A Paper Reprinted from

THE HYDROGRAPHIC JOURNAL

No. 76

APRIL 1995

The Hydrographic Society

UNIVERSITY OF EAST LONDON · LONGBRIDGE ROAD · DAGENHAM ESSEX RM8 2AS · ENGLAND · TELEPHONE: 0181-597 1946 · FAX: 0181-590 9730

Reliability Analysis in Marine Seismic Networks

N. Zinn and P.J.V. Rapatz*

Abstract

This paper describes the application of Delft-method reliability analysis to the observations and positions of a marine seismic network processed in a Kalman filter that integrates heterogeneous data into a total solution.

The United Kingdom Offshore Operators Association has recommended the internal and external reliability measures of the Delft (or B) method of quality control for differential GPS signals processed in a least-squares, point-positioning algorithm. The extension of these recommendations to the quality control of marine seismic networks is likely.

The Delft method is an appropriate technique for quality control of marine seismic network positioning, especially when previously-accepted measures (such as angles of cut) are less relevant in an integrated solution. However, the geophysical industry has yet to specify acceptable values for reliability measures in this context.

Engaging the debate, this paper examines expected internal and external reliability values for a theoretical network that are determined in preanalysis. Actual values determined for a similar-but-real network by processing real data in Western Geophysical's TOTALNET[®] algorithm are offered for comparison and analysis. The paper concludes with recommendations for appropriate quality control analysis based on comparisons with the results from the simulated and real networks.

Résumé

Cet article décrit l'application de l'analyse d'exactitude Delft aux observations et localisations d'un réseau sismique maritime traité dans un filtre Kalman qui intègre des données hétérogènes dans une solution totale.

L'Association d'Opérateurs Offshore du Royaume Uni a recommandé les mesures d'exactitude internes et externes de la méthode Delft (ou B) de contrôle de qualité pour les signaux du GPS différentiel traitées avec un algorithme de moyens carrés de positionnement ponctuel. L'extension de ces recommandations au contrôle de qualité des réseaux sismiques maritimes est similaire.

La méthode Delft est une technique adéquate pour le contrôle de qualité de positionnement des réseaux sismiques maritimes, en particulier quand les mesures acceptées antérieurement (telles que les angles d'intersection) ont moins d'importance dans une solution intégrée. Pourtant, l'industrie géophysique doit encore préciser des valeurs acceptables pour les mesures d'exactitude dans ce contexte.

Pour ouvrir le débat, cet article examine les valeurs d'exactitude interne et externe pour un réseau théorique, déterminées dans une analyse préliminaire. Les valeurs réelles déterminées par un réseau semblable mais réel, en traitant les données réelles avec l'algorithme TOTALNET, de la Western Geophysical, sont données pour qu'elles puissent être comparées et analysées. Cet article conclut par des recommandations pour les contrôles de qualité adéquats, basés sur les comparaisons avec les résultats provenant de réseaux simulés et réels.

Resumen

Este artículo describe la aplicación del análisis de exactitud Delft a las observaciones y localizaciones de una red sísmica marítima procesada en un filtro Kalman que integra datos heterogéneos en una solución total.

La Asociación de Operadores Offshore del Reino Unido ha recomendado las medidas de exactitud internas y externas del método Delft (o B) de control de calidad para las señales del GPS diferencial procesadas an un algoritmo de mínimos cuadrados de posicionamiento puntual. La extensión de estas recomendaciones al control de calidad de les redes sísmicas marítimas es parecida.

El método Delft es una técnica adecuada para el control de calidad del posicionmiento de las redes sísmicas marítimas, especialmente cuando las medidas aceptadas previamente (tales como ángulos de corte) tienen menos importancia en una solución integrada. Sin embargo, la industria geofísica tiene aún que especificar valores aceptables para las medidas de exactitud en este contexto.

Abriendo el debate, este artículo examina los valores de exactitud internos y externos para una red teórica, determinados en un análisis previo. Los valores reales determinados por una red similar pero real, procesando datos reales con el algoritmo TOTALNET, de la Western Geophysical, son dados para que puedan ser comparados y analizados. Este artículo concluye con recommendadciones para los controles de calidad adecuados, basados en las comparciones con los resultados procedentes de redes simuladas y reales.

1.0 Introduction

Marine-seismic positioning networks deployed in the geophysical industry today are large and complicated. Even the relatively-basic marine-seismic 'spread' analysed in this paper (single vessel, three energy sources and three long cables) has 57 cable compasses, 36 acoustic devices, 6 in-the-water differential GPS (DGPS) devices and an observational redundancy (degrees of freedom) of more than 100. Precise, tested and reliable positions are required today in 'real-time', i.e. seismic-event time or about every 6 to 10 seconds. The multi-vessel, multi-streamer marine seismic enterprise and

the challenge of processing the available navigational observations are well described in previous Hydrographic Journal papers (Naylor, 1990; Zeelst, 1991) and are not elaborated upon here. A comprehensive, seismic-network processing algorithm has also been proposed in this journal (Houtenbos, 1989), although the algorithm used in this paper differs (Zinn and Rapatz, 1993).

Precision (the propagation of observational random errors into positional random errors by the adjustment algorithm), statistical testing (of the unit variance and w statistics) and reliability (internal and external) in a least-squares adjustment algorithm are key elements of the UKOOA- recommended quality-control strategy for DGPS, the primary surface navigation system used in the seismic industry today. This strategy was recently described in The Hydrographic Journal (Cross, Hawksbee and Nicolai, 1994). Although precision reports and testing for blunders (spikes or outliers) by one method or another have been commonly implemented in DGPS least-squares algorithms, Delftmethod reliability analysis has been less common. UKOOA's recommendations apply specifically to the least-squares adjustment of DGPS observations.

Kalman filters are adapted quite successfully to DGPS processing and can provide benefits over simple least squares processing, especially in dynamic navigation. Whereas Bmethod analogues for Kalman filters have been described by Delft geodesists (see references under Teunissen and Salzmann), UKOOA has yet to make specific quality-control recommendations for the Kalman filtering of DGPS observations. As UKOOA's recommendations become accepted, this extension will be required.

Given the certain acceptance of UKOOA's recommendation of B-method reliability analysis for DGPS, reliability analysis is likely to become an industry-wide requirement not only for DGPS, but for the marine-seismic positioning of energy sources and cable receiver groups. These longanticipated features are currently available in Western Geophysical's TOTALNET real-time network algorithm and UNAVCHK® post-processing network algorithm, both of which use extended Kalman filters.

In addition to the impetus provided by UKOOA's recent recommendations, there is an added issue of these new measures (precision, testing and reliability) replacing previously-accepted, network quality-control measures such as angles of cut of lines of position (LOPs), numbers of LOPs, dilution of precision (DOP), positional comparisons and sensor functioning status. Unfortunately, as of this writing, there are no published (or unpublished) industry guidelines about what constitutes 'acceptable' reliability in a marine seismic network processed in a Kalman filter. Furthermore, there are some surprises in the application of the Delft concept of reliability to marine seismic networks with their sparse and non-uniform distribution of redundancy.

As a beginning, this paper offers two analyses of a typical marine seismic network using the Delft technique modified for an extended Kalman filter. First, the network is simplified, simulated and preanalyzed to provide base-line expectations of the real-life situation. These values represent a best-case scenario under the given constraints. The reanalysis of the simulated network is contrasted with the analysis of the real network with the real-time software. In the real case, results will be affected by varying measurement quality, missing or removed data and changing geometry. The comparison of these two analyses and the interpretation of the reliability in the real case will support our recommendations. This paper is a beginning of the discussion of this issue. As more investigations like this are undertaken, our understanding of the analysis tools at the disposal of the marine surveyor will mature and our confidence in our final results will increase.

2.0 A Comment on Kalman Filtering

The Kalman filter is in the family of least-squares adjustment techniques, i.e. it can be derived using the leastsquares principle (Cross 1983). The advantage of the Kalman filter over least-squares estimation for a node or

network in motion is that it uses a dynamic model in addition to the measurement model. The measurement model provides current positions by processing observations. The dynamic model provides current positions by applying some rule of motion to previous positions. The filter arbitrates between these positions statistically. Because more information (positional history and a transitional rule) is used in a Kalman filter than in least-squares estimation, resulting positions can be more precise and, more to the point of this paper, external reliability can be better. The analysis in this paper is based upon the Kalman filtering of marine seismic network data, with least-squares reliability definitions being given and then extended to Kalman filters. An extended abstract, based upon a least-squares reliability analysis of several similar networks that also includes cost factors, is available elsewhere (Zinn and Humber, 1994).

A Kalman filter provides more features for tuning than does least-squares estimation. An important feature that can be tuned is the amount and type of transition (or process) 'noise' applied between measurements, i.e. the increase in positional uncertainty during motion. Added noise increases the predicted variances of the innovations (the predicted less the observed data) and, consequently, the reliability statistics examined in this paper. The details of the data snooping strategy, discussed in this paper, also have an affect on the tuning of a Kalman filter. A Kalman filter is tuned empirically by processing combinations of simulated and real data until near-optimal results are achieved; a skill as much as a science. Reliability statistics can be affected more by tuning in a Kalman filter than by tuning in a least-squares algorithm, which the reader of this and other similar papers should consider.

3.0 Data Snooping and Reliability

Reliability can mean many things. In the context of this paper it has the technical meaning in surveying. Reliability is a hypothetical consequence of the Delft method of data snooping, which is being adopted for blunder detection by many navigation applications used in the geophysical industry. The Delft method (also known as the B method) was formalized by the Dutch geodesist, W. Baarda (1968). Baarda makes for abstruse reading, but his ideas have been explained and expanded by successive generations of Delft geodesists (Kok, 1984; Bakker et al, 1989; Teunissen, 1988, 1989 and 1990; Salzmann, 1991 and 1994; Nicolai, 1988) and by the perspicacious British geodesist P.A. Cross (1983 and 1993). From Delft these ideas have found their way throughout the offshore industry.

Before quantifying the actual values we can expect of reliability in marine seismic networks, we first briefly and qualitatively describe the Delft method of data snooping and reliability. For this entire discussion, uncorrelated normally distributed observations are assumed.

Presume that the adjustment model applied in a navigational situation is appropriate. Individual observations can be tested as potential outliers by using the normallydistributed w-statistic. In least-squares estimation, a wstatistic is an observation's residual divided by the standard deviation of the residual. Given some choice for the twosided significance of the w-statistic test (called alpha), an observation may be rejected as a blunder if its w-statistic is too large in absolute value. The relationship between multiples of the w-statistic and probability is defined by the normal probability distribution.

In a Kalman filter, an observation's w-statistic is defined differently. It is an observation's innovation divided by the standard deviation of the innovation. Testing is the same as in least-squares estimation except that blunder detection can be done before, rather than after, processing. This is a distinct advantage since processing need not be repeated.

3.1 Reliability

Reliability is based upon the concept of the power of a statistical test. Whereas alpha (defined above) is the two-sided probability of rejecting good data (e.g. a direct acoustic arrival), beta is the one-sided probability of accepting bad data (e.g. a reflected acoustic arrival). Power is 1 minus beta. The most powerful test is the one with the smallest beta. (Note: Delft terminology reverses these definitions of beta and power.) Choices for alpha and beta are arbitrary; 1% and 20% respectively are often cited in the literature. Given choices for alpha and beta we can define the 'non-centrality' parameter delta δ (see Figure 1) as the number of innovation standard deviations between the mean of the population of outlying data (such as reflected arrivals). Table 1 gives some possible values of δ .



Fig. 1: MDE and δ in a Kalman Filter

alpha / beta	20%	10%
0.27%	3.85	4.29
0.5%	3.65	4.09
1.0%	3.42	3.86
5.0%	2.81	3.24

Table 1: Non-centrality Parameter δ

3.2 Internal Reliability

Internal reliability is the marginally detectable error (MDE) of an observation. In a least-squares algorithm the MDE is δ times the variance of the observation divided by the standard deviation of the residual. In a Kalman filter the MDE is approximated as δ times the standard deviation of the innovation, a somewhat different number. Because the standard deviation of the innovation depends upon the size of the uncertainty matrix (P or C_x, depending on notation), the issue of process noise (Q) has a direct bearing on the size of the MDE. In both cases the MDE is hypothetical, being defined by alpha, beta, the observational standard deviations and network geometry, but not by any actual observational value. The MDE is the smallest outlier than can be detected by the Delft method of data snooping at a particular significance and power of

the test. MDEs can be preanalyzed for a particular configuration in much the same way that a surveyor can preanalyze precision when geometry and observational standard deviations are known.

Figure 1 defines δ (in units of innovation standard deviation multiples) and the MDE (in the same units as the observation) for a Kalman filter.

3.3 External Reliability

External reliability carries the concept one step farther. It is the hypothetical effect on nodal position of an MDE (if there were an undetected, unrejected actual blunder of that size). External reliability is (we believe) the more important concept. It is the effect of the potential failure of our blunder detection mechanism (the Delft method) on our results (nodal coordinates). This nodal shift is produced by processing each observational MDE in turn and noting the positional shifts. It is important to stress that both the MDE and external reliability are hypothetical concepts. The probability of suffering a marginally undetected error and its induced positional shifts may be small, but because blunders are unpredictable, this probability cannot be ascertained.

3.4 Reliability Analysis

Internal and external reliability are the 'ribbons and bow' on an algorithm's 'package' of positional error assessment. In TOTALNET, for example, we quantify observational random errors by defining base standard deviations values (from manufacturers' specifications, studies or experience) and by monitoring actual performance with linear regression schemes. We detect biases by studying a whole-line statistical summary that includes innovation sequence mean and standard deviation for all observations. We detect blunders with the Delft method. Observational random errors are propagated by the Kalman filter into nodal precision. Nodal precision can be propagated to the horizontal midpoint (HMP) between any source node and any receiver node, where seismic data is binned in the field. Nodal and HMP error assessment is 'reliable' when the maximum shift in any HMP induced by any MDE is within some acceptable relationship with HMP precision and the client's error specification. Unfortunately, the industry has not yet specified this 'acceptable relationship', i.e. satisfactory numbers for observational MDEs or maximum shifts at any node or HMP.

3.5 Redundancy and the Evolution of the Reliability Requirement

Baarda developed his data snooping method for use in highly redundant land-surveying networks. The main example network in his 1968 publication shows a fairly uniform distribution of 126% redundancy. An early paper stressing reliability in the offshore industry (Nicolai, 1988) also exhibits a situation of significant (100%) redundancy. Since 1991 UKOOA committees have studied the issue of quality control in DGPS applied to the seismic industry (Jensen et al, 1992; Cross et al 1993) and their recommendations stress the requirement of redundancy (among other factors). Since DGPS involves only one node (the antenna position) redundancy is per force 'uniformly distributed'.

But what of the extension of Delft/UKOOA method reliability analysis to marine-seismic networks? The mathematics of the Delft/UKOOA method favor networks of uniformly distributed redundancy i.e. the reliability of those observations which are inadequately supported by redundant observations is poor. The numerous nodes and inhomogeneity of marine-seismic networks are another matter.



Fig. 2: Analysis Network At 15 to 1 Aspect Ratio

Redundancy is amply distributed at the front and tail of the network, and sometimes in the middle, but is poorly distributed along the unsupported sections of the cables (see Figure 2). We can expect that Delft/UKOOA method reliability will be poor along the poorly redundant cable and this is the case.

4.0 Integrated Marine Networks

Fully integrated network processing algorithms bring several advantages.

- (1) The synergism of mixing distance and azimuth observation types is exploited. For example, distances constrain along the axis between two nodes, azimuths constrain across the axis between two nodes. Nodal precisions are better when all observation types are integrated into one network.
- (2) An integrated network is totally interdependent. For example, improvements to tailbuoy positioning can improve the positions of the sources!
- (3) The precision of the horizontal midpoint (HMP) can be rigorously computed if source and cable stations are connected by the complete variance-covariance matrix of a total network; HMP precision must be estimated otherwise (Zinn, 1991). Because of quantifiable source and receiver error cancelation, the precision of the HMP can be better than either source or receiver precision!
- (4) Acoustic observations can be placed anywhere along the cable as part of an integrated solution.

To integrate compass azimuths along a cable into a network of survey nodes (sensor locations), some method of reducing tangential azimuths *at* nodes to connected azimuths *between* nodes is necessary. The technique of 'azimuthal decomposition' applied in this paper was developed at a major oil company and purchased by Western as part of a navigational post-processing package. The statistical error propagation characteristics of azimuthal decomposition were worked out entirely at Western. This technique approximates the cable as a concatenation of gentle circular arc segments between compass and acoustic devices. With this simple assumption, the necessary chordal observation equations linking the total network for adjustment can be written. The stochastic model is somewhat more complicated.

A competing method for dealing with cable compasses is the polynomial 'shaping' of the cable, i.e. interpreting compass azimuths as the differentials of a polynomial. One advantage of this method is the preservation of degrees of freedom along the cable given some *a priori* knowledge of cable shape (since, for example, 19 compasses in a fourth order polynomial yields significant redundancy). Azimuthal decomposition, on the other hand, is exactly determined over much of the cable. One disadvantage of polynomial shaping is the inevitable artifact of compass residuals at the polynomial tangents, an adjustment before the adjustment. Another is the requirement of breaking the polynomial at acoustic nodes to integrate the distance observation type. Often, polynomial shaping is used to connect partial (i.e. non-integrated) networks at the front and tail.

4.1 Legacy Quality Control Requirements

One perceived disadvantage of integrated networks is the obviation of legacy quality control measures such as angles of cut of lines of position (LOPs), numbers of LOPs, dilution of precision (DOP), positional comparisons, sensor malfunction and subnet comparisons (such as tailbuoy surface navigation versus cable compass traverse versus cross-buoy acoustics or cable traverse versus cross-cable acoustics). These metrics, once used so extensively in radio positioning and applied to the marine seismic spread, can be augmented (if not superceded) in heterogenous, integrated positioning solutions by the UKOOA recommendations of precision, statistical testing and reliability analysis applied to observations and positions. For example, it is problematic to qualify or disqualify a position based on a 30-150 degree rule for particular LOPs when integrated into that position via a fully-populated variance-covariance matrix are DGPS, compass, and acoustic observations from many sensors. The Delft method can provide a more realistic assessment of the reliability of an observation or a position and serve to replace, or at least augment, historical quality-control measures.

4.2 HMP Precision and Reliability

Integrated network algorithms automatically and rigorously provide the precision of all nodes in the networks as consequences of data quality, geometry and sensor function, i.e. as consequences of many legacy quality control considerations. Furthermore, the fully-populated variancecovariance matrix of an integrated solution makes it possible to rigorously determine the precision of the HMPs themselves. This may be specified any number of ways, but 2dRMS is used in this paper. And because of the multiplicity of HMPs, only the maximum value among all HMPs is reported in real time and plotted. This statistic is a geophysically-valuable (albeit pessimistic) measure for the overall network precision. Offshore operators are today specifying acceptable seismic navigation results (rather than details) in terms of seismic bin size and the HMP. For example, a binning standard deviation of 33% of the bin dimensions for a 12.5 meter by 25 meter seismic bin translates to a maximum HMP 2dRMS precision of 18.6 meters.

It is natural to extend the concept of external reliability to the HMP. Integrated network algorithms facilitate the computation of HMP positional shifts due to an observational MDE. We will show in the analyses that follow that HMP external reliability is more sensitive to observational redundancy and quality than is HMP precision. Therefore, reliability is a more useful tool for monitoring network performance.

4.3 Compass Data Handling

We will also show in the analyses that follow that cable compasses, arrayed along observationally non-redundant stretches of the cable, are the main contributors to the hypothetical shifts in HMP positions called external reliability. In other words, given common marine-seismic network configurations, the Delft-method of data snooping is less effective for cable compass observations than for other observation types. Therefore, TOTALNET employs a more-stringent, observational-sequence-mean, blunder detector than the Delft method for cable compass data. In keeping with a raw-data philosophy in real time, this is not a prefiltering or preadjustment of compass data. It is an outlier detector based on experience and a knowledge of cable motion during the marine-seismic enterprise and is called the preeditor. Preediting does affect empirically-derived observational variances.

5.0 Network and Processing Description

The marine seismic spread analyzed in this paper is chosen for its simplicity. It consists of a single vessel, three source arrays, three 6000-meter cables and the three active tailbuoys. The data are derived from most common sensor types found in today's modern seismic navigation package: DGPS, acoustics, cable compasses, gyro compass, depth sensors and velocimeters. There are 19 cable compasses per cable, proprietary and vendor-supplied acoustics on the front end, cross-cable acoustics at two places along the cable and acoustic quadrilaterals at the tail. There are DGPS sensors on each source array and tailbuoy generating range and azimuth observations relative to the vessel. Network geometry is defined by source separations of 50 meters, cable separations of 150 meters, source step-backs of 250 meters and cable step-backs of 480 meters.

The real data analyzed comes from an actual production line and spans one hundred shotpoints. There are 102 nodes in the network and approximately 300 observations per shot cycle. The network has been simplified for the preanalysis. This is accomplished by reducing nodes to a minimum, e.g. all acoustics and GPS locations on a source array attach to a single node and all acoustic nodes are co-located with compass nodes. Among 67 compound preanalysis nodes there are 227 observations.

The processing algorithms used for both the preanalysis and the real-time system are similar in nature and tuned in the same manner and degree. Choices for observational variances and statistical thresholds have been standardized between the two systems to facilitate comparison of the analysis results.

Reliability is defined by alpha, beta, network geometry and the observational standard deviations. Alpha is the 0.27% probability associated with being more than 3 standard deviations on either side of center. Beta is 20% (or a power of 80%). These choices result in a δ of 3.85. Observational variances were chosen to reflect the observed behaviour of each sensor. In the preanalysis algorithm these values are fixed. In the real-time system, these variances are dynamically estimated. The chosen observational standard deviations are 2.0 meters in latitude and longitude on the vessel, 0.8 meters for all acoustic distances, 0.4 degrees for all cable compasses azimuths and 3.0 meters in each axis for in-the-water DGPS relative to the vessel (measured four times per shotpoint and appropriately adjusted). Along-cable distances are processed as distance observations with standard deviations of 1.9 meters between nodes. Both

precision and reliability depend upon these choices of observational standard deviations and we compare precision with external reliability at the HMP.

Whereas internal reliability is a straightforward calculation, external reliability is not. Each observational MDE is associated with a shift in the position of every node in a totally integrated network. For the preanalysis case of 67 nodes and 227 observations, this results in 15,209 shifts and in the real-time case this increases to 30,600 shifts, each in two dimensions. This unwieldy number of measures is reduced to two plots and then only one number. First, only source and receiver nodes that have geophysical significance are counted. One plot is of the maximum shift in any source or receiver node for each MDE. Then shifts in source and receiver nodes are propagated to the many possible HMPs that have even more geophysical significance. Another plot is of the maximum shift in any HMP for each MDE. The key number is the maximum shift in any HMP for any MDE (excluding vessel navigation). This is the worst case for one failure of our blunder detection strategy and it can be compared with the largest HMP random error.

6.0 Network Preanalysis

Preanalysis is accomplished with a script written in the Matlab[®], matrix-manipulation language. The script propagates the steady-state variance-covariance matrix, computes the largest HMP precision, computes the MDEs for all observations, individually propagates each MDE into shifts in the positions of all source and cable nodes, computes the largest shift at any HMP for each MDE and computes the largest shift at any JMP for all MDEs. However, unlike the real-time application, the Matlab preanalysis script does not solve for cable stretch and magnetic declination bias.

A study of preanalysis results is facilitated by Table 2, which lists every observation in this simulated network by number range and type. These number ranges are the abscissas (x-axes) of three plots. By noting the plot value versus the abscissa, the MDE or maximum external reliability (node or HMP) for a particular observation can be read.

Observation	Description of Observation
1-2	Vessel navigation in latitude and longitude at aft hull receiver
3-4	'Distance' and gyrocompass azimuth between hull receivers
5-22	Cable 1 chord 'distances' (i.e. configuration measurements)
23-40	Cable 2 chord 'distances' (i.e. configuration measurements)
41-58	Cable 3 chord 'distances' (i.e. configuration measurements)
59-76	Cable 1 compass chords (i.e. azimuthal decomposition)
77-94	Cable 2 compass chords (i.e. azimuthal decomposition)
95-112	Cable 3 compass chords (i.e. azimuthal decomposition)
113-131	Proprietary, front-end acoustics
132-167	Supplementary, front-end acoustics
168-179	Cross-cable acoustics at the middle
180-215	Tail-end acoustics
216-221	DGPS distance and azimuth to three tailbuoys from aft hull receiver
222-227	DGPS distance and azimuth to three sources from aft hull receiver

Table 2: Preanalysis Observation Numbers and Description



Plot 1: Preanalysis Marginally Detectable Errors (MDE)

6.1 Internal Reliability: The MDE

Plot 1 gives the marginally detectable error in either meters or degrees (depending upon the observation) for the 227 observations of the network. The three near-zero-degree MDEs at observations 217, 219 and 221 are the relative azimuths to the three tailbuoys. These MDEs are small because the standard deviations of these relative DGPS azimuths are small due to the 3 meter positional standard deviation and the considerable distance between the vessel and the tailbuoys. (That is, the arc tangent of 3 meters divided by the distance to the tailbuoy is a small number.) Note that the MDEs of the cable chord configuration distances (observations 5 through 58) are about 10 meters. Once configuration blunders are corrected at job startup chord distances between cable sensors change only moderately due to stretch and curvature and are tested no further. Cable compass chord azimuths (observations 59 through 112) have marginally detectable errors of about 2 degrees. This means that a cable compass blunder has to be more than 2 degrees before it can be detected using the Delft method of data snooping at the specified alpha and beta in this Kalman filter. Acoustic MDEs are all about 4 meters (observations 132 through 315). Relative DGPS observations are last.

6.2 External Reliability: The Maximum Shift

Internal reliability is interesting, but how do we evaluate the significance of a compass blunder of 2 degrees or an acoustic blunder of 4 meters? The answer is to measure their effect on our results, viz. nodal or HMP positions. Plot 2 gives the maximum shift among all the source and cable notes in radial meters for the 227 network observations processed in an extended Kalman filter. Vessel navigation (observations 1 and 2) MDEs have a 10 meter effect on some node. Cable chord distance nodal external reliability would be in the 6 to 8 meter range if cable chord distances were affected by blunders. Cable chord azimuth MDEs produce maximum nodal shifts of between 8 and 10 meters. Cable compass azimuths are critical observations and these are significant positional shifts at the margins of Delft-method data snooping. These numbers suggest a need for more redundant networks or supplementary blunder detection strategies. In fact, the real-time application supplements the Delft method with a cable-compass preeditor. Acoustic MDEs produce maximum nodal shifts of about 2 meters, an



Plot 2: Maximum Preanalysis External Reliability at any Node

indication of the power of the Delft method given ample redundancy. A marginally undetected relative DGPS blunder may affect some node in the amount of 4 to 5 meters.



Plot 3: Maximum Preanalysis External Reliability at any HMP

A more geophysically-significant representation of external reliability is with respect to the HMP. Plot 3 gives the maximum shift among all possible HMPs between all source and all cable nodes combinations in radial meters for the 227 observations of the network processed in a Kalman filter. Notice that these external reliability statistics are about half those of the previous plot with the exception of vessel navigation, which is excluded from maximum external reliability computation. This is because shifts at the highlyredundant sources are small relative to the shifts on the poorly-redundant cables. These shifts are averaged at the HMP, certainly a more favorable presentation. For comparison, the maximum uncertainty at any HMP (due to random error propagation) is 7.3 meters 2dRMS (95% to 98% probability) in this Kalman-filtered solution. Notice that the maximum external reliability at the HMP due to an undetected cable compass azimuth is about 6 meters. The external reliability of all acoustics at the HMP is better than 2 meters. An MDE-sized, undetected relative DGPS blunder on the sources can have a 4 meter effect at the HMP.

7.0 Real Data Analysis

The TOTALNET package used for real data processing has quality control and analysis tools that include dynamic observation variance estimation, innovation, observation and MDE plots, nodal error ellipses, HMP error estimation, *a posteriori* variance factor, bias detection and worst-case HMP external reliability. These tools help assess network behavior and the precision and reliability of the seismic positioning. Because an operator's capability to detect, identify and correct problems is hampered by the increasing complexity of modern networks, simplicity is desired in a real-time system. A single quality assurance value that is sensitive enough to detect and identify problems is invaluable. Maximum HMP external reliability is computed every shot and displayed real-time. No single blunder can affect any HMP positional estimate by more than this amount.

The dynamic nature of network processing on-line forces us to monitor this statistic. External reliability is a hypothetical value that can be computed without any real data at all. However, a real network can vary dramatically in a short time. Observations may be de-weighted due to signal noise or eliminated entirely. Devices may malfunction and geometry may change. A rise in the HMP external reliability indicates weakness in the network. The source of this weakness could be a lack of observational redundancy in a critical area or a large, estimated, dynamic variance for a critical observation. Histories of the observational MDEs, variance estimates and spike edits can be consulted to identify the problem.

Two different processing 'runs' of the data set are presented to highlight the responsiveness of the external reliability statistic. The first processing run uncovers two cable compass observations that suffer increased observational variance. The second run improves the preediting for these two observations and the resulting reliability statistics are shown. From among an enormous number of statistical summaries and plots, only the maximum HMP external reliability statistic and the maximum HMP precision are shown.

7.1 Run 1

Plot 4 gives maximum HMP external reliability. Maximum HMP 2dRMS value is shown in Plot 5. The reliability plot shows a general floor value of 6 meters with peaks reaching as high as 10. Over a 20 shotpoint range there is an extended rise that reaches a maximum of 14 meters. The single peaks are the result of observations being removed from the network due to data snooping. This causes a local reduction of redundancy for a 1 or 2 shot period. forcing a temporary increase in the external reliability of the related HMPs. The extended rise is another matter and bears closer examination.

Between shotpoints 16510 and 16530 the empiricallyderived observational variances of two cable compasses increase in response to undetected outliers in the signal. As the observational standard deviation increases, so does the MDE and, consequently, also the maximum HMP external reliability. The effect is dramatic because these two compass observations are in a region of the network not wellsupported by other observations. Preanalysis tells us that a blunder in this area can have a large effect upon nodal position estimates. Since HMP precision does not explicitly



Plot 4: Maximum HMP Exeternal Reliability for Run 1



Plot 5: Maximum HMP Precision (2dRMS) for Run 1

indicate a problem, it is reassuring that HMP external reliability does.

7.2 Run 2

To gauge algorithm responsiveness, the same data set was reprocessed using a revised cable compass preeditor. Improved variance estimates improve blunder detection using the w-statistic and, therefore, the reliability of the HMP positions. This is evidenced by Plot 6, which shows that the sharp peaks are still present as expected, but that the rise between 16510 and 16530 is now completely gone. Plot 7 shows that HMP 2dRMS precision improves only moderately.

8.0 Conclusions

The real data results agree with the preanalysis results. Preanalysis maximum HMP precision is 7.3 meters 2dRMS. Real-time maximum HMP precision floors out at about 7.6 meters 2dRMS Preanalysis maximum HMP external reliability is 6.0 meters (due to cable compasses). Real-time maximum HMP external reliability precision floors out at about 6.0 meters. The changing character of the real data plot is a consequence of the changing geometry, observational standard deviations and redundancy of the network. Large deviations from the floor values are reasons for investigation and correction.

Real-data results for a well-performing, Kalman-filtered network show that maximum HMP external reliability typically runs higher than the 2dRMS value for maximum HMP precision. It is our recommendation that the following procedure be adopted when specifying and using HMP external reliability



Plot 6: Maximum HMP External Reliability for Run 2



Plot 7: Maximum HMP Precision (2dRMS) for Run 2

- HMP external reliability should not be allowed to exceed 50% more than the 2dRMS value specified for maximum HMP precision.
- (2) When HMP external reliability exceeds the 2dRMS value specified for maximum HMP precision, the cause should be investigated.
- (3) Periods of 1 or 2 shotpoints where external reliability behaves as described in (1) or (2) above should not be considered as serious as when the situation lasts for a longer period of time. Extending the example of Section 4.2 for a typical marine seismic network, maximum HMP 2dRMS precision would be specified at 18.6 meters and maximum HMP external reliability would be specified at the 3dRMS value of 27.9 meters.

The Delft-method external reliability statistic is sensitive to redundancy. Preanalysis shows that the poorly redundant cable compasses are the cause of maximum HMP external reliability. Real data analysis shows that external reliability is sensitive to statistical confidence in the cable compass data in the non-redundant section of the network. The preediting of compass data based on some knowledge of cable motion is a useful supplement to the Delft method in today's networks.

Cable compasses notwithstanding, the Delft technique of reliability analysis is an effective tool for problem detection in a totally-integrated, marine-seismic, Kalman-filter processing algorithm. This addition to the navigator's suite of tools fulfills the spirit of the recent UKOOA recommendations for marine-seismic networks thus processed.

TOTALNET and UNAVCHK are registered trademarks of Western Geophysical Company, Inc., and Matlab is a registered trademark of The MathWorks, Inc.

References

- Baarda, W. (1968) A Testing Procedure For Use In Geodetic Networks. Netherlands Geodetic Commission.
- Bakker, G., de Munch, J.C., Strang van Hees, G.L. (1989) Radio Positioning at Sea. Delft University Press.
- Cross, P.A. (1983) Advanced least squares applied to position-fixing. University of East London.
- Cross, P.A., Hawksbee, D.J. and Roberts, W.D.S. (1993) Quality Measures For Offshore Differential GPS. United Kingdom Offshore Operators' Association.
- Houtenbos, A.P.E.M. (April 1989) Integrated Processing of 3D Marine Seismic Positioning Data. The Hydrographic Journal.
- Jensen, M.H.B., Nicolai, R. (June 1990) Some practical examples of the use of standardised statistical testing of positioning for seismic and engineering surveys. International Federation of Surveyors, XVIX Congress, Helsinki.
- Jensen, M.H.B. and Drewett, A.A. (March 1992) GPS in Offshore Oil and Gas Exploration. United Kingdom Offshore Operators' Association.
- Kok, J.J. (1984) On Data Snooping and Multiple Outlier Testing. NOAA Technical Report NOS NGS 30, U.S. Department of Commerce.
- Naylor, R. (October 1990) Positioning Requirements for Complex Multi-vessel Seismic Acquisition. The Hydrographic Journal.
- Nicolai, R. (1988) Statistics in Positioning Quality Control. Proceedings of Hydro 88, The Hydrographic Society.
- Saltzmann, M.A. (1991) MDB: A design tool for integrated navigation systems. Bulletin Geodesique Vol. 65(2), pp.109-115.
- Saltzmann, M.A. (April 1994) A Real-time Quality Control Procedure for use in Integrated Navigation Systems. The Hydrographic Journal.
- Teunissen, P.J.G. and Salzmann, M.A. (1988) Performance Analysis of Kalman Filters. Technical University Delft.
- Teunissen, P.J.G. and Salzmann, M.A. (1989) A recursive slippage test for use in state-space filtering. Manuscripta Geodaetica Vol. 14(6), pp.383-390.
- Teunissen, P.J.G. (1990) Quality Control in Integrated Navigation Systems, Proceedings IEEE PLANS 1990, pp.158-165.
- UKOOA (June 1992) Guidelines for the Measurement of Quality and Basic Quality Control of Offshore Positioning Data. United Kingdom Offshore Operators' Association.
- UKOOA (September 1994) Guidelines for the Use of Differential GPS in Offshore Surveying. United Kingdom Offshore Operators' Association.
- van Zeelst, J. (January 1991) Further Considerations in Positioning of 3D Seismic Surveys. The Hydrographic Journal.
- Zinn, N. (1991) Horizontal Midpoint (HMP) Accuracy in Marine Seismic. Society of Exploration Geophysicists Annual Meeting, Houston.
- Zinn, N. and Rapatz, P.J.V. (1993) Positioning Networks in 3D Marine Seismic. Offshore Technology Conference, Houston.
- Zinn, N. and Humbert, K. (1994) The Cost of Reliability in Marine Seismic Networks. European Association of Exploration Geophysicists Annual Meeting, Vienna.

The Hydrographic Journal No. 76 April 1995

© 1995 - The Hydrographic Society