

6-2013

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Recommended Citation

Schmidt, Val E.; Weber, Thomas C.; and Lurton, Xavier, "Optimizing Resolution and Uncertainty in Bathymetric Sonar Systems" (2013). *Underwater Acoustics International Conference and Exhibition: Technologies and Results*. 848.
<https://scholars.unh.edu/ccom/848>

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OPTIMIZING RESOLUTION AND UNCERTAINTY IN BATHYMETRIC SONAR SYSTEMS

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Abstract: *Bathymetric sonar systems (whether multibeam or phase-differencing sidescan) contain an inherent trade-off between resolution and uncertainty. Systems are traditionally designed with a fixed spatial resolution, and the parameter settings are optimized to minimize the uncertainty in the soundings within that constraint. By fixing the spatial resolution of the system, current generation sonars operate sub-optimally when the SNR is high, producing soundings with lower resolution than is supportable by the data, and inefficiently when the SNR is low, producing high-uncertainty soundings of little value. Here we propose fixing the sounding measurement uncertainty instead, and optimizing the resolution of the system within that uncertainty constraint. Fixing the sounding measurement uncertainty produces a swath with a variable number of bathymetric estimates per ping, in which each estimate's spatial resolution is optimized by combining measurements only until the desired depth uncertainty is achieved. When the signal to noise ratio is sufficiently high such that the desired depth uncertainty is achieved with individual measurements, bathymetric estimates are produced at the sonar's full resolution capability. Correspondingly, a sonar's resolution is no-longer only considered as a property of the sonar (based on, for example, beamwidth and bandwidth,) but now incorporates geometrical aspects of the measurements and environmental factors (e.g., seafloor scattering strength). Examples are shown from both multibeam and phase-differencing sonar systems.*

Keywords: *sidescan, multibeam, interferometric, phase-differencing, uncertainty, resolution*

INTRODUCTION

Bathymetric sonar systems (whether multibeam or phase-differencing sidescan) contain an inherent trade-off between the resolution and uncertainty of their soundings. To better understand the trade-off, consider the traditional measures of system resolution. Resolution is a system's ability to distinguish adjacent objects. (This should not be confused with a system's ability to detect an object, which is related, but wholly different.) For multibeam sonar systems, the resolution of the system differs depending on the geometry of the beam width the seafloor. For beams intersecting the seafloor at near normal incidence, the seafloor within the whole of the beam is ensonified nearly instantaneously and the resolution of the measurement is determined by the along-track and across-track extent of the beam. In this case we say the resolution is "beam limited". For beams intersecting the seafloor at oblique incidence, the transmitted signal ensonifies only portions of the intersection of the beam and the seafloor at each instant. In this case the resolution is usually said to be given by the along-track extent of the beam, in the along-track direction, and half the projection of the effective transmit pulse length onto the seafloor, in the across-track direction. The effective transmit pulse length is approximately one over the bandwidth of the signal. For beams intersecting the seafloor at oblique incidence we say the resolution is "pulse-limited".

For phase-differencing sidescan systems, the resolution of the system can be described by the pulse-limited case explained above, in which the along-track resolution is defined by the along-track extent of the beam width and the across-track resolution is defined by half the effective transmit pulse projected onto the seafloor. Like multibeam systems, near normal incidence, large portions of the seafloor are ensonified instantaneously due to the geometry of the intersection of the transmit pulse and the seafloor. But unlike multibeam systems, for phase-differencing sidescans, the portion of the seafloor ensonified is not constrained by the across-track beamwidth, which is wide in the across-track direction. The large amount of seafloor ensonified with each measurement results in particularly poor resolution there and these soundings are often discarded. For either system in the pulse limited case an underlying assumption is that the sample rate of the system is matched to half the projection of the effective transmit pulse length onto the seafloor, such that each parcel of seafloor is sampled at least once. For the purposes of this paper, we assume that this sampling criterion has been met. A detailed discussion of resolution with regard to both multibeam and phase-differencing systems can be found in [1].

Because beamwidths and sample rates are usually fixed by the sonar hardware and transmit bandwidth is not typically adjusted dynamically, we define the expression "maximum resolution of the system" to be the resolution that results from a fixed combination of these parameters and when individual measurements are used to produce soundings. However, soundings are more often generated from a combination of multiple measurements, and it is this combination that we seek to optimize the trade-off between resolution and uncertainty. We acknowledge, and discuss later, that additional parameters (e.g. transmit bandwidth, power etc.) might also be adjusted to better balance these trade-offs, but this is largely left to future work.

Under a fixed set of beamwidths, transmit bandwidth and sample rate, systems may be optimised for high resolution by considering every sample independently with little to no averaging or estimation methods applied to reduce noise. However, the resulting soundings contain relatively high uncertainty. Such is the case, for example, in phase-differencing sidescan systems whose full sample rate data is designed for appealing sidescan imagery rather than noise-free bathymetry. 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 optimised for low uncertainty, having averaging or estimation methods that combine measurements to reduce the noise of their individual measurements. For example, multibeam sonar systems commonly estimate bathymetry within a beam 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 travel time associated with the sounding for that beam. While soundings could be generated from each differential phase measurement in the curve, 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. By comparison, the post-processing of multibeam bathymetric sonar data, having lower noise in their soundings, is relatively straightforward. However when the signal to noise ratio (SNR) is sufficiently high, 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.

In this paper, we propose a method to optimize the trade-off between resolution and uncertainty in multibeam and phase-differencing sidescan bathymetric sonar systems. Specifically, we propose estimating the receive angle or phase measurement uncertainty empirically, followed by the use of this estimate to predict the depth uncertainty, and finally, the combination of individual receive angle measurements in an uncertainty weighted mean until the predicted depth uncertainty of their combination falls below a user specified limit. When the depth uncertainty limit is achieved, only those measurements required to achieve it contribute to the reported sounding. In this way, for a given beam configuration, bandwidth and sample rate the maximum resolution of the system is provided within the desired uncertainty constraint.

METHOD

The proposed method, whether implemented for multibeam or phase-differencing sidescan systems begins with a time series of the acoustic receive angle measurements for each of the port and starboard sides of the swath. Algorithms for phase-differencing sidescan processing (Vernier, CAATI [2], etc.), which involve determining receive angle from phase-differences between pairs or rows of staves need not be altered and we may use the receive angle time series for each side of the swath that results. However typical processing steps of multibeam sonar data, which measure the two-way travel time at fixed beam angles, must be modified to produce the receive angle time series we desire.

In multibeam sonar systems, seafloor detections are made from beam-formed data by signal amplitude, for near-normal incidence beams, or by determining the “zero-crossing” of the phase difference of two receive sub-arrays, for oblique incidence beams. Methods proposed here are limited to phase-difference detections only.

The phase-difference zero-crossing marks the instant the transmit pulse (and its return) passes through the intersection of the broadside direction of the beam and the seafloor. A phase ramp time series from an outer beam is shown in Fig 1. In typical multibeam system processing, a curve is fit to this phase ramp from which the zero crossing, and hence the two-way travel time of the transmitted pulse, is determined. Older generation systems produce just a single sounding from the zero-crossing itself for each beam, while newer systems fit several curves or average fixed subsets of the phase ramp producing several soundings from

each beam [3]. In either case the across-track resolution of the resulting soundings, as defined by the horizontal extent of the curve fitting or averaging length, is predetermined.

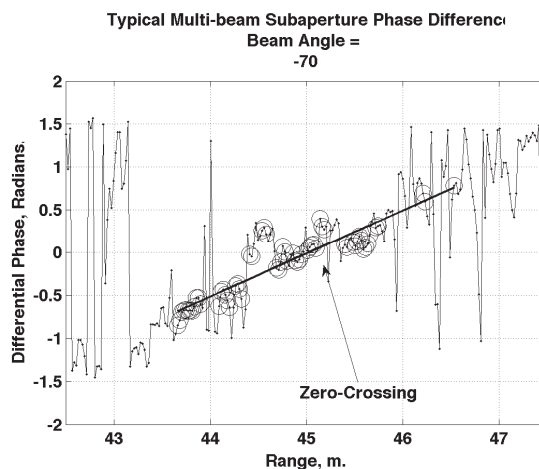


Fig 1. The sub-aperture differential phase is plotted as a function of range, for an outer beam of a multibeam system. The passage of the transmit pulse through the intersection of the beam and the seafloor is evident at ranges of 43-47 meters. Circled measurements indicate those measurements falling within $\frac{1}{2}$ beamwidth of the center of the beam and meeting an SNR threshold. A curve is fit to this data to determine the “zero-crossing” of the phase ramp as shown, from which a single sounding is determined.

For the method proposed here, individual phase difference measurements are extracted from the beam sub-aperture phase difference data that fall within \pm one half the full-array beamwidth from the center of the beam as marked by the zero crossing. These are further limited by those measurements meeting a minimum SNR threshold, typically 15dB, where the SNR is estimated from the increase in signal level due to the seafloor return above noise generated by the system, side-lobes and other sources.

Receive angles relative to broadside of the beam are determined from these phase differences using Equation 1, where θ_i is the receive angle, $\Delta\phi_i$ is phase difference, λ is the acoustic wavelength and d is the sub-aperture separation.

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

These beam-relative angles are then added to the beam pointing direction giving a receive angle relative to the sonar for each measurement. Measurements from all the beams are stitched together in time to produce a time series of receive angle measurements for each of the port and starboard sides of the swath. Where beams overlap, coincident receive angle measurements from adjacent beams may result. These measurements are averaged to give just a single measurement per time-series sample.

Multibeam data processed in this way resembles phase differencing sidescan data after initial phase-differencing processing for each system is complete, in that both systems produce a time series of receive angle measurements for each side of the array (Fig 2). These individual phase difference measurements are noisy compared to zero-crossing derived data, but occur at spatial intervals approaching the maximum resolution of the system, given the transmit pulse length, beam widths and sample rate. The optimization method that follows is implemented on receive angle time series such as those shown here for either sonar type.

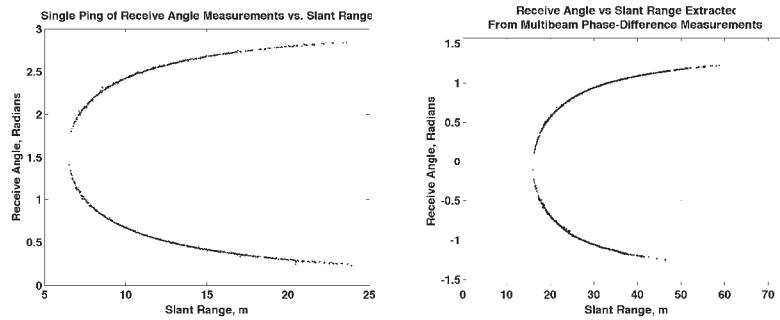


Fig. 2 Receive angle vs range is plotted for both a phase-differencing sonar system (left) and a multibeam sonar system (right). In both cases individual phase difference measurements are converted to receive angle relative to the array and are plotted. It is from these time series that the proposed optimization method operates. Because data shown were collected under different circumstances in different places qualitative comparisons between these plots is inappropriate and not intended.

First, an estimate of the receive angle uncertainty is made over constant interval horizontal range bins, where horizontal distances are calculated assuming a flat seafloor having the nadir depth. To estimate the uncertainty in each range bin, a 2nd degree polynomial curve is fit to the receive angle measurements vs. slant range and the root mean square (RMS) of the residuals is calculated (Fig. 3). This RMS value is then used as an estimate of the uncertainty for all individual measurements within the segment.

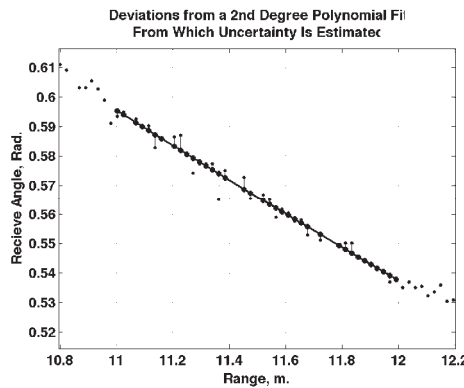


Fig. 3 A polynomial curve is fit to 1-m portions of the receive angle time series. The RMS of the residuals to that curve, as illustrated above, provides an estimate to the uncertainty in the individual measurements.

The depth uncertainty, σ_{z_i} that results from the receive angle uncertainty of each measurement is next calculated as shown in Equation 2, where R_i is the slant range, θ_i is the receive angle relative to horizontal and σ_{θ_i} is the uncertainty of the receive angle.

$$\sigma_{z_i} = \left| \frac{\partial z}{\partial \theta} \sigma_{\theta_i} \right| \tag{2}$$

The depth uncertainty, $\sigma_{\hat{d}}$, is then compared to a depth uncertainty limit set by the operator, perhaps 0.1% of the mean water depth. When the predicted depth uncertainty is less than the limit, the receive angle measurement is retained to produce a sounding. However, when the predicted depth uncertainty is more than the limit, the receive angle measurement is combined in an uncertainty weighted mean with adjacent measurements as shown in Equation 3. The predicted uncertainty of this mean value is given by Equation 4.

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

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

In these expressions, the weights, w_i , are the reciprocal of the angle uncertainty expressed as a variance. The number of points, N , 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 (Equation 2 with the predicted receive angle uncertainty of the weighted mean, $\sigma_{\hat{d}}$ substituted for the measured receive angle uncertainty of the individual measurement, σ_{θ_i}). The process is repeated across the swath, either producing soundings from single measurements when the SNR and other factors are sufficiently favourable to produce measurements whose depth uncertainty is below the desired limit, or combining measurements automatically to meet the desired uncertainty limit where it is not.

RESULTS AND DISCUSSION

Phase-differencing sidescan and multibeam data samples have been processed using the method described in Section 2 for illustration. For the multibeam system, beam-formed data (256 beams, 150 degree swath) has been processed to produce sounding data sets with optimized resolution for maximum predicted uncertainty limits of 1%, 0.3% and 0.1% of the water depth. In addition, sounding data sets have been created using the individual receive angle measurements with no averaging (i.e. the full resolution of the system) and from the traditional zero-crossing methodology (producing just a single sounding per beam). For phase-differencing sidescan, data samples have been processed (out to 4xWD to each side) to produce sounding data sets having the same uncertainty limits of 1%, 0.3% and 0.1 % of water depth. In addition, a sounding data set is included using individual receive angle measurements (again, the full resolution of the system).

In the zero-crossing processing, the curve from which the zero-crossing is extracted, is calculated as a weighted least-squares fit to those points falling one half beamwidth from the maximum amplitude of the beam and meeting the SNR threshold of 15dB. The estimated SNR of each measurement is roughly proportional to the variance of the phase-difference measurement and therefore serves as its weight. The fit is evaluated for outliers, which are removed in a subsequent fit before the zero-crossing is finally evaluated.

The average across-track resolution was calculated for each data set. For individual measurements, whether multibeam or phase-differencing sidescan, resolution is calculated as half the pulselength projected onto the seafloor for the given geometry. For soundings resulting from the optimization process or for zero-crossing derived soundings, resolution is calculated as the horizontal extent over which individual measurements are combined, or

over which the curve is fit, as appropriate. Resolution for both sonar types is plotted in Fig. 4. vs across-track range as a percentage of water depth.

The average uncertainty was also calculated for each data set. In all cases, the variance of the resulting soundings was calculated in non-overlapping horizontal bins in the across-track direction. The average of these variance values was calculated over several pings and the square root of the result (the standard deviation) is plotted vs across-track range also in Fig. 4. The multibeam data was not motion corrected and although only a few seconds of data collected under benign conditions is shown, the resulting uncertainty estimates are noisy and may be artificially inflated. This omission does not affect the analysis.

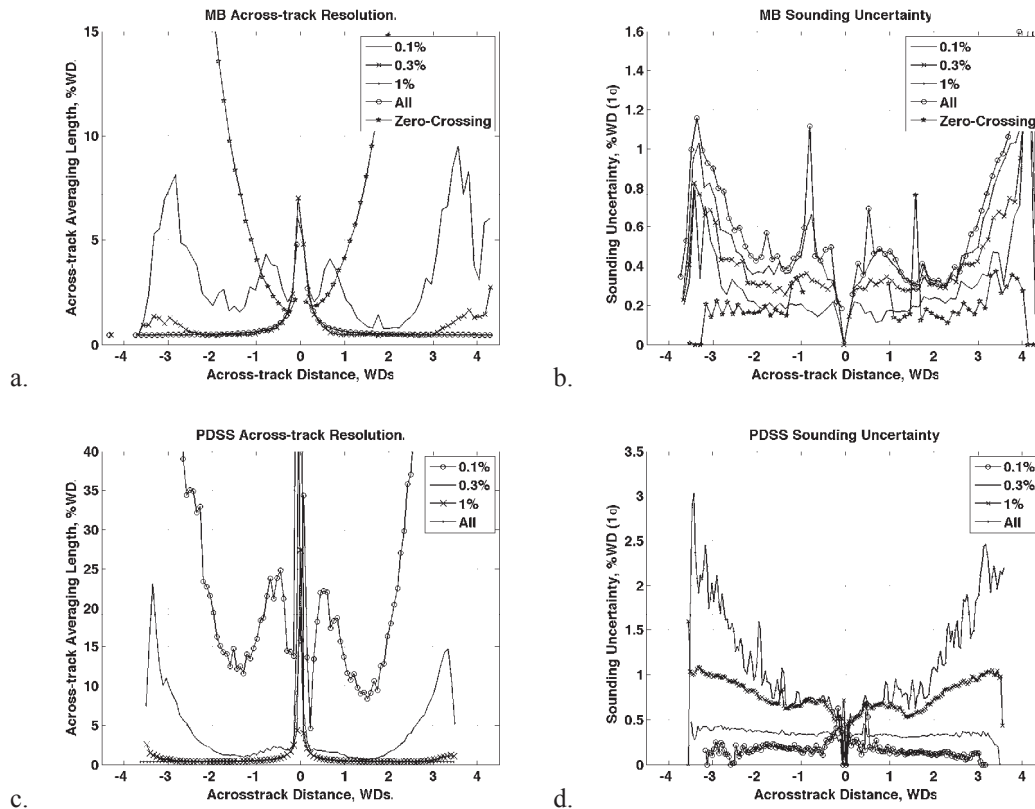


Fig. 4 Multibeam across-track resolution and uncertainty are shown in plots a. and b. in which resolution has been optimized within uncertainty constraints of 1%, 0.3% and 0.1% of the water depth. In addition, resolution and uncertainty are shown for soundings created from all phase measurements and soundings resulting from zero-crossing bottom detections. Phase-differencing sidescan resolution and uncertainty are shown in plots c. and d. for the same uncertainty constraints and also from individual measurements.

By fixing the desired uncertainty, one is able to optimize the resolution within that constraint. For both multibeam and phase-differencing sidescan systems, as the uncertainty limit is decreased, additional measurements must be combined and the resolution degrades. For multibeam systems, depth uncertainty values comparable to that provided by zero-crossing detections may be made with far fewer measurements allowing a greater resolution across the swath than zero-crossing detections provide. In effect, excess SNR goes unused in the zero-crossing method. For phase-differencing sidescan systems, uncertainty may be

reduced to levels comparable to multibeam systems by the combination of soundings. A comparable resolution results.

Swaths of data produced by either system in this way will require a shift in thinking by surveyors. Rather than a fixed number of soundings per ping, sounding numbers and spacing will vary across a ping, with fewer sounding indicating where measurements were poor (had high uncertainty) and additional survey time may be warranted. In addition, when resolution is not a constraint, wider swath widths should be possible without the commensurate difficulty of excessively noisy soundings. What is more, by monitoring the uncertainty of the measurements in real time a system might automatically adjust other parameters such as transmit power and bandwidth, to compensate for SNR decreases that might result from a suddenly low backscatter seafloor or other environmental factors.

Although the method is promising, there is potential danger in empirically estimating the uncertainty from the data itself. Specifically, the assumption inherent in estimating uncertainty from residuals to a curve fit results in an over-estimation of uncertainty when objects on the seafloor produce outliers to that curve. In this case, a bloated uncertainty results in the need to combine more measurements to meet the uncertainty constraint, at a moment when it would otherwise be advantageous to maximize resolution. While this smoothing of real seafloor features routinely happens in zero-crossing derived soundings, future developments of this method might better handle this scenario, perhaps by modelling the phase-difference measurement uncertainty based on SNR and measurement geometry.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Captain Ben Smith of the R/V Coastal Surveyor, and Dr. Art Trembanis at the University of Delaware for assistance in collecting the multibeam and phase-differencing sidescan data presented here. This work is supported by NOAA Grant NA10NOS4000073.

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