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Streamlining Sound Speed Profile Pre-Processing: Case Studies and Field Trials

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Abstract

High rate sound speed profiling systems have the potential to maximize the efficiency of multibeam echosounder systems (MBES) by increasing the accuracy at the outer edges of the swath where refraction effects are at their worst. In some cases, high rate sampling on the order of tens of casts per hour is required to capture the spatio-temporal oceanographic variability and this increased sampling rate can challenge the data acquisition workflow if refraction corrections are to be applied in real-time. Common bottlenecks result from sound speed profile (SSP) pre-processing requirements, e.g. file format conversion, cast extension, reduction of the number of points in the cast, filtering, etc. Without the ability to quickly pre-process SSP data, the MBES operator can quickly become overwhelmed with SSP related tasks, potentially to the detriment of their other duties.

A series of algorithms are proposed in which SSPs are automatically pre-processed to meet input criteria of MBES acquisition systems, specifically the problems of cast extrapolation and thinning are addressed. The algorithmic performance will be assessed in terms of sounding uncertainty through a series of case studies in a variety of oceanographic conditions and water depths. Results from a field trial in the French Mediterranean will be used to assess the improvement in real-time MBES acquisition workflow and survey accuracy and will also highlight where further improvements can be made in the pre-processing pipeline.

Introduction

Knowledge of the vertical variation of the speed of sound in the water column is critical to the acquisition of high accuracy depth measurements with multibeam echosounders (MBES). The speed of sound is traditionally measured by lowering a velocimeter or conductivity-temperature-depth (CTD) instrument as deep as possible while the survey vessel remains stationary. The resulting sound speed profile (SSP) is then used in a ray bending model that accounts for the refraction of the acoustic ray path between the sounder and the seafloor. With stationary profiling instruments, it is often impractical to sample the water column at the high rates that are sometimes necessary in a dynamic environment. In the case where water mass variability is primarily spatial in nature, hydrographic surveys are necessarily limited to the spatial extent over which the single water column measurement is a reasonable representation thereof.

Underway profiling systems such as Moving Vessel Profilers (MVP) (Furlong, 1997) and Underway CTDs (Rudnick and Klinke, 2007) remove this fundamental limitation by allowing the hydrographer to sample the water mass at a high rate while underway. This can lead to increases in survey efficiencies through reduction of time spent in turns as the surveyor is now free to run long survey lines instead of conducting several small "postage stamp" type surveys to cover the same area. Furthermore, as there is no time cost associated with high rate sound speed profiling, the surveyor can acquire many sound speed profiles and maintain better control over refraction based uncertainties in the outermost portions of the swath. This allows for a gain in efficiency through an increase in line spacing. Lastly, efficiencies are also gained through near complete elimination of the time required to measure sound speed profiles (SSP) from a static platform, a process which can take anywhere from tens of minutes to a few hours, depending on water depth.

These gains in efficiencies can be quickly lost, however, if the surveyor is spending time on various pre-processing tasks that are often required prior to uploading the SSP into the data acquisition system. This is particularly problematic in mapping workflows where real-time refraction corrected soundings are desired and the SSP should be applied as soon as possible after acquisition. Simple tasks such as file format conversion and upload to the acquisition system can become burdensome in cases where high rate sampling is required. Continuous distractions can detract from the surveyor's ability to monitor other mapping systems and can lead to problems such as data holidays when the surveyor's attention is split amongst system monitoring and SSP pre-processing tasks. Additional watch personnel can alleviate these problems, however, this brings additional cost.

In March of 2011 the French Research Institute for Exploitation of the Sea (IFREMER) took delivery of a Moving Vessel Profiler 200 (MVP200) from ODIM Brooke Ocean[1]. The MVP200 system allows for underway measurement of sound speed profiles (SSP) to depths of 200 meters while travelling at speeds up to 12 kts (Furlong, 1997). The MVP system was installed on the R/V Le Suroît, an IFREMER vessel equipped with a 30 kHz Kongsberg Maritime (KM) EM302 MBES (Kongsberg Maritime, 2006). A key requirement outlined by IFREMER was the ability to have the MVP controller software extend the sound speed profile to full ocean depth in the case where the depth exceeds the sampling ability of the MVP200 system. A further desire was for the application of sound speed profiles to be done in real-time with little or no operator intervention at all. As will be shown, this requires further extension of the SSP to a depth up 12,000 m when used with KM MBES systems. These additional pre-processing requirements led to this work.

In this paper, we propose algorithms to automate some of the most common tasks involved with SSP pre-processing, in this case we examine (a) vertical extrapolation of profile beyond the maximum SSP profiling depth to, at least, the maximum expected water depth, and (b) reduction of the number of data points in the SSP. The proposed solutions to both problems are evaluated

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via ray tracing simulation analysis methods that express the algorithmic performance in terms of their effects on sounding uncertainty. This is followed by a discussion of the implementation of these algorithms in the MVP controller software in such a manner as to allow automatic integration of measured MVP SSPs into KM MBES in a manner that requires very little operator interaction. Finally, preliminary results from a field trial of the MVP controller software in the French Mediterranean are presented in the last section of this work followed by a discussion of remaining work.

Methods

Profile Extension

Though it is almost always desirable to measure the speed of sound over the entire vertical extent of the water column, this is not always practical due to instrumentation limitations such as maximum pressure ratings or a limit on the amount of line or wire available to deploy the instrument. A further practical limitation with MVP systems is that the maximum achievable sampling depth is reduced with increasing vessel speed as more and more cable is required to allow for the forward advance of the vessel during the free fall stage of the probe (see Table 1). In the case that the water depth is deeper than the maximum achievable depth at a given speed, the vessel can slow down to allow for deeper profiles. This remedy, however, is limited by the maximum amount of cable available and alternate sources of sound speed should be considered in order to provide at least an approximation of the sound speed structure below the maximum sampling depth.

Table 1. MVP maximum sampling depths (ODIM, 2010).

Speed (knots)	Maximum sampling depth (meters)				
	MVP30	MVP30-350	MVP200	MVP300	MVP800
0	175	350	600	3400	5000
6	50	145	320	1250	1850
12	30	30	200	300	800

In this work, we explore the idea of using (a) infrequent in-situ deep casts acquired occasionally during the survey while stationary or at reduced speed and (b) synthetic sound speed profiles derived from three dimensional oceanographic grids of temperature/salinity, also known as climatologies, such as the World Ocean Atlas (WOA) (Antonov et al., 2010; Locarnini et al., 2010) or the Generalized Digital Environmental Model (GDEM) (NAVO, 2002). The underlying assumption of this method, which should be verified on a case-by-case basis when used in practice, is that spatio-temporal variability in temperature and salinity at depth is much less pronounced than at the surface. There are of course many counter-examples of this found throughout the world's oceans and these approaches may yield unsatisfactory results in these areas, as will be shown in the case studies at the end of this section. Previous work provides some guidance on the use of climatologies in support of MBES operations, but is specific to the region investigated (Beaudoin et al., 2006).

The proposed cast extension methodology is straightforward in that the deeper portions of deep casts are simply appended to shallower casts, as shown in Figure 1. In the event that the pseudo-profile derived from a climatology is not deep enough to cover the range of expected depths (which is not uncommon), similar extension methods can be used join climatological profiles derived from deeper locations nearby.

By simply appending the deeper portion of the deep cast to the shallow cast, discontinuities in the sound speed gradient can result, leading to an abrupt kink in ray paths at the depth of the discontinuity (see the transition from shallow to deep cast at a depth of ~38m in Figure 1(b)). Methods to smooth the transition between piece-wise sections of sound speed profiles do exist, e.g. Teague et al. (1990), however, methods such as these address the symptom and not the underlying problem: discontinuities are indicative of a discrepancy between the short and deep casts that perhaps should be remedied through the acquisition of another deep cast instead of smoothing the transition. Acquisition of a deep cast can be trivial during routine hydrographic mapping operations, e.g. slowing down dramatically during a turn at the end of a survey line could allow for deep casts at the end of every survey line. It should be noted that this option may not be feasible for operations that involve towing other instrumentation behind the vessel. At present these discontinuities are left in the SSPs though methods are being explored to help the user gauge the severity of discontinuities and decide whether or not another deep cast is required.

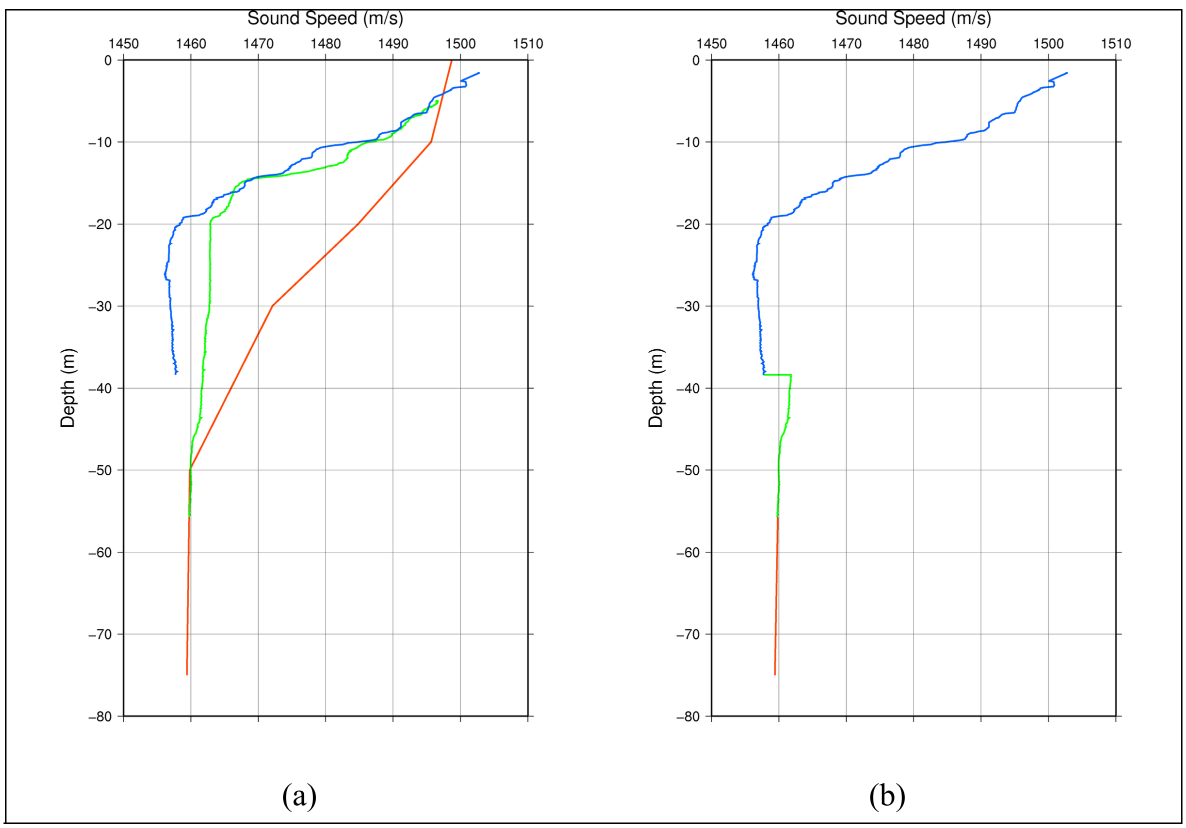

Figure 1. Cast extension example. Panel (a) shows a speed limited shallow cast in blue, a deep cast acquired prior to the survey in green and a WOA pseudo-cast in red. Note the coarse vertical resolution of the WOA cast relative to the measured casts. Panel (b) demonstrates the piece-wise construction of the extended shallow cast from (a) with color coding matching panel (a) to clearly demonstrate how each cast in (a) contributes to the extended cast in (b).

Thinning

Reduction of the number of points in a SSP may be desirable simply for the sake of increasing the efficiency of ray tracing algorithms but it is more often required due to software design considerations which may constrain the number of points in a SSP. For example, KM MBES systems limit the number of points in the SSP that can be input to the processing unit for real-time ray tracing calculations:

> *"There is a limitation on the size of the sound velocity profile. The file used by the PU must be maximum 30 kB and limited to a maximum number of depth points. Maximum 1000 points for EM710, EM302 and EM 122. Maximum 570 points for older sounders."* (Kongsberg, 2010)

Typical existing procedures involve sub-sampling the profile by calculating the mean in vertical bins of fixed size. This is not necessarily straightforward, however, when measured SSPs of relatively high vertical resolution (with potentially several samples per bin) are vertically extended with a climatologically derived SSP with low vertical resolution (samples can be separated by tens of meters, and even hundreds of meters at great depth).

For this work, extended SSPs are thinned using a variant of the Douglas-Peucker (DP) line reduction algorithm, which is a common method used for line simplification in computer display applications in which highly complex multi-segment graphical line objects, such as coastlines, must be reduced for efficiency purposes (Douglas and Peucker, 1973). The sole parameter to the algorithm is a user-specified tolerance which limits the maximum allowable distance between the original and thinned line object, as shown in Figure 2. The traditional DP algorithm, referred to from now on as DP_{2D}, was designed for two-dimensional line objects whose units are the same in both dimensions, for example, units of eastings and northings in the case of a shoreline. One can treat a SSP as a set of line segments defined by the set of depth/speed pairs, however, the calculation of two-dimensional distance has meaningless units and it may be preferable instead to specify the maximum tolerance in units of sound speed. For this reason, the DP_{2D} algorithm has been modified to calculate the distance in the speed dimension only, as shown in the bottom panel of Figure 2. The modified algorithm is referred to as DP_{1D} in this work. Figure 3 shows results from the applying the algorithm to a SSP with tolerance increasing by a factor of two from 0.25 m to 8.0 m. With a low tolerance value (0.25 m), the number of points in the cast is reduced from 564 to 70 points, a reduction of nearly 90%.

Case Study

Two case studies were done to assess the impact of the thinning and extension algorithms under realistic water column conditions. Uncertainty Analysis (UA) methods were used to assess the algorithms in terms of sounding uncertainty (Beaudoin et al., 2009). Briefly, these methods involve comparing ray paths as derived from a ray trace through a reference SSP and a candidate SSP that is to be tested against the reference. Comparisons are made for points with a common two-way travel time (TWTT) along the ray paths yielding a set of depth and horizontal discrepancies between the ray paths over the entire ray path and for a range of incidence angles.

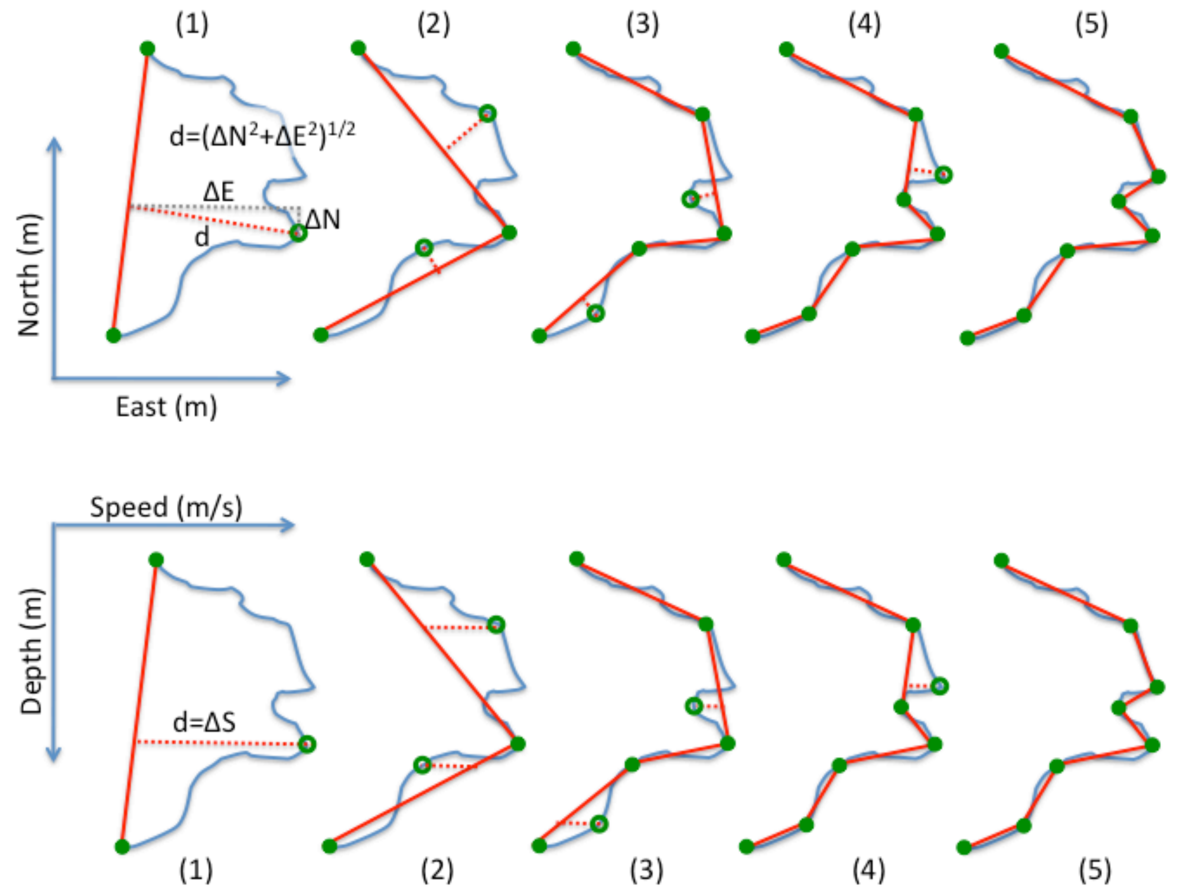

Figure 2. Cartoon example of DP line reduction for computer graphics applications (upper) and sound speed profile thinning (lower). The aim of the procedure is to retain sufficient points in the line such that no section of any line segment in the thinned line exceeds a specified tolerance distance from the original line. The procedure, which is performed iteratively, begins by marking the two terminal points of the line object as points that should be kept (solid green dots), this is followed by finding the most distal point on the section of the original line between the point from the red line connecting the two end points (marked by a green circle). If the most distant point is greater than the specified tolerance, then the distal point is preserved in the thinned output. If it is not, then the process for this segment is complete. The procedure is performed recursively for the two resulting line segments until all points on all thinned line segments are within the specified tolerance distance from the original line. The 2D and 1D algorithms differ only in their calculation of the distance between the original and thinned lines.

This method allows for estimation of the net effect of the difference in SSPs on sounding uncertainty. Repeating the procedure with large data sets of SSPs allows for estimation of the effect over a range of conditions with summary statistics providing a sense of the potential impact on sounding uncertainty.

The test data set used for evaluating the DP thinning algorithms consists of 2,147 SSPs collected by an MVP30 in the Rotterdam Waterway over a two-week period in March/April of 2009. The data set and environment is more fully described in Beaudoin et al. (2009). This data set was chosen as it represents a comprehensive sampling of the range of possible water column conditions in a highly stratified and dynamic salt wedge estuary. Sound speeds range from 1440 m/s in the fresh and relatively warm river outflow to 1472 m/s in the salty and cold water from the North Sea that intrudes below the river outflow, as shown in Figure 4.

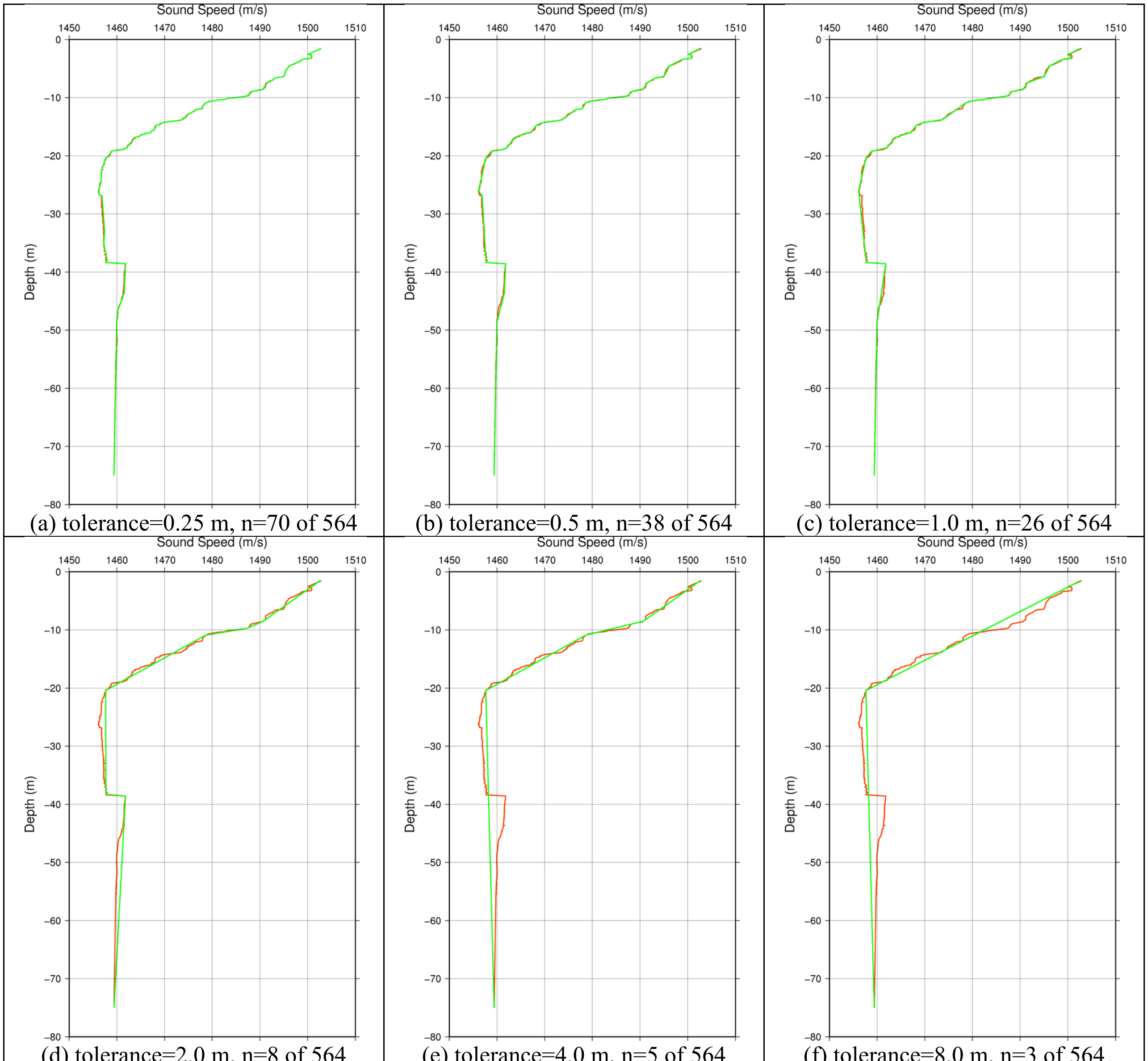

Figure 3. Example of one-dimensional DP_{1D} line reduction algorithm on extended cast of Figure 1. In all panels, the red cast is the raw cast (564 points), the green is the thinned cast. Tolerance increases by factors of two through panels (a) through (f).

The goal in this portion of the case study is to clearly identify the sounding uncertainty that results from the use of the DP_{1D} and DP_{2D} algorithms and to see how this evolves with increasing tolerance, i.e. more aggressive thinning.

For a specified thinning tolerance, the data set was processed as such:

1. A set of thinned casts was generated from the raw casts using the specified tolerance using the DP_{1D} and then the DP_{2D} methods.
2. The thinned casts were then compared to their respective source casts and the depth bias of the beam at 60° at the end of the ray trace was kept as the output of the comparison.

The mean and standard deviation of this set of values was then computed for both the DP_{1D} and DP_{2D} methods.

Steps (1) and (2) were repeated for a range of tolerance levels, results are listed in Table 2 and plotted as a function of tolerance in Figure 5. The mean bias is nearly zero over the range of tolerances examined and increasing the tolerance level results in an increase in the depth uncertainty due to the ever-decreasing fidelity of the thinned SSP (refer to Figure 3f for an example of a low fidelity representation). At low tolerance levels, i.e. high fidelity thinned casts, the DP_{1D} method follows uncertainty growth associated with sensor noise (lower dotted line in Figure 5). This is to be expected as the portions of the cast that are removed are high frequency in nature, and would have the same effect as a noisy sound speed sensor.

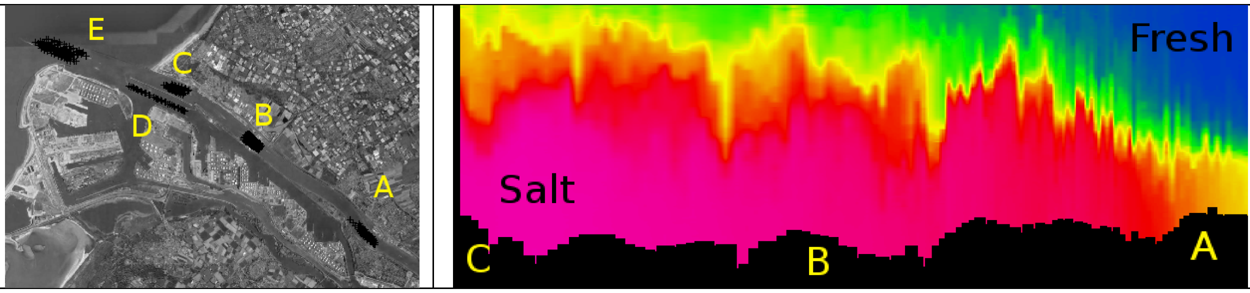

Figure 4. Location map and vertical salinity section of the Rotterdam Waterway as sampled in March/April of 2009. The salinity section is 20 m in the vertical and 11.5 km in the horizontal. Salinities ranged from 0-32ppt (Beaudoin et al., 2009). Labels along the bottom of the salinity section correspond to those in the location map.

Table 2. Results of DP_{1D} and DP_{2D} thinning assessment.

Tolerance	μ_{1D} (%w.d.)	μ_{2D} (%w.d.)	σ_{1D} (%w.d.)	σ_{2D} (%w.d.)
0.1	0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.00	0.01
0.5	0.00	0.00	0.01	0.02
1.0	0.00	0.00	0.02	0.04
2.0	0.01	0.01	0.04	0.08
3.0	0.01	0.01	0.06	0.13
4.0	0.01	-0.01	0.08	0.20
5.0	0.02	0.00	0.12	0.29
6.0	0.02	0.00	0.16	0.39
7.0	0.02	0.00	0.20	0.47
8.0	0.02	0.01	0.27	0.50
9.0	0.03	0.03	0.33	0.52
10.0	0.03	0.04	0.39	0.53

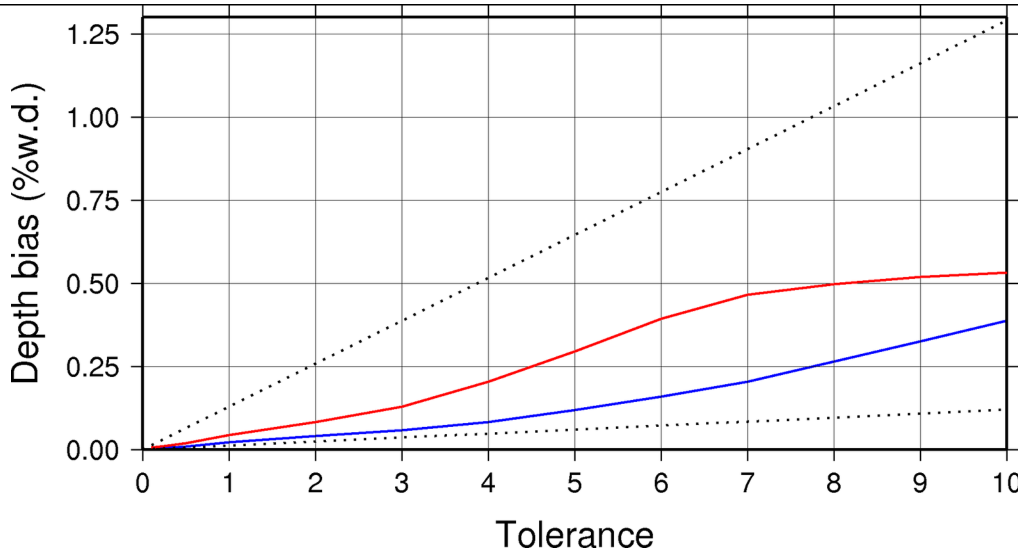

Figure 5. Results of DP line reduction algorithm uncertainty analysis on the Rotterdam Waterway data set for soundings at 60° angle of incidence. DP_{1D} and DP_{2D} results are plotted in blue and red, respectively. Dotted lines represent the expected sounding uncertainty resulting from "tolerance" m/s of sounding noise (lower) and bias (upper); these dotted lines are from unpublished numerical simulations, which separately model the effect of sound speed sensor bias and noise.

With larger tolerances, i.e. low fidelity thinned casts, the uncertainty grows non-linearly in both cases, suggesting that both algorithms begin to induce depth bias magnitudes more typically observed with a biased sound speed sensor. This is explained by considering the worst-case scenario of the thinning algorithms in which a raw cast is reduced to its two end-points. Many of the SSPs in this data set can be approximated as a two-layer stratified water mass, with fresh river water of low sound speed on top and salty oceanic water of high sound speed underneath. Figure 6 demonstrates how the DP_{2D} algorithm will always trim more aggressively than the DP_{1D} method: the inflection points at the velocline in the raw SSP will always be removed by the DP_{2D} method at a lower tolerance than the DP_{1D} method since their two-dimensional distances from the line connecting the end-points will always be smaller than the one-dimensional distance used by the DP_{1D} method (d_{2D} and d_{1D} in the figure). In the case shown in Figure 6, the depth bias resulting from use of the thinned cast will be small as the area integral between the two casts tends to zero as long as the velocline is situated midway between the sea surface and the seabed (Geng and Zielinksi, 1999). For cases where the velocline deviates from this ideal mid-depth position, the resulting thinned cast will always provide a biased sounding as the integration of the area between the sound speed curves will be non-zero. The DP_{2D} thinned casts tend to biased cases with low tolerances relative to the DP_{1D} method, thus explaining the larger growth in uncertainty observed in Figure 5. The same effect will eventually occur with the DP_{1D} method, but at much higher tolerances.

Examining the rate at which SSPs are reduced to two-points, as in Figure 7, explains much of the observed uncertainty growth for both approaches. The DP_{2D} uncertainty grows at a much higher rate than the DP_{1D}, this is due to the larger number of SSPs that are reduced to two-point thinned SSPs at low tolerance levels (see Figure 7). The flattening of the DP_{2D} curve at a tolerance of 7 (recall that tolerance units are meaningless for DP_{2D}) is associated with the tapering off of the number of thinned SSPs containing just two points. At this point, nearly all SSPs have been reduced to two-points and increasing the tolerance does not increase the uncertainty: this is as bad as it can possibly get! Extrapolating the DP_{1D} curve in Figure 7 suggests that the same would happen for the DP_{1D} case at tolerances of approximately 12 m/s.

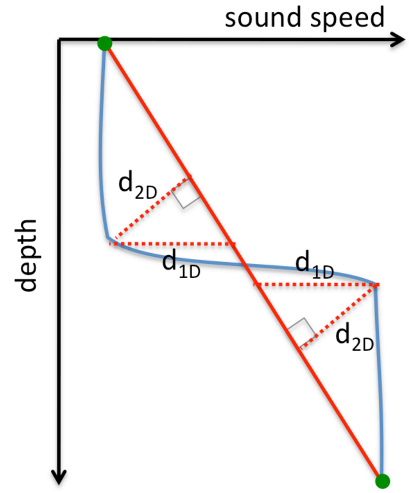

Figure 6. Cartoon example showing how two-dimensional distance criteria used with DP_{2D} will always fall below tolerance before the one-dimensional case with DP_{1D}.

As with many engineering problems, a trade off is sought between maximizing thinning and minimizing uncertainty. Plotting the mean number of points in the thinned SSPs as a function of tolerance, as in Figure 8, can help make this type of decision. Considering that the mean number of points in the SSPs is 184, thinning the SSPs with a modest tolerance of 0.1m/s yielded a data reduction of 74% (from 184 to 48). This is a remarkable gain considering that soundings at 60° incidence angle suffer negligible uncertainty, less than 0.001%w.d. (1-σ). Pushing the tolerance to 1 m/s gives a dramatic increase in data reduction (95%, from 184 to 9), again with a small penalty to pay in terms of sounding uncertainty: 0.02%w.d. (1-σ). The findings from this case study suggest that the DP_{1D} method could likely be used for data reduction purposes in shallow water hydrographic applications with little impact at all on sounding uncertainty.

We turn now to the deep water case and examine the effect of using climatologically derived profiles for extension of casts. In this case we address the question: "how deep should we be striving to measure". This is particularly of concern in deep water as this is where we expect systems such as MVPs to be limited in their ability to sample the entire water column. To answer this question, we examine a set of CTD casts extracted from the World Ocean Database (WOD) (Boyer et al., 2006), specifically 4,581 North Atlantic CTD casts falling within a 1° latitudinal band centered roughly about 36°N. Having areas of thermohaline structure at depth is instrumental to exercising the automated extension algorithm, this particular section of the ocean was chosen as it is bounded by the Gulf Stream on the west side of the basin (thermal structure down to ~1,500m) and includes the mouth of the Mediterranean whose outflow at depth creates thermohaline structures which can form Mediterranean water eddies (meddies) at depths ranging from 700-1300 m (Richardson, 1991). Figure 9 shows samples of sound speed casts from both regions. Both of these regions also exhibit spatio-temporal variability at depth at spatial and temporal scales that are not preserved in climatologies such as WOA or GDEM, they are thus good candidates for this case study.

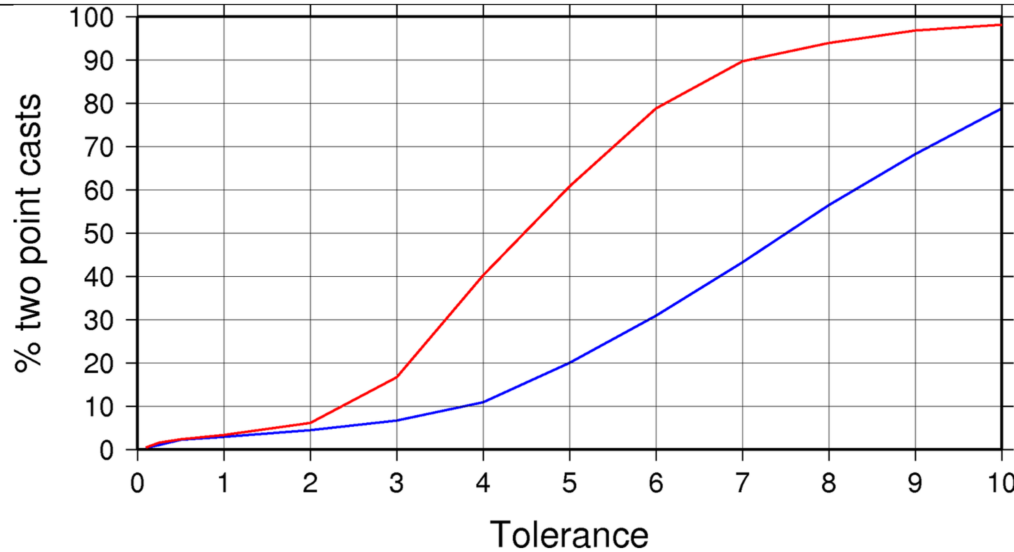

Figure 7. Percentage of casts reduced to two points as a function of tolerance (blue is DP_{1D}, red is DP_{2D}).

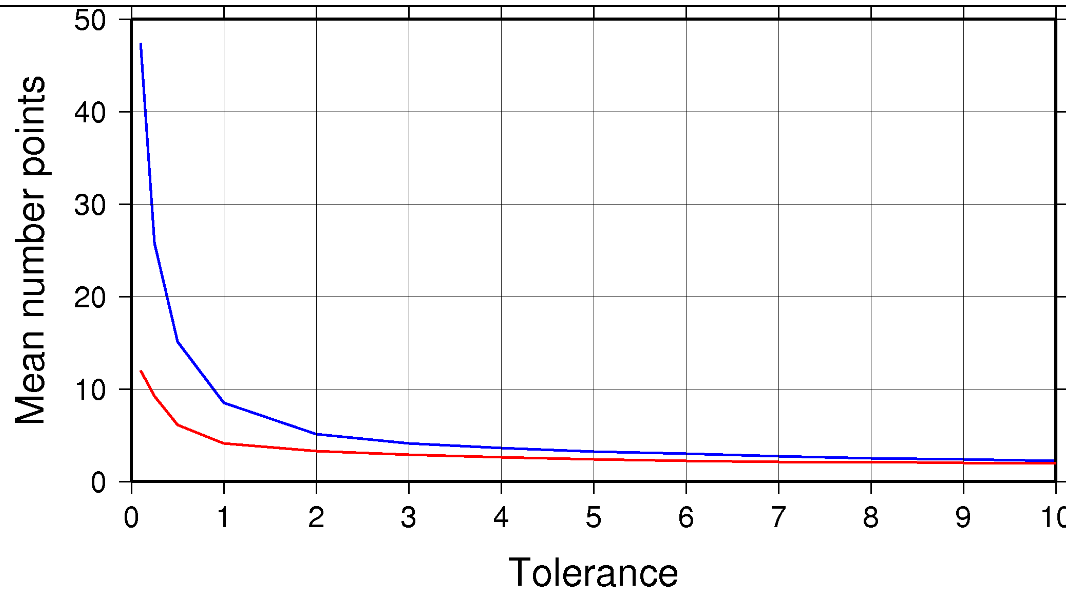

Figure 8. Mean number of samples in thinned casts after DP_{1D} (blue) and DP_{2D} (red). The mean number of samples in the raw casts was 184, thus even with a modest tolerance of 0.1m, the DP_{1D} reduced the number of points to ~25% of the original value.

For this investigation, each CTD cast is examined over a range of depths to simulate the situation where one was limited in ability to sample the entire water column due to constraints imposed by the sampling hardware. For each depth investigated, all casts are treated to the following sequence of operations:

1. SSPs were computed for all CTD casts using the UNESCO equation relating temperature, pressure and salinity to speed of sound (Fofonoff and Millard, 1983).
2. Clipped versions of the CTD casts were generated by removing all portions of the casts below the prescribed depth.
3. The clipped casts were then extended using WOA using the extension method described earlier with the UNESCO sound speed equation being used to compute sound speed from the WOA temperature and salinity values (Fofonoff and Millard, 1983). The clipped and extended SSPs form the set of candidate SSPs to be tested against the original casts.
4. The clipped and extended casts were then compared to their respective source casts and the depth bias of the beam at 60° at the end of the ray trace was kept as the output of the comparison. The mean bias and RMS bias were computed for the entire set of casts at each depth level.

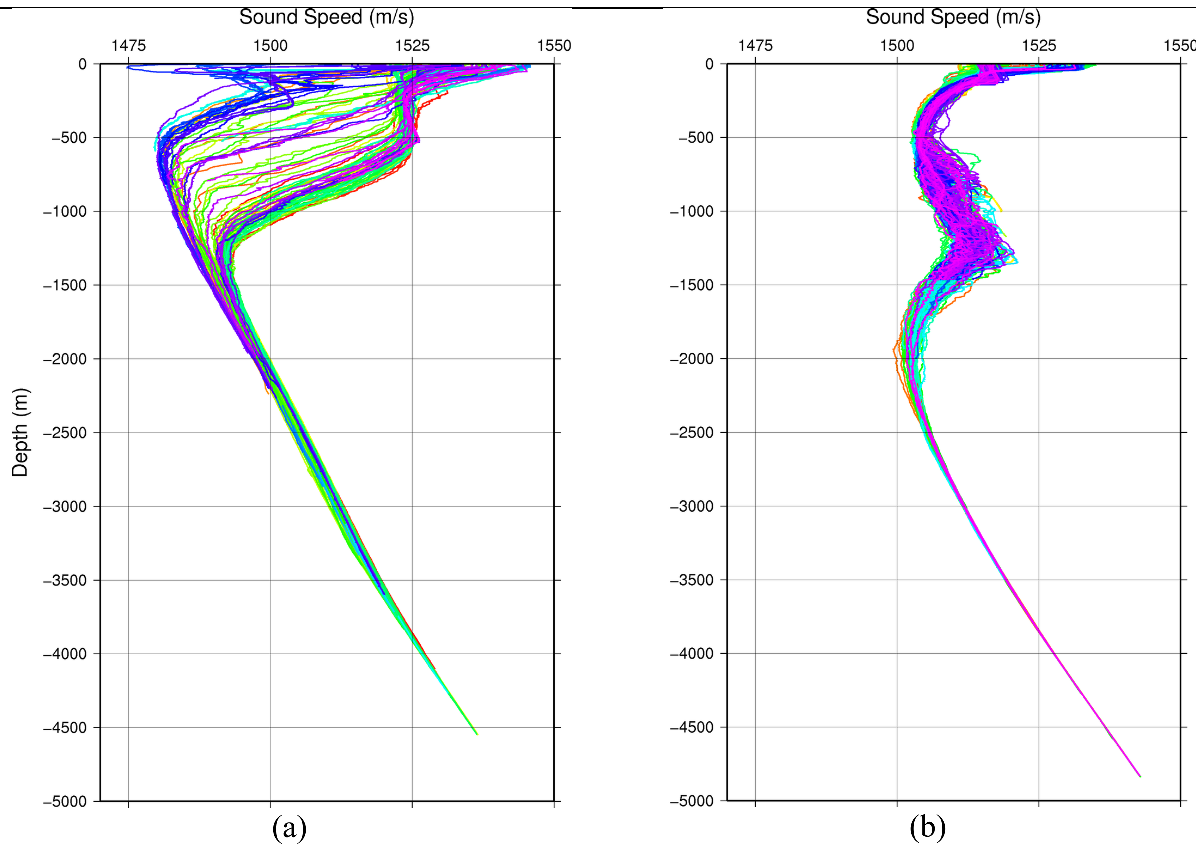

Figure 9. Sound speed profiles from western (a) and eastern (b) ends of the section.

Summary statistics for each depth level are presented in Table 3. The special case of zero depth demonstrates how poorly climatologies would perform if used as a complete substitute for in situ measurements: results would be significantly biased on average (-0.4%w.d.) and the RMS bias of 1.13%w.d., once scaled to 95% confidence level, is on the order of the 2.3%w.d. allowable depth uncertainty for IHO Order 2 (IHO, 2008). For a case that shows the contrary, see Beaudoin et al. (2006). Of course, this does not apply to the entire set of casts. Depth bias results from the above set of operations are plotted against longitude for all investigated depths in Figure 10. Examining the case of zero depth, it is clear that the mean and RMS biases are dominated by poor performance on the US continental shelf at the western end of the section. Open ocean performance is not as poor as the summary statistics suggest, the mean and RMS bias for data between 70°W and 10°W is -0.05%w.d. and 0.19%w.d., respectively, suggesting that climatologies could likely be used as a substitute for in-situ measurement in the open ocean with small impacts on accuracy relative to IHO Order 2. As expected, the western and eastern regions experience higher uncertainties relative to the central portion due to spatio-temporal variability associated with the Gulf Stream and the Mediterranean outflow. This effect persists down to a depth level of 500 m, suggesting that these locations might require that more of the water column be sampled in order to maintain sounding accuracy.

As expected, the RMS bias diminishes with depth, i.e. the deeper we sample, the less we rely on climatologies and the better the performance of the extension algorithm as more and more of the variable upper water column is measured. From the summary statistics, it would appear that one could measure to 200 m depth and capture enough of the variability to ensure sounding uncertainty does not exceed 0.17%w.d. (1-σ). These results, of course, apply only to this section of ocean and are both observation limited and biased. This case study, however, does provide a framework on how data sets such as the WOD and methods such as UA can be used to choose appropriate water column sampling equipment and strategies before deployment in the field.

Table 3. Summary statistics for climatology extension study.

Depth (m)	Mean bias (%w.d.)	RMS bias (%w.d.)	Mean bias 70°W to 10°W (%w.d.)	RMS bias 70°W to 10°W (%w.d.)
0	-0.40	1.13	-0.05	0.19
100	-0.06	0.23	-0.04	0.16
200	-0.03	0.17	-0.04	0.15
300	-0.03	0.15	-0.04	0.13
400	-0.02	0.13	-0.03	0.12
500	-0.01	0.11	-0.02	0.10

As a test of the combined extension and thinning algorithms, the 200 m depth subset was investigated further by adding the DP_{1D} thinning with a tolerance of 0.1 m/s as an additional step between steps 3 and 4 described earlier. The change in resulting summary statistics was negligible with differences less than 0.001%w.d. for both the mean bias and RMS bias. The thinning algorithm was able to reduce the number of points in the cast from an average of 717 samples to 43 samples after clipping and thinning, with the largest cast being reduced from 5585 samples to 49 samples. This high degree of data reduction in deep ocean casts is critical when considering the limit on the number of SSP samples imposed by KM echosounders, as will be discussed in the next section.

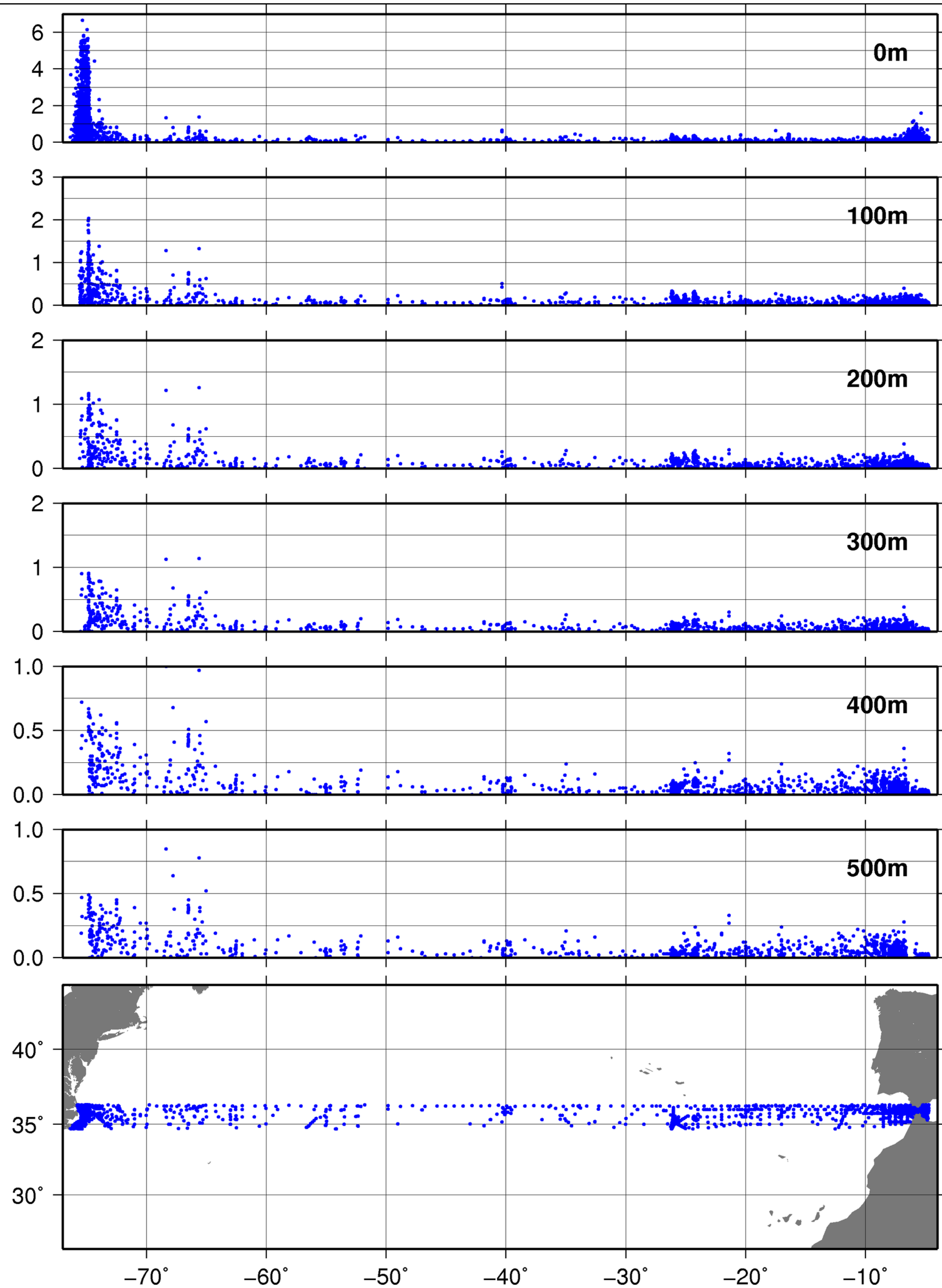

Figure 10. Results of UA of WOD profiles for a 1° band centered on ~36° latitude in the North Atlantic. The y-axis in the upper 6 plots is terminal depth bias for a 60° beam in units of %w.d. Plots are labeled in the upper right with the simulated sampling depth, ranging from 0 m in the upper plot to 500 m in the lower plot. The lower most plot shows the geographic location of the WOD casts used in this analysis. Note that the vertical scale changes with depth.

Implementation and Field Trials

The thinning and extension algorithms have been implemented in the version of the MVP controller software that is now being shipped with MVP systems. The implementation follows the procedure outlined in this work with additional details provided below (ODIM, 2010).

The extension and thinning algorithm were implemented to satisfy input criteria for KM MBES such that casts could be input automatically to the MBES and used immediately without operator intervention. KM input criteria are documented in the KM input/output datagram format descriptor (Kongsberg, 2010) and are listed below:

1. The maximum profile size depends on echo sounder type :
    a. Old generation echo sounders (i.e. EM120, EM300, EM1002, EM2000, EM3000) accept a maximum of 570 samples.
    b. New generation echo sounders (i.e. EM122, EM302, EM710, EM2040, EM3002) accept a maximum of 1000 samples.
2. Profiles must contain at least 2 data points.
3. Sound speed values must fall within the range 1400.0–1700. 0 m/s.
4. Depth values must fall within the range 0.0–12000.0 m.
5. Depths must be constantly increasing.
6. Depths must be more than 1 cm apart.
7. The profile must extend to 12000.0 m.
8. Acceptable Conductivity range, if measured: 0.0-70.0 (mS/cm).
9. Acceptable Temperature range, if measured: -5.0-45.0 (°C).
10. Acceptable Salinity range, if measured: 0.0-45.0 (psu).

To meet criteria (2), (4), (7), the MVP controller extends the measured SSP first by the operator specified deep cast. The deep cast can derive from the MVP itself or from an expendable bathythermograph (XBT) or CTD measurement (.edf or .cnv file format, respectively). The primary extension is followed by a secondary extension using either the GDEM or WOA climatologies for the date and location of the cast. The GDEM/WOA cast is extended to 12,000 m by holding the last temperature and salinity in the database SSP constant down to 12,000 m and then computing sound speed using these two values and the pressure at 12,000 m. The cast is also extended upward in a similar manner to the sea surface, however, the uppermost temperature and salinity measurements are used with a zero pressure to estimate the surface sound speed. In the case that the MVP does not measure temperature or salinity, i.e. velocity alone is measured, the shallowest velocity measurement is extended to the surface. The extension algorithm can be performed automatically at the end of each cast (the “Auto Xtend” feature) or can be done manually in post-processing (ODIM, 2010).

To meet the limiting maximum number of samples criteria (1), the DP_{1D} algorithm is used with a tolerance of 0.1m/s. If the first round of thinning does not reduce the number of sample points to the required value, the thinning tolerance parameter is incrementally increased by 20% until the SSP is sufficiently thinned. If the extension/thinning procedures are executed manually through the MVP controller, the extended SSP can be edited, for example, to remove outliers. Other basic filtering options are available such as mean filtering and downsampling the data with a user defined bin size, these can also be applied automatically (ODIM, 2010).

Once pre-processing tasks are complete, the cast is then delivered to the MBES either by a serial connection or a UDP transmission over the ship's network. This can be done manually or automatically with each cast. The format of the datagram being transferred implies whether or not it should be applied immediately by the KM data acquisition system Seafloor Information System (SIS) (Kongsberg, 2007). If the datagram is of type S01, S02, S03, S04, S05 or S06, SIS will attempt to apply it immediately. In all other cases of possible SSP input datagrams, the SIS SVP editor will display the received file but user intervention will be required for it to be applied in real-time processing (Kongsberg, 2010).

Field trials of the new MVP controller software abilities were conducted during the IFREMER sea acceptance trial for the MVP200 in March of 2011. The MVP200 system was successfully integrated with the KM EM302 and was able to provide SSPs such that only minimal MVP operator intervention was required. Minor issues were found with the automated extension of the GDEM data base profiles in the Mediterranean: since the Mediterranean is much warmer at depth compared to open ocean conditions, the extension of ~13°C/38.4ppt water found at 2,000 m to 12,000 m resulted in sound speeds exceeding the 1,700 m/s upper limit imposed by the KM SSP input criteria. This was corrected by editing the base GDEM profile used for extension in offline testing with manually transmitted files, however, this required MVP operator intervention for each cast during real-time operations. Once this issue is resolved, the pre-processing procedures should require no intervention at all on the part of the MVP operator.

SIS was able to receive and apply SSPs sent from the MVP workstation without SIS operator intervention. An unsuspected finding from the trial was that SIS does not warn the operator if a SSP designated for immediate application fails to meet the input criteria (specifically the GDEM profiles with sound speeds in excess of 1700 m/s). Unfortunately, SIS rejects the cast yet behaves exactly as it does when it receives a valid profile: the profile name is updated in the runtime parameter display window where SSPs are selected and the SIS SVP editor is refreshed with the received profile. There is no indication that the profile was rejected and the operator must actively investigate by instructing the SIS to apply the SSP, at which point the software informs the operator that the profile was rejected with a warning message. A warning message sent upon detection of a faulty cast would be much more preferable and would be in the spirit of minimizing operator intervention in the SSP transfer/upload process. An additional useful feature would be an "age of last cast" field in the numerical display such that the SIS operator can quickly confirm whether or not the cast was successfully applied.

Future Work

Further work could be done to refine the SSP thinning procedure such that casts are thinned in such a manner that the integral of the area between the thinned and original SSPs does not exceed a prescribed amount. This would be an improvement over the DP_{1D} and DP_{2D} algorithms as neither of the DP versions make any attempt to minimize the area between the curves, this can lead to systematic biases in the case where profiles are entirely convex/concave as the area between the raw and thinned SSPs is proportional to the sounding bias that would result from the use of the thinned profile (Geng and Zielinksi, 1999). For the small tolerances used to thin SSPs in this work, this is likely not an issue but having an algorithm that guarantees an equivalent profile with a minimum resulting sounding bias would be preferable.

Climatologies such as WOA and GDEM are time-invariant and more sophisticated time-varying oceanographic models may provide more accurate depictions of current or forecasted water mass conditions. These alternate sources of sound speed information should be explored, however, the limited communications bandwidth typical of offshore environments may limit the ability to download model output while at sea.

Though the thinning algorithms were shown to perform adequately in shallow water environments, further testing of the extension algorithms should be done as the underlying assumptions used in this work are often not true in shallower environments such as estuaries or even on the continental shelf. More research should be done in these challenging environments to see if the extension algorithm, and the sampling methodology that relies on it, could be used.

Future plans for the MVP controller software include the ability to inform the user when another deep profile is required using UA techniques that have been implemented already in the MVP controller (Peyton et al., 2009). Plans are also in the works to have the controller software provide guidance to the user for optimal sampling depths for deep and shallow casts as well as optimal sampling rates.

Conclusions

Sound speed pre-processing algorithms for thinning and extending SSPs have been presented and successfully implemented in MVP controller software such that minimal operator intervention is required for the measured SSPs to be applied immediately during acquisition in SIS. The algorithms have been assessed in terms of sounding uncertainty with positive results indicating that the current implementation in the MVP controller software should prove adequate for hydrographic applications in deep water depths. Case-by-case analyses should be undertaken using data sets such as WOD to assess whether the techniques would provide a sufficiently accurate model of the water column for ray tracing purposes.

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