Fansweep 20 Total Propigated Uncertainty, Does It Reflect Reality?

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SUMMARY

The Royal Australian Navy (RAN) has recently started using the Combined Uncertainty and Bathymetric Estimator (CUBE) as a tool to assist the validation of its Multibeam bathymetry. To achieve this, the RAN replaced its Hydromap offline software package with CARIS HIPS and SIPS. CUBE relies on a priori uncertainty assessments, which in the RAN's case are provided by a software derived Total Propagated Uncertainty (TPU). The RAN utilise the Atlas Hydrographic Fansweep 20 (FS20), a bathymetric sidescan with a TPU algorithm unique to the sonar.

CARIS are implementing the FS20 TPU algorithm for the RAN. As part of this process a study has been undertaken into the continued suitability of the Atlas FS20 TPU algorithm. By using the per beam standard deviation of a consecutive series of 100 pings across a flat area, it has been shown that the FS20 TPU does provide a good assessment of the relative beam to beam accuracies that a bathymetric sonar would experience.

Additionally, cross-line comparisons were run on two datasets, both processed using CUBE. The first dataset had Atlas FS20 TPU applied, the second had a beam forming TPU applied. It was found that the beam forming TPU gave the nadir beams of the FS20 an unrealistic, optimistic accuracy that caused the CUBE processing to favour the most inaccurate part of the FS20.

By using the standard deviation checks and cross-line comparisons, it was found that the Atlas FS20 TPU still remains the most relevant and appropriate a priori uncertainty estimate for the RAN to use.

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1. INTRODUCTION

The introduction of Multi-Beam Echo Sounders (MBES) and advances in the Global Navigation Satellite System (GNSS) have seen a dramatic increase in both the quantity of data collected and the required accuracy standards of the requesting organisation. Traditional Hydrography has generally involved low data rates and subjective assessments of accuracy. In the RAN, a priori and a posteriori assessments of accuracy of Single Beam Echo Sounders (SBES) are still a largely subjective exercise, where surveyors' best estimate of two sigma values for the sources of uncertainty are the fundamental sources of information (Royal Australian Navy, 2006). In applying robust scientific practice to surveying, all measurements require an assessment of the accuracy achieved. The subjective nature of these assessments for hydrographic work evolved largely out of necessity. Statistical analysis may be the most objective assessment of accuracy available but the very nature of statistics requires the collection of redundant measurements for analysis. For the land surveyor this was easily achieved by taking multiple rounds of observations. The hydrographic surveyor, however, has traditionally dealt with little to no redundant data. From the subjective accuracy assessment, to the practice of shoal biasing, there has, for hundreds of years, been inherent mistrust by hydrographic surveyors in the data they collect.

MBES provide the hydrographic surveyor with something previously unattainable—that is, redundant data. The second paragraph in the Combined Uncertainty and Bathymetry Estimator (CUBE) users' guide elegantly states the monumental shift in thinking. Rather than asking "How good is this sounding?" we are now trying to determine "What is the depth and how well do we know it?" (Calder & Wells, 2007). By accepting statistical analysis of hydrographic data, the surveyor must accept the concept of the "outlier" and that the most probable depth may be deeper than the shoalest measurement. For a surveyor who has been shoal biasing their products for their entire career, some degree of apprehension is expected. Consequently, in order to change to a statistical data analysis approach, we need rigorously tested error modelling techniques to provide suitable confidence in the quality of the final product.

This inevitable change is driven by the sheer volumes of data that are collected by modern systems. It is reasonable to expect a modern shallow water MBES to collect over one million soundings in an hour. It would be unreasonable; however, to expect a surveyor to pass a subjective eye over every sounding, hence the requirement for area based editing, where blocks of soundings are validated as a whole. Subjective area based editing or "dot killing" as it is colloquially known, is not without its own problems. Historically, subjective area based editing is time consuming and has a very low repeatability. Two surveyors will not always accept the same data, which introduces the very real risk of significant features being overlooked or removed.

These problems are well known and have prompted the creation of statistical area based editing tools, with the archetypal example being CUBE. Common to all statistical area based editing tools is the requirement for an objective assessment of the uncertainty in the soundings. To once again quote from the CUBE users guide, "unlike men, not all soundings are created equal" (Calder & Wells, 2007). With uncertainty estimates and processing algorithms it becomes possible to assess every sounding in a viable time frame with a higher likelihood of achieving repeatable results. However, as with all algorithms, the quality of the end result reflects the quality of the input. Incorrect uncertainty estimates will produce flawed results, i.e. "garbage in, garbage out".

The accepted term for the accumulated uncertainty in sounding measurements is Total Propagated Uncertainty (TPU). The most widely accepted and implemented models for TPU are based on beam forming sonars (Hare R. , Error Budget Analysis for US Naval Oceanographic Office Hydrographic Survey Systems, 2001). However, as this paper will show, bathymetric sidescan sonars which use interferometry or phase differencing techniques propagate their uncertainties differently to beam forming MBES.

Built upon the principle of a traditional sidescan sonar, the bathymetric sidescan was created to allow for the return angle of the echoes to be measured. A traditional sidescan only notes the arrival time, as its geometry is unable to measure the arrival angle. A bathymetric sidescan sonar measures the arrival angle of the echo in one of two ways—firstly, through interferometry and secondly, through phase difference measurements (de Moustier, 2008).

Interferometry works on the principle of counting nulls in the beam pattern. Separating the receive staves of the bathymetric sidescan by a multiple of the wavelength produces a beam pattern with distinct lobes. The resulting image gained from the sidescan will show bands of light and dark fringes. The location of the light areas correspond with the nulls of the beam pattern, hence the arrival angle of the echoes can be deduced (de Moustier, 2008).

Phase difference measurements are a more precise method of determining the angle of the return echo. Phase difference measurements rely on the fact the measurements across multiple staves allow the phase of the returning echo to be measured. By using phase advances and delays between the received wavefronts at the receiving array, it becomes possible to determine the angle of arrival (de Moustier, 2008).

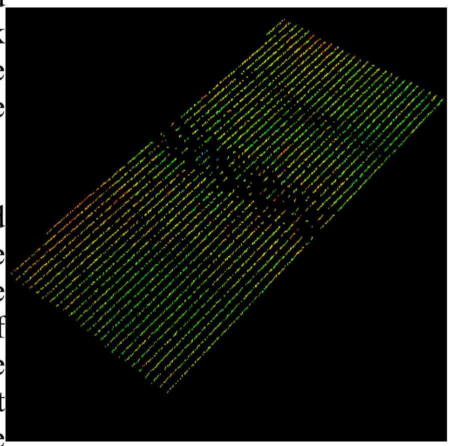

Figure 1: FS20 Swath Data

However, the resolution of interferometry and phase differencing techniques degrades in the nadir region. For interferometry, the nadir returns will generally arrive at the same time from

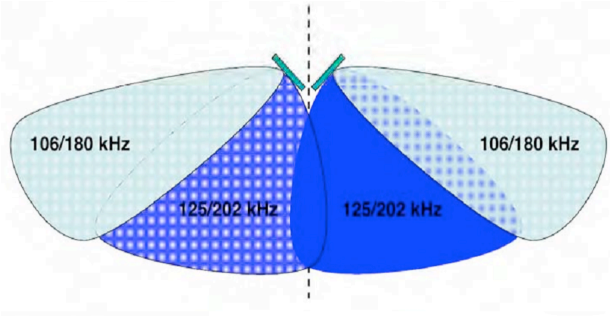

Figure 2: FS20 Beam Pattern

shallow angles and for phase differencing bottom detection there will be very little phase offset. This is contrary to a beam forming sonar, where amplitude based bottom detection with minimal beam steering in the nadir region shows the highest degree of accuracy.

The Royal Australian Navy (RAN) selected the Atlas Hydrographic Fan Sweep 20 (FS20), a bathymetric sidescan sonar, as the MBES for the Leeuwin class Hydrographic Ship (HS). As part of the acquisition, the Hydromap suite of programs was purchased as the Hydrographic Data, Logging, Acquisition and Processing System (HYDLAPS). The *Hydromap* suite consists primarily of two software packages, *Hydromap Online* and *Hydromap Off-line*. *Hydromap Online* allowed mission planning and data acquisition, whereas *Hydromap Off-line* allowed data processing and rendering functionality. As part of the HS project, the provided HYDLAPS had to calculate the Total Propagated Error (TPE), now known as TPU, for each sounding. Atlas Hydrographic developed a set of algorithms for the FS20 to undertake a TPU assessment for each sounding.

The total solution for Atlas TPE involved both *Hydromap Online* and *Hydromap Off-line*. However, the recent replacement of *Hydromap Off-line* by *Caris HIPS & SIPS* has resulted in a request for *HIPS & SIPS* to implement the FS20 algorithms for TPU. In order to support these requests, the RAN recently conducted several tests to independently validate FS20 TPU, the results of which are provided in this paper.

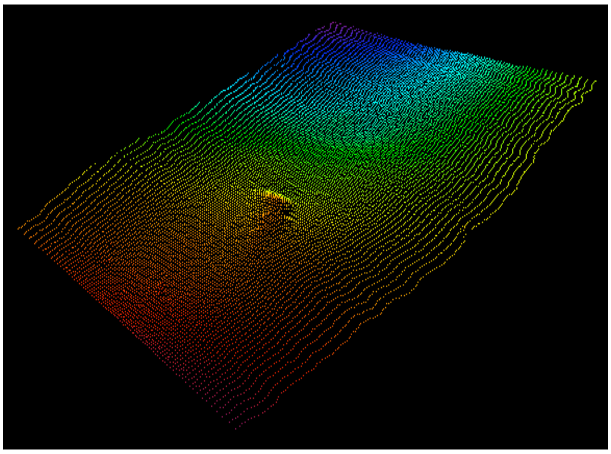

Figure 3: Reson 8101 Swath Data

2. FS20 TPU

The FS20 produces a distinct beam pattern that possesses key differences from a beam former's beam pattern. **Figure 1** shows a selection of FS20 data collected in a depth of 30m with a swath width of 4 times the water depth. The key features of the FS20 swath are:

- Sparse data density in the nadir region with denser data at the extremities, and
- Intermittent data drop-outs halfway across the swath.

These key features can be explained by the configuration of the transducers and the limitations of phase detection techniques.

Firstly, a return from the nadir region produces very little change in phase for phase detection techniques to work effectively. **Figure 2** shows a stylised representation of the resulting beam pattern from a FS20. The two sides overlap in the nadir, but this does not entirely solve the problem, resulting in the data gaps in **Figure 1**.

Secondly, in order to solve the problem of bottom multiples, the FS20 has two transmit beam patterns on each side. The overlap of the two transmit beams does produce some problems for the bottom detection routines of the FS20 as is evident by the two trails of intermittent data in the vicinity of the overlap between transmit beams.

By visually comparing the swath data at **Figure 1** to that in **Figure 3**, a section of Reson 8101

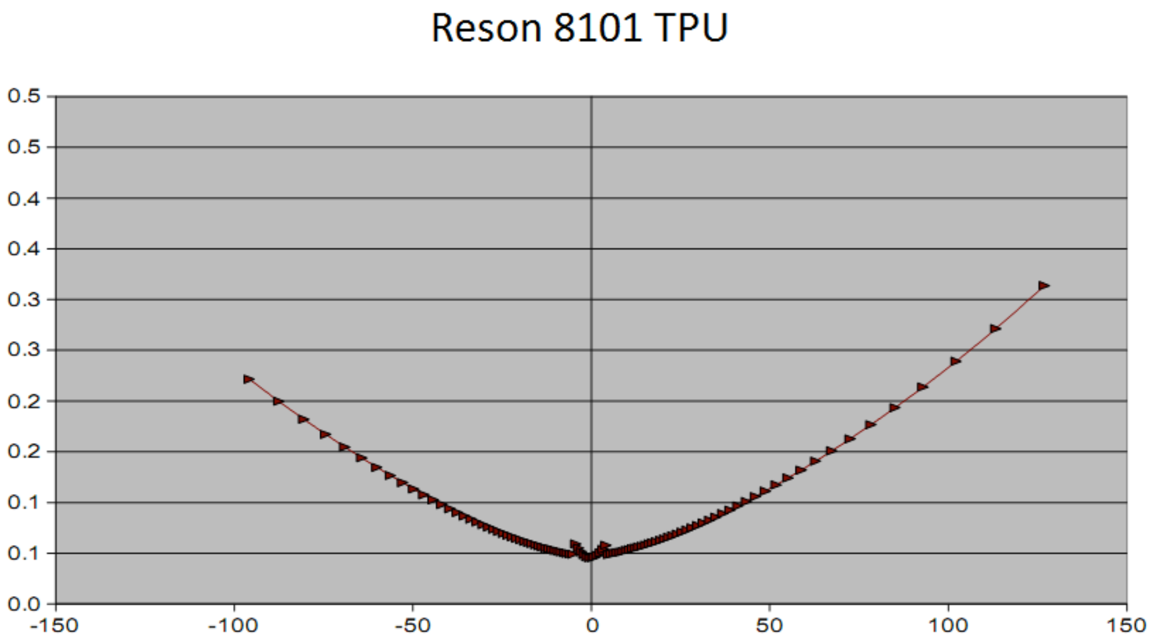

Figure 4: Reson 8101 TPU Depth Graph 4 x WD (Hare R. , Reson 8101 Preanalysis, 2001)

(beam forming) data, it can be seen that the two sonars produce entirely different beam patterns. This difference is reflected in the TPU values for each swath. **Figure 4** shows an a priori assessment of TPU depth for the Reson 8101 using a spreadsheet developed by Dr Hare (Hare R. , Reson 8101 Preanalysis, 2001). **Figure 5** shows an a priori assessment of TPU depth for the FS20 using algorithms developed by Atlas Hydrographic.

Like the beam patterns, the TPU for both sounders are fundamentally different. The nadir of the Reson 8101 is the most accurate section of the swath, whereas the nadir of the FS20 is its most inaccurate. It can be seen that the FS20 is still improving in its accuracy when the swath is curtailed at 4 times the water depth.

The big caveat is that all of these figures are a priori assessments of uncertainty, and are only as good as the TPU models and the uncertainty variances they use. Fortunately, for beam forming sonar users, the beam forming TPU models have undergone a rigorous design and testing process. They are the most widely used MBES and have subsequently been the main focus of recent research (Hare R. , Error Budget Analysis for US Naval Oceanographic Office Hydrographic Survey Systems, 2001). The FS20, however, uses techniques and technologies that are unique to one sonar manufacturer and are only common across a small number of sonar models.

Understandably, apart from the initial design work undertaken by Atlas Hydrographic, there has been very little independent academic verification to confirm if FS20 TPU reflects the depth uncertainty it produces.

While FS20 TPU produces results for the x, y and z axis, this paper will be concentrating on

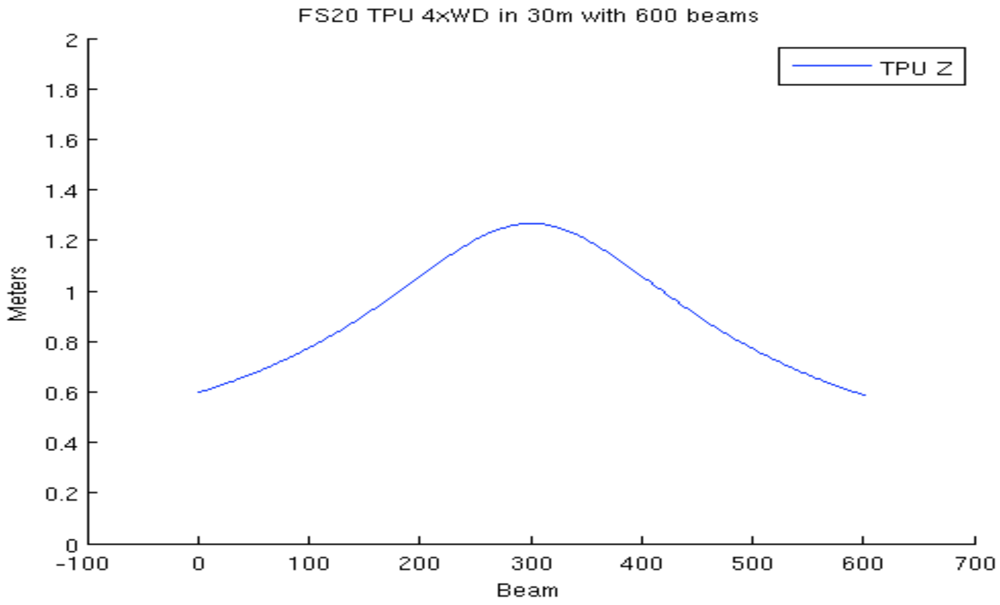

Figure 5: FS20 TPU Depth Graph 4 x WD

the z axis only. At its simplest level, FS20 TPU follows sound statistical practice in the way it propagates uncertainties. All uncertainty constituents are fed into the model at the 2σ (95%) level and are assumed to be normally distributed (STN Atlas, 1998). The final result is the Root Mean Square (RMS) of the respective components.

FS20 TPU(z) comprises:

- heave uncertainty;
- tidal uncertainty;
- motion uncertainty (z axis);
- echo time measurement uncertainty (z axis);
- sea floor slope (z axis); and
- sound velocity uncertainty (z axis).

$$dZPos = svEff \times \frac{(dEchoT + tmtDurn)}{2} \times \cos(baEff)$$

Equation 0: Echo time measurement uncertainty

SvEff: The effective sound velocity error
dEchoT: Error in echo time measurement
tmtDurn: Transmit duration
baEff: The effective beam angle

As seen in **Figure 6**, the most indicative minor constituent of the final shape of the FS20 TPU graph is the Echo time measurement uncertainty. The term minor constituent is used as the FS20 TPU algorithm combines a number of the constituents together to form additional constituents before the RMS process takes place.

An extract from the FS20 TPU algorithm can be found in Equation 1 (STN Atlas, 1998). This equation shows the calculation of the echo time measurement uncertainty (z axis) . It is the cosine of the launch angle that produces the signature shape. The magnitude of the echo time measurement uncertainty is modified mainly by the uncertainty in the sound velocity measurement as the error in echo time measurement (*dEchoT*) and the transmit duration (*tmtDurn*) are set by the manufacturer.

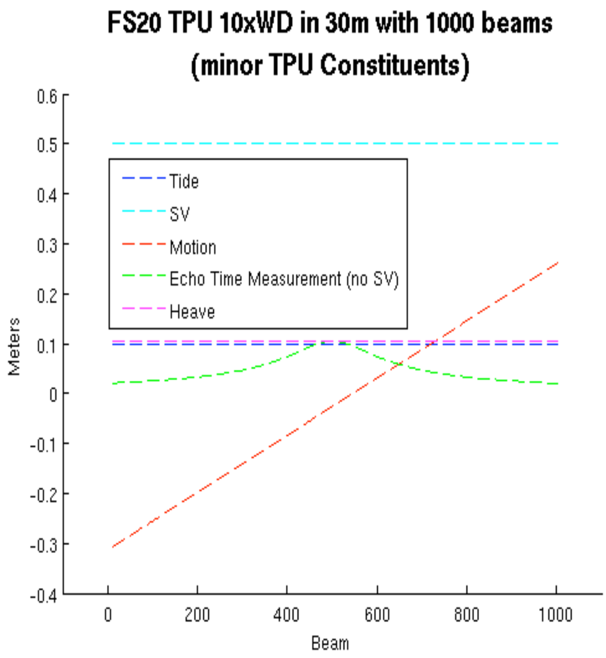

Figure 6: FS20 TPU Minor Constituents

Now that the cause of the FS20 TPU's signature shape has been identified, the question still remains—does the theoretical TPU reflect the reality?

Simple statistical analysis was chosen as a gross check of correctness for the FS20 TPU. This decision was influenced by Chapter 5 of the MB System Cookbook, which describes a technique of using the standard deviation of individual beams taken from a consecutive series of pings, presented as a percentage of water depth to check for gross errors in the sonar array (Schmidt, Chayes, & Carress). By calculating a measure of dispersion of a series of consecutive beams we present an arbitrary measure of the level of noise across the swath. For the purpose of this paper, we assume that beams with a higher standard deviation, or more noise, have higher uncertainty. If the FS20 TPU does accurately model the performance of the system, we expect that a plot of the standard deviation of the beams in a continuous data set will mimic the general shape of the FS20 TPU curve.

Additionally, we propose that if the FS20 TPU accurately models the performance of the system, a cross-line comparison across a CUBE surface generated using FS20 TPU should indicate very high confidence in the surface across the entire cross-line swath. Accordingly, we present an analysis of cross-line comparisons conducted with FS20 TPU and also the less appropriate beam-forming TPU model.

3. DATA COLLECTION

Data sets used for this work were collected using three separate survey platforms, across three different regions in order to aid in isolating statistically significant environmental interference. The platforms were RAN Survey Motor Boats (SMBs) *Fantome, Duyfken* and *John Gowlland.* All three are of the same class with similar survey equipment. Each is fitted with Atlas FS20 shallow water bathymetric sidescan sonar, with position and orientation information integrated by an Applanix PosMV system and gained from Trimble carrier-phase measuring GPS and Fugro Seastar wide-area differential GPS. Sound velocity profiles are determined from hull and towed Conductivity/Temperature/Depth (CTD) probes.

The datasets used for statistical beam pattern analysis were collected in the Hunters Bay area in Port Jackson, New South Wales, and also Trinity Inlet, Cairns Harbour, Queensland. These areas are markedly different. The Hunters Bay area is a low turbidity area with water temperatures around 24°C and a sandy seabed. In contrast, the Trinity Inlet area is a high turbidity area, with water temperatures around 29°C and a soft mud seabed. A comparison of the data from these two areas helps to alleviate the possibility that any observed statistical trends might be biased by seabed type, turbidity or sound velocity profile.

Data collected in Hunters Bay was obtained with *John Gowlland* during a recent deployed survey conducted by the RAN Hydrographic School. This survey was conducted using 800 beams, with 1000% depth coverage in 6-8 meters. Selected blocks of sequential data was then extracted from survey areas with minimal seabed variation to ensure that statistical variation of beam patterns would be representative of the inherent variation in the FS20 system rather than the result of the bathymetry.

Data collected in Trinity Inlet was obtained with *Fantome* by steering a 150m line, parallel to depth contours, in a maintained depth area of 12-14 metres. The Trinity Inlet data was collected with 1000 beams, and 1000% depth coverage. Again, the survey area was selected to ensure that the statistical variation of beam patterns would be representative of the performance of the system itself rather than the bathymetry.

4. DATA ANALYSIS

Data analysis was conducted using a combination of CARIS HIPS & SIPS, OpenOffice.org Calc and Octave. Raw FS20 SURF files were imported into HIPS & SIPS using the appropriate vessel configuration file. No corrections or edits were applied to the data. Five continuous blocks of the data of 100 pings were exported to comma separated files for analysis in Octave. Utilising Octave, a number of statistics were generated. For each swath the mean and the range of the depths in the swath were generated. Additionally, TPU was calculated for each sounding in the swath using the FS20 TPU algorithms. For each beam number the mean, standard deviation and range were generated.

4.1 Results

Figure 7 shows a typical graph for the standard deviation of a dataset collected in Hunters Bay. The standard deviation of the beams peaked around beam 400, the nadir of the FS20, and significantly improved either side. Additionally around beams 150 and 550 a slight increase in the standard deviation is visible. This is a likely indication of the overlap of the inner and outer beam patterns. Overlaying the standard deviation graph is the TPU for a swath indicative of the area. While the TPU has been graphed using a different scale, the change is an offset only and does not skew or distort the TPU curve. The FS20 used on the SMBs has a manufacturers quoted accuracy of 0.05m ± 0.2% of water depth up to 6 times the

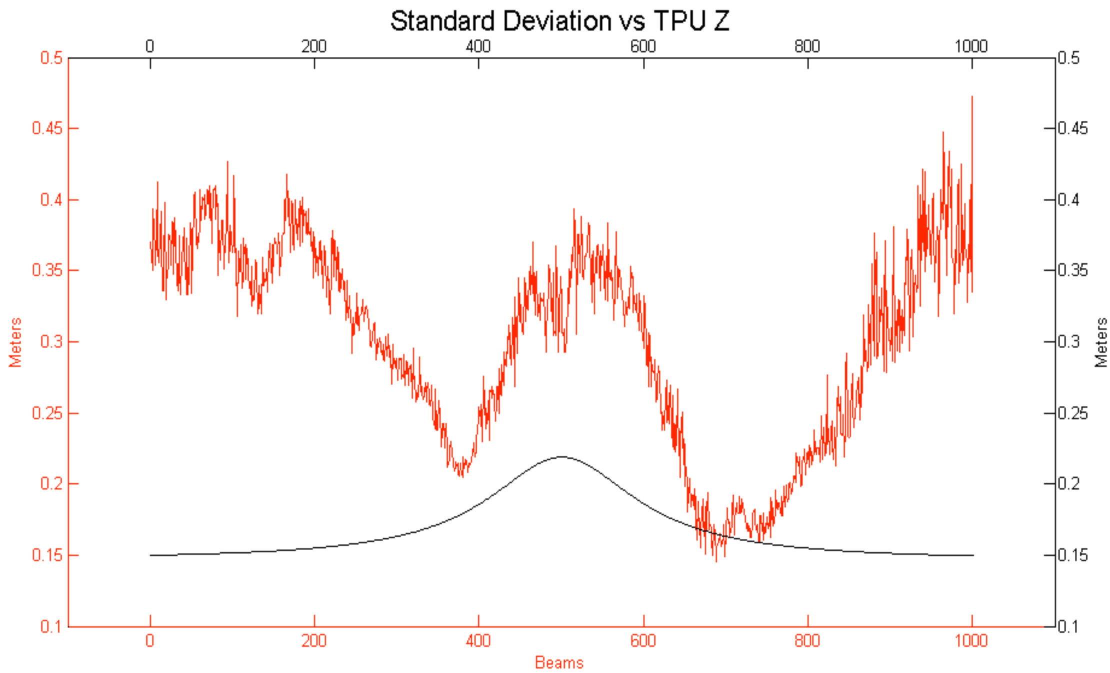

Figure 8: FS20 Standard Deviation from Trinity Inlet

water depth (STN Atlas, 1998). No confidence interval is given but the industry standard of 68% is assumed. Accordingly, the results obtained validate the manufacturer's accuracy claim and also the demonstrate behaviour as predicted by the TPU model.

Unfortunately, the data collected from Trinity Inlet was not as useful. Figure 8 shows a plot of the analysis undertaken on the Trinity Inlet data. While generally conforming to the trends identified from the Hunters Bay analysis, the range calculations both per beam and per swath were significantly greater. The mean range of the depths per beam was 0.34m in Hunters Bay and 1.42m in Trinity Inlet. The mean range of the depths per swath was 0.25m in Hunters Bay and 2.54 in Trinity Inlet. This uneven seabed encountered in Trinity Inlet has proven unsuitable for this experiment, highlighting the need for a very flat seabed in order to use this analysis technique.

4.2 Cross-line Comparison

The datasets used for the cross-line comparisons were collected using both SMB *Duyfken* and SMB *Fantome* in the Gannet Passage sandwave area. This area was surveyed in two equal halves, one by each boat. All crosslines were conducted by each boat, so that each crossed both its own, and the other's mainlines. The undulating, sand-wave nature of this seabed makes it an ideal area for the comparison of cross-lines across the CUBE surface as any deficiency in the error model used to generate the CUBE surface would be quickly identified as a drop in confidence in the surface when compared with the cross-lines. The main-lines and cross-lines used for cross-line comparison were collected with 600 beams and 400%

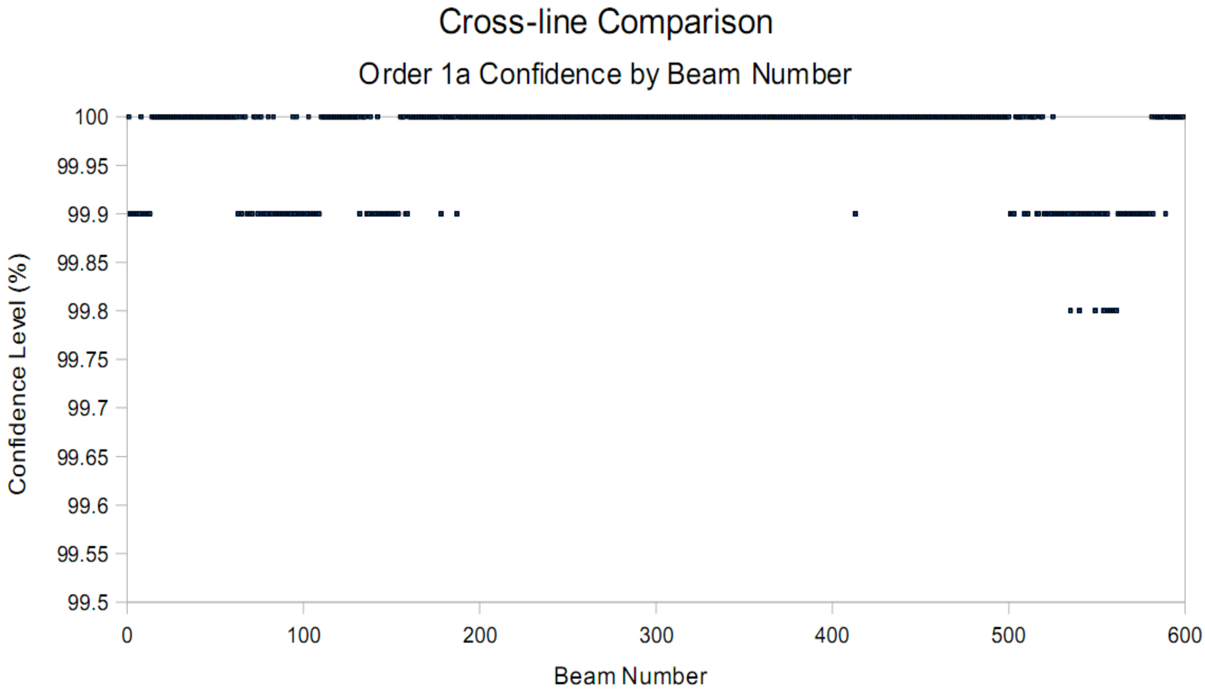

Figure 9: Cross-line Comparison for SMB using FS20 TPU

depth coverage.

The graph in **Figure 9** shows the results of the cross-line comparison at Gannet Passage. Noting that the RAN's cut off limit for Order 1a is 95% (Royal Australian Navy, 2006) and that all results were above 99.8%, the CUBE surface appears well formed. This indicates that the tidal model was correct and that the uncertainty model was representative of the FS20's performance.

The contrasting cross-line comparison shown in **Figure 10** demonstrates the effect of using an inappropriate TPU model in CUBE surface creation. When the RAN initially acquired the *CARIS HIPS & SIPS* processing system, attempts were made to use the inbuilt beam forming TPU calculator for the FS20 data. The cross-line comparison in **Figure 10** was the result. It is worth noting that the data in **Figure 10** was collected using the HS platform in late 2006, so the results should not be directly compared to **Figure 9**. Nevertheless, the key feature of this graph is that the nadir beams do not meet Order 1 to the required degree of confidence.

Using a beam forming TPU model resulted in the nadir beams having the lowest uncertainty out of all of the beams. However, as explained in this paper, the nadir of the FS20 should have almost the highest uncertainty of all beams in the swath, with the possible exception of the outer beams. By providing the CUBE algorithm with an unrepresentative uncertainty model, the nadir beams have been inappropriately weighted and have had a significant influence on the resulting CUBE surface. The high confidence cross-line comparison

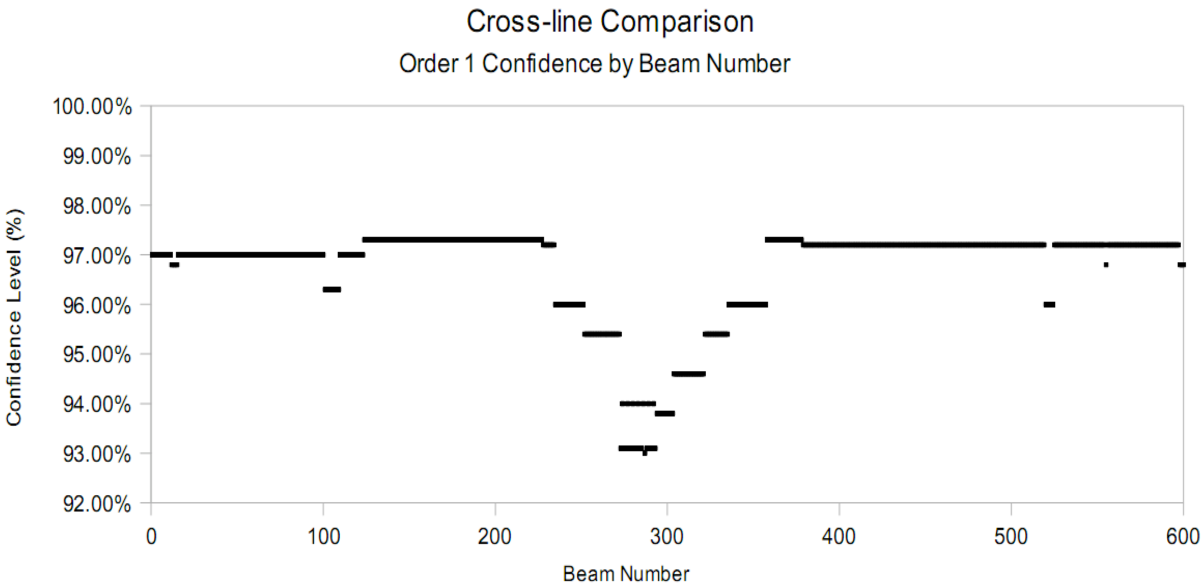

Figure 10: Crossline Comparison for Hydrographic Ship using a FS20 with Beam Forming TPU

achieved using the FS20 TPU, however, provides further evidence of the validity of the TPU model.

5. CONCLUSION

The FS20 by the nature of its design as a bathymetric sidescan performs differently to the beam forming MBES on the market. The TPU algorithms designed for the FS20 produce a curve that is practically the opposite of that produced by a beam forming TPU algorithm. As part of the introduction of CARIS HIPS & SIPS into the processing pipeline, CARIS has been requested to implement the FS20 TPU algorithm as part of their compute TPU functionality.

As part of this request an analysis of the FS20 TPU was undertaken to validate its suitability. An analysis of the TPU algorithms found it was the cosine of the launch angle in the echo time measurement uncertainty function that resulted in the TPU's distinctive shape. To confirm the suitability of the TPU shape it was decided to look at the per beam standard deviation of a consecutive block of data across a flat seabed. Results on a flat piece of seabed confirmed the general shape of the TPU to be valid. There was a distinct spike in the standard deviation for the nadir beams with an immediate improvement either side. The suitability was further confirmed with the cross-line comparison analysis. The cross-line comparison conducted with Atlas TPU showed a very high correlation opposed to a comparison that had a beam forming TPU applied.

The Atlas TPU was specifically designed for the FS20, and its unique characteristics. Its suitability has been confirmed by this paper and its use should be retained for the life of the sonar.

REFERENCES

Calder, B., & Wells, D. (2007). *CUBE User's Manual.*

de Moustier, C. (2008). Side Scan Sonar Methods. *47th Multibeam Sonar Training Course*, (pp. 26-28). Amsterdam.

Hare, R. (2001). *Error Budget Analysis for US Naval Oceanographic Office Hydrographic Survey Systems.*

Hare, R. (2001). Reson 8101 Preanalysis.

Hare, R., Godin, A., & Mayer, L. (1995). *1995 Canadian Hydrographic Service Multibeam Echo Sounder Errors Report.*

Royal Australian Navy. (2006). Australian Hydrographic Orders and Instructions.

Schmidt, V., Chayes, D., & Carress, D. (n.d.). *The MB-System Cookbook*. Retrieved December 12, 2009, from Monterey Bay Aquarium Research Institute : http://www.mbari.org/data/mbsystem/mb-cookbook/

STN Atlas. (1998). *Total Propagated Error (TPE) Operational Description.*

BIOGRAPHICAL NOTES

Dean Battilana joined the Royal Australian Navy in 1996 and attended the Australian Defence Force Academy. He graduated in 1998 with his BSc and specialised as a surveyor in 2001. He has had experience in Singlebeam, Multibeam and LIDAR surveys. Dean obtained his Masters in Hydrographic Science at the University of Southern Mississippi in 2008 and has subsequently served as the Instructor for the Royal Australian Navy's Category B course.

Geoffrey Lawes joined the Royal Australian Navy in 2002 and attended the Australian Defence Force Academy. Graduating in 2005 with his BSc he subsequently completed an honours year. Geoffrey specialised as a surveyor in 2009 and is currently engaged in Multibeam surveying.

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