections of the exploration industry so their use needs also to be justified from an accuracy point of view (it is clearly not a sufficient argument to use them just because they are convenient), and a series of tests have been carried out in order to do this. These tests involved the fitting of a series of polynomials, of a variety of orders, to real compass data and comparing the results with those obtained from the universally accepted rolling quadratic method. The mathematics and the results are described in the next section.

2.2 Testing of the polynomial approximation

In these tests the only information used is that derived from the magnetic compasses fixed along the length of the cable. This was done in order to compare the polynomial approach with the accepted method (which treats such data independently of any other). In such a case the final accuracy of a streamer position is a function of raw compass data, the local magnetic declination, individual compass corrections and the algorithm used for processing the data. The polynomial observation equations can be written as:

$$B_i = a_0 + a_1 l_i + a_2 l_i^2 + \ldots + a_n l_i^n \qquad (1)$$

where:

- B_i : is the compass reading
- l_i : is the offset of the i-th compass from its reference point
- a : is the polynomial coefficient

The solution of this equation system, using a least squares method, gives the values of the polynomial coefficients. If we consider the geometrical configuration to be as shown in Fig. 2.10, we have:

$$\theta_{(rad)} = \operatorname{atan}(dv / du) \cong \operatorname{atan}(dv / dl) \qquad (2)$$

which for any θ in (-1°,1°) becomes:

$$\theta_{(rad)} \cong \tan\theta = dv / du \cong dv / dl \qquad (3)$$

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