

Article



The Use of Phase Measuring (Interferometric) Sonars: Choosing Appropriate Data Processing Methodologies

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Abstract

Phase measuring bathymetric sonars (often mislabelled 'interferometers') are a popular tool for wide swath shallow water hydrography. Factors which affect the data quality from the newest generation of such systems are presented along with the data processing methodologies required to achieve high quality bathymetric maps meeting current survey standards. A brief look at a more formal statistical approach is taken in order to show that these processing methods (and the assumptions made) have a sound background. Data and charts from a widely used commercial system are included which illustrate the practical application of this theory.



Résumé

Les sonars bathymétriques de mesure de phase (souvent appelés de manière abusive « interféromètres ») constituent un outil très apprécié pour l'hydrographie à l'aide de systèmes à balayage latéral en eaux peu profondes. Les facteurs qui affectent la qualité des données issues de la plus récente génération de systèmes, sont présentés en même temps que les méthodes de traitement des données requises pour parvenir à des cartes bathymétriques de haute qualité qui répondent aux normes hydrographiques actuelles. Un bref aperçu d'une approche statistique plus formelle est donné afin de montrer que ces méthodes de traitement (et les hypothèses faites) reposent sur un contexte solide. Les données et les cartes d'un système commercial largement utilisé sont incluses, ce qui permet d'illustrer l'application pratique de cette théorie.



Resumen

Los sonares batimétricos que miden las fases (a menudo designados erróneamente 'interferómetros') son instrumentos populares para la hidrografía de bandas en aguas someras. Se presentan los factores que afectan a la calidad de datos procedentes de la última generación de dichos sistemas, junto con las metodologías utilizadas para el procesado de datos, requeridas para realizar cartas batimétricas de alta calidad que cumplan las normas hidrográficas actuales. Se estudia brevemente un enfoque estadístico más formal para mostrar que estos métodos de procesado (y las suposiciones efectuadas) tienen unos antecedentes sólidos. Se incluyen datos y cartas de un sistema comercial ampliamente utilizado, que ilustra la aplicación práctica de esta teoría.

Introduction

The recent generation of shallow water swath sonars are now accepted as a useful part of the engineer's and hydrographer's toolkit. In 2004 phase measuring bathymetric sonars, PMBSs, (also called interferometric multibeam or bathymetric side-scans) are thought to have made up about 20% of shallow water swath sonar sales to commercial organisations. These sonars are usually mobilised on small boats and operated in water depths up to 200m. The advantages of low cost, ease of deployment, wide swath width and co-registered side-scan of the PMBS are most noticeable when deployed in water depths of 40m or less, an operational zone where swath sonar technology has become much more established recently. Phase measuring bathymetric sonars are in use world-wide for full coverage high accuracy hydrographic work in commercial, military, academic and civil hydrography programmes.

The PMBS records a time series of phases and amplitudes on several receive transducer staves. Vernier deconvolution of the phases in the software gives a unique angle for each range, with the range calculated from the arrival times (multiple receive staves are required in single frequency systems for unambiguous phase deconvolution). Most current commercial systems can trace their development back to work done by R.L.Cloet and C.R.Edwards around the late 1970s (see, for example, Cloet 1986).

The bathymetric data quality shown in maps produced by modern PMBS systems compares with the best current beamforming multibeam echosounders (MBES, often shortened to 'beamformer'). This has especially been noted during comparative trials imaging small relief seabed features in 1x1m gridded data (i.e. Jonkman 2004), a gridding regime typical of most shallow water surveys. However, it has also been noted that the Standard Deviation (SD) of the depth distribution of the full raw data set is often higher for a PMBS than would be expected from a beamformer. This apparent contradiction was addressed in Hiller & Lewis (2004) which showed that the very high data density effectively compensates for the higher raw data standard deviation, resulting in mean bin soundings that are very accurate and repeatable. This high data density allows statistical analysis of

the bin depths, giving a measure of the survey accuracy on a local, bin-by-bin, *a-posteriori* basis. It was described how the standard error of the mean (SEM, given by the square root of the variance divided by the square root of the number of samples) gives an accurate estimate of the bin depth error, even with non-normal bin distributions. The present paper will expand on this theory. Numerical examples from full surveys (and comparisons with other sounding methods) were shown in Hiller & Lewis (2004) so are not repeated here.

In the present paper a brief overview of shallow water survey standards is included to help set the background. Standard basic data processing methods currently used for extracting a measurement of local seafloor depth are then presented. A critical look is taken at each of these stages and the assumptions made. The statistics of the data distribution are discussed in order to show that these processing methods and assumptions have a sound background, and to illustrate flaws seen in some other methods of analysis. The sonar physics behind an interferometer's data distribution is then discussed and the factors that cause the data to spread are highlighted. Throughout this paper data from a widely used commercial PMBS system, the GeoAcoustics GeoSwath Plus (see GeoAcoustics 2005), is included to illustrate the practical application of the theory. Examples from the 250kHz system are used.

This paper concentrates on the processing methodologies appropriate for getting the most out of PMBS data. Not covered here are the best PMBS survey planning strategies, survey practicalities (i.e. detection and mitigation of external noise sources) and detailed comparisons with alternative technologies. The authors plan to address these issues in a future paper.

Survey Standards

Equipment manufacturers, chart producers and responsible authorities are aware that chart users will not always have sufficient background (or interest) in the technology deployed to make informed decisions about the data collected. The assumptions, background and problems with the technology need to be recognised if survey results are to be used in the proper context, and more importantly if

they are not to be misused. Survey standards are intended to address this and help maximise the value of data collected. They enable manufacturers, practitioners, commissioning authorities and chart users to have a common language. A key example is, of course, the recent edition of the International Hydrographic Organisation Special Publication 44, IHO S-44 edition 4 (IHO 1998).

Survey technology has always been driven by the desire for better results in particular applications, so a general survey specification will often play catch-up. The necessity of a pragmatic approach to specifications must be recognised; if a survey is useful then it is a good survey. Useful requires an engineering definition here – in most hydrographic cases a 'useful' survey will be one that produces a Digital Elevation Model (DEM) with sufficient accuracy and resolution for the work in hand at a known and acceptable level of confidence. General survey specifications and the re-interpretation of these specifications in survey tenders and issued charts must recognise this definition. In the IHO case this process is seen in the re-interpretations of IHO S-44 edition 4 by responsible authorities to produce specifications which are 'useful' in their specific context. Examples of this are: the UK Royal Navy's 'Hydrographic Quality Assurance Instructions (HQAI)' (UKRN 2004); Land Information New Zealand's 'Hydrographic Survey Specifications (HYSPEC)' (LINZ 2001); and the Swedish Maritime Administration's 'The Swedish Implementation of S-44 (SMA SS-44)' (Jakobsson 2000). These are operational documents that are undergoing evolution through use and will, in turn, inform future editions of S-44. The IHO S-44 edition 5 Working Group starts work on this early 2005.

These standards divide the specifications by sensitivity of areas, with most applied specifications following similar plans to S-44 edition 4 adjusted for specific local requirements. In the most sensitive areas standards for surveys in less than 40m water depth might be as shown in Table 1.

Proof of meeting these survey standards is key for survey providers and chart producers. A core contribution to the error budget is the accuracy with which the sonar measures the position of the seafloor from the transducer head. Processing of data in a way that is repeatable and can be shown to provide accurate data is vital. Surveyors should understand the processing issues that affect the data from a particular technology and the steps that are required to make accurate charts from raw data. They also need to know how the data can be checked for quality and consistency.

The PMBS data that is seen by the surveyor is very different to MBES data, as we will see below. In the past some PMBS manufacturers have tried to hide this difference by having a 'black box' between the data collection and the surveyor, effectively converting the data displayed into a beamformer-like form. But the raw data of the two techniques is fundamentally different, so any 'black box' had to apply a significant amount of data interpretation. Data interpretation is filtering, and applying filtering via a black box is risky. Experience showed this was not satisfactory – if the survey situation was at all unusual then the filters could behave in unexpected ways.

The current approach is threefold: educate the surveyor in what to expect from a PMBS data set; help them and charting authorities understand the processing flow from raw data to chart; and provide the tools required to utilise the data efficiently. An enabling technology for this has been the huge recent advances in computing power and software technology for handling large data sets. The raw data sets are substantial (over 1 order of magnitude larger than a typical beamformer). This data can now be viewed and manipulated by the surveyor in intuitive ways, and a wide range of tools are available to aid data analysis and quality control. These tools recognise the differences between PMBS and MBES data sets.

The basic difference is that the PMBS collects a range series of angle measurements while the

Criteria	Specification
Horizontal accuracy on seabed	2m
Depth accuracy (of reduced depths, at the 95% confidence level)	$(0.25^2 + (0.0075 \times \text{depth})^2)^{0.5}$
Maximum bin size	2m
Object detection	0.5m object

Table 1: An example shallow water survey standard.

MBES collects an angle series of ranges. The PMBS will usually have a wide field of view (240° or more) while the MBES will have a restricted fan of beams (typically 120° to 150°, made up of beams of 0.5° to 1.5° depending on the model). The separation of the PMBS range series can be very small (over 40 per meter), which results in the high data density seen in the raw data, and the angle measurement is very precise (0.03 degrees at boresight might be typical).

In order to understand the following discussion we must be clear about what a PMBS measures. It records relative phases of an incoming sound wave over several transducers and uses this to determine the angle of incidence of the sonar signal at an instant in time. The noise in this angle is the main source of depth noise in the xyz data output. The precision of the angle measurement depends on the stove spacing and the number of bits in the phase digitisation. The accuracy of the measured angle

depends on the hardware (transducer and electronics), phase to angle conversion algorithms and calibration. Relating the range and angle measurement to an xyz point then depends on other factors, such as the angle to the boresight, the sonar signal to noise ratio, and ray bending. Finally, the xyz point is one measurement of the seafloor position, and the relationship between a series of xyz points from a PMBS to the true seafloor profile must be considered. This paper concentrates on the angle noise arising from the scattering properties of the seafloor and sea noise – these are core characteristics of this type of phase measurement technique. Other noise sources such as vessel noise are not considered here.

The PMBS Data Processing Path

The standard PMBS data path is shown in Figure 1. The georeferencing of data is a standard step relying

on the input of ancillary data such as tide, SVP (for ray bending), position and motion. The contribution of errors in these measurements is not covered here: any ancillary data error contribution is assumed to be small in order to highlight the features of PMBS sonar technology. In a full error budget analysis these errors will also need to be taken into account.

The bulk of this paper covers the steps of outlier rejection, statistical combination (binning of data) and methods of data thinning for plotted chart soundings.

Outlier Rejection

In sonar data an 'outlier' is an unrepresentative sample of the depth, probably because it aris-

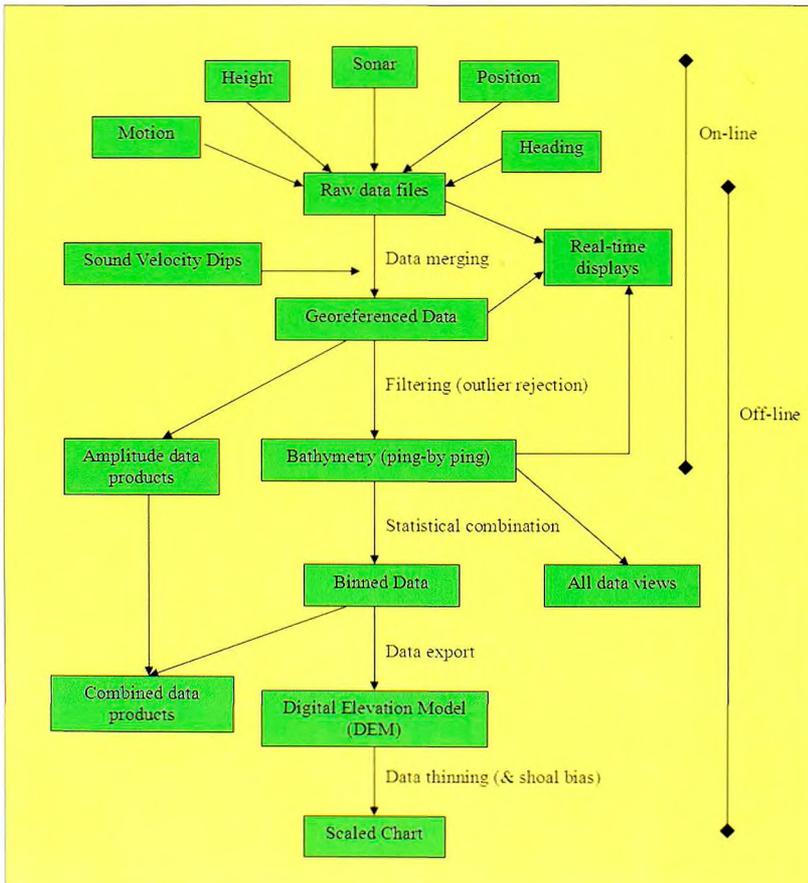


Figure 1: Typical phase measuring bathymetric sonar data path.

es not from a measurement of the seafloor but of noise or reflections off other objects. Noise in PMBS data mostly results in angle errors, as described above. Survey data is often delivered as a regular grid of depth estimations, and here the 'errors' concerned will be depth errors. Away from normal incidence these two errors will correspond well (due to the geometry and grid sizes used).

A PMBS gives a distribution of depths characterised by a near-normal main distribution with a long 'tail', and possibly second reflections (Lurton 2000). In PMBS surveys the data density allows an adaptation of Nair's method for rejecting outliers (see Kennedy & Neville 1986 p235). In this method the maximum deviation from the sample mean that can be expected for single values in samples of size n is related to the estimated variance of the population. The estimated variance must be based on a larger sample than the one containing the outlier. This is applied in a survey by estimating the population variance in 1m bins from the distribution in many densely populated bins. An estimate can be made of the greatest deviation from the mean that can be expected in a sample of size n at a given significance level, say 1%. These are given as multiples of the standard deviation in 'tables of extreme deviate' in standard statistical texts. If a sounding deviates from the mean by more than this estimate it may be rejected as being significantly different from the remainder of the sample. The level of significance at which the rejection is decided (here 1%) means there is a 1% probability that we have rejected a valid sample. This can be applied to individual bins or individual segments of a ping. Note that the population variance is likely to vary over features and slopes – usually a pragmatic approach is taken and the outlier rejection is applied at twice that for 1% significance (or more).

Rejection of outliers by filtering with too restricted limits will not produce high quality results. It is possible to reject all data that are more than a few cm from the mean in a bin (i.e. only take the centre of the depth distribution). This will give a nice-looking survey. 3D plots of the full filtered data set will appear clean, and the statistics will be great. However this method will reject samples that are in fact valid measurements of the depth, and the resulting data set will not give the most accurate mean depths. An estimate of the error in a mean found

from the filtered data could be very inaccurate, particularly for sparse data sets.

Any method which over-culls the tails of a distribution will reject valid data and provide unrealistic error estimates. This is especially true if the sample standard deviation on which the outlier rejection is based is estimated from a-priori calculations of Total Propagated Error (TPE) using manufacturer's data sheets alone, and ignores situations where the observed distribution shows this estimate to be invalid (as is often seen when using a-priori TPE on slopes).

Means, Golden Soundings, and Shoal Bias

We have discussed the raw data filters used to remove outliers in PMBS data. How should this processed data now be turned into chartable soundings, at a specific chart scale?

In commercial PMBS systems the standard technique in shallow waters is to use small bin sizes (1m or 2m bins are typical, 0.5m is sometimes used in very shallow areas). One sounding is obtained from the data in each bin using a mean or amplitude weighted mean. The distribution of data in the bin (or in several local bins) is used to estimate the error in this mean.

While this is accepted practice for engineering surveys, hydrography for navigation often requires some type of shoal bias method and retention of 'golden soundings' for charting (i.e. every plotted depth, at whatever scale, can be traced back to one raw data point). In this section we look at how this should and should not be applied to dense data sets.

Consider a survey of a flat seafloor in 10m water depth using a sounding technique which results in soundings with a 10cm standard deviation. Here the 95% confidence level (2SDs) will be less than 25cm, so this complies with IHO S-44 ed.4 Special Order. Looking at a 10m x 10m patch of seafloor with 1 sounding per 1m bin this system is likely to have 5 of the 100 soundings 20cm from the true depth, and one or two may be beyond 25cm (since 2.5 SDs = 99% confidence level). Therefore it is likely that a shoal bias chart based on 10m sound-

ing spacing will be outside IHO specifications for half the charted soundings. While this at first seems an academic example, note that port approaches are often nominally dredged flat and shoal bias sounding is used to find under-keel clearance figures. In the example used here the surface used for navigation can be expected to be about 25cm too shoal. While use of a too shoal navigation surface is laudable, a little thought about the process above shows that here the too shoal surface is being created purely by relying on the statistics of the tail of the depth distribution. A far better way to create a too-shoal surface would be to create a best estimate engineering surface, then offset by a considered amount (either fixed, based on system accuracy, use of *a-posteriori* statistics, or use a 'rolling ball' method). This will create a 'navigation surface' based on best use of the data (depth and error in depth) available.

The processing of PMBS data is aimed at achieving the best estimate engineering surface. It is worth looking at the assumptions made in this processing. These are:

- The sounding distribution on a flat seafloor is approximately normal.
- The smallest significant feature size, sonar footprint and bin size are similar (we refer to this regime as having 'small bins' in the rest of this paper).

The first assumption is widely accepted in sonar survey analysis. Later in this paper the error distribution seen with PMBS data is discussed in more detail. The second assumption above needs looking at more closely - in the opposite case where the sounding density is low compared to the smallest significant feature then shoal bias can sensibly be used: this will pick out the ping that hit the rock over the ones that only hit the seafloor around the rock. This situation arises in single beam surveys and when beamforming multibeams are used in shallow water at shallow grazing angles.

In a real port approach a surveyor will not know if a shoal sounding is shoal because of the statistical distribution of the sounding system or because the dredger missed a bit. So in practice if the survey data density only just allows a bin size of the order of the minimum significant feature size (i.e. 1 sounding in a 1m x 1m bin) then a shoal bias analysis is appropriate, although not ideal. Where better information about the true depth in a bin is available, as long as the assumptions listed above are valid, then shoal bias methods are not satisfactory.

A detailed example is appropriate here. It is straightforward to create a model survey dataset with the following characteristics:

- a flat area of 10m x 10m at 10m depth,
- a survey giving 20 soundings per 1m bin,
- soundings having a normal distribution with mean of 10m and SD of 10cm.

Three 10 by 10 (1m binned) XYZ datasets were created from this model as follows:

- Bin depth given by a single (random) sounding from each bin.
- Bin depth given by the mean of each bin.
- Bin depth given by the shoalest sounding from each bin.

Table 2 shows the statistics from the model survey.

The sounding distributions of a model created this way are plotted in Figure 2. In this figure the area under each curve is normalised to 1. The significant features are:

- The much sharper distribution of the means compared to the single soundings; this illustrates that the Standard Error of the Mean (SEM) is smaller than the SD (recall there were 20 soundings per bin, so the SEM is expected to be ~0.22 of the SD).
- The offset mean of the shoal soundings.

Type of Analysis	Min bin depth in area	Max bin depth in area	Mean depth of bins	SD of bin depths
One random Sounding	9.76m	10.32m	10.00m	0.10m
Mean of 20	9.94m	10.05m	10.00m	0.02m*
Shoalest of 20	9.67m	9.93m	9.81m	0.05m**

*= this is the measured Standard Error of the Mean.

**=distribution is not normal so the figure given is the square root of the variance.

Table 2: Statistics of the model survey data.

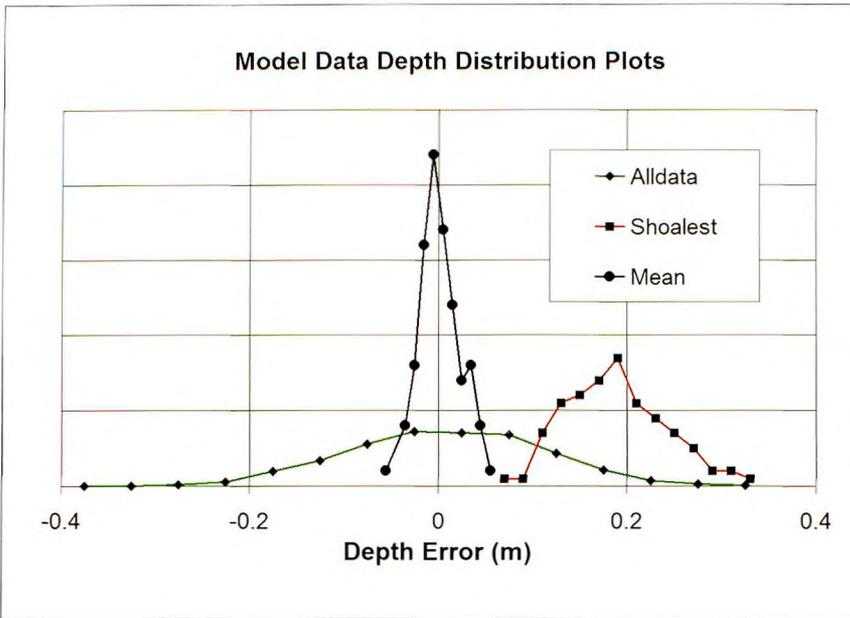


Figure 2: Bin sounding distribution from mean and shoalest bin depths compared to the full data distribution (model data).

- The skew of the shoal bias distribution caused by the way it is created (by, in effect, random sampling of the tail of the normal curve). This skew also means that SD is not a true measure of the error of a shoal bias survey.

If this was chart data, and the chart was scaled using a shoal bias method to use one sounding to represent the 10m x 10m area, the value plotted would be:

- single soundings: 9.76m (24cm shoal).
- means: 9.94m (6cm shoal).
- shoal bias bins: 9.67m (33cm shoal) = the shoalest 'golden sounding'.

As would be expected the shoalest depth of these 2,000 soundings is about 3.5 SDs from the mean. This demonstrates that shoal bias will not work acceptably for dense data sets.

As a further illustration, the model survey area was tilted to simulate a 10m x 10m survey of a slope. This shoaled from 10.5m to 10m water depth across the area, and contour plots were created for the 3 survey analysis methods described above (Figure 3). Contours are shown at 5cms, the colour depth scale is the same for all 3 images, 5x vertical exaggeration has been used. Ideally we would see a plane: a featureless slope. In the model surveys the features to note are:

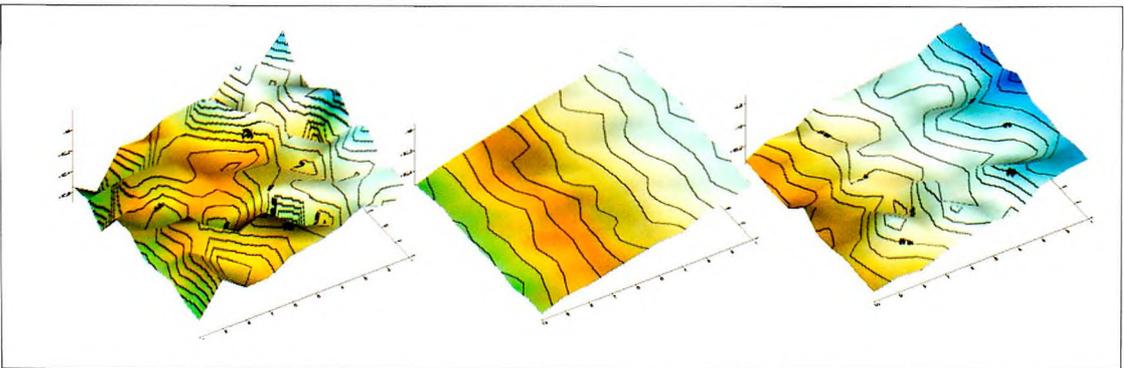


Figure 3: Survey model data (10m by 10m sloping model – see text) showing the effects of different bin depth selection algorithms. Left: single sounding, middle: mean, right: shoal bias. Vertical scales are identical (5x exaggerated), with 20cm vertical ticks on the axes. 5cm contours are shown.

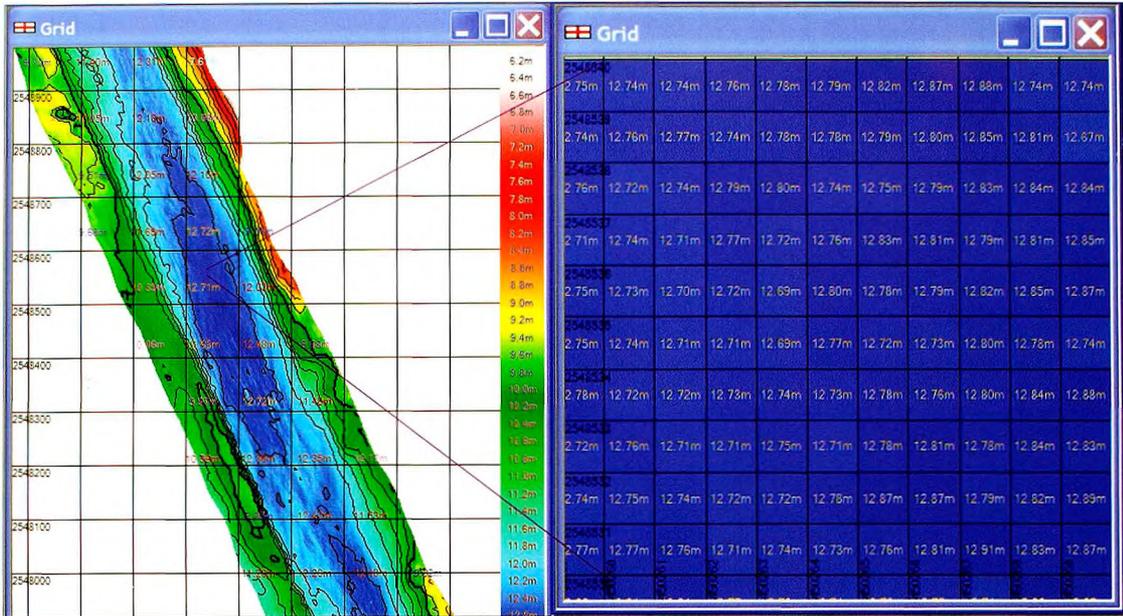


Figure 4: An overview of the Xin Sha Channel survey showing the detailed analysis area.

- The noise in the single sounding image creating false roughness (left).
- The smoothness of the mean sounding plot (middle).
- The offset of the shoal bias soundings, and the noise still present which has created apparent seafloor 'features' (right).

Of course the smoothness of the images plotted

relates directly to the ability to detect small real features in bathymetric maps.

The above analysis allows three main conclusions to be drawn about shoal bias methods:

- Shoal bias is not a good measure (as defined by IHO specifications) of depth in a densely populated small bin (small as defined by the assumptions listed above).
- Picking one shoalest sounding (a so-called 'golden sounding') from a large densely populated area is likely to lead to a large and unpredictable error, an error which depends mostly on subtle characteristics of the tail of the normal curve.
- Shoal bias is a useful way to pick one bin depth to plot from a large area of small bins, where the small bins have accurate depths.

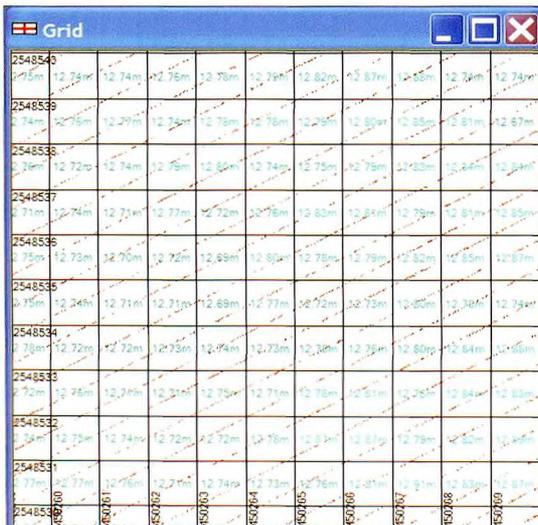


Figure 5: XYZ data location of the raw data from the analysis area from the Xin Sha Channel.

It should be stressed that this not only applies to PMBS data; in a study of a high resolution, multi-pass high density MBES survey of the Piscataqua

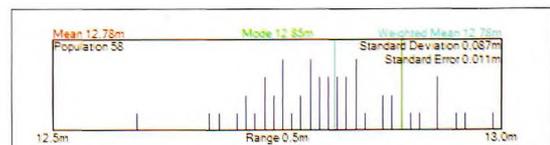


Figure 6: Example depth distribution of raw data from one bin in the analysis area.

Data Source	Population	Mean depth	Min depth	Max depth	SD of depths
All data	5054	12.78m	11.28m	14.21m	0.18m
Mean	100	12.78m	12.67m	12.91m	0.05m
Shoalest in bin	100	12.35m	11.28m	12.71m	0.37m**

**=distribution is not normal so the figure given is the square root of the variance.

Table 3: Statistics of the real survey data.

River, New Hampshire, Smith et. al. (2002) found that most of the shoal biased soundings passed on for charting came from the beamformer's outer beams. These points were slightly shoaler than the other depths in the bin due to the effects of random errors (such as refraction, motion artefacts and bottom picking noise).

Smith et. al. (2002) go on to state 'In this example the two outermost beams on either side were rejected. However, the outermost accepted beams on each side are disproportionately represented in the final smooth plot, and these are precisely the beams that are prone to the largest errors'. Shoal biasing (combined with binary editing) will always result in the least accurate parts of the swath being disproportionately represented – soundings that are too shoal will be selected over accurate depths. Collecting more soundings makes this problem worse.

A Real Example

We now apply the above analysis to a real PMBS data set. The example below is a nominally flat

area from the middle of the Xin Sha shipping channel, on the Pearl River about 30km East of GuangZhou, China (data taken from a December 2004 demonstration survey, see Qi & Hiller 2004). Figure 4 shows an overview of part of the survey and shows the location of the analysis area.

Again we take a 10m x 10m section, containing 5054 raw data points after outlier rejection. The mean population density was 42 per 1m bin (between 22 and 68), and the location of the raw data points are shown in Figure 5. A typical distribution of depths in one bin is shown in Figure 6. We can again plot the distribution of all data, the distribution of means and the distribution of shoal bias bins in this area (see Figure 7). Comparing these with the model in the previous section shows that the expected characteristics of this type of dataset are all present. Table 3 shows the statistics of this real dataset (c.f. Table 2).

Points to note about the distributions are:

- The average standard deviation of data in a bin was 13cm, while the average standard error of the mean was 2.2cm (as expected from the data density).
- There is a more pronounced skew of the shoalest

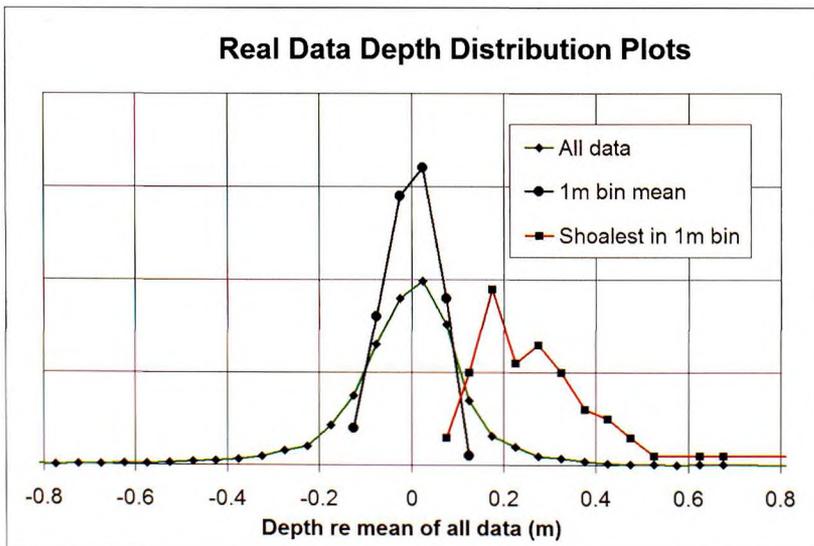


Figure 7: The distribution of all data, means and shoal bias bins from real survey data (c.f. figure 2). Horizontal axis offset to put mean of all data at 0 (mean depth was 12.78m).

- sounding curve. This is due to the extended 'tails' in real data compared with the normal distribution.
- The SDs are slightly higher than expected, and the bin mean peak is slightly wider. This is probably due to real seafloor relief on the 5cm to 10cm scale over this 10m x 10m area.
 - This data is from a real survey, so includes all random error contributions from ancillary equipment.

In the above example the data has been taken from one survey line. In an area where multiple survey lines overlap the spread in the total distribution in a bin will have contributions from ancillary error sources (tide error, roll error, etc.). Here care needs to be taken in using the statistical information in a bin – it will not only include the sonar contribution to the error budget. Note that a bin distribution from a few overlapping lines will also not give a good measure of the full error budget: although there could be hundreds of data points in the bin, each *line* should be considered as a separate sample of the ancillary errors. Usually there will not be enough samples (lines) to allow a reliable estimate of the overall error. Note that the SD from bins in an overlap area can be used to estimate a first approximation of the sonar contribution to the error budget, as it will always be an overestimate (i.e. the other error sources will cause the data to spread).

A Look at the Use of Mean Depth in Bins

In this section we examine the assumptions made in the processing to chart in more detail. First we consider the expected and observed distribution of soundings.

The physics behind the distribution of soundings can be illustrated using phasor diagrams. In Figure 8 two elements of a PMBS transducer are shown along with the transmit stave (in real systems there are multiple receive elements to allow vernier deconvolution). The phasor diagrams show how the phase measured on each stave is made up of the coherent addition of the contribution from each scatterer in that stave's field of view. Note that the signal at one instant on stave A arises from a slightly different set of scatterers than seen by stave B. This is due to the vertical separation of the staves, so the patches of seafloor seen at one instant are not fully correlated between the two staves. This is known as decorrelation noise. Compare this to the variation in phase with time that arises as scatterers move into and out of the footprint – this is the 'glint' seen in radar signals. Note that in this paper we have as a first approximation ignored any pulse shape effects and the horizontal extent of the beams.

Analysis of the simple situation shown in the figure shows that the angle measured from the phase signal will be randomly distributed about the true angle to the centre of the ensonified scatterers, with a near normal distribution (also see the analysis in Lurton 2000). The distribution is unlike a normal distribution because it is an angle error with a cut-off at $\pm 90^\circ$. It will also have a longer tail than the normal distribution; if the signal to noise ratio (S/N) is too low or the phase on each stave is uncorrelated (for example if Sc1 is much stronger than Sc2-5) then the vernier deconvolution algorithms could place the return anywhere in the 180° sector (in this paper we will ignore multi-stave phase confidence filters and smoothing tech-

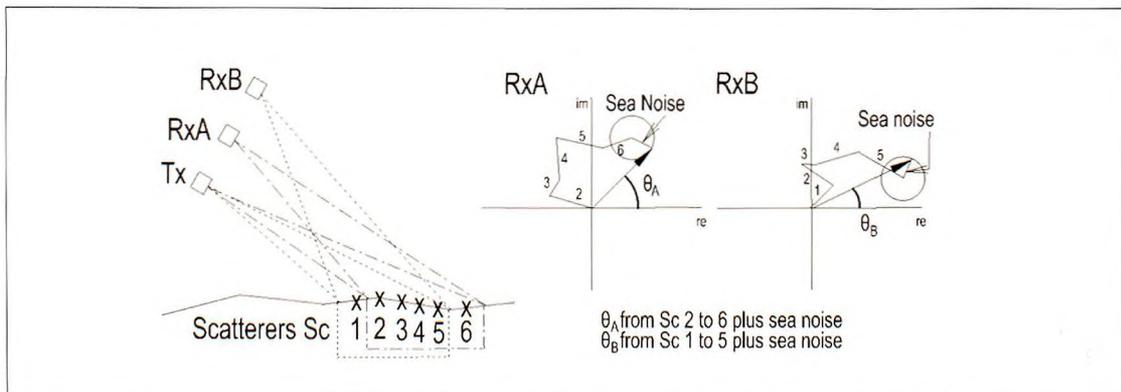


Figure 8: Phasor diagrams (right) illustrating the operation of a phase measuring sonar (left). Phase of signal on stave RxA (θ_A) results from path length Transmit (Tx) – Scatterers (Sc#) – Receiver (RxA) (original figure from Hiller & Lewis 2004).

niques). However, the majority of the soundings for S/N above ~ 30 dB will be normally distributed around the true centre of the ensonified patch of seafloor scatterers. Note that there is typically about 90dB between the transmit pulse and sea noise levels, depending on frequency, bandwidth and transducer characteristics. The signal to sea noise ratio can be estimated directly from the measured signal amplitude, so raw data can be weighted towards higher returns and harder targets – this is where amplitude weighted means have an advantage.

In conclusion the mean (or amplitude weighted mean) of the raw data distribution will be a good measure of the true seafloor depth, providing outlier rejection has been used. Amplitude filtering is also appropriate to restrict the signal to sea noise levels. The raw data remaining will approximate a normal distribution.

Once the mean depth of a bin has been obtained we need to estimate the error in this depth. This is found from the Standard Error of the Mean (SEM), which in statistical terms gives an estimate of the error of the sample mean using the number of samples and the sample variance (in the same way standard deviation gives an estimate of the population variance deduced from the sample variance). It can be shown that the SEM is given by the SD divided by the square root of the number of samples. Note that strictly the SEM uses the square root of the variance, not the SD (they are only identical for normal distributions). This means that where a variance can be calculated the SEM is a meaningful measure of the error in the mean depth, whatever the underlying distribution of samples. This arises from an application of the central limit theorem, and is true if there are enough samples in the mean (the closer the underlying distribution is to normal the fewer samples are needed to make this apply). In PMBS data this starts to become useful at surprisingly low numbers of samples - about 10 samples per bin is adequate (see Kennedy & Neville (1986) chapter 6 for more detail on this).

This result should be stressed: the central limit theorem shows that the SEM will be a good estimate of the error in the mean and that $2 \times$ SEM will be a good estimate of the 95% confidence level even where the raw data is not normally distributed. The raw data can have any distribution (even skew) – as long as a variance can be calculated the

mean and SEM will be meaningful. For example a survey on a slope or feature will still have a bin mean and SEM, and a 95% confidence level of the mean can be obtained. In this case a single sounding will give no indication of the underlying distribution and a-priori Total Propagated Error (TPE) will not be accurate.

One important question should be addressed: are the samples independent? We are referring to repeated measurements of the angle to a seafloor patch about $1\text{m} \times 1\text{m}$ in extent using a $\sim 10\text{cm}$ long sonar pulse about 1° wide. The scatterers will be randomly distributed on the seafloor, and the sonar ping will ensonify a subset of these scatterers. This subset will change as the ping moves across the seafloor. The question of independent measurements can be rephrased: is there no more than a weak correlation between the scatterers contributing to the measured phase at time t and time $t+\Delta t$ (with Δt being the time between samples)? This will be true if there is a significant change in the ensonified patch in this time. As an estimate about a 50% change in ensonified area will be sufficient, so a Δt corresponding to $\frac{1}{4}$ of the pulse length is adequate. With a typical pulse length of $\sim 10\text{cm}$ ($\sim 60\mu\text{s}$) this allows a sample rate corresponding to ~ 40 per m slant range.

We have shown that the mean is an acceptable measure of the depth in small bins with high data density, and that data density of about 10 per bin is required to use the SEM as a measure of the depth error. We have described what is meant by a 'small' bin and shown that the depth measurements in such a bin are essentially independent repeat measurements. For all this to apply the smallest significant feature size, sonar footprint and bin size should be similar. This applies with standard PMBS systems in shallow water surveying to IHO S-44 edition 4 specifications when using $\sim 1\text{m}$ bins. Confirmation of the accuracy of a commercial PMBS system when surveying in this regime has been demonstrated elsewhere by comparison with single beam and MBES surveys, see Hogarth (2003), Hiller (2004), Jonkman (2004) and Hiller & Lewis (2004).

Conclusions

The data from a Phase Measuring Bathymetric Sonar (PMBS) has been analysed in some detail. The reasons for the observed distribution of the

data have been detailed, and it has been shown that effective and appropriate processing techniques can be applied. This processing uses averaging in small bins and can result in very accurate charted depth data, with a sonar contribution to the depth accuracy (given by the standard error of the mean, SEM) on a centimetric scale. This SEM can be obtained a-posteriori from local survey data. It was also shown that care needs to be taken not to apply inappropriate processing methods which could result in poor data and poor estimates of accuracy.

Detailed analysis of a subset of real survey data has demonstrated that a commercial system behaves as expected from the physical models. Given appropriate data processing PMBS systems can provide very accurate and reliable chart data.

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Biography of the Authors

Dr Tom Hiller trained as an experimental physicist in the semiconductor industry. Since coming to the marine field Tom has worked in technical sales, application engineering and product management for several UK sonar manufacturers. In early 2003 Tom set up Anka Ltd of Bristol, UK, to provide hydrographic consultancy, systems engineering and training to the marine survey industry and government organisations. Since January 2005 Tom has been based full time at GeoAcoustics Ltd. in Great Yarmouth, UK, working on the development of a range of new technologies for the sonar survey market.

Peter Hogarth is the technical director at GeoAcoustics Ltd. He is a Fellow of the Institute of Elec-

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