A New Method for Generation of Soundings from Phase-Difference Measurements

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Abstract:
A desirable feature of bathymetric sonar systems is the production of statistically independent soundings allowing a system to achieve its full capability in resolution and object detection. Moreover gridding algorithms such as the Combined Uncertainty Bathymetric Estimator (CUBE) rely on the statistical independence of soundings to properly estimate depth and discriminate outliers. Common methods of filtering to mitigate uncertainty in the signal processing of both multibeam and phase-differencing sidescan systems (curve fitting in zero-crossing detections and differential phase filtering respectively) can produce correlated soundings. Here we propose an alternative method for the generation of soundings from differential phase measurements made by either sonar type to produce statistically independent soundings. The method extracts individual, non-overlapping and unfiltered, phase-difference measurements (from either sonar type) converting these to sonar-relative receive angle, estimates their uncertainty, fixes the desired depth uncertainty level and combines these individual measurements into an uncertainty-weighted mean to achieve the desired depth uncertainty, and no more. When the signal to noise ratio is sufficiently high such that the desired depth uncertainty is achieved with an individual measurement, bathymetric estimates are produced at the sonar's full resolution capability. When multiple measurements are required, the filtering automatically adjusts to maintain the desired uncertainty level, degrading the resolution only as necessary. Because no two measurements contribute to a single reported sounding, the resulting estimated soundings are statistically independent and therefore better resolve adjacent objects, increase object detectability and are more suitable for statistical gridding methodologies.

Introduction
A desirable feature of bathymetric sonar systems is the production of statistically independent soundings. Independent soundings allow a system to achieve its full resolution capability by eliminating the smoothing effect of correlated measurements on soundings of the seafloor. The effect can be demonstrated by analogy in which a randomly generated set of input data simulates a collection of "raw" measurements of the seafloor (Figure 1), these measurements being statistically independent samples. One can then filter this data to simulate an internal estimation process within the sonar from which "soundings", as reported by the sonar, are generated. The filter might be a simple box-car filter, in which a window is slid across the data and the mean of the measurements within the window is calculated at each step. If steps are chosen such that the windows of adjacent calculations overlap, the resulting filtered data will be correlated with a

correlation length roughly equal to the overlap in window size. If instead, the steps are chosen such that the windows of adjacent calculations do not overlap, or equivalently, the box-car filtered data is decimated by the window size, the resulting values will remain statistically independent.

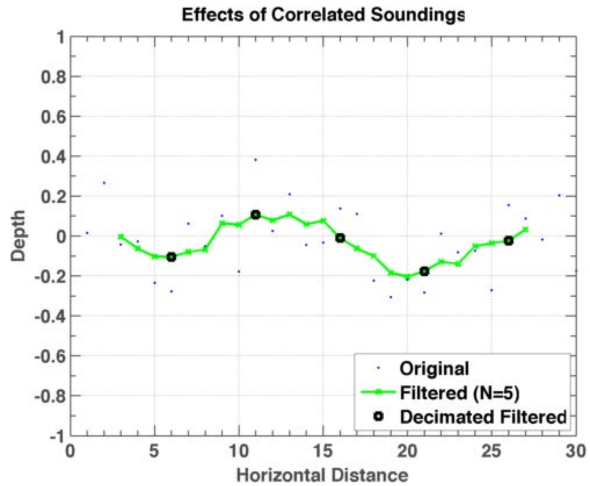

Figure 1. A simulated collection of raw measurements is shown with a box-car (n=5) filtered version of these points. Filtered points that would be retained to ensure statistical independence are marked.

In the discussion above and throughout this paper the term *measurement* is used to describe an individual sample of the sonar, while the term *sounding* is used to describe the result of some estimation or averaging process within the sonar. This estimation process may incorporate any number of individual measurements into the sounding. By way of example, multibeam echo sounders (MBES) utilize bottom detection algorithms (amplitude-weighted mean for near-nadir beams and sub-aperture differential phase zero-crossing detects for outer beams), each of which combine many individual measurements to produce a sounding. Phase-measuring bathymetric sidescan (PMBS) sonars may apply some smoothing filter to the raw measurements, reporting the resulting filtered measurements as soundings. In either case, when individual measurements contribute to more than one sounding, for example when overlapping data is used in adjacent beams in the case of a MBES or a sliding window filter is applied in a PMBS, the resulting soundings will be correlated.

The value of statistically independent soundings cannot be overstated. Many estimation algorithms for seafloor parameters (depth, depth variance, slope, rugosity, etc.) begin with the assumption that the soundings are statistically independent. The Combined Uncertainty Bathymetric Estimator (CUBE) is an example of one such process [1]. In CUBE individual soundings and their estimated uncertainty are compared to an *a-priori* depth estimate at a local grid node and its associated uncertainty. When a sounding is deemed not statistically different than the *a priori* depth, the sounding is incorporated into that depth estimate through an uncertainty weighted mean, and because the sounding is assumed to be statistically independent of the *a priori* depth estimate, the uncertainty of the new estimate is reduced. However, if the sounding is statistically correlated with the *a priori* depth (itself derived from individual measurements), the true reduction in uncertainty will be smaller than that predicted by CUBE. CUBE may then unnecessarily generate multiple hypotheses and an erroneously low uncertainty for the final surface.

In addition, when soundings are not statistically independent an artificial smoothing of the seafloor takes place that propagates into gridded data products and can lull operators into a false sense of security. Smooth data is intuitively thought of as of higher quality than noisy data, therefore it must be a higher-fidelity representation of the seafloor. When the source of the noise is measurement error, this is often the case. However when the source of the noise is actual variation in seafloor features, efforts to reduce this noise artificially smooth them. Statistically correlated data can mask actual seafloor features and reduce the resolving capability of the sonar, not to mention fail to represent rugosity, local seafloor slope and other parameters correctly.

The method proposed here aims to produce soundings from both MBES and PMBS bathymetric sonars that are statistically independent by returning to their individual measurements and producing seafloor depth estimates (soundings) in a statistically robust way. To do so, the method uses either an *a-priori* or empirical estimate of the uncertainty in the measurements to inform the sounding estimation process. Fewer measurements are combined to produce a sounding when the signal-to-noise (SNR), multipath and other factors produce low uncertainty measurements, and more measurements are combined to produce a sounding when they do not. In either circumstance no individual measurement contributes to more than a single sounding ensuring each reported sounding is statistically independent.

In addition to producing statistically independent soundings, the method proposed also seeks to actively manage the tradeoff between resolution and uncertainty rather than rely on a fixed set of parameters (e.g. beam width, bandwidth, etc.). To understand exactly what this means and to describe a framework within which the method may be applied to MBES and PMBS systems alike, some review of methods commonly used by bathymetric sonar systems is required.

Under a fixed set of beam widths, transmit bandwidth and sample rate, systems may be optimized for either maximum resolution or minimum uncertainty. PMBS systems, for example, consider every sample independently, usually with little to no averaging or estimation methods applied to reduce noise. The full sample rate data is preferred for appealing sidescan imagery rather than noise-free bathymetry. The resulting soundings contain relatively high uncertainty and the volume of data and noise inherent in such systems can make processing difficult and the usability of the bathymetry limited. Alternatively, systems may be optimized for low uncertainty, having averaging or estimation methods that combine measurements to reduce their uncertainty. For example, MBES systems commonly estimate bathymetry in their outer beams by fitting a curve to a time series of differential phase measured from two sub-apertures of the receive array, and choosing the “zero-crossing” of the phase ramp that results when the transmit pulse passes through the intersection of the beam’s broadside and the seafloor. The zero-crossing marks the two-way travel time associated with the sounding for that beam. While soundings could be generated from each differential phase measurement in the ramp, the curve-fitting procedure is an averaging process that produces just a single sounding whose uncertainty is greatly reduced. The curve fitting process also reduces the resolution of the system, roughly to the distance corresponding to the length of the curve fit. In addition, adjacent beams often overlap, meaning that phase-difference measurements from a single segment of seafloor contribute to the zero-crossing detection produced in many beams. By comparison to PMBS systems, the post-processing of MBES bathymetric sonar data, having lower noise in their soundings, is relatively straightforward. However small adjacent objects that might have been resolved by the system's individual phase measurements may be left unresolved due to the averaging inherent in the curve fitting process and the correlation of soundings due to the large overlap in adjacent beams.

Method

The method proposed here operates on receive angle measurements relative to the sonar from PMBS or MBES sonars, requiring some pre-processing steps for each system. For PMBS systems, methods that convert phase-difference to receive angle (i.e. Vernier, CAATI or their variants) remain unchanged. However measurements that are clear blunders or have SNR lower than 10 dB are removed from subsequent processing. In addition, filters possibly applied to the differential phase values before conversion to receive angle must be omitted to prevent the correlation of measurements that the algorithm seeks to avoid.

For MBESs the method proposed here only applies to beams within which sub-aperture phase-difference zero-crossing detections are performed. (Amplitude detections remain the same, as near-nadir beams where they are performed do not produce correlated soundings to the extent that outer beams do.). Zero-crossing detections are performed in the normal way, namely, steering of the receive array to form beams at fixed angles, splitting of the steered array into two sub-apertures, calculation of the phase-difference between the sub-apertures at each measurement time, curve fitting of the phase-ramp associated with the seafloor and estimating the two-way travel time associated with the zero-crossing. A more detailed explanation of these steps can be found in [2]. The next step is to use the zero-crossing detection as a guide around which to extract a portion of the differential phase measurements from which it is derived. In our prototype method we have extracted ½ of the ramp centered on the zero-crossing, helping to ensure no data points are selected that might result from "phase-wrapped" measurements. Like the method for PMBS systems, points are omitted whose SNR is estimated to be less than 10 dB. The resulting collection of phase-ramps for each beam is shown in Figure 2a, with a closer look for a single phase-ramp in Figure 2b.

N.B. Although the discussion is here focused on phase-difference measuring systems, it is interesting to notice that amplitude detection applied in central beams of MBES suffer a similar intrinsic limitation of their achievable resolution. The classical detection method is then a computation of the center of gravity of the amplitude envelope of the time signal in reception; clearly this process uses all the measurement samples encompassed inside the "main lobe" of the time echo, to produce only one sounding.

MBES Sub-aperture Phase Difference Data

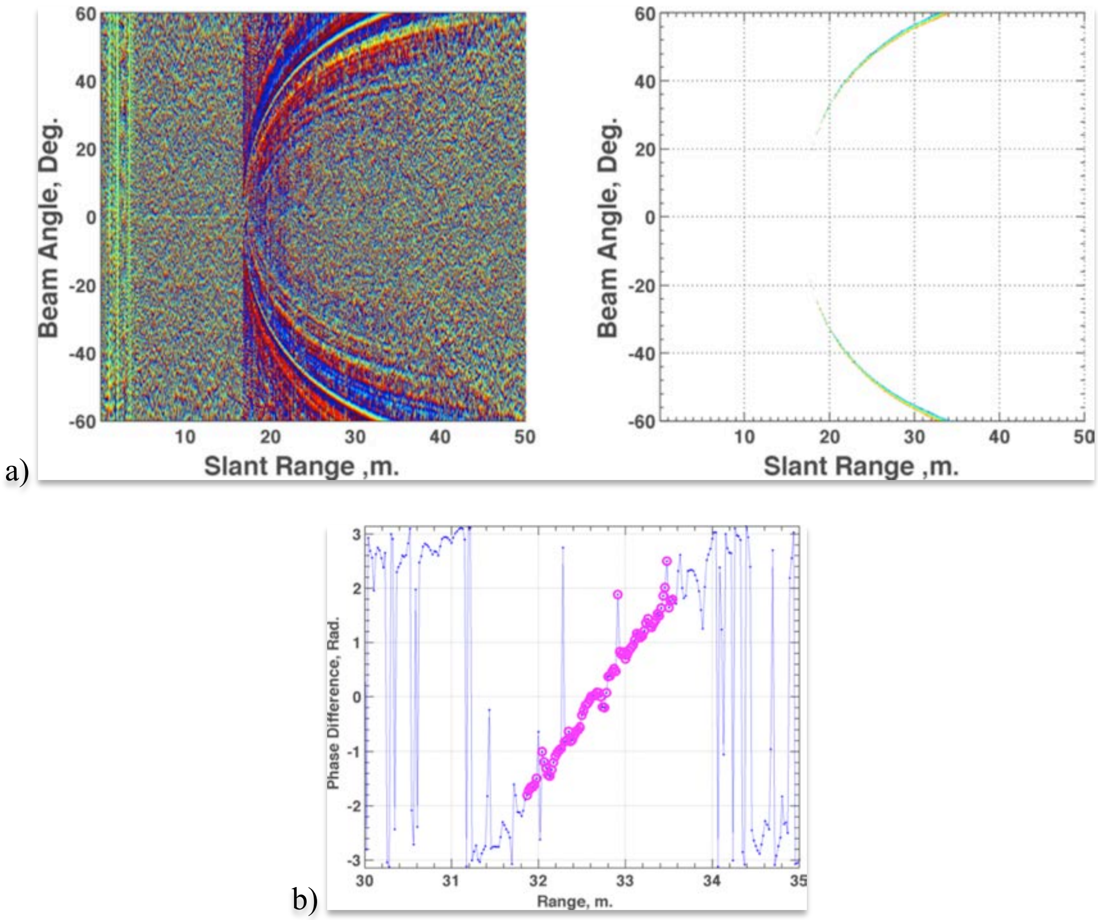

Figure 2. RESON 7125 MBES sub-aperture phase difference measurements for a full ping a) unfiltered (left) and filtered (right). A single beam of measurements focused on the zero-crossing is shown in b) with points extracted indicated by circles.

The phase difference data is next converted to receive angle relative to the sonar array using Equation (1)…

$$\theta_i = \text{asin}\left(\frac{\Delta\phi_i}{2\pi}\frac{\lambda}{d}\right) + \varphi \qquad (1)$$

where $\Delta\phi_i$ is the measured phase difference, λ is the sonar's operating frequency, d is the distance between the center of the sonar's two sub-apertures from which the phase difference measurement is made and φ is the bore-site beam angle relative to the sonar's receive array.

The data is then split into port and starboard sides and receive angle measurements occurring coincidently in time are averaged under the assumption that they are measuring the same portion of seafloor. This gives a single receive angle measurement for each time step per side, similar to PMBS sonars.

Results thus far are illustrated in Figure 3. where PMBS and MBES receive angle vs range measurements are shown. It is worth noting, as an aside, that it is at this point that a somewhat meaningful comparison of system performance can be made when data is collected in similar environments by two systems. Unfortunately, most comparisons between PMBS and MBES data compare raw measurements from the former and amplitude or zero-crossing derived soundings from the latter. This comparison of individual measurements to soundings composed of many individual measurements and benefiting from substantial averaging, are rarely meaningful.

PMBS and MBES Receive Angle Measurements

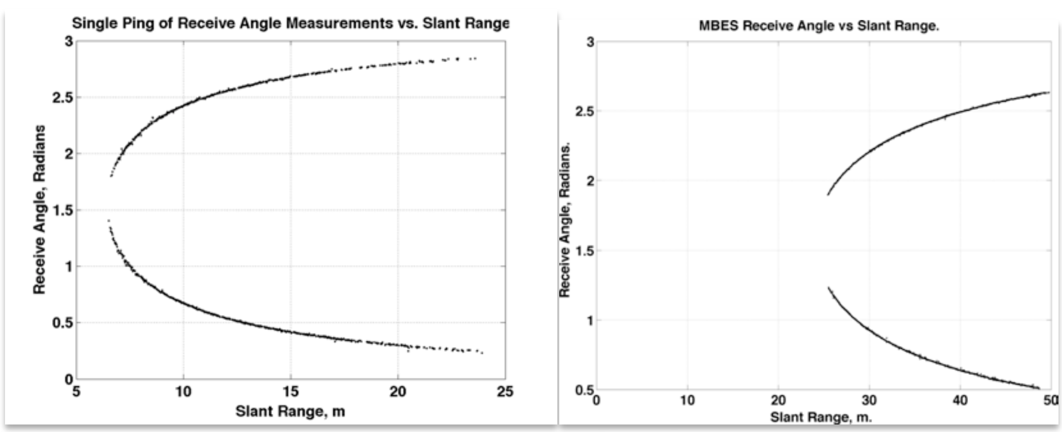

Figure 3. GeoAcoustics Geosawth PMBS (left) and RESON 7125 MBES (right) receive angle vs slant range, both from individual, unsmoothed, phase difference measurements.

It is at this point, namely receive angle vs. slant range curves, that the algorithm continues identically for either system (port and starboard sides are processed independently but identically). The first step is to obtain an estimate of the uncertainty in the receive angle measurements. When uncertainty of each measurement is estimated by system modeling and other parameters, this value is generally preferable. However when no such value is available, the uncertainty can be estimated empirically. One method, borrowed from those proposed for estimation of bathymetric Quality Factors [3], involves segmenting the receive angle data into fixed width, non-overlapping bins, fitting a 2nd degree polynomial to the data and calculation of the RMS error about the curve to estimate the receive angle uncertainty of the points contributing to the bin.

Soundings are then estimated by first establishing a maximum desired depth uncertainty for the survey. Generally this is considered a user selectable value, chosen for the application at hand. For example, given an error budget designated by an IHO standard or project deliverables one might estimate the maximum uncertainty available to the sounder given nominal values for other depth uncertainty contributors.

Then, working from nadir, the receive angle corresponding to the first measurement and its corresponding uncertainty are considered. The receive angle uncertainty is propagated to depth through Equation 2

$$_{z_i} = \left| R_i cos(\theta_i)\sigma_{\theta_i} \right| \quad (2)$$

where R_i is the range to the sample, θ_i is the measured angle, σ_{θ_i} is the receive angle uncertainty and σ_{z_i} is the desired depth uncertainty. This propagated uncertainty is then compared to the established depth uncertainty limit. When the measurement's uncertainty is less than the limit, the measurement is retained as a single-point sounding estimate. However, when the estimated depth uncertainty is greater than the desired limit, the receive angle measurement is combined with the next adjacent receive angle measurement in an uncertainty-weighted mean according to Equation (3).

$$\hat{\theta} = \frac{\sum_{i=1}^{N} w_i \theta_i}{\sum_{i=1}^{N} w_i}, \text{ where } w_i = \frac{1}{\sigma_{\theta_i}^2} \quad (3)$$

$$\sigma_{\hat{\theta}} = \sqrt{\frac{1}{\sum_{i=1}^{N} w_i}} \quad (4)$$

where θ_i is the ith receive angle measurement, w_i is its weight expressed as the inverse of the receive angle variance and $\hat{\theta}$ is the new sounding estimate. The predicted receive angle uncertainty of the new estimate is then calculated according to Equation 4 and this uncertainty again propagated to depth (Equation (2)). If the predicted depth uncertainty from the new weighted-mean receive angle is less than the desired depth uncertainty, this estimate is retained as a sounding. Otherwise the process is repeated, assimilating additional measurements until the desired depth uncertainty is reached and no more. Ultimately, the number of points combined in the receive angle estimate is determined by the number of points required to reduce the predicted depth uncertainty below the user defined limit.

In this way, when signal to noise and other conditions allow for low-noise measurements the system will report soundings at the maximum across-track resolution of the system as dictated by its beam width, bandwidth and sampling rate. However when the uncertainty in the individual measurements is too large, measurements are combined to reduce the depth uncertainty. The toll of resolution reduction required to achieve the desired uncertainty is paid automatically.

Results and Discussion

A method has been proposed for the generation of statistically independent soundings for bathymetric sonar systems. The method generates sounding estimates from combinations of receive angle measurements such that no individual measurement contributes to more than one sounding. In this way, statistical independence of the reported soundings is maintained.

In addition, optimal resolution of soundings within a depth uncertainty constraint are achieved by dynamically combining adjacent receive angle measurements to achieve the constraint and no more. As the SNR, measurement geometry, or other factors increase uncertainty in individual measurements, the process compensates automatically, combining more measurements to achieve the desired uncertainty while decreasing the resolution of the soundings across the swath. As knowledge of the seafloor decreases, fewer soundings are reported providing guidance to operators where additional survey effort is warranted.

The dynamic nature of the algorithm, prevents effectively throwing away excess SNR, which can happen in MBES systems whose fixed zero-crossing detect algorithm produces a single sounding regardless of the quality of the measurements. When the SNR is high, a MBES may now produce independent soundings at the full capability of the sonar, achieving a much higher across-track resolution of statistically independent soundings than would otherwise be possible.

N.B. In some MBES systems, a “high density” mode is proposed to users [**4**], based on a splitting of the phase ramp into a number of segments (typically 3) of predetermined length. For each segment the phase-ramp fitting leads to an averaged angle estimate and a sounding value, hence providing more than one sounding per beam. The method proposed here can be thought of as an adaptive processing of this phase-ramp splitting, based on objective estimates of the bathymetry performance.

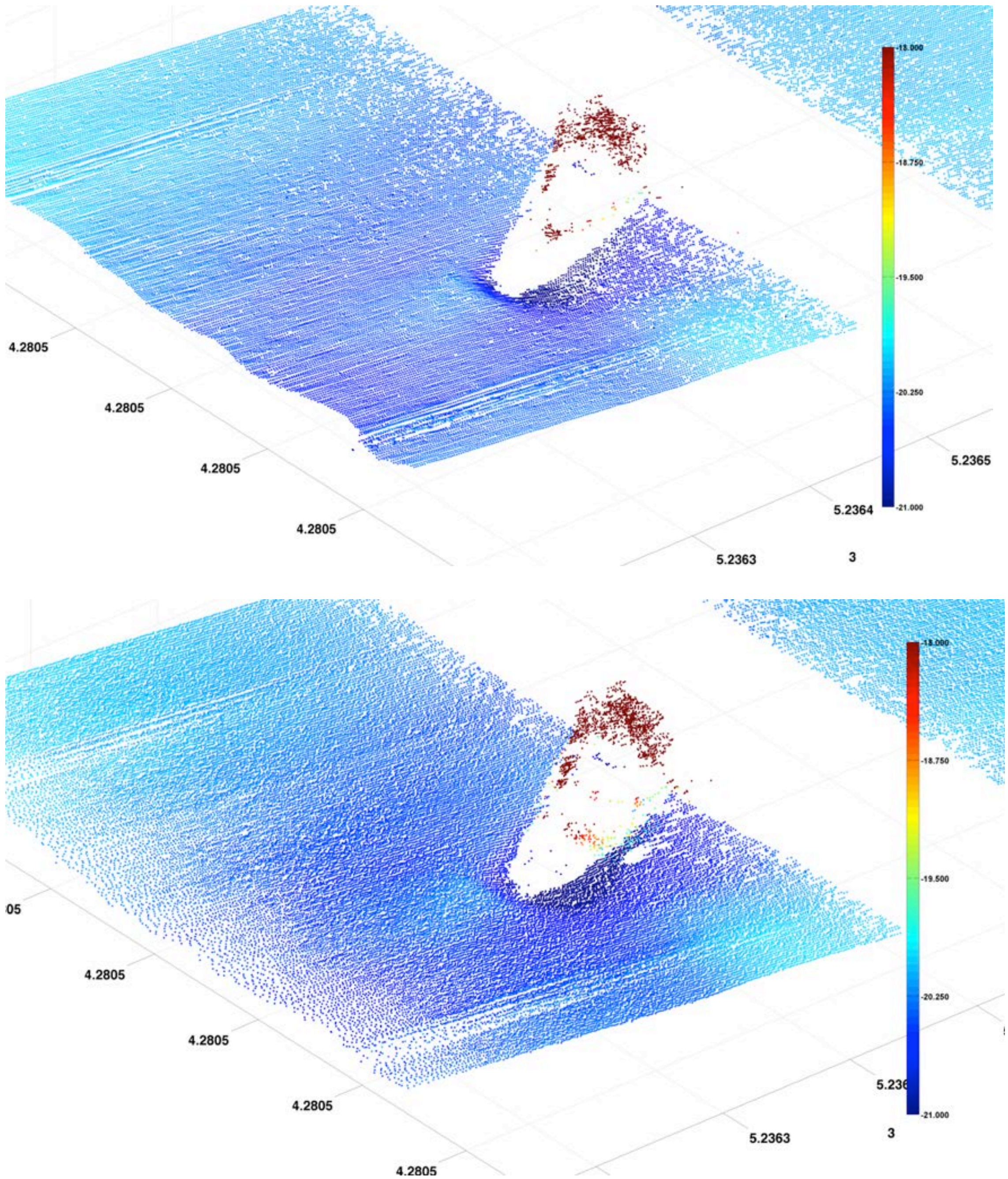

Figure 4. MBES Zero-crossing detects (top) and estimated soundings produced by the algorithm (0.1% WD uncertainty limit) (bottom). Qualitatively, one can see the smoothing effect that correlated soundings produce in zero-crossing detects. Moreover, soundings near nadir and the outer reaches of the swath in the lower plot show decreased sounding density where the uncertainty of the individual measurements was insufficient to achieve the uncertainty limit. Greater sounding density is achieved in the mid-swath were uncertainty of individual measurements is low.

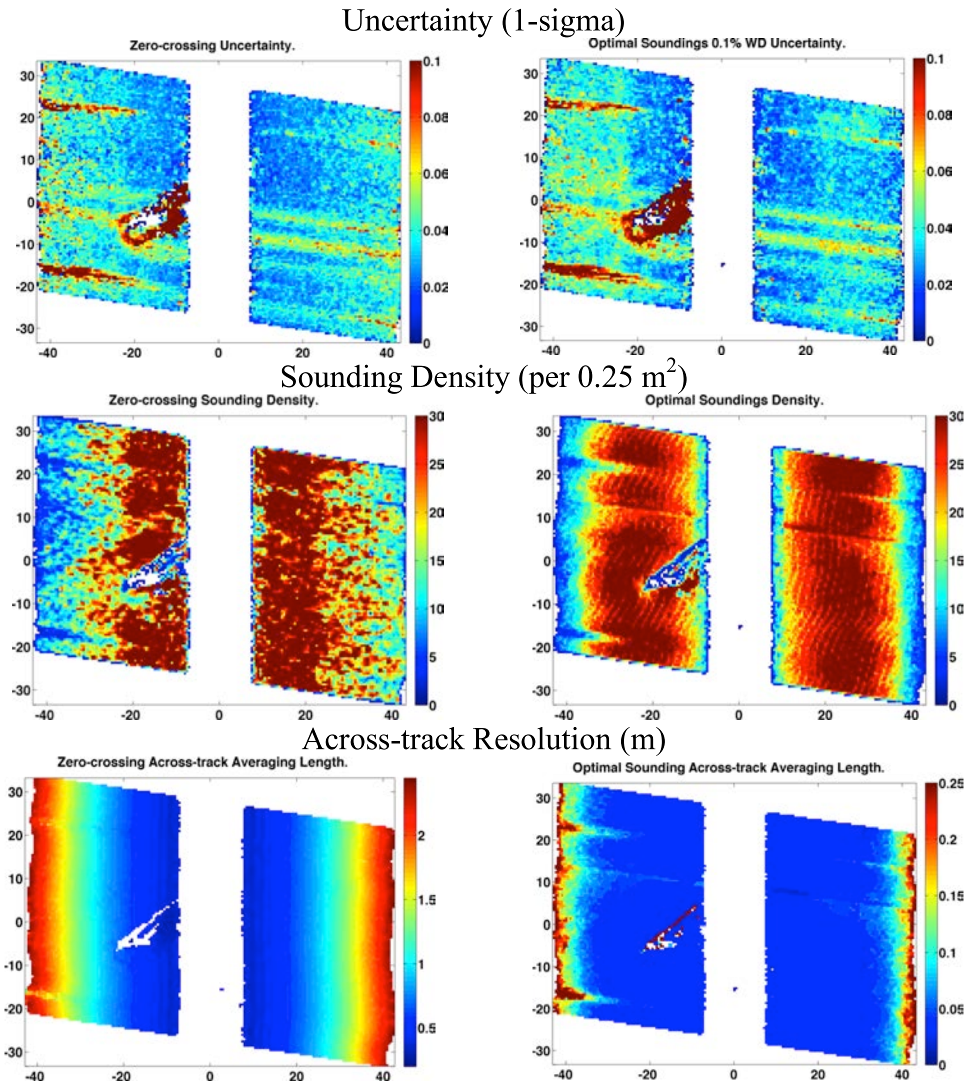

Figure 5. Standard deviation of data per 0.5 m grid cell is shown in the upper pair of plots for zero-crossing detects (left) and estimated soundings produced by the algorithm (0.1% WD uncertainty limit) (right). Sounding density for each is shown in the middle plots. The across-track resolution is shown in the lower plots, as measured by the across-track extent of the phase ramp projected onto the seafloor for zero-crossing detects (left) and the across-track extent of measurements contributing to each sounding (right), for those produced from the proposed algorithm. Note the color scale is different for these two lower plots, (0-2m left, 0-0.25m right)

When the SNR decreases and uncertainty grows, the algorithm checks this growth by combining measurements accordingly. Hence the "bow-tie" effect common to PMBS systems in which increasing receive angle uncertainty contributes to ever increasing depth uncertainty across the swath is avoided. This effect is known to cause artifacts in gridded surface products when noisy outer portions of the swath are invariably combined with noisy outer portions of an adjacent swath. Because the algorithm fixes the maximum desired depth uncertainty, the bow-tie effect is replaced with a reduction in soundings commensurate with one's knowledge of the seafloor. Gridding artifacts are removed and operators may adjust their survey practice to accommodate the variation in sounding density. Figures 4, 5 and 6 illustrate these effects in both a qualitative and quantitative way.

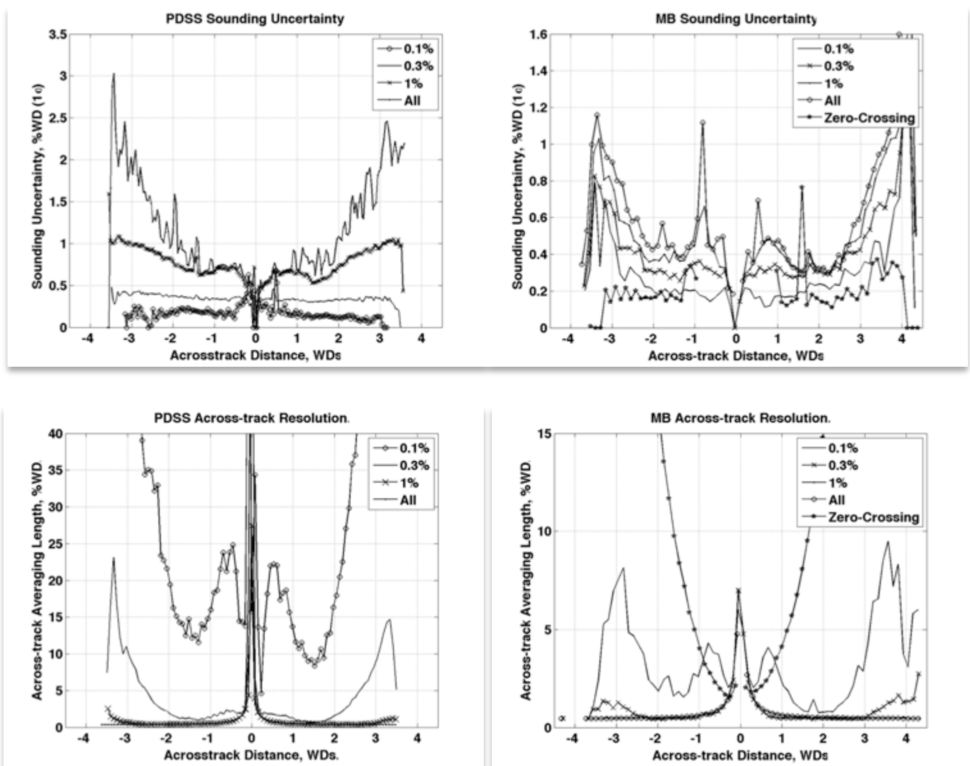

Figure 6. In these figures, sounding uncertainty has been empirically measured (top) for PMBS (left) and MBES (right) systems for individual measurements as well as the proposed sounding estimation algorithm with fixed maximum uncertainty limits as shown. Decreases in sounding uncertainty correspond with increases in the spacing between across track measurements (bottom figures PMBS left and MBES right). The bow-tie effect common to PMBS systems is removed and for a given uncertainty level the across-track resolution of MBES zero-crossing detects is enhanced.

The number of soundings produced with each ping is no longer tied to a fixed set of beams. Where in traditional bathymetric sonars the swath width is effectively set by the uncertainty achievable across the swath, use of the proposed algorithm sets the swath width by the data density achievable across the swath given the quality of the measurements attainable. Soundings are simply not created where there is insufficient knowledge to predict a meaningful depth.

In addition, in forcing the results to be statistically independent, one must generally accept a lower sounding density to achieve the same level of noise reduction produced by heavily filtered PMBS and MBES systems. Sounding density per grid node, while not required by standards set by the IHO, is a common practical survey requirement for hydrographic organizations to ensure reliability of their results. However rarely does the requirement *explicitly* require statistically independent soundings and most surveyors do not check for it. However by forcing the soundings produced by the sonar to be statistically independent, the sounding density is matched to the true information available in the measurements rather than smoothing and oversampling the data in the way bathymetric sonars commonly do. In this way the spirit of sounding density requirements may be properly met and safety of navigation better ensured.

When the uncertainty in receive angle measurement is estimated empirically by the RMS of the residuals rather than from model, objects proud of the seafloor may, by the nature of the discontinuity they present, produce an otherwise inflated uncertainty. These measurements may then be given smaller weights contributing proportionally less to the estimated sounding, arguably precisely when one would want them to influence the sounding proportionally more. The tradeoff lies in the method used to empirically estimate the sounding uncertainty, specifically the order of the curve fit and the length of the window used for fitting. Herein, lies an assumption of the continuity of the seafloor and deviations from this assumption represent less knowledge of the true depth and hence increased uncertainty. Because the estimated soundings are produced from an uncertainty weighted mean, these measurements contribute less to the final sounding estimate with a commensurate reduction in sounding density.

Like any assumption, operators are required to understand the assumption and its limitations and adjust their practice accordingly. The window over which uncertainty is estimated should be short enough to capture typical changes in seafloor bathymetry but long enough to generate a meaningful uncertainty estimate. For shallow water hydrographic systems window sizes of 1 m seem to work well and in our testing objects proud of the seafloor smaller than this dimension have generally been retained, albeit at a lower data density. In any event, operators are cautioned to remember that a scarcity of soundings is a clear indicator that the individual measurements do not agree and further investigation is warranted. Finally, when uncertainty can be estimated by other measurement (e.g. SNR and models of system performance), objects proud of the seafloor that can be measured with low uncertainty are likely to be retained at higher density in the final seafloor soundings than when uncertainty is estimated empirically.

Author Biographies

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Val Schmidt received his Bachelor of Science degree in Physics from the University of the South, Sewanee, TN and his Master of Science in Ocean Engineering from the University of New Hampshire. He served as an officer in the US submarine fleet from 1994 to 1999. He is currently a research engineer at the Center for Coastal and Ocean Mapping / Joint Hydrographic Center at the University of New Hampshire where his work focuses on sonar signal processing and hydrographic surveys from autonomous underwater vehicles.

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Xavier Lurton received the PhD degree in Applied Acoustics from the University of Le Mans (France) in 1979. He then worked for eight years with Thomson-Sintra ASM, mainly specializing in sound propagation modeling for naval applications. In 1989 he joined Ifremer in Brest as an R&D engineer for underwater acoustical applications to oceanography. He is now in charge of technological research programs on advanced methods for seabed-mapping sonars, his current interests being both in sonar signal processing for seabed backscatter and bathymetry, underwater acoustic modeling, and engineering of sonar systems, especially multibeam echosounders. He has been teaching for many years underwater acoustics in French technical universities

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