Error Estimation in Positioning and Orientation Systems

Peter Canter
Director, Applanix Marine Systems
85 Leek Crescent
Richmond Hill, Ontario
L4B 3B3
Telephone – 905-709-4600
pcanter@applanix.com

Co-Author:
Doug Lockhart
Chief Scientist
Fugro-Pelagos
San Diego, California
DLockhardt@fugro.com

Co-Author
Corey Collins
Technical Support Consultant
Caris Customer Services & Training, Marine Division
Fredericton, New Brunswick
corey.collins@caris.com

Introduction

Total Propagated Error (TPE) and Combined Uncertainty Bathymetric Estimator (CUBE) are tools and concepts designed for use with hydrographic survey data to minimize subjective user intervention and to help automate data cleaning and filtering. With the trend in hydrographic surveying towards objective estimation of data quality, these methods rely heavily on the error estimates generated by the geo-referencing and motion compensation systems installed on hydrographic survey vessels.

POS MV (Position and Orientation System for Marine Vessels) is a GPS-aided Inertial Navigation System that has been specifically designed to produce an accurate estimate of the echo sounder position and orientation on the ellipsoid in all vessel dynamics. POS MV computes all motion variables including latitude, longitude, altitude, heading, pitch, roll, and heave. This data is computed at 200 Hz and can be output with micro-second-accurate time tagging. Kalman filter error estimates for each motion variable are produced at 1 Hz.

The selection of GPS and inertial sensors and the integration of these complimentary sensors will affect the errors in the position and orientation data. Any method for quality analysis must therefore include ways to normalize error estimation.

This paper will identify the requirements for error estimation in hydrographic positioning and attitude systems and to analyze the effects on final hydrographic data quality. This paper will also discuss the methods Applanix has developed for making this data available to its POS MV users in the absence of a suitable industry standard.

Discussion

"The total variance of the sounding's final position is the sum of all the variances calculated that are related to the positioning within the swath system."[1]

$$\sigma^2_{pfinal} = \sigma^2_{p} + \sigma^2_{pa} + \sigma^2_{pt}$$

where $\sigma^2_{p} =$ offset uncertainties plus distance root mean square (drms)

$\sigma^2_{pa} =$ offset uncertainties in the transducer with respect to the positioning antenna

$\sigma^2_{pt} =$ the uncertainty in the latency offset

and where

$\sigma^2_{pa} =$ the sum of the errors in radial position plus the sum of the variances in roll, pitch and heading[2]

The question then arises as to how each of the variances is computed.

The RMS computation in POS MV is as follows. It applies to position and orientation:

RMS=root mean square (diagonal elements of P matrix)
P is the error covariance matrix of the Kalman filter
P = E{(X(k)-Xe(k))(X(k)-Xe(k))'}
Where X(k) is the true value at time K
Xe(k) is the optimal estimate of the true value at time K
E is the Mathematical Expectation

In the position sense, RMS is not to be confused (which it often is) with the *semi-major axis a* of the error ellipse. In the case of POS MV, *a* is derived by taking the maximum Eigenvalue of the horizontal P matrix from the error covariance matrix of the Kalman filter.

The way in which the estimates of error are computed can vary with navigation system providers. The size of the RMS and/or error ellipse is very much dependent on the modelling of the expected error for an assortment of navigation sensor measurements. The Mathematical Expectation is also a function of the complexity of the Kalman filter model which varies widely amongst position and orientation system providers.

[1] Corey Collins , The Study of Propagated Error in Hydrographic Survey, Senior Thesis, University of New Brunswick, Fredericton, N.B., Canada

[2] Same as 1 above

The reliability of the error statistic is highly dependent on the geometry of the GPS satellites, which are used to compute vessel antenna position, and the quality of the sensor data and offsets, which move the antenna position to the echo sounder.

What this means to TPE is yet to be determined, however one thing is certain, there can be variation in error estimates according to positioning and attitude system type. The most reliable error estimates come from the systems with the highest quality sensors and the ability to accurately model the error at the sensor level in the Kalman filter.

The aim of TPE is to automate the processing of hydrographic data, and therefore it is extremely important to pay attention to how error estimates are weighted in TPE.

Data Analysis

The TPE algorithm which the majority of applications use, including CARIS HIPS, applies only single-error estimations for each contributing dynamic measurement, regardless of the variation in sensor accuracies throughout a survey. That is, sensors which are continuously providing measurements to determine the attitude of the vessel and the position of a sounding, are represented by uncertainty values determined in a non-survey environment. With the POS MV, the user has the ability to obtain derived uncertainty estimations associated with each and every measurement of position, heading, roll, pitch and heave. The use of these values in the TPE computation would provide a more rigorous determination of the overall error budget. Furthermore, it will aid in the process of automated data cleaning by identifying areas of varying uncertainties instead of the processor having to identify these areas through investigation. It will also highlight areas of concern which are currently concealed in the TPE computation.

In CARIS HIPS the user enters single values for the uncertainty of position, heading, roll, and pitch (as well as other values). The user defines these values in the HIPS Vessel File (HVF) which is then used to supply the error estimations to the TPE computation. Figure 1 illustrates the published uncertainties associated with the POS MV.

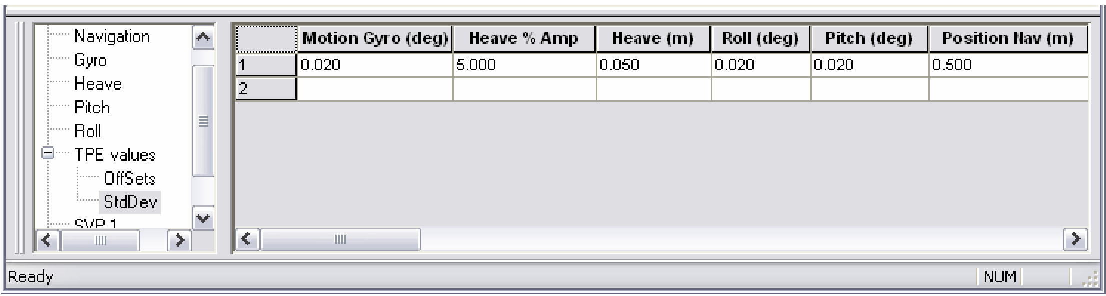

Figure 1
Manufacturer-defined uncertainties for the POS MV

For this analysis it was necessary to compare the TPE computation as it is currently implemented in HIPS, to a TPE computation using the POS MV-produced RMS values (modified HIPS TPE computation by using a continuous update of RMS values). It was observed that the RMS values within the POS MV file closely resembled the published values from the manufacturer (Applanix). Figure 2 contains a list of the average RMS values produced by the POS MV.

Motion Gyro (deg)	Heave (% amp)	Heave (m)	Roll (deg)	Pitch (deg)	Position (m)
0.030	N/A	N/A	0.030	0.030	0.523

Figure 2
Average RMS values produced by POS MV

Figures 1 & 2 show that the published uncertainty values closely resemble the average RMS values produced by the POS MV. However, major differences were observed between the published values and the largest RMS during a recent survey by Fugro-Pelagos, see Figure 3.

Motion Gyro (deg)	Heave (% amp)	Heave (m)	Roll (deg)	Pitch (deg)	Position (m)
0.048	N/A	N/A	0.036	0.036	11.143

Figure3
Largest RMS values produced by POS MV

Figure 2 shows little variation from the Applanix published values with regards to the gyro, roll and pitch. However, it is clearly seen that there was a significant variation in the positioning RMS as compared to the published value that most POS MV users are including in the current TPE computation.

In the following analysis, the TPE computation found in the latest released version of HIPS will be compared to an updated TPE computation in HIPS, where the POS MV-provided RMS values are utilized.

The TPE algorithm was enhanced to use these RMS values produced at each epoch, in an effort to evaluate the benefits of using the POS MV-derived RMS value for each ping, rather than the single HVF entries. In all cases the Depth Total Propagated Error (DpTPE) and Horizontal Total Propagated Error (HzTPE) were compared using the two different computation methods for the overall error estimation.

Due to the high reliability of the attitude measurements (small RMS variation), there was very little difference seen between the two computational methods with regard to the DpTPE. It should be noted that this was the result of careful attention to data acquisition quality, procedure, and a high-end positioning and orientation system. In some surveys attitude RMS can be expected to vary and the DpTPE would be the subject of a separate analysis. However, there were some interesting results seen with regards to the HzTPE due to the significant variation in the POS MV computed positioning RMS values (in limited cases). Due to this fact the HzTPE will be the focus of this analysis. Figure 4 highlights the difference between the DpTPE and HzTPE in the current TPE computation as compared to the modified computation.

	Profile	Beam	Depth (m)	Dp TPE (m)	Hz TPE (m)
Current	751	97	80.99	1.023	1.058
Modified	751	97	80.99	1.027	21.164

Figure 4
Current TPE computation compared to modified computation

Within the current TPE computation of the HIPS application, the TPE section of the HVF is used to define the error estimations of the sensors to the TPE algorithm. For each ping a DpTPE and an HzTPE is computed, both of which use the same sensor error estimation from ping to ping. This is a robust way of estimating the overall error but it lacks sophistication, as it does not model any survey-inherent variation of sensor uncertainty (e.g. positioning uncertainty). By using the error estimations from the POS MV in the TPE computation, areas where the RMS values vary from the norm are highlighted. Figure 5 illustrates the HzTPE values of a survey line computed using the current version of HIPS.

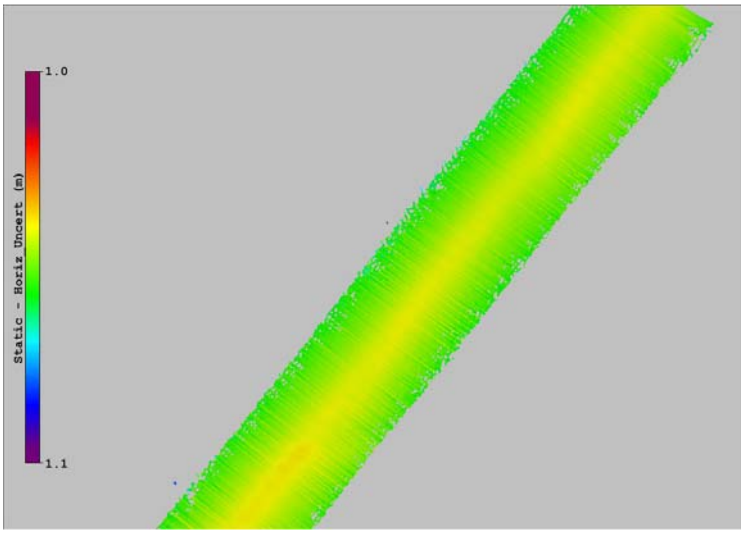

Figure 5
Horizontal uncertainty (95% CL) surface representing TPE values using manufacturer-defined values

Figure 5 shows the HzTPE ranging between 1.04 m and 1.06 m. The only variation seen is from the inner beams to the outer beams, which is characteristic of an individual profile. We see no variation of the trend along track, in fact the only visible variation along track will be dependant on depth variation (and slight variations due to attitude variation) and not sensor uncertainty variation. As long as survey conditions are stable and there is no variation in the performance of the auxiliary sensors, this is a robust way of representing the overall uncertainty of the survey line.

However, when we examine several days of survey data we find periods of sub-optimum GPS data collection.

In Figure 6, a comparison is made between the constant manufacturer-defined RMS value (0.50 m) and the POS MV-derived values for this period. Please note, this example is the exception, which required very close scrutiny and analysis to find this period of poor positioning performance. GPS outages do occur and should be given particular attention in acoustic data processing.

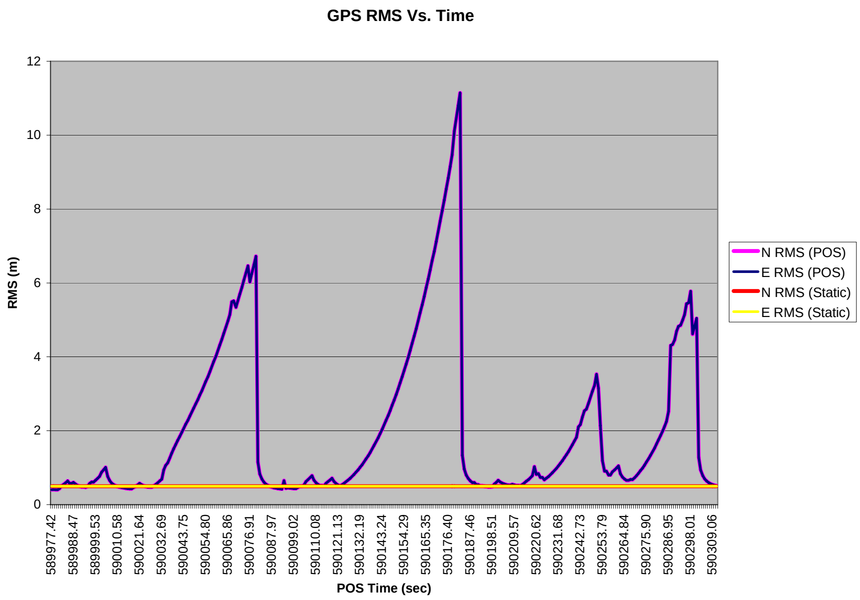

Figure 6
POS MV-derived positioning RMS values Vs. Manufacturer's published values

The high variation in the positioning RMS values can be attributed to the system reverting to *inertial-only* positioning during the periods of GPS outage. An inertial-only-derived solution is susceptible to drift, hence the high RMS values. When looking at the equation $\sigma^2_{pfinal} \approx drms^2 + \sigma^2_{ps} + \sigma^2_{pa} + \sigma^2_{pt}$, it is seen that the N and E RMS values (drms) are significant contributors to the overall computation of HzTPE. When the RMS values from the POS MV are used in the TPE algorithm, a difference is seen in the overall HzTPE of the survey line. Figure 7 illustrates the effect of using continuous-feed RMS values provided by the POS MV, in the overall TPE computation with CARIS HIPS.

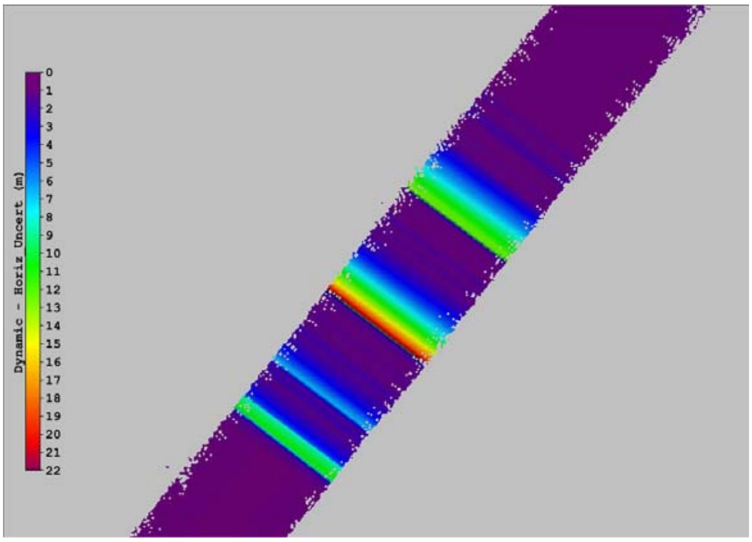

Figure 7
Horizontal uncertainty (95% CL) surface representing TPE values using POS MV RMS values

By comparing Figure5 and Figure7, it is easy to see how the present method of computing TPE can mask the dynamic characteristics of sensor performance in dealing with uncertainty. By using dynamic values provided by Applanix the TPE computation is able to highlight areas of possible concern. The HzTPE is used in the determination of the depth layer of the HIPS BASE Surface. By comparing the depth layer produced using the current implementation of computing TPE, with the enhanced way of computing TPE (continuous feed of uncertainty values), we can see a discrepancy between the two.

Figure 8 shows a difference surface created by subtracting the depth layer of an uncertainty surface, using the POS MV RMS values, from the depth layer of an uncertainty surface using the manufacturer's values.

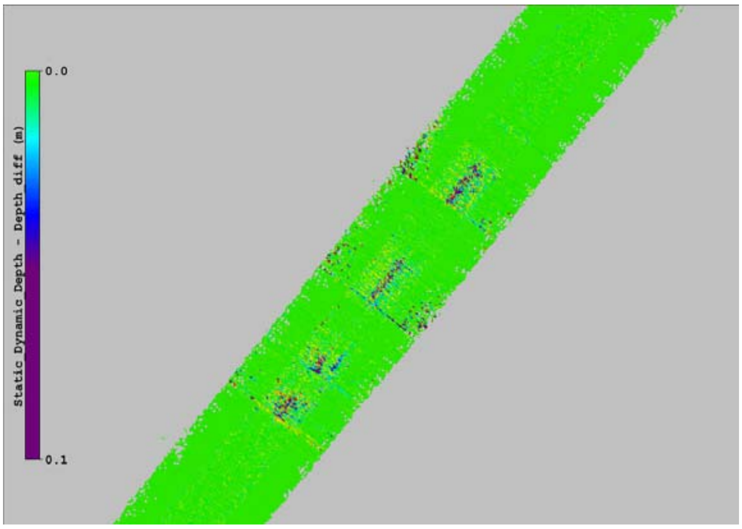

Figure 8
Depth difference surface of static minus dynamic uncertainty values

It is evident that the use of the POS MV uncertainty values in the TPE computation can result in a depth difference of up to 10 cm, when compared to the current way of error modelling and utilization in HIPS. In an effort to robustly compute the error model of a multibeam swath system, it is beneficial to use the RMS values computed for each measurement acquired.

From this analysis, the benefits of utilizing continuously updated sensor uncertainties become readily apparent. It was seen that the current TPE computation does not allow for the modelling of changing sensor uncertainties throughout data collection. With auxiliary sensors, including swath sonar, the associated uncertainties continuously vary. Therefore, it is more robust to use these derived values within the TPE computation. Using continuously updated uncertainty values throughout the TPE computation will aid in the data processing workflow. It will quickly highlight potential problems and areas of concern, as the computed TPE values model the dynamic characteristics of the sensor uncertainties, as opposed to assuming constant uncertainty values throughout data collection. Even though this analysis focused on the HzTPE, it will also benefit the DpTPE if there are variations in the sensor uncertainties which contribute heavily to the DpTPE of a sounding.

Error Data Delivery

In conventional multibeam hydrographic survey, the navigation system's positioning and attitude data is delivered to the echo sounder acquisition or processing system via NMEA serial data. This includes the following NMEA data types:

- GGA – Fix data
- HDT - Heading
- VTG – Speed Data
- GST – Statistics Data
- PASHR – Attitude Data
- PRDID – Attitude Data
- ZDA – Time and Date

Of these only GGA, GST and PASHR contain estimates of error.
In addition:

- GGA quality is not suitable for use in TPE
- GST data contains a measure of the semi major axis and semi minor of the error ellipse and the standard deviations in latitude, longitude and altitude. Note this may or may not be for the position of the echo sounder, depending on how the navigation system is configured
- PASHR record types include accuracy figures for roll, pitch and heading which are not necessarily tied to a standard

In the POS MV a record (see figure 9) is available over Ethernet which is referred to as Sensor Position, Velocity, and Attitude Performance Metrics. This record type contains the following information for each and every sensor at a rate of up to 200 Hz.

Item	Bytes	Format	Value	Units
Group start	4	char	$GRP	N/A
Group ID	2	ushort	104	N/A
Byte count	2	ushort	68	bytes
Applanix Fields	26	*n/a*		
N position RMS	4	float	[0,)	m
E position RMS	4	float	[0,)	m
D position RMS	4	float	[0,)	m
Along track velocity RMS error	4	float	[0,)	m/s
Across track velocity RMS error	4	float	[0,)	m/s
Down velocity RMS error	4	float	[0,)	m/s
Roll RMS error	4	float	[0,)	deg
Pitch RMS error	4	float	[0,)	deg
Heading RMS error	4	float	[0,)	deg
Pad	2	byte	0	N/A
Checksum	2	ushort	N/A	N/A

Figure 9
POS MV record format

This record is available for either of two positions on the vessel as defined by the user. This paper suggests that it would be beneficial for users of positioning and orientation data who are undertaking hydrographic surveys, to take advantage of these data and use the format as a standard.

Conclusion

This paper clearly identifies the benefits of utilizing continuously updated sensor uncertainties. It was seen that the current methodology of TPE computation does not allow for the modelling of changing sensor uncertainties throughout data collection. With auxiliary sensors, including the use of swath sonar, the associated uncertainties are constantly varying and it is prudent therefore to use these derived values within the TPE computation, to achieve a more robust result.

Using continuously updated uncertainty values throughout the TPE computation, will aid in the data processing workflow. It has been seen to quickly identify potential problems and areas of concern. With the computed TPE values there is an ability to model the dynamic characteristics of the sensor uncertainties, as opposed to assuming constant uncertainty values throughout data collection. Even though this analysis focused on the HzTPE, the benefits also apply to the DpTPE if there are variations in the sensor uncertainties that influence the DpTPE of a sounding.

The use of data standards, which allow the exchange of instantaneous estimations of position and attitude error, will undoubtedly benefit the hydrographic survey community in its pursuit of increased data accuracy.