# Rapid Sound Speed Profiling in Plymouth Sound (Part 2)

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Part 1 of this article (published in **soundings** No. 67) considered a dataset collected in Plymouth Sound in November 2015, showing a large variation in sound speed across the Barn Pool area, was presented. In the discussion of this dataset, two questions were posed:

- How often should I take a sound speed profile?
- What is the effect of this variability on my data?

To attempt to answer these questions, a second study was planned and carried out in collaboration between Plymouth University, Fugro Academy and Valeport Ltd. It also formed the basis of an MSc Hydrography dissertation [Gray, 2016].

The study's aims were to:

- map and quantify the spatio-temporal sound speed variability of the survey site via high-density sound speed profiles (collected using the rapidCAST-SWiFT system)
- then explain sound speed variability in terms of physical oceanographic properties
- investigate the potential effect of this variability on bathymetric data collection.

## Location

Plymouth Sound presents a challenging environment for surveyors as significant variations in sound speed can occur both spatially and temporally due to the complex dynamics of water bodies in an estuarine-influenced environment. The current study posits that sound speed variations would be predominately affected by salinity variations induced by the tidal mixing of fresh water from the rivers Tamar, Tavy, Plym, Lyhner and saline water from the Sound. The Tamar Estuary is a partially mixed and flood dominant estuary, with tidal ranges of between approximately 2m and 6m [Uncles *et al*., 1985] and an approximate mean outflow of the Tamar of 22.5m$^3$/s [Dyer, 1997].

The red rectangle in Figure 1 denotes the main area of interest, intended to cover a region of high spatio-temporal sound speed variability. The survey block includes areas of Barnpool, Drake's Channel, Vanguard Bank and the mouth of the Tamar (Narrows). The survey site is a widely used section of waterway, was chosen as one of the data collection areas for Shallow Survey 2005 and 2015, and is also of high importance to commercial, military and leisure sectors. Bathymetry and seabed features are highly variable, ranging from 5m to 32m depth with bottom compositions of sand and rock. The site comprises a deep navigation channel, shallow areas with a sloping gradient and rock reef.

## Sound Speed Variability and its Effects on Bathymetric Data

To gain sufficiently accurate representations of bathymetry and seabed features from multibeam echo sounder (MBES) datasets, sound speed profiles (SSP) need to be applied and processed to account for potential acoustic wave refraction effects. The

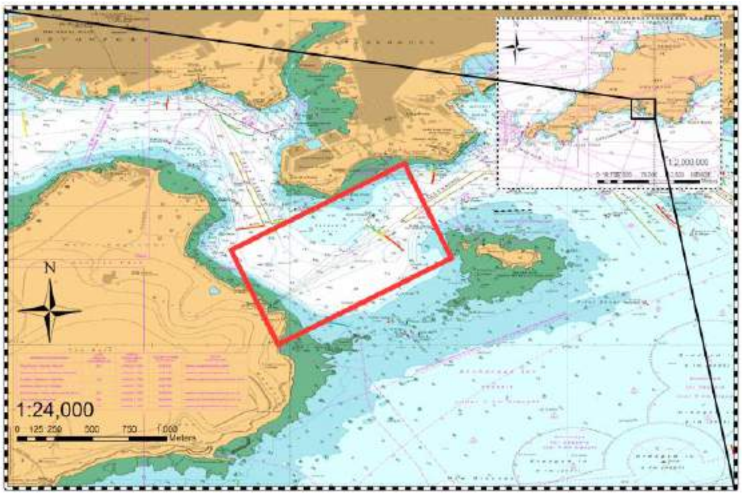


**Figure 1: Area of study at the mouth of the Tamar estuary in Plymouth Sound**



integration of SSPs into MBES processing allows for ray tracing computations of individual beams and thus reduces each sounding's positional uncertainty by accounting for propagation and refraction of the beam, derived from the SSP.

Beaudoin *et al*. [2009], utilising the ODIM Moving Vessel Profiler (MVP), developed 'uncertainty wedge analysis' by tracking the divergence of acoustic ray paths coupled with differing SSPs representative of the water column. The study illustrated depth uncertainty wedges associated with two observed SSPs. Where draft, depression angle and angular sector remained constant, depth uncertainties of up to 0.55m were evident in depths of 15m and across-track of 50m. The potential for depth uncertainties as a product of imperfect sound speed knowledge is more prevalent in locations of highly variable sound speed. Clearly, regular and accurate sound velocity profiles are required to minimise such errors and achieve a level of Total Propagated Uncertainty (TPU) which sufficiently satisfies the chosen standard/survey specification.

The sound speed element of TPU is a function of the measurement instrument, its associated calculations, calibration and the environmental variability with respect to space and time. TPU can be split into further sub-categories of Total Horizontal Uncertainty (THU) and Total Vertical Uncertainty (TVU) with sound speed influencing both.

| Order | Special | 1a |
|---|---|---|
| Maximum allowable Total Horizontal Uncertainty at 95% confidence level | 2m | 5m + 5% of depth |
| Derived THU for Study area | ±2m | ±5.775m |
| Maximum allowable Total Vertical Uncertainty at 95% confidence level | a = 0.25m<br>b = 0.0075m | a = 0.5 m<br>b = 0.013m |
| Derived TVU for Study area | ±0.276m | ±0.539m |
| TVU equation derived from: $\pm\sqrt{[a^2 + (bxd)^2]}$<br>where a = constant depth error, b = factor of depth dependent error and d = depth | | |

**Table 1: IHO minimum standards for hydrographic surveys, adapted for site** [IHO S-44, 5thEdition, 2008]

The International Hydrographic Organization's (IHO) *Standards for Hydrographic Surveys S-44* [5th Edition, 2008] are designed to meet nautical charting criteria and span four Orders (Special, 1a, 1b and 2) the use of which is dependent on the area of interest. In relation to this site, IHO Special Order would be applicable as it is concerned with harbours and critical channels. Table 1 summarises IHO's S-44, for survey Orders Special and 1a, for the survey area of this study. The survey area has an average depth of 15.5m and accuracy standards have been calculated from this value.

## Equipment

The Teledyne OceanScience rapidCAST system is an underway automated casting profiler system, enabling the capture of profiles whilst underway at a maximum speed of 8 knots without the need for an operator on deck. During the study a survey speed of approximately 4 knots was used. In addition, a new bottom-tracking mode was successfully tested, allowing a real-time echo sounder feed into the winch, enabling automated control of cast depth, making safe operation over rapidly varying bathymetry considerably easier than during the initial study.


Figure 2: Teledyne OceanScience rapidCAST

Figure 2 shows the rapidCast system mobilised on the starboard quarter deck of the Plymouth University vessel R/V *Falcon Spirit* – the vessel used for the study. The three main components of the rapidCast system are evident: the casting arm, winch box and deck controls.


Figure 3: Valeport SWiFT SVP

The Valeport SWiFT SVP (sound velocity profiler) provides survey-grade data with the benefit of Bluetooth connectivity, allowing casts to be easily reviewed and downloaded. It also incorporates a GPS module providing accurate positioning for each cast and is downloadable in common SVP formats for use in bathymetry processing packages.

## Data Collection

All data acquisition for this study took place over a full spring tidal cycle on 7th June 2016. The survey area was designed so that it could be completed within a one-hour period in an effort to gain full block coverage for each hour of the tidal cycle (i.e. HW, HW+1, etc.). Survey lines were run alternately to optimise the temporal spread of SSPs within each block (see Figure 4).

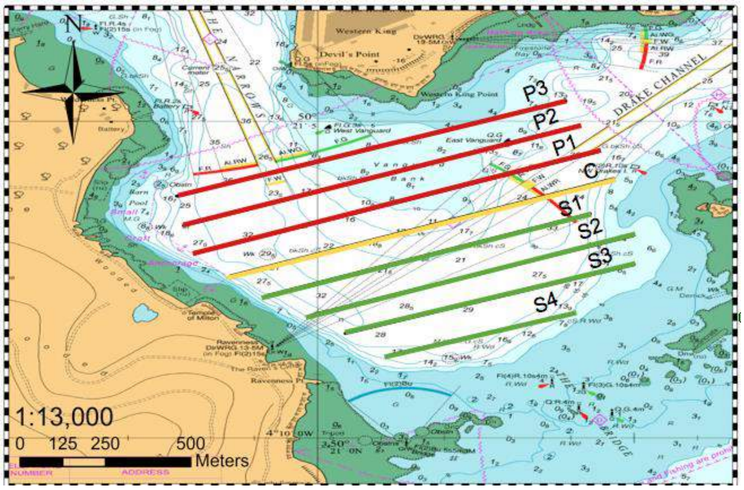


Figure 4: Various survey lines run repeatedly during data collection



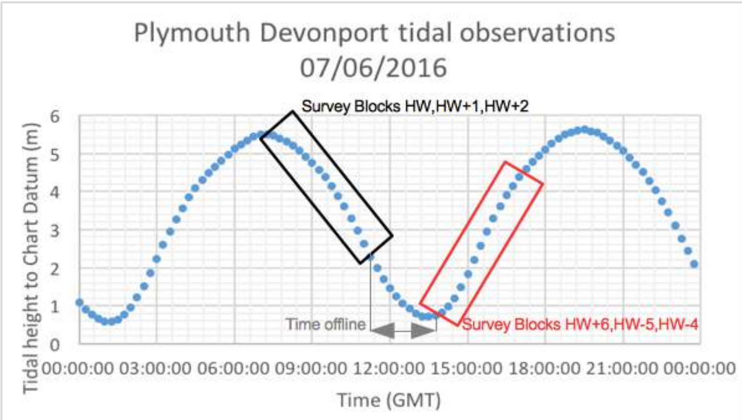


Figure 5: Data acquisition periods showing survey blocks completed through the tidal cycle

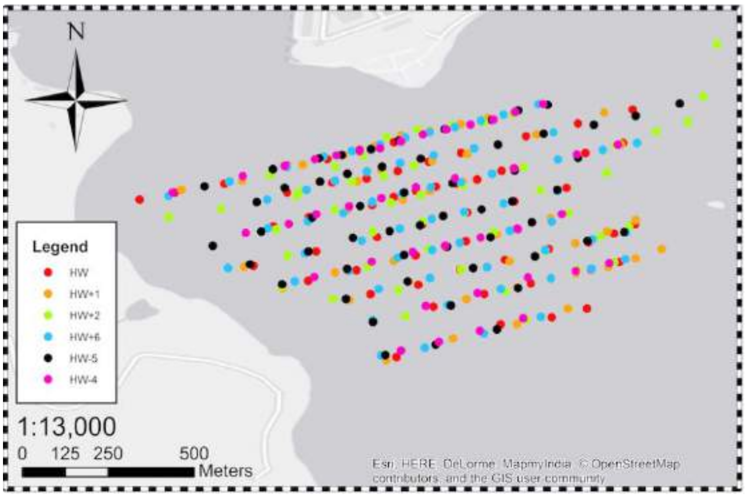


Figure 6: The distribution of all cast over the survey area, colour coded by survey block

Six full blocks were completed corresponding to high water (HW), HW+1, HW+2, HW+6, HW-5, HW-4 tidal states (Figure 5). The operation ran from 07:38 to 18:26 GMT, with downtime (technical difficulties) between 11:08 and 13:57. In addition, there were various restrictions and interruptions to the data acquisition, mainly due to vessel movements (Naval, commercial and leisure), buoys and moorings.

Online speed over ground was maintained at 4 knots to gain high-density and evenly distributed data. In the shallower sections of the survey area, total turnaround time per cast was ~40 seconds, whereas in the deeper sections this time increased to ~1 minute. Casts were downloaded via Bluetooth at the end of each line, with each cast individually time- and geo-stamped in UTC and WGS 84 respectively. Deployment and recovery of the probe was fully-automated, with operator intervention only required for the download procedure or if survey operations had to be put on hold. Figure 6 shows the total number of casts (259) included in the dataset, denoted by which block they were collected in. On average, 51 profiles were collected for each survey block with a minimum of 40 (HW-4) and a maximum of 62 (HW+6).

## Results

Figure 7 shows all SSP casts in the dataset, colour-coded by survey. A clear trend is evident, with casts 'grouped' within their corresponding time blocks. One might expect that a reduction of salinity would occur in the sampled water mass during the lower tidal periods, which would reduce sound speed [Dyer, 1997].

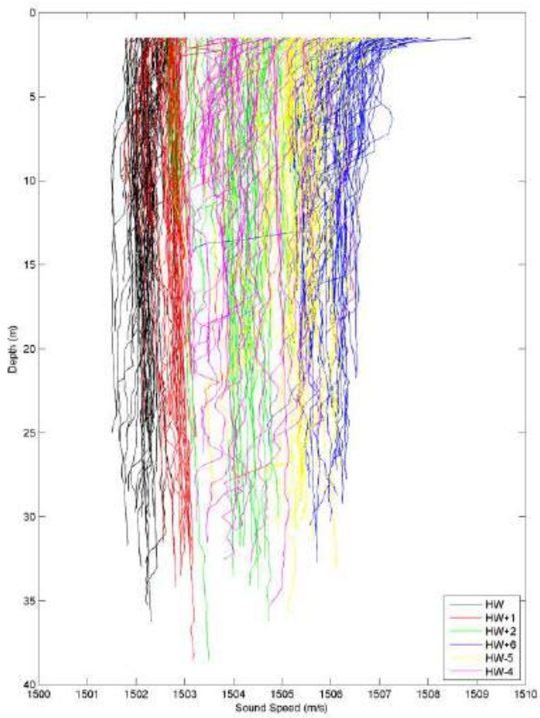


Figure 7: All the sound speed profiles, colour coded by survey block

Counterintuitively, sound speed actually increases from HW to HW+6, before decreasing thereafter. Temperature data collected during SSPs indicate that speed of sound is correlated to temperature variations/structure, and may be associated with the migration of the Tamar mixing front moving offshore though the sample region, reaching an offshore maximum at low water. At low water there is a greater proportion of estuarine water mass (warmer in spring) in the survey region than seawater (colder in spring). Variance in sound speed is most pronounced across both spatial and temporal parameters at near-surface level from 1.5m to 10m depth, with a range of 7.393m/s from a minimum of 1501.483m/s at HW to a maximum of 1508.876m/s at HW+6.

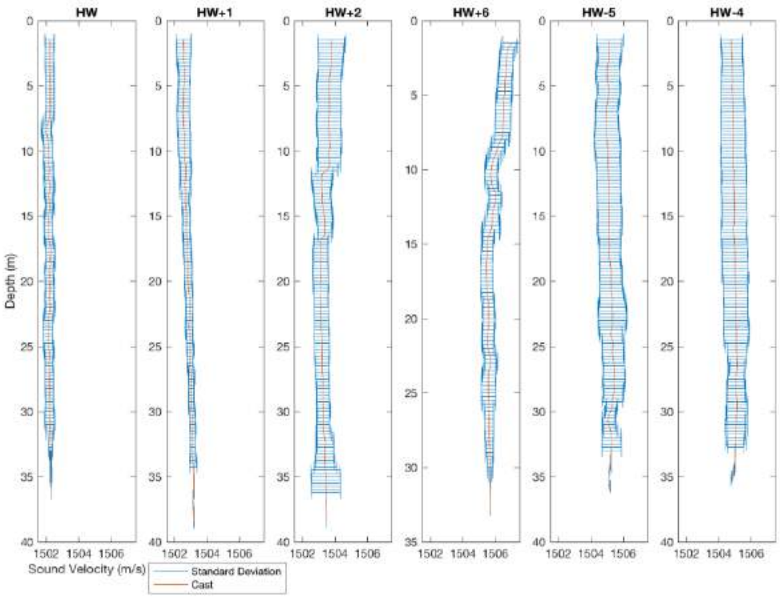


Figure 8: Block variance (deepest cast compared to all other profiles within block)

Figure 8 shows a representative deep cast taken within each survey block and the associated standard deviation (SD) of all data from its corresponding survey block. To ensure that SD values are spatially representative, speed of sound values are interpolated both horizontally (1m) and vertically (0.5m) across the whole block for each hour. The maximum SD was observed during transitional periods from HW and LW structures.

## Ray Tracing Results

To assess the impact of the observed sound speed variability, a ray tracing exercise was carried out for each survey block. The ray tracing was carried out in MATLAB using a ray trace function developed by Val Schmidt at CCOM [Schmidt, 2009]. To quantify the error that can be attributed to sound speed profile variability, an idealised flat seabed, 30m deep, was used as a target. Ray paths for beam angles (measured from vertical) between 5° and 70° at 1° intervals were calculated for the first sound speed profile collected in each survey block. Each subsequent profile from that survey block was then used to calculate the horizontal and vertical error of each beam that would be reported if the original profile continued to be used. This was intended to simulate the common practice of collecting a SSP on commencement of a survey block.

Table 2 summarises the sound speed ranges observed and resultant errors observed for each block, and for comparison with a subset of the transect collected in November 2015 (see Part 1 of this article). While none of the survey blocks show errors in excess of the IHO Special Order requirement, sound speed error is only a single component of the TVU and THU and in the more variable blocks, making a contribution of up to 60% of the acceptable error. Figures 9 and 10 show the error graphically for HW and HW+6 (IHO Special Order limits are marked on the charts as dashed lines).

Errors are magnified in the outer beams and the classic multibeam 'bow tie' effect can be clearly observed in both blocks. The greater vertical structure in sound speed observed at HW+6 (Figure 8) magnifies these errors further.

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| Block | Sound Speed (m/s) | | | Max Vertical Error (m) | | % of error budget | Max Horizontal Error (m) | | % of error budget |
|---|---|---|---|---|---|---|---|---|---|
| IHO Special Order | | | | ±0.276 | | | ±2.000 | | |
| | Min | Max | Range | | | | | | |
| HW | 1501.48 | 1502.92 | 1.5 | -0.07 | +0.09 | 32% | -0.21 | +0.26 | 12% |
| HW+1 | 1501.73 | 1504.86 | 3.13 | -0.04 | +0.16 | 36% | -0.11 | +0.45 | 14% |
| HW +2 | 1502.59 | 1506.17 | 3.58 | -0.13 | +0.08 | 38% | -0.37 | +0.24 | 15% |
| HW+6 | 1503.18 | 1508.87 | 5.69 | -0.11 | +0.22 | 59% | -0.30 | +0.62 | 23% |
| HW-5 | 1502.78 | 1507.39 | 4.61 | -0.16 | +0.14 | 54% | -0.46 | +0.38 | 21% |
| HW-4 | 1502.86 | 1506.48 | 3.62 | -0.14 | +0.15 | 52% | -0.39 | +0.46 | 21% |
| November HW-3 | 1493.92 | 1503.07 | 9.15 | -0.12 | +0.74 | 155% | -0.36 | +2.14 | 63% |

Table 2: Measured sound speed uncertainty contributions by survey block

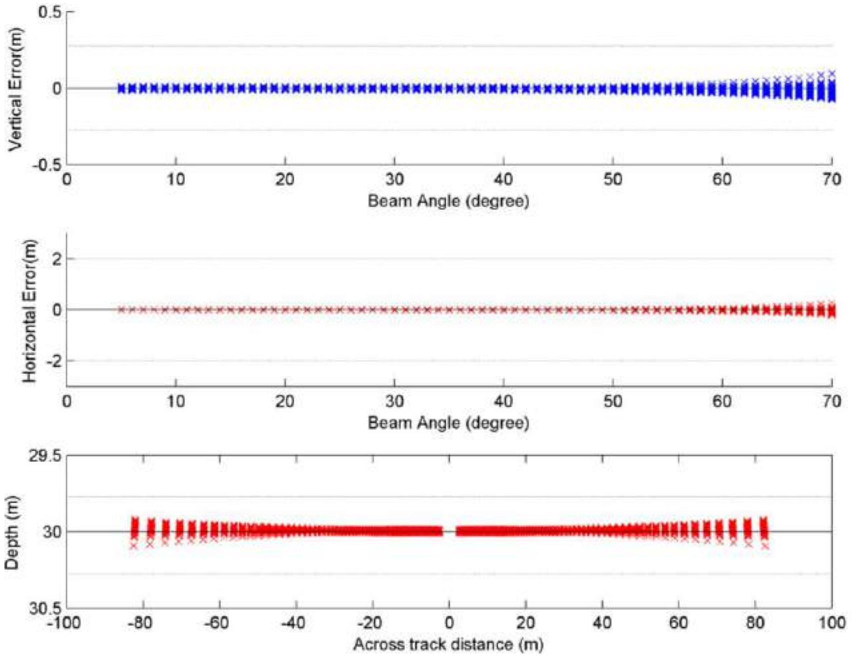


Figure 9: Ray tracing errors for HW (dashed lines represent IHO special order limits)

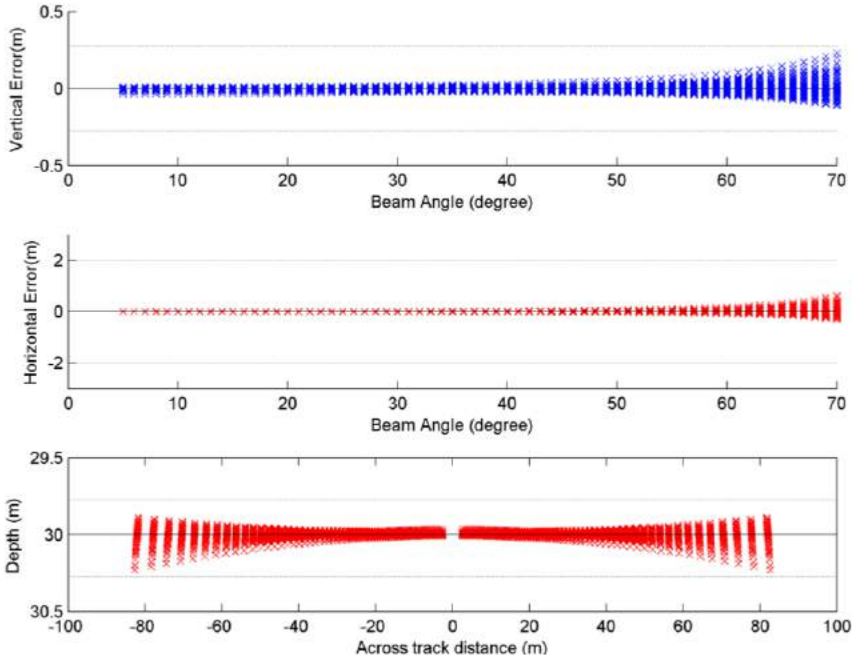


Figure 10: Ray tracing errors for HW+6 (dashed lines represent IHO special order limits)

For comparison, the dataset from Part 1 of this article was revisited. A subset of one of the transects intersecting with the study area was processed with the same ray tracing routine (Figure 11). In the earlier dataset there had been significant rainfall in the period leading up to the data collection and much stronger sound speed, temperature and salinity gradients were observed in the study area. This transect was collected on a dropping tide (neaps) at ~HW+3. This is clearly demonstrated in the ray tracing results which show vertical and horizontal errors up to three times greater than those observed during the June 2016 data collection.

## Discussion

### What's the effect of this variability on data?

It is apparent that sound speed variability within the study area in June 2016 was significantly lower than was observed in the results from November 2015, presented in Part 1 of this article. However, in all the survey blocks observed during the June survey, sound speed variability makes a significant contribution to both the TVU and THU error budgets, particularly in the outer beams. In some cases sound speed variability contributes up to 59% of the TVU error budget with a minimum contribution of over 30% with relatively modest sound speed variability across the block of ~1.5m/s.

For comparison, the dataset collected in November would exceed the IHO Special Order limits both in the TPU and TVU. However, the magnitude of the errors presented should be immediately apparent to the online surveyor, whereas the more subtle errors observed during the June survey may not be instantly recognised.

In the context of this article the authors have concentrated on the IHO bathymetry requirement for charting. While SSP variability in this study may not exceed the IHO limits, when considered in relation to dredging or scientific study into seabed volume changes, vertical accuracy can have a very significant impact in difference volume calculations.

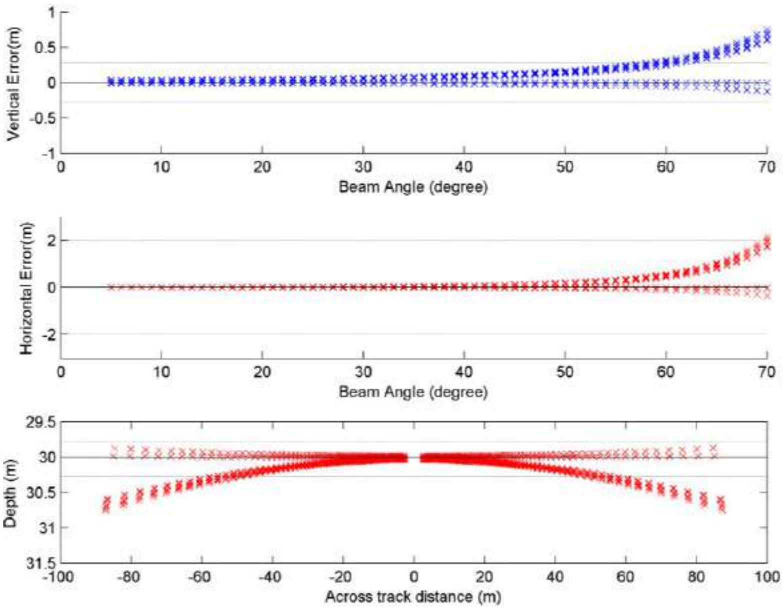


Figure 11: Ray tracing errors for November 2015 transect (dashed lines represent IHO special order limits)

## How often to take a sound speed profile

To quantify the frequency of sound speed profile collection required prior to survey operations, it would be necessary to also have good prior knowledge of the temporal and spatial oceanographic variability of the survey area and the controlling factors.

With traditional sound speed profile gathering techniques, it has always been a balancing act – the limiting factor on the number of profiles collected has been the effort required to collect a profile and the impact of the downtime required to stop the vessel and collect a profile. In this study, rapid and automated collection of sound speed profiles, without requiring a break in operations, was demonstrated to be both feasible and practical with little impact on survey operations. It was seen to be good practice to gather sound speed profiles routinely whilst underway.

Finally, casts taken at higher frequencies have been shown to capture spatial and temporal variability in sound speed more effectively, thus lowering overall uncertainty values. It is better to have data you don't need than to not have data you do need.

## References

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## The Authors

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Jim started his career as an Oceanographic Analyst at the UKHO. He left that position after eight years to join Valeport as Product Manager in 2008. In this role he focuses on new product development as well as customer sales, support and training.

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His research interests include beach and submarine geomorphology, rip current dynamics, storm impact and coastal hazards. These have resulted in 14 peer-reviewed articles in international journal and numerous conference papers and reports. Tim has also conducted a number of consultancy projects, including working closely with the RNLI to improve understanding of physical coastal hazards and develop operational risk assessment tools. In addition, he has recently acted as expert witness in rip current drowning cases.

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**Iain Slade** is a Survey Trainer at the Fugro Academy. He is a graduate of Plymouth University - MSc Hydrography and BSc (Hons) Ocean Science - with 12 years' industry experience.

His current training portfolio covers a broad range of topics reflecting his experience, knowledge and skills gained in a wide range of roles across the hydrographic industry.

Iain began his career as a Marine Cartographer at the UKHO, before moving into data analysis as a Bathymetric Appraisal Officer in the Seabed Data Centre. Civil engineering at a number of commercial consultancies mainly in the nearshore/coastal, civil hydrography and port sectors followed. A move to Fugro exposed him to offshore site surveys, debris surveys, geotechnical investigations, rig moves, ROV construction and IRM work.

Iain recently assisted the Marine Learning Alliance with the delivery of their Advanced Practical Techniques in Hydrography Module.

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