

# *DIRECT COMPARISON USING 2005 COMMON DATASET*

## Motion Sensor Performance

Integral components of a swathe bathymetry system are the motion and heading sensors. The current trend is to offer a system that combines both components in one package, either as an aided inertial sensor or as two sensors linked by component software. The quality of these inertial sensors has a direct effect on the quality of the final survey. This paper compares five leading available sensors, concluding that they produce markedly differing results.

Most surveyors when purchasing or specifying a particular inertial system for a project will base their decision on information generated by the manufacturers, which often shows all systems to offer comparable performance but at greatly differing prices. The comparisons are presented in two ways: as time-varying displays showing individual sensor performance, and in terms of the actual quality of the acquired bathymetric data when merged with each set of motion-sensor data. This paper concludes that the sensors tested produced markedly differing results, and that serial data logging introduced significant errors in attitude measurement.

### Introductory Remarks

This motion-sensor trial was performed in order to produce data that anyone could then take for their own purposes. Any reader using it to aid their purchase of a multi-beam system should be aware that there are many factors to consider, including the nature of the survey work to be performed, installation of the equipment on the vessel and, in particular, the sonar head and IMU. This paper presents one comparison of the data. The authors have no allegiance to any of the manufacturers mentioned, and nor do they wish to misrepresent any commercial product. The reader is encouraged to take the data and arrive at their own views based on their own requirements. Due to problems in acquiring a suitable vessel in the Plymouth Common Dataset 2005 area, the trials described here were conducted using the Coastal Surveyor belonging to The Center for Coastal and Ocean Mapping at University of New Hampshire. The trial area was therefore taken from the Shallow Survey 2001 area, a flat area just North of Newcastle Island. As well as logging the motion-sensor data simultaneously, multi-beam data (from a Reson Seabat 8125) and GPS positioning from a Trimble 5700 RTK system was also acquired. In this way the differences between the motion sensors could also be observed by looking at the different depth values obtained. The motion sensor systems tested were:

- Applanix POS RS
- Applanix POS MV 320
- CodaOctopus F180
- IXsea Octans
- Kongsberg Seatex Seapath 200
- TSS Marinus.

The views and opinions expressed in this paper are our own personal opinion and do not necessarily reflect those of our employing establishments or the UK Ministry of Defence.

### POS RS

The Applanix POS RS is a Position and Orientation System designed for use as a Reference System to measure the performance of other motion sensors, and was kindly loaned by Applanix to aid the trials. The system provides navigation and attitude data, and post-processed measurements of roll and pitch are stated to be accurate to  $\pm 0.0025^\circ$ . Heading measurements are accurate to  $\pm 0.008^\circ$  with GPS aiding (single antenna).

### Data Acquisition

All data was simultaneously time-stamped and acquired using QPS QINSy ver 7.5. Two serial inputs were taken for each system, one for the attitude data and one for heading (with position if applicable). A 1- Pulse Per Second (PPS) signal was taken from the POSMV 320 and fed into the acquisition computer via a QPS TTL device attached to COM 1. This pulse is taken from the onboard GPS receiver and is accurate to  $\pm 100$ ns with the atomic standard GPS time. The pulse can be used for exact time tagging. The PPS pulse is generated as a pulse on an output port of a GPS receiver. Within 900 milliseconds after the PPS pulse is received at the COM port, a ZDA output string with the exact UTC time of the pulse should be available at a control port of the receiver. The data was time-stamped upon arrival at the computer. QINSy uses a very sophisticated timing routine based on the PPS option available on almost all GPS receivers. All incoming and outgoing data was accurately time-stamped with an UTC time label. Internally, QINSy uses so-called "observation ring buffers"™, so that data values may be interpolated for the exact moment of the event or ping.

### Swathe Bathymetry

A Reson SeaBat 8125 was used to acquire simultaneous multi-beam data. This system was chosen as it is generally regarded as the

highest-resolution system commercially available today. The system operates at 455kHz and incorporates 240 discrete beams per ping. The Reson Seabat 8125 can resolve depths to 6mm precision and this allowed accurate surface-difference computations between bathymetric datasets derived from the different sensors.

#### Data Output

During acquisition all motion-sensor, GPS and multi-beam data was recorded in one logged file per line. One XTF (eXtensible Transfer Format – Triton Imaging Inc.) file was created for each motion sensor for each line containing the unique data for that motion sensor, together with the common data (multi-beam and GPS). Therefore the only difference between the XTF files was going to be in roll, pitch, heave and heading values.

#### Motion Sensor Specs

Whilst there is substantial variation in price between the five motion sensors tested, all appear to offer identical performance in heave, and the roll/pitch accuracies vary only from  $0.01^\circ$  to  $0.025^\circ$ . This apparent similarity in capability provided the impetus for this study: did all of these motion sensors really have comparable performance?

#### Tests Undertaken

To evaluate the performance of each motion sensor a series of test survey-lines and manoeuvres were undertaken to simulate the motion experienced by a vessel during typical harbour survey. A reference surface was also surveyed to allow bathymetric comparison. The manoeuvres included  $180^\circ$  turns (normal occurrence during survey at end of line), erratic manoeuvres (designed to stretch to the operating parameters of each system), manoeuvres in a poor GPS environment (masking) under the I 95 bridge, and a straight survey line with high roll rate and amplitude.

During the two days of the trial the region was subject to high atmospheric pressure, resulting in very calm weather. The trials were therefore conducted in very flat water, with no measurable swell or waves. Whilst it would have been useful to have collected some of the data in a moderate sea state, having flat, calm conditions did provide one advantage: we knew that any heave recorded was a result of inaccuracies in each motion sensor, rather than real vertical displacement of the vessel. The main factor that we would be looking at was heave settlement time.

To gain a baseline for heave comparison, recorded heave values from the POSMV were post-processed to produce TrueHeave values. It was believed that this was the closest we could get to establishment of the actual heave experienced on the vessel. Heave is not an output of the POSRS, and it would not necessarily be any better than the post-processed POSMV. It would, of course, be possible to examine and compare all outputs from each motion sensor: roll, pitch, heave, heading and position (where applicable). But it was decided to focus on the elements of the data that have the largest impact on the measured bathymetry: heave and roll.

Since the original presentation of these results at Shallow Survey 2005, TSS International and Kongsberg Seatex have found errors in their systems used for the trials. Therefore version 2.0 onwards in this paper includes in the results some reprocessed data.

#### Reading the Results

When combined with the multi-beam and positioning systems, all the motion sensors on test produced bathymetry that was compliant with IHO Order 1 standards for depth accuracy (Figure 2). The results were further analysed in two different ways. Direct comparison analysis was done of each component from each motion sensor, represented as a time series to show individual sensor performance, and analysis in terms of the vertical accuracy of the acquired bathymetric data when merged with each set of motion-sensor data.

The direct comparison uses graphs to show the heave or roll logged simultaneously from each motion sensor. The heave graphs also show the post-processed TrueHeave from the POSMV, and the roll graphs show the post-processed roll from the POSRS.

To show the vertical accuracy of the acquired bathymetric data the following processing procedure was undertaken:

- patch-testing of each system to derive roll, pitch and yaw values for each
- insertion of POS RS positions into each of the data files to exclude discrepancies due to positional deviations between systems
- taking raw XTF files and applying the same sound velocity, tide and filters, i.e. treating each line in exactly the same way
- creating for each survey line a reference line using the POS RS roll, pitch and heading information, and heave from the TrueHeave file
- creating a 0.5-metre DTM using the same weighting parameters for each line
- surface-difference computation for each line and applying the same colour map to enable ease of interpretation.

Some commentary is included to explain the nature of the manoeuvres undertaken and the achieved results, but in many ways the performance of each system during each stage of the trials is self-evident from the plotted data.

#### Heave Comparisons

##### Heave Line 23 $180^\circ$ Turn

Line 23 (Figure 3) and Line 29 (Figure 5) are really looking at how well the Z acceleration component is “strapped down” in the motion sensors. The better the delineation of the Z acceleration the less likely the sensor is to be affected by large horizontal accelerations such as those experienced in a tight turn. Data logging began at the end of one survey line (point A) as the turn onto the new line commenced (at point B).

F180 and Marinus show deviation of up to 10cm during and immediately after the turn, but settle within 20 seconds of straight running. POSMV shows good agreement with TrueHeave throughout. Seapath shows deviation in heave of up to 15cm during the turn, but does not fully settle for 11/2 minutes. The Octans III was not available at this point in the trials due to the late arrival of the equipment. The surface-difference computations mirror the findings of the graphs (Figure 4). The F180 without a post-processed solution varies by approximately +/- 15cm, but using iHeave (CodaOctopus’s post-processed heave data) the difference is nominally about 1 or 2cm. The Marinus results show what appears to be roll/pitch cross-talk in the data. Notably, the Marinus was the only sensor that did not have a straight edge with which to align the sensor to the centre line. The Marinus heave values vary by approximately +/- 20cm. The POSMV real-time heave corresponded very closely with the TrueHeave, varying by approximately 1 – 2cm, but there is an obvious effect in the variation due to the turn compared with the True Heave post-processed solution. The Seapath surface difference varies by +30cm to -12cm. Kongsberg Seatex suspected an error and subsequently sent some reprocessed data for inclusion in the results. This data improved the initial heave going into the turn, but the rest of the line was out by up to +40cm and -20cm.

##### Heave Line 29 $180^\circ$ Turn

This was a “normal” survey line through the area (typical for an enclosed harbour survey), followed by a  $180^\circ$  turn onto a new line.

The data logged begins during the turn onto line, with the start of the survey line (i.e. straight running) at point A. This line took just under two minutes to complete, and then the vessel turned 180° to starboard to commence the next line (at point B). Octans, F180 and POSMV show good agreement with TrueHeave whilst on-line. Marinus shows some initial deviation of up to 12cm at the very beginning of each survey line but settles quickly. Seapath shows a maximum deviation of 15cm and takes more than one minute to come back within specified levels of accuracy. The considerable heave-settlement time would mean that the Seapath would measure heave more reliably if the vessel had an extended run-in after each turn before data logging commenced. In the confined waters of the survey area this was not possible. The results are shown in Figure 5.

Similarly to Line 23, the surface-difference plots show close correlation with the graphs (see Figure 6). The Octans and the POS MV show little difference from the reference system (+/- 1 or 2cm). The F180 was not post-processed with iHeave for this line, but the real-time differences are of the order of +/- 5cm. The Marinus again shows signs of pitch/roll cross-talk but the differences are kept to between +/- 10cm. The Seapath only really starts to settle at the end of the line and was previously varying between +/- 20cm from the reference system.

### Heave Line 26 - Erratic Manoeuvres

A series of erratic manoeuvres were undertaken over the course of six minutes, including 180° and 360° spins (see Figure 7). The aim here was to unsettle each of the motion sensors as much as possible. Although this does not perhaps represent a "normal" survey operations, a number of surveys have been received at the UKHO where a vessel in confined waters has had to survey very erratically to avoid moorings, structures and other vessels. Such manoeuvres have included 180° spins whilst acquiring data, so whilst the above situation may not be considered a "normal", it can at least be regarded as a "real world", and it is important that users surveying in such a manner understand the limitations of their systems. These surveys have often had measurable heave artefacts in the data during turns.

F180, Octans and POSMV show good agreement with TrueHeave throughout, with deviations typically less than 5cm. Seapath and Marinus both have heave differences from the post-processed TrueHeave in excess of 20cm. The corrected Marinus data (see Section 5) shows heave deviation of up to 15cm.

### Heave Line 30 – Intermittent GPS

This data is from a set of short lines and turns under the Interstate 95 road bridge at the upper end of Portsmouth Harbour (see Figure 8). The combination of wide bridge structure and fairly steep-sided river value caused intermittent GPS position drop-outs and limited the available satellite constellation, thus increasing HDOP and GDOP values throughout the data collection period. It was hoped that the poor GPS performance in this area would highlight the importance of GPS aiding for each motion sensor and any subsequent degradation in motion-sensor performance.

Data logging was begun as the survey vessel first entered the area under the bridge. Several short lines were run up and downstream in a strong tidal flow, with data being continuously logged. Generally, the Octans and POSMV show only a slight degradation in heave performance based upon previous results, with deviation from the TrueHeave values lower than 5cm. The F180 shows a significant decrease in heave performance, with heave deviation of up to 15cm. The Marinus heave is generally in reasonable agreement, but is shown to have more "heave spikes" than on previous lines (see Section 5). The Seapath has the largest heave deviation, with maximum values in excess of 40cm during the longest period of GPS drop-out.

### Roll Line 29 180° Turn - POSRS Roll Comparison

As with the heave comparison for line 29, these were regarded as a "normal" conditions for a harbour-type survey. The data logged begins during the turn onto line, with the start of the survey line (i.e. straight running) at point A. This line took just under two minutes to complete, and then the vessel turned 180° to starboard to commence the next line (at point B). The only significant roll experienced was during and immediately after each turn (partly due to travelling through own wake). A small roll bias between each sensor was evident, and this was adjusted to "calibrate" each motion sensor to the POSRS. As any roll errors would be impossible to see when simply plotting roll values, it is necessary to subtract roll values from the benchmark POSRS roll values to produce a difference plot (see Figure 9).

To create this plot, all co-registered values (i.e. where a roll message from any single motion sensor corresponded with a simultaneous roll message from the POSRS) were subtracted from the POSRS value to calculate the difference. As the POSRS was logged at 200Hz (every 5 milliseconds) and each motion sensor was typically outputting at 50Hz (every 20 milliseconds), each survey line produced many thousands of simultaneous data points for comparison. It was felt that this offered a more robust comparison than continuous interpolation of the data between roll messages. Table 2 shows achieved accuracy values as compared to manufacturers' quoted accuracy.

When this comparison was first undertaken it was discovered that there was a small time shift in the recorded data that manifested itself as an error strongly associated with rate of change or roll. This error was present for all motion sensors when compared against the POSRS. This was later found to be caused by latency in taking asynchronous data (from the sensors under test) through a serial connection and digiboard into the acquisition computer, where each message has to be read and time-tagged. To mitigate for this latency the POS RS data was shifted by +24 milliseconds, which achieved the minimum standard deviation in roll error for each of the individual motion sensors. In effect, this is correcting for the average latency in asynchronous serial data from each of the sensors, and so some residual effect will remain for each sensor, depending on how the latency of each message differs from the average "i.e. jitter".

It is clear from the graph that there appear to be two types of error present in each of the motion sensors: a high-frequency noise (possibly associated with timing jitter) and a longer period drift. With the exception of the Seapath, all units are operating within their own specified accuracies (at the one-sigma level). The maximum deviation recorded with the Seapath is 0.08°, four times higher than the specified accuracy. However, this also ties in with a settlement period after each end-of-line turn, so it is assumed that longer survey lines would have allowed the Seapath to settle, and roll accuracy to improve.

### Roll Line 27 High Roll Rate - POSRS Roll Comparison

For this line the vessel was rolled substantially by rocking the rudder. This generated roll of up to 12°, with a high rate of change of roll (up to 8° per second). It was hoped this would simulate the roll experienced in a small vessel in rough sea conditions although there were no real waves present (Figure 10).

It is clear that with the exception of the Marinus, none of the motion sensors are operating within their own specified roll-accuracy levels (Marinus is only just outside). As with line 29, there appear to be two types of error present in each of the motion sensors: a high-frequency noise and a longer period drift. Table 2 shows the quoted roll accuracy vs. achieved roll accuracy for line 29 and line 27 using a serial interface.

The Octans and Seapath seem most affected by the high roll rate: the

Seapath is drifting either side of zero, and whilst the Octans also drifts either side of zero there are also occasional spikes in the data. It is

likely that this is being caused by clock jitter so that the timing is varying around the “true” value, although it is very difficult to prove this. After presenting these results at Shallow Survey 2005 it was thought that the area of timing should be looked at closely for Line 27, as with 8° of roll per second motion the consequence of a 1 millisecond time error is approximately 0.01° of roll error, a substantial amount. Rather than try to look at the data coming into QINSy, we decided to look at data that had been acquired separately and was logged internally with GPS time-stamps. This data was the POS RS and POS MV data. POSpac software from Applanix was used to post-process both sets.

#### Further Comparisons

##### Reference System vs. Real Time POS MV320

During the tests the base station was broadcasting RTK (CMR format) corrections. However, during the actual time-period in question (14:44:18 to 14:45:44 UTC) the POS MV real-time solution was unable to compute a fixed RTK solution throughout, probably because overheating of the base radio modem was causing intermittent performance. This illustrates one of the limitations of RTK: that of broadcasting the base-station data in real time.

By comparing roll and pitch between the POS RS (Reference System) and the real-time POS MV 320 solution (using sub-optimal RTK aiding as described above), the following differences were found (see Figure 11). Note that the differences are plotted in arc-minutes (1 arcmin = 1/60°) and also that, since the data has been logged with microsecond accurate time stamping via the POS MV ethernet interface, any timing errors have been minimised. The statistics (in degrees) associated with this time period are as follows:

- Number of data points: 8,600. Time interval: 398658.002 - 398743.990 seconds.

The large roll error is due to the alignment of the sensor within the POS RS housing, and this correlated closely with the Roll Patch Test results of the two systems, which were as follows:

##### Reference System vs Post Processed POS MV320

By comparing roll and pitch between the POS RS and POS MV (this time post-processed with POSpac and using post-processed, and therefore robust, kinematic GPS aiding), the following differences were found (see Figure 12).

The statistics (in degrees) associated with this time period are as follows:

Number of data points: 17,200. Time interval: 398658.002- 398743.995 seconds. Note the presence of twice the number of data points in the post-processed solution as compared to the real-time data. This is because the real-time solution was logged at a rate of 100Hz, whereas the postprocessed solution was created at 200Hz.

#### Timing Conclusions

The results show that the POS MV was working within its specifications during the high-roll oscillation Line 26. Comparing both post-processed sets of data it is clear that timing is the cause of the large roll-error variations we saw when taking the motion-sensor data in real time. There was nothing that could have been done during the acquisition stage to improve upon the timing accuracy that was achieved. These findings indicate that when large and rapid oscillations are expected either another means of timing must be found or the survey swath limit must be reduced. Utilising Ethernet logging where the data is time-stamped at source could improve timing.

#### Conclusions

Though some of the manoeuvres performed could be described as “extreme”, all these situations have occurred when trying to complete a survey and, as such, the data should be regarded as representing likely scenarios. It would be fair to say that the only line where you would have probably stopped surveying was Line 27, with the high-level roll oscillations. We can therefore state the following conclusions based on our interpretation of the results:

- All systems tested will comply with IHO Order 1 requirements (disregarding other elements of the error budget) under “normal” survey conditions.
- To achieve best performance during survey, allow one minute after turns for Marinus, and two minutes for Seapath.
- F180 and Seapath appear to be the most reliant on good GPS to aid the IMU; performance degrades markedly in poor GPS environment.
- Marketing specifications should make reference to the heave-settlement time.
- All motion sensors tested, with the exception of Seapath, operated within their specified roll accuracies during low roll-amplitude/rate of change conditions. However, when the roll-amplitude/rate of change was high the logged data showed that none of the motion sensors met their published roll-accuracy specifications (although the Marinus was only 16% beyond manufacturer’s specified accuracy). The serial data interface used is thought to be a primary component of this error.
- Very accurate time synchronisation for attitude, in particular roll, is critical, and for high roll oscillations 1 PPS timing with an asynchronous serial interface is insufficient.
- Post-processing IMU data provides improved accuracy and reliability, especially in heave. This eliminates the need to wait for the sensor to stabilise prior to starting the survey line.
- Even though the marketing material appears to portray each motion sensor as being of comparable performance, the results suggest otherwise.

#### Software/Firmware Updates

TSS (International) Ltd has informed us of a problem with remote heave in the firmware we used in the sensor trial. The X [athwartships] offset was applied in the opposite sense, causing artificial heave when any roll was experienced. New, reprocessed data was received from TSS on 7th November 2005 and with the above problem corrected the heave results were significantly improved, as demonstrated in Figure 13. As previously stated, Kongsberg Seatex also believed it had a software/firmware fault that degraded the performance of its system. Future upgrades may therefore improve performance.

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<https://www.hydro-international.com/content/article/motion-sensor-performance>

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