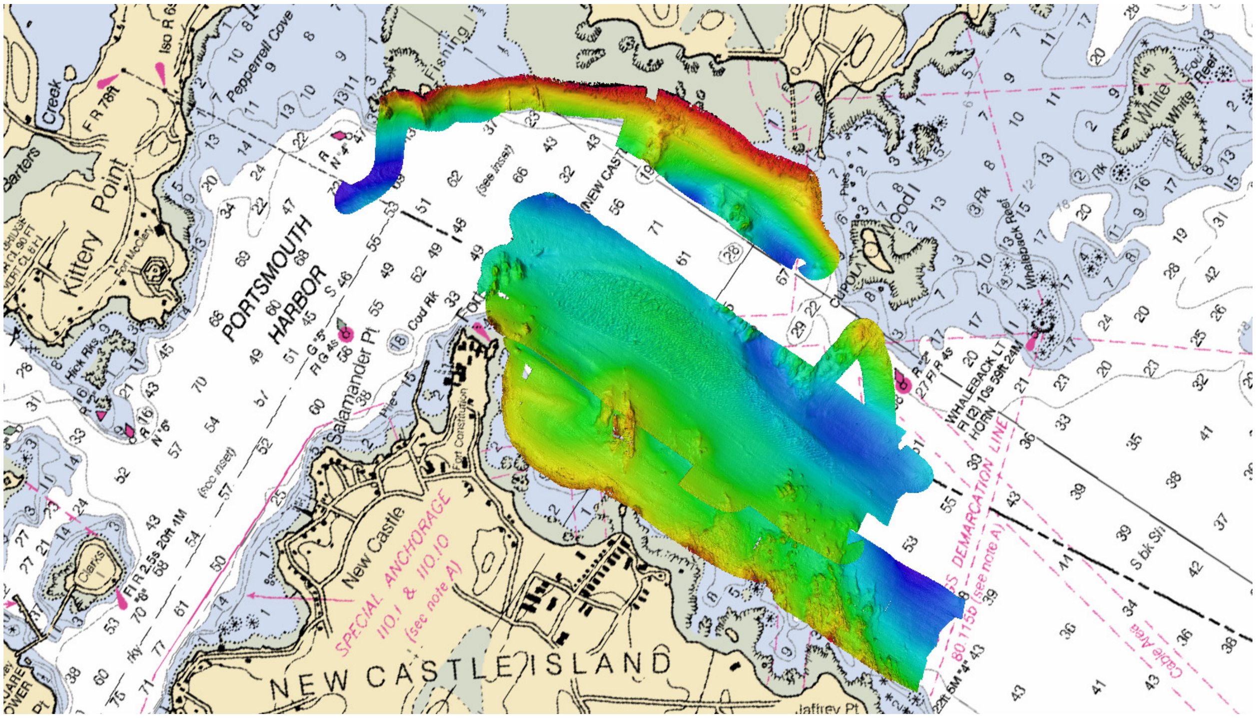
Efficacy of an interferometric sonar for hydrographic surveying:

Do interferometers warrant an in depth examination?



A Preliminary Study

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Non-Technical Summary:

Nautical charting is integral to safe maritime navigation and directly linked to a substantial portion of the nation's economy. Over the last several decades considerable advances have been made in the methods used to acquire hydrographic data for nautical charting. Today, full bottom coverage is achievable through the use of side scan and shallow water multibeam sonar systems. The acquisition of bathymetry in very shallow water areas with beam-forming systems, however, remains relatively time consuming due to angular limitations on swath width. Shallow water inshore boatwork is dangerous and requires a disproportionate amount of time to complete making it desirable to integrate more efficient shallow water bathymetric data acquisition technologies into our arsenal of survey equipment.

One technology that provides increased swath width in shallow water is interferometric phase differencing sonar, however, the technology has not yet been studied thoroughly enough to establish its suitability for use in NOAA's nautical charting survey work. This paper describes a preliminary evaluation of the GeoAcoustics GeoSwath sonar which was selected for testing as a representative interferometric system. The goal was to determine whether a full scale examination of interferometers is warranted to ascertain their effectiveness for use in shallow water hydrographic survey work. GeoSwath data acquisition was conducted in Portsmouth Harbor, New Hampshire on 29 June 2004. The GeoSwath data were statistically and visually compared to previously acquired Reson 8125 and Simrad EM3002 shallow water multibeam data coverage of the same region.

The standard deviation of the GeoSwath data sampled in several 5m x 5m regions ranged from 11.8cm to 20.7cm; approximately 3 – 5 times greater than the Reson and Simrad data. This range is in agreement with a previous industry report which argued that due to higher data density the grid generated from interferometric data with a higher standard deviation would be similar to a grid generated from multibeam sonar data. A point-to-surface comparison showed this to be true. In all comparisons with Reson and Simrad grids, the GeoSwath point data met International Hydrographic Organization Order 1 requirements or better. A visual comparison between the GeoSwath and Simrad datasets showed that the GeoSwath faithfully reproduced sandwaves as small as 0.1m in amplitude. Visual comparison between the GeoSwath, Reson, and Simrad showed less ephemeral features such as boulders and rock outcrops as small as 2m across and several decimeters high were present in all datasets. With these findings, it is recommended that an official study be undertaken to determine if recent advances in algorithms, electronics, and manufacturing have improved interferometers enough for use in nautical charting hydrographic survey work.

Efficacy of an Interferometric Sonar for Hydrographic Surveying:

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Introduction:

Marine commerce is a vital part of today's world economy. According to the U.S. Department of Commerce, over 98% of the United States foreign trade by weight travels by sea; 1.2 billion metric tons of cargo valued in excess of $800 Billion in 2003 (NOAA 1999; U.S. Army Corps of Engineers 2004). Ever increasing usage of the nation's waterways as transportation corridors creates a demand for more accurate information about the physical characteristics of those waterways, particularly their depths. Congress has tasked the National Oceanic and Atmospheric Administration (NOAA) with creating and maintaining a suite of nautical charts to aid in the achievement of safe navigation within the US Exclusive Economic Zone (EEZ). The methods used to acquire data for compiling these nautical charts have advanced significantly over the last century, but new, more efficient and accurate techniques are always of interest. Interferometric sonar systems are one possible tool which may be capable of significantly improving the efficiency and safety of hydrographic survey operations in shoal waters, thereby improving the overall safety of navigation in US waters. Interferometers have not yet been formally evaluated by NOAA for use in hydrographic surveying for nautical charting purposes. This is a preliminary study to determine whether a full scale official study will be worthwhile in conducting.

Requirement to Improve Efficiency in Shallow Water:

Working in shallow water presents a host of challenges to nautical charting survey crews. The areas frequently have not been surveyed for some time, if ever, and the possibility of rocks and obstructions is present at every turn. Additionally, in very shoal water, the typical three times water depth limitation of SWMB becomes a restrictive factor (e.g., when working in 4m of water the usable swath width will only be ≈ 12m wide) meaning that a disproportionate amount of time must be spent surveying relatively small regions which are hazardous to work in. For cost and safety reasons, it is desirable to minimize the amount of time personnel must spend in shallow water areas.

Interferometric Sonar Systems:

Interferometric sonar (IFMS) is an emergent technology that may provide significant advantages in shoal areas where LIDAR use is not feasible or of too low a resolution to be useful. IFMS provides co-located bathymetry and imagery enabling advanced display and quality control capabilities with seafloor datasets. IFMS systems are not beam-forming, but accurately measure depths at precise locations on the seafloor via the use of exactly spaced phase differencing transducer elements which measure the phase offsets of acoustic returns. The phase offset is used to calculate the angle (θ) from which the return was received. The angle, in combination with range based on two way travel time, is used to calculate the position of the seafloor and objects upon it relative to the instrument. This provides accurate bathymetric data co-located with SSS imagery which can be used to create either side-scan sonar (SSS) imagery, bathymetry, or imagery with associated depths (Figure 1). One of several methods for calculating angle of origin is as follows (similar to Denbigh's 1989 technique):

$$\theta = \alpha_n - \alpha_{n+1} \qquad (1)$$

where $\alpha = \text{atan}\,(I / Q)$, n = interferometric receive element
and I = in-phase[1] component and Q = quadrature[1] component

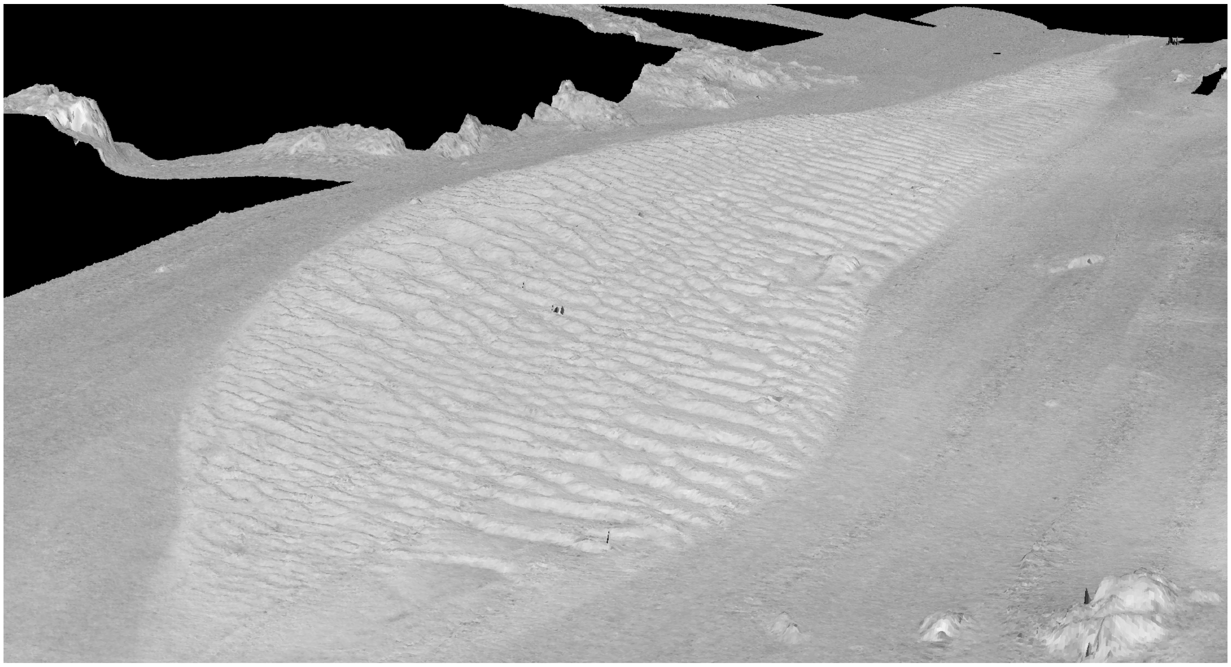


Figure 1 – Co-located imagery and bathymetry from Portsmouth Harbor, New Hampshire. Bathymetry data were gridded at 50cm and draped with mosaicked sidescan imagery binned at 50cm. The sidescan has been "normalized for transducer attitude and local slope. High backscatter is represented by light grey while low backscatter is shown with dark grey. A small amount of sun illumination was applied to accentuate the sand-ripples. All data manipulation performed within GeoAcoustics proprietary GeoTexture software package.

Historic Problems with Interferometers –

Interferometric sonar systems have been in existence in one form or another for several decades. Traditionally, interferometrics had issues with ambient and internal noise as well as difficulties in resolving multiple angles of arrival (i.e., multiple returns from different angles at the same time). The inability to differentiate between multiple angles of arrival was determined to limit bathymetric resolution to ≈ 2-3% of water depth (DeMoustier 1993). Recent improvements in electronics and algorithm advancements combined with the use of increased numbers of receive elements have greatly improved the precision of the technology (Griffiths, et al. 1997, Kraeutner and Bird 1999, Wilby 1999).

Another issue has been baseline decorrelation, whereby the heterogeneity of the seafloor results in slightly different apparent signals at varying relative angles to a given region of seafloor (Jin and Tang 1996). This results in a somewhat different seafloor experienced by each of the multiple receivers in an interferometric sonar array. A similar phenomenon, the *shifting footprint effect* (the result of acoustic returns originating from slightly different portions of the seabed being received at different receive elements simultaneously) was deemed by Lurton to be another significant factor affecting phase fluctuations in interferometric sonar data; he recommended addressing the problem through iterative computational methods (1998, 2000). While these problems were significant, recent advances in electronics, transducer manufacturing, and algorithms have dramatically improved the performance and reliability of interferometers.

Advantages of Interferometers –

There are several advantages associated with the use of an IFMS system. An interferometric sonar typically has a swath width of 12-times the altitude of the instrument, up to the selected range scale (whichever is less). This means that in 4m water depth the IFMS should be capable of attaining bathymetric data to a range of close to 50m. This is a significant improvement over a SWMB's typical 12-15m swath width under similar conditions, meaning that IFMS could be capable of improving inshore efficiency by a factor of nearly four. This would dramatically reduce the amount of time that survey crews must spend working in dangerous inshore regions and greatly improving productivity.

Additionally, sea surface chop, low lying clouds, and water clarity are not limiting factors with IFMS as they are with LIDAR, enabling high resolution surveying of critical inshore regions when the data is desired and not when strict environmental conditions necessary for

LIDAR acquisition have been met. Interferometers also provide high density data (on the order of one angle-range measurement every few centimeters across track, see system specs in the Appendix) with uniform cross-swath pattern and co-located sidescan imagery and bathymetry to increase confidence of feature detection and aid in data interpretation (Cloet 1988).

Interferometric technology could prove highly beneficial to NOAA's nautical charting program, however, IFMS is still considered a developing technology within the nautical charting industry. While there have been numerous papers written on the theoretical functionality of these systems and a variety of manufacturer studies conducted, there have been few independent analyses of their *in situ* performance. The GeoAcoustics GeoSwath interferometric sonar which was widely available commercially at the time of this research was seen as an ideal candidate for study.

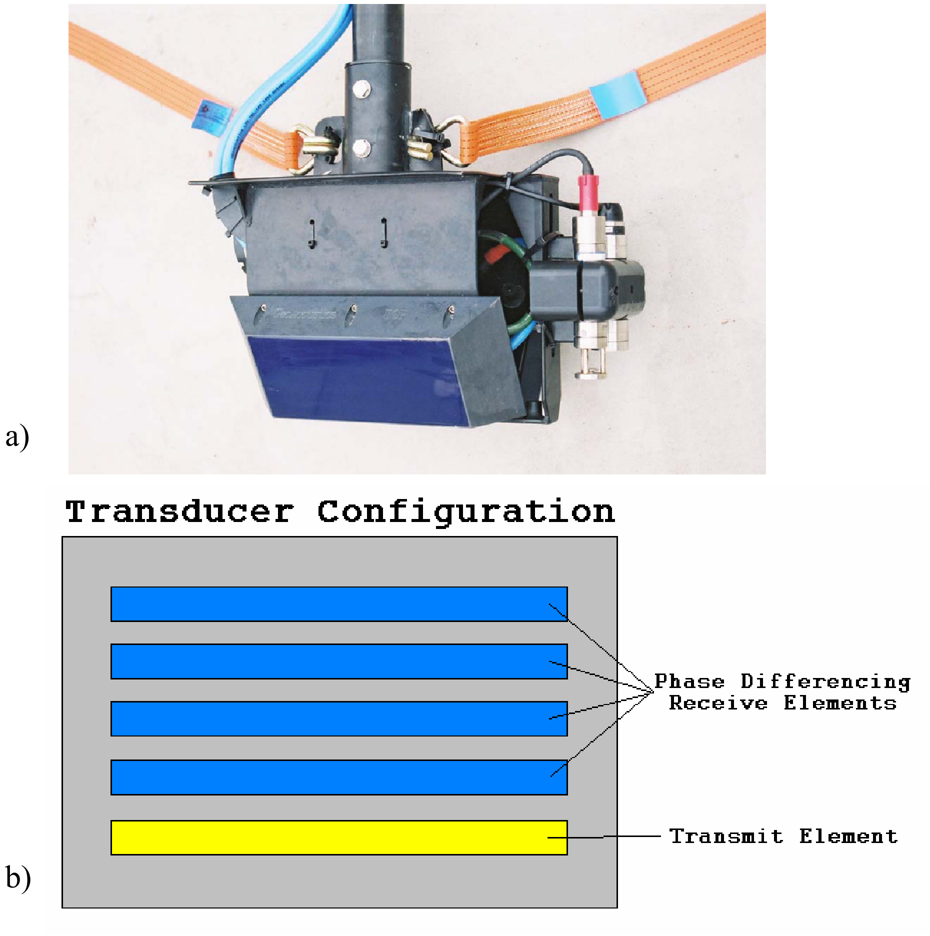


Figure 2 – a) Photograph of the GeoSwath interferometric sonar head. The system has dual transducers deflected ≈ 30° from the vertical resulting in an increased number of measurements at nadir. Note the single beam transducer and sound velocity probe on the right side of the image. **b)** Simplified schematic of the GeoSwath interferometric sonar head configuration. The system is equipped with a single transmit element and four phase-differencing receive elements per side.

GeoSwath System Description:

The GeoSwath system is comprised of two major physical components which are cabled together; the sonar head and the processing unit. The sonar head is composed of two transducers, a single beam echosounder, and a sound speed sensor all mounted on a V-plate. Each of the two transducers are equipped with five elements (Figure 2). The bottom element on each transducer is a transmitter while the remaining four elements are phase differencing interferometric and sidescan receivers; a design suggested by Denbigh to reduce phase ambiguity and the effects of ambient noise (1994).

At the time of this study there were three GeoSwath sonar models available operating at 125kHz, 250kHz, and 500kHz. The system chosen for this study operated at 250kHz, producing high resolution imagery and bathymetry with greater across track data density than its SWMB counterparts. The across track sampling density is 1.2cm and vertical resolution is estimated to be on the order of ± 1-2cm (see manufacturer specifications in the Appendix). In conjunction with appropriate ancillary equipment and careful attention to operating procedures, the system should be capable of meeting International Hydrographic Organization (IHO) Special Order specifications requirements for vertical accuracy. Equation 2 describes the minimum standard for vertical depth accuracy required for a Special Order survey and Figure 3 provides a graphical depiction of the accuracy required for several orders of survey work (IHO S-44 1998).

$$\pm \sqrt{0.25\text{m} + (0.0075 * \text{depth})^2} \tag{2}$$

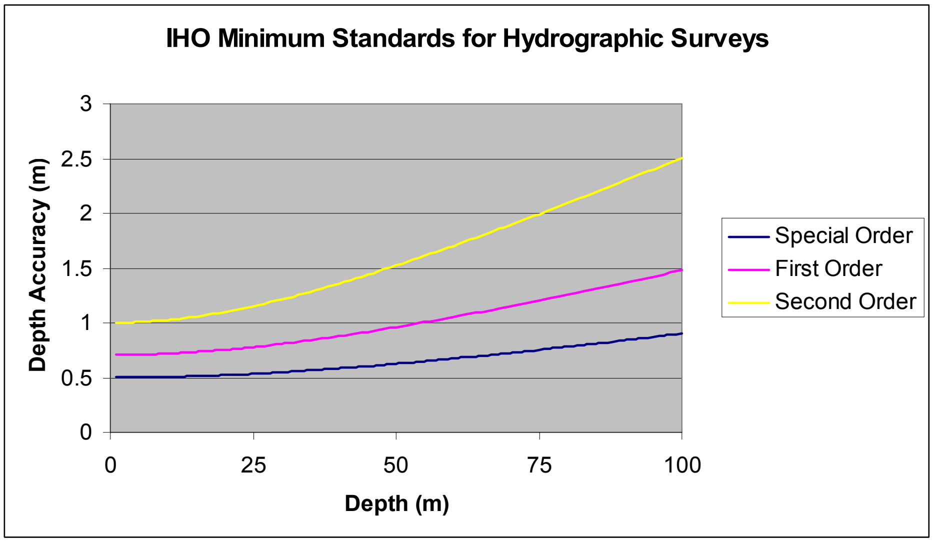


Figure 3 – IHO requirements for vertical accuracy during hydrographic survey work. All requirements are at a 95% confidence interval using reduced depths (IHO S-44).

● Opportunity for Study –

In June 2004, GeoAcoustics made their GeoSwath system available for testing to the NOAA – University of New Hampshire (UNH) Joint Hydrographic Center. While the GeoSwath is fairly well distributed within the industry its effectiveness for use in hydrographic surveying has not yet been evaluated by NOAA. This study aims to determine whether an in-depth official study of interferometric technology for use in shallow water nautical charting survey work is warranted. This determination was made through the acquisition and analysis of data with the GeoSwath sonar system, and the comparison of that data to data acquired using Reson 8125 and Simrad EM3002 SWMB sonar systems. It is recognized that further research will be required prior to adding interferometric systems to NOAA's battery of hydrographic survey instruments; this study aims to determine whether that research is worthwhile in pursuing.

Methods:

In order to evaluate the effectiveness of the GeoSwath interferometric sonar system for use in hydrographic surveying it was necessary to collect data for analysis. Field testing consisted of acquiring soundings with the GeoSwath IFMS over a region where data had previously been collected using several SWMB systems with known quality data. The SWMB data was used as the bathymetric standard by which the GeoSwath data was judged. IFMS data were collected aboard the UNH R/V Coastal Surveyor 27 – 29 June 2004 in Portsmouth Harbor, New Hampshire. GeoSwath data were processed in Swath32 prior to export as ASCII xyz files for analysis. Simrad and Reson datasets were processed in Caris HIPS/SIPS and also exported to ASCII xyz files. The cleaned datasets were then imported into Fledermaus for analysis.

• Survey Area –

Portsmouth Harbor is located at the mouth of the Piscataqua River and provides an excellent testing ground for shallow water sonar systems. The harbor has depths ranging from shoreline to approximately 25m and numerous previous bathymetric studies have been completed in the area. The survey area selected (Figure 4) provided for coverage of a variety of discrete objects on the seafloor, as well as flat regions, and a sand ripple field. The site is directly adjacent to NOAA Tide Station 8423898 (Fort Point / New Castle) resulting in optimal tidal correctors. Skies were partly cloudy, there was light wind, no precipitation, and 0 – 1 foot of swell with minimal chop during the survey period.

- **Vessel –**

The UNH Research Vessel Coastal Surveyor (Figure 5) was built primarily as a hydrographic research/acquisition platform. It was designed with active roll stabilization features to limit vessel motion (i.e., heave, pitch, and roll) making it particularly well suited for shallow water hull mounted sonar operations. The Coastal Surveyor is 40-feet in length with a draft of slightly greater than 1m. Optimal roll stabilization occurs at 5-knots or greater speed-through-water, which was maintained throughout the majority of survey operations.

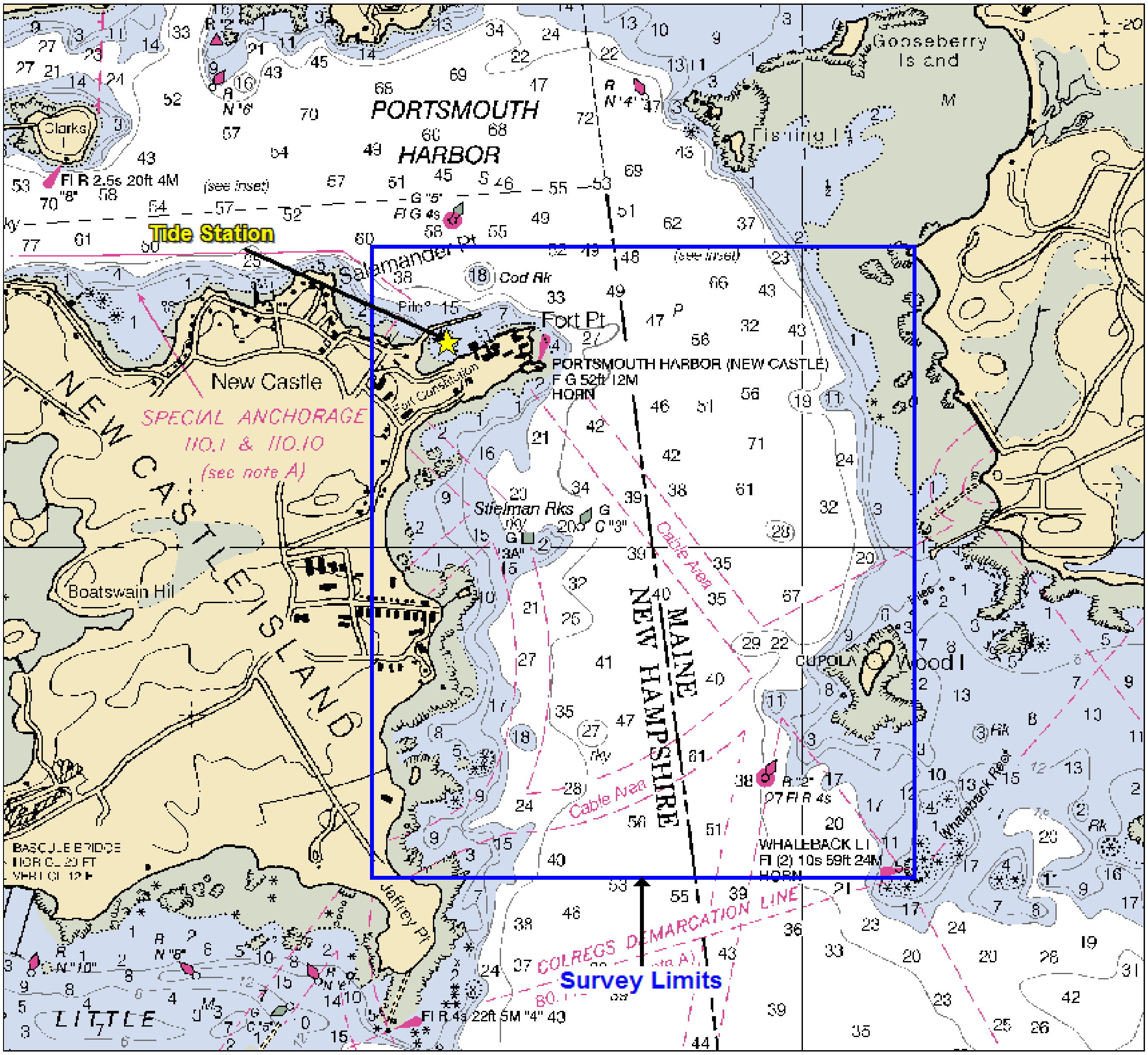


Figure 4 – Survey area and vicinity for interferometric sonar hydrographic survey work conducted 28 – 29 June 2004. Note proximity of the New Castle tide station within the working grounds. (Image taken from NOAA nautical chart 13283).

Figure 5 – University of New Hampshire R/V Coastal Surveyor. Note the adjustable bow ram which allows the hard mounting of a variety of sonar heads or other scientific equipment.

- **Sonar Installation and Patch Test –**

The sonar system and ancillary equipment were installed on the UNH R/V Coastal Surveyor on 27 June 2004. Installation consisted of physically mounting the sonar head on the vessel's custom bow-ram (Figure 5), connecting the PC to the C-NAV positioning and POS/MV motion correction equipment, and entering the appropriate settings and offsets into the software. The vessel offsets and lever-arms had been measured several weeks prior, so only verification was required for most measurements. Three personnel completed the installation in approximately four hours with minimal difficulty.

To calibrate for slight deviations in equipment orientation and time latencies a patch test was conducted with data acquired during the transit from Adams Point to Portsmouth Harbor the same day as installation. The data were analyzed in GeoSwath32 and correction offsets for heave, pitch, roll, and time latency were entered prior to project related data acquisition.

- **Sound Velocity Corrections –**

In order to compensate for variations in the velocity of sound through water it is necessary to have an understanding of sound speed at the transducer face and through the water column. We made sound speed measurements through the water column with an Odom Digibar Pro several times throughout the survey operations. Sound speed was taken in the vicinity of data acquisition at least every four-hours which was determined sufficient to meet the requirements set forth in NOAA's *NOS Hydrographic Surveys Specifications and Deliverables* manual. Measurements were made with 0.5m resolution from the surface to the seafloor and the results were applied during post-acquisition data processing using the GeoSwath32 software package to account for the actual ray path of the acoustic pulses through the water. Additionally, a Valeport *mini*SVS sound velocity probe was mounted at the sonar head to provide realtime sound speed at the transducer face during acquisition. The *mini*SVS data was used to calculate launch and return angle as well as phase separation of the transducer elements at the sonar head.

- **Tidal Corrections –**

Water level was monitored throughout the survey via use of NOAA tide station 8423898, which is located in New Castle, NH, directly adjacent to the survey area. The tide gauge was leveled on 04 June 2004, several weeks prior to survey; all measurements were consistent with previous levels and no adjustments were necessary to the local gauge datum. All depths are relative to mean-lower-low water (MLLW).

- **Data Acquisition –**

All three datasets used in this analysis were acquired on the same survey platform, the UNH R/V Coastal Surveyor. The sonar heads were mounted on the custom bow-ram in each case. The vessel motion correctors for all datasets were obtained via an Applanix POS/MV Model 320. Variations in other ancillary equipment are described below.

GeoSwath interferometric bathymetric data were acquired on 28 – 29 June 2004. The sonar head was controlled and data were recorded using the GeoSwath processing unit. Navigation was accomplished with Nobeltec, which has rudimentary line control features. The entire survey area was covered on the 28th using a dual antenna Trimble DGPS system for positioning. Unfortunately, irreparable heave artifacts were present in the data due to an incorrect setting in the POS/MV "IMU Frame w.r.t. Reference Frame" parameters. The majority of the region was again surveyed on the 29th with proper POS/MV settings, this time using C&C Technologies C-Nav proprietary wide-area-DGPS for positioning. Only data acquired on 29 June were used for analysis. Conditions were excellent for survey work on both days with ~ 1-foot swell and clear to partly overcast skies and no precipitation. Data were copied to DVD and an external hard-drive for later processing and analysis.

The Simrad EM3002 shallow-water multibeam data was acquired 17 – 21 June 2004. Sonar controls, data recording, and navigation were all managed using Simrad's Seafloor Information System software on the desktop computer supplied with the sonar. Positioning was achieved with a dual antenna Trimble DGPS system. A blunder in the vertical offset of the sonar head was later remedied using MATLAB. Data were copied to DVD and an external hard-drive for processing and analysis.

The Reson SeaBat 8125 shallow-water multibeam data was acquired in May 2002. Sonar interface was achieved through Triton-Elics Isis software. Data recording and navigation were managed via Hypack's HypackMax software suite. Positioning was achieved with a dual antenna Trimble DGPS system.

• Data Processing and Preparation –

Several datasets were used for this analysis: the GeoSwath data acquired late June 2004, Simrad EM3002 data acquired earlier in the month of June 2004, and Reson SeaBat 8125 data acquired in May 2002. Each dataset was processed independently but care was taken to ensure that all comparisons were made between like quantities in Fledermaus. Point comparisons were made between processed, cleaned, undecimated datasets. All grids and surfaces were created using a weighted moving average algorithm at 1m resolution with a weight diameter of three.

Both the Reson 8125 and the Simrad EM-series of sonars have been extensively tested and approved for use as NOAA hydrographic surveying tools. The Reson system is among the highest resolution mass-marketed SWMB sonars available at the time of this study. The EM3002 is the most recent addition to Simrad's series of sonars and employs state of the art electronics and algorithms providing exceptionally clean data. Their acceptance as hydrographic instruments, coupled with the fact that datasets in the survey area are readily available, made these systems excellent candidates for comparison.

Analysis through inter-system comparison is recommended, and has been employed, by John Hughes Clarke of the internationally renowned Ocean Mapping Group (1996, 1997). While Hughes Clarke's comparisons were between a larger number of bathymetric sonar systems, the value of an inter-system comparison holds true in this case; the comparison of multiple sets of bathymetric depths representing the same surface is analogous.

The GeoSwath data was processed and automatically cleaned using GeoAcoustics' proprietary Swath32 software package. The software employs a sophisticated moving average box filter with user set parameters to remove erroneous bathymetric measurements without extensive user interface. The software generated cleaned bathymetric data for analysis as well as normalized sidescan imagery which was mosaicked and draped over the bathymetry as an additional product. The cleaned bathymetry was exported as ASCII xyz files using the FileFunct program. The ASCII xyz files were imported into Fledermaus via PFMDirect for statistical point data comparisons and via Avggrid and DMagic for surface comparisons and visual analysis. All data was imported in UTM Zone 19N. Grids were created at 1m resolution using a weighted moving average algorithm with a weighting diameter of three and the z-column inverted so the data would display as depths as opposed to elevations.

The Simrad EM3002 data was processed and manually cleaned in Caris HIPS/SIPS Version 5.4. Heave, pitch, roll, dynamic draft, and tidal correctors were applied. Obviously erroneous soundings were manually removed using the swath editor function. Data were exported as ASCII xyz files. A blunder in the vertical offsets entered during acquisition was corrected for by subtracting 1.2m from all depths in the dataset using MATLAB. Data were imported into Fledermaus via PFMDirect for statistical point data comparisons and via Avggrid and DMagic for surface comparisons and visual analysis. All data was imported in UTM Zone 19N. Grids were created at 1m resolution using a weighted moving average algorithm with a weighting diameter of three and the z-column inverted so the data would display as depths instead of elevations.

The Reson 8125 dataset was acquired in May 2002 and was processed and cleaned in Caris HIPS/SIPS by CCOM research personnel. The raw data were no longer available but a complete ASCII xyz file of the region was. Data were imported into Fledermaus via PFMDirect for statistical point data comparisons and via Avggrid and DMagic for surface comparisons and visual analysis. All data was imported in UTM Zone 19N. Grids were created at 1m resolution using a weighted moving average algorithm with a weighting diameter of three and the z-column was inverted so the data would display as depths as opposed to elevations.

- **Data Analysis –**

Due to time constraints it was necessary to limit the tests carried out to a less than an optimal number, however, quantitative results were still achievable. Several comparisons were possible in the timeframe available. Two standard deviation comparisons, a surface difference comparison, and a visual analysis were ultimately decided upon.

– Statistical Comparisons:

In order to meet IHO specifications for a special order survey the average separation of reduced depth data points from the true surface plus twice the standard deviation must be less than the value yielded by Equation 2. Standard deviation is calculated in Fledermaus as shown in Equation 3 where χ represents the value of a given data point, χ is the average of all the data points, and η is the number of data points.

$$\text{Standard Deviation} = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - n\bar{x}^2}{n-1}} \tag{3}$$

The GeoSwath, Reson, and Simrad datasets were imported as grids into Fledermaus using Avggrid. Several relatively flat 5m x 5m regions covered by all three datasets were defined. The point data comprising these regions were converted into *.pfm files via PFMDirect. The *.pfm files were then each imported into Fledermaus and the bin statistics were calculated. The results for standard deviation were recorded for comparison.

As a second and more robust measure of standard deviation, Fledermaus' CrossCheck software was used. CrossCheck was developed as a means for statistically analyzing point data relative to a reference surface. The reference surface may be based either upon ground truth data or another point dataset. The depth of each point in the dataset being analyzed is geographically compared to the depth of the reference surface at the same position. The difference in heights for each point is recorded and the compiled results are ultimately used to calculate several statistics as described in Appendix Table A1 (Fledermaus 2004).

In this instance the Reson, Simrad, and GeoSwath data were each iteratively used as reference surfaces and the Simrad and GeoSwath data were compared to them. Due to processor limitations, the software was capable of handling files of only up to approximately 130MB in size. This limited the GeoSwath lines that could be used for comparisons, as many of the files were greater than 200MB, and eliminated the possibility of comparing the Reson point data to the other reference surfaces as it was a single 1.5GB file. GeoSwath point data were compared to both Simrad and Reson reference surfaces and Simrad point data were compared to GeoSwath and Reson reference surfaces. Varying sized point data samples from a few dozen pings up to entire lines were compared.

– Surface Difference:

A surface difference analysis was also conducted examining the differences between the three datasets. The 1m resolution grids that were generated using Avggrid and DMagic were opened in Fledermaus and difference surfaces were generated using the Surface Difference command. Surface differencing generates a new grid with node values equivalent to the vertical difference between nodes in the two surfaces being queried. The GeoSwath data was differenced from each the Simrad and Reson datasets and the Simrad data was also differenced from the Reson data to provide a baseline difference surface. The difference surfaces were then each opened in CrossCheck and compared to the Simrad point data which covered the entire region. This provided an average of each difference surface to be used as an indicator of overall similarity between the surfaces generated from the different sonar datasets.

– Visual Comparison:

Additionally, a visual analysis of the gridded surfaces was conducted. The presence and minimum depths of discrete features such as boulders and outcrops were compared between all three datasets. Smaller scale ephemeral features such as sandwaves 0.1 – 0.2m in amplitude were also compared in the GeoSwath and EM3002 datasets. The datasets were acquired within a few weeks of one another making the comparison meaningful. While there are a few larger sandwaves that may be of a permanent enough nature to use for comparison between all three datasets, the SeaBat data was acquired two-years prior, which was determined to be too great a temporal separation for comparison of smaller features to be of significance.

Results:

• Sonar Installation and Patch Test –

The sonar head was measured to be 8.94m forward, 0.21m starboard, and 1.61m below the POS/MV Inertial Motion Unit (IMU). The center of motion for the vessel was estimated to be located at 1.4m forward and 0.2m to starboard of the IMU. The patch test produced a time latency of 0.07 seconds, heave offset of 1.14, and negligible pitch offset. The transducer head was manufactured so the individual transducer heads were deflected 30° from the vertical; roll offsets were determined to be 1.41° on the port and -0.63° on the starboard.

- **Sound Velocity –**

Figure 6 shows the sound speed profiles acquired throughout the GeoSwath survey. Six casts were successfully completed and the water column was generally fairly well mixed with the exception on the afternoon of the 28th when two casts were taken consecutively to ensure accuracy. Sound velocity at 1m varied from 1490.2m/sec to 1501.6m/sec throughout the two days of data acquisition and no adverse effects were noted during either data acquisition or processing. Sound velocities were applied as part of data processing using Swath32.

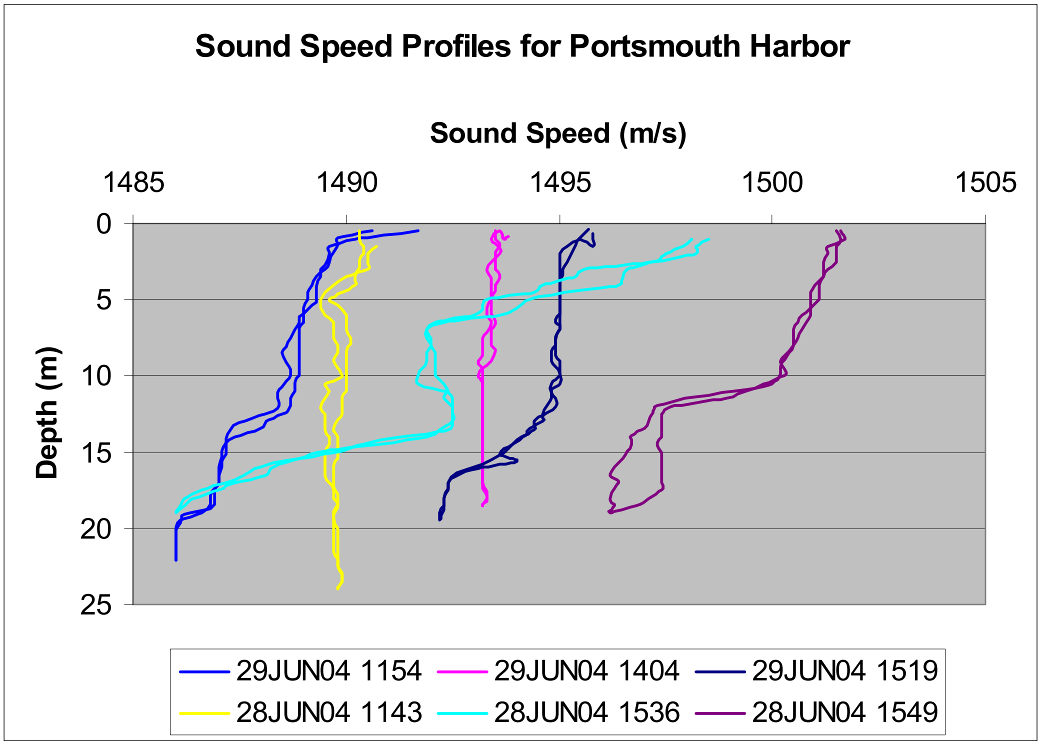


Figure 6 – Sound velocity profiles taken during bathymetric data acquisition. All times are local.

- **Tidal Corrections –**

Tides were measured at six-minute intervals via the NOAA tide gauge located in New Castle, New Hampshire. Verified tidal correctors were downloaded from the CO-OPS website and applied to the data via Swath32. There was an approximately 3m tidal range during survey operations. A general depiction of the tides may be seen in Figure 7.

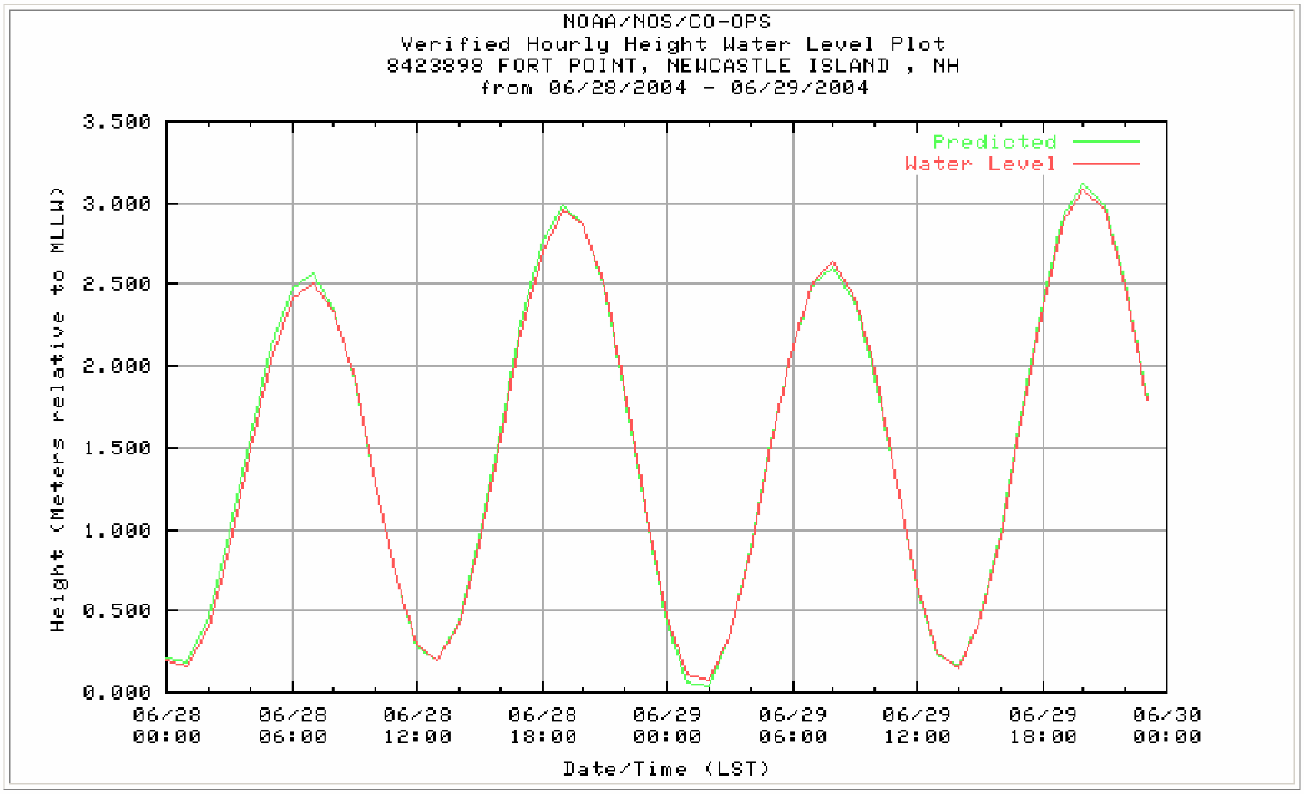


Figure 7 – Water levels during data acquisition. The tide station was located immediately adjacent to the survey area resulting in exceptionally accurate tidal correctors.

● Sonar Data Comparisons –

The three methods used to evaluate the data (statistical comparisons, difference surfaces, and visual comparison) lead to the conclusion that the current capability of interferometric sonar warrants further evaluation of the technology. The results of all the tests indicate that the GeoSwath interferometric system provides bathymetric data that may be used to generate grids of the seafloor that vary only a few centimeters from grids created using data from beam-forming shallow water multibeam systems.

– Statistical Tests:

Two statistical tests were conducted. The first examined several 5m x 5m regions of relatively flat seafloor common to each GeoSwath, Reson, and Simrad bathymetry datasets. The second utilized Fledermaus' CrossCheck to compare soundings from the GeoSwath and Simrad sonar systems to surfaces generated from soundings from GeoSwath, Reson, and Simrad datasets.

The first test showed that the standard deviation of the GeoSwath data tended to be between 3 and 6 times as high as that of the Reson or Simrad datasets (Figure 8). The 95% confidence interval (two times standard deviation) ranged from 23.5cm to 41.4cm. The Reson values ranged from 7.5cm to 8.9cm and the Simrad values fell between 5.3cm and 13.6cm. These values are in agreement with a recent study by Hiller and Lewis and do not preclude the creation of an accurate gridded representation of the seafloor from the GeoSwath data (2004).

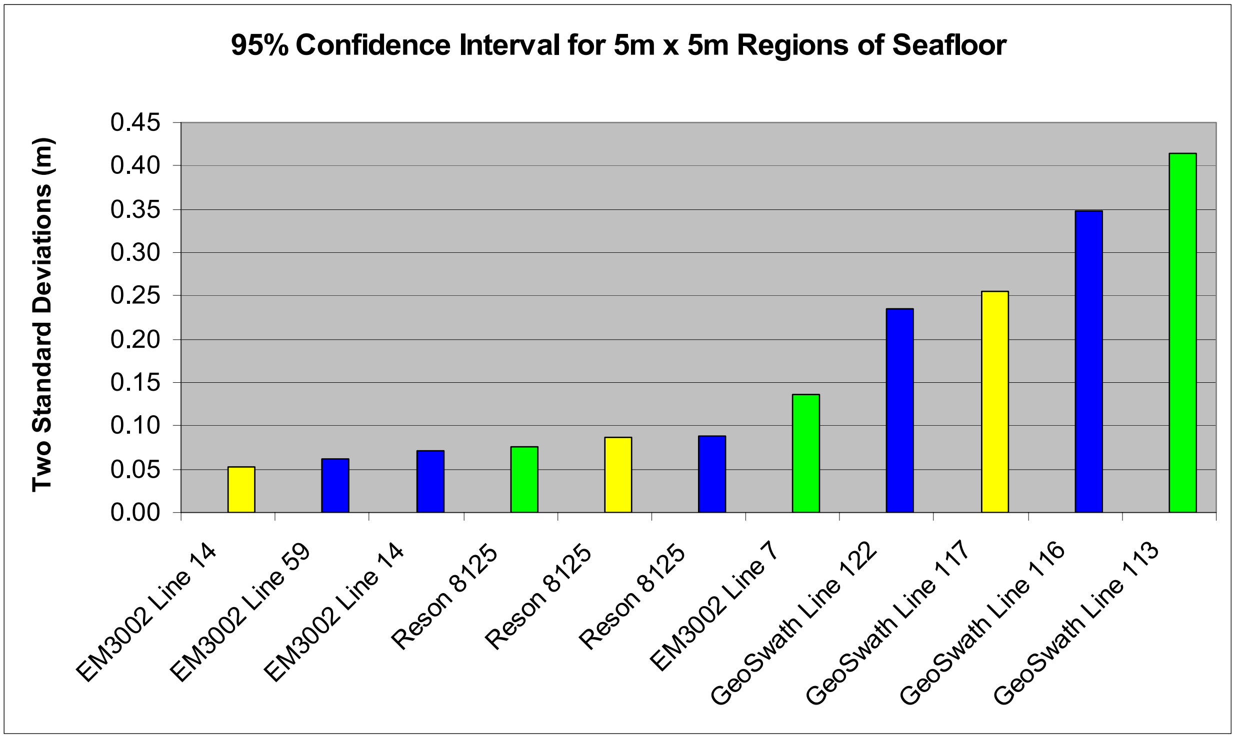


Figure 8 – The 95% confidence intervals for three 5m x 5m regions of seafloor. Different colors represent different test regions.

The second statistical test, which used Fledermaus CrossCheck to compare point data from one sonar system to a grid generated from the point data of another sonar system, produced much more encouraging results. The average 95% confidence interval was slightly higher for the GeoSwath point data than the Simrad point data in each case, but by a negligible amount; 1.1cm higher when compared to the GeoSwath grid, 8.7cm higher when compared to the Reson grid, and 4.2cm higher when compared to the Simrad grid. Additionally, the mean differences of the GeoSwath and Simrad point data differed by no more than 1.2cm for any surface and were as small as 0.2cm in relation to the Simrad surface (Table 1).

Grid Source	Point Source	95% Confidence Interval (m)	Mean Difference (m)
GeoSwath	GeoSwath	0.318	-0.009
	Simrad	0.307	0.005
Reson	GeoSwath	0.369	-0.031
	Simrad	0.282	0.019
Simrad	GeoSwath	0.207	0.009
	Simrad	0.165	0.011

Table 1 – Variance and average distance of point data for the GeoSwath and Simrad sonars relative to grids made from GeoSwath, Reson, and Simrad datasets. Values are averages of all comparisons made between the grid and point source in question.

– Surface Difference:

The surface difference comparison indicates that on average there is a less than 10cm variation between the surfaces generated by the GeoSwath, Simrad, and Reson datasets. The GeoSwath surface was on average 5cm shoaler than the Simrad surface and 9cm shoaler than the Reson surface. As follows, the Simrad surface was on average 4cm shoaler than the Reson surface (Figure 9).

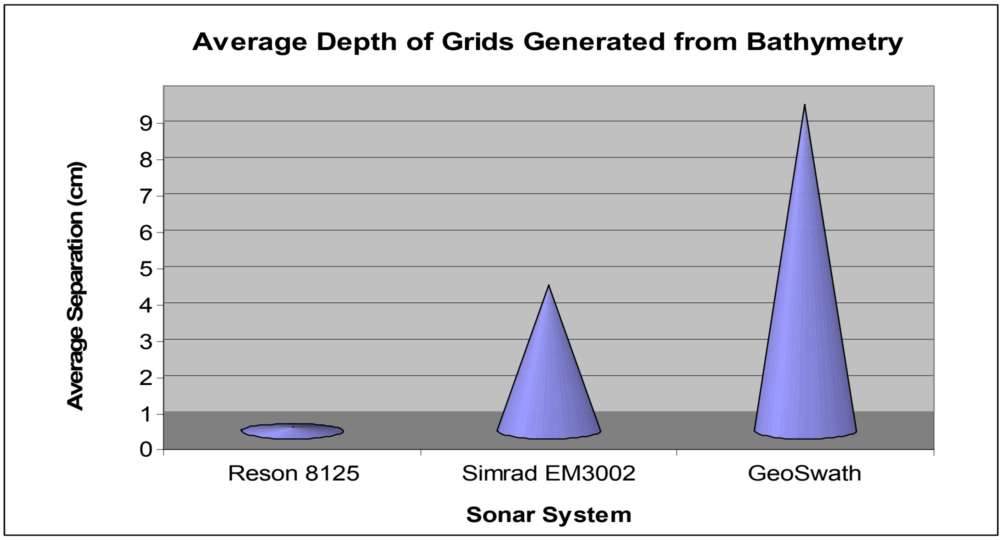


Figure 9 – Average separation of grids generated from bathymetry acquired with the three sonar systems listed. The depths are relative to the Reson 8125 grid, thus the Reson is depicted as 0cm. The Simrad grid was on average 4cm shoaler than the Reson grid and the GeoSwath grid was on average 5cm shoaler than the Simrad grid. As a visual reference the vertical scale is shown at approximately 1:2.

– Visual Comparison:

The visual comparison revealed that the GeoSwath was capable of resolving objects and accurately positioned them on the seafloor. Sandwaves as small as 0.1m in amplitude and discrete objects as small as 2m across and several decimeters high were resolved by all three sonars. The GeoSwath bathymetry is most visually similar to the Simrad likely due to the operating frequencies. Following is a brief series of comparison images and descriptions:

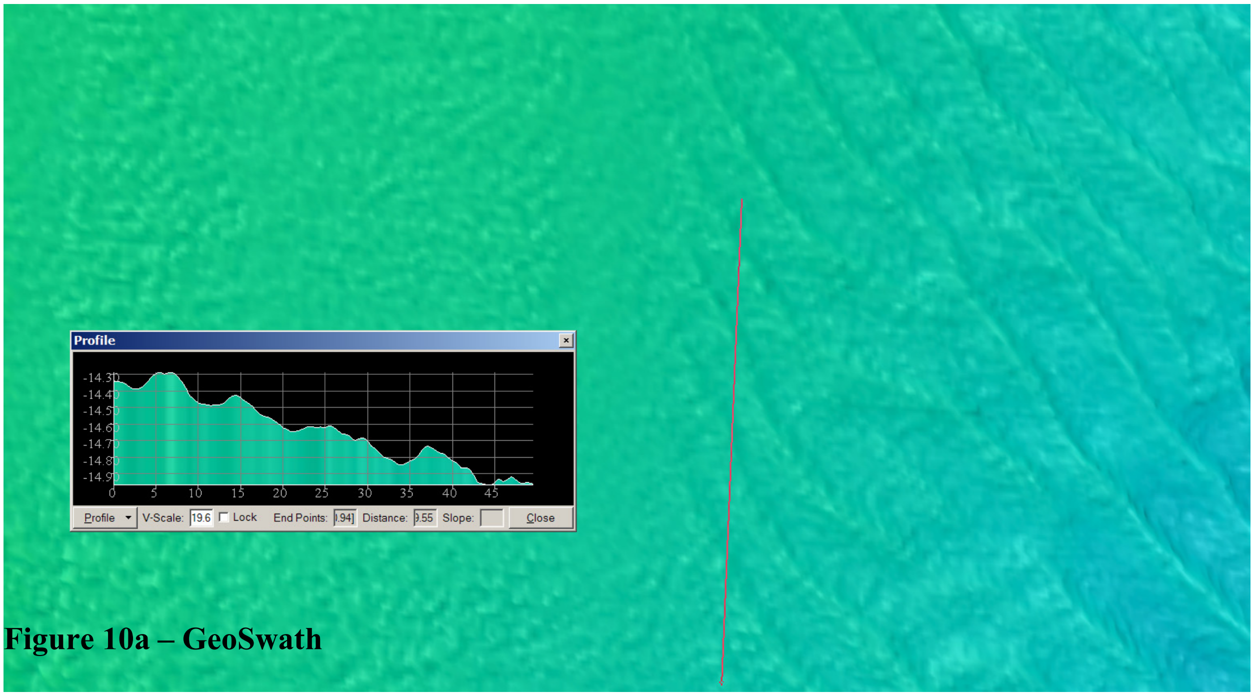


Figure 10a – GeoSwath

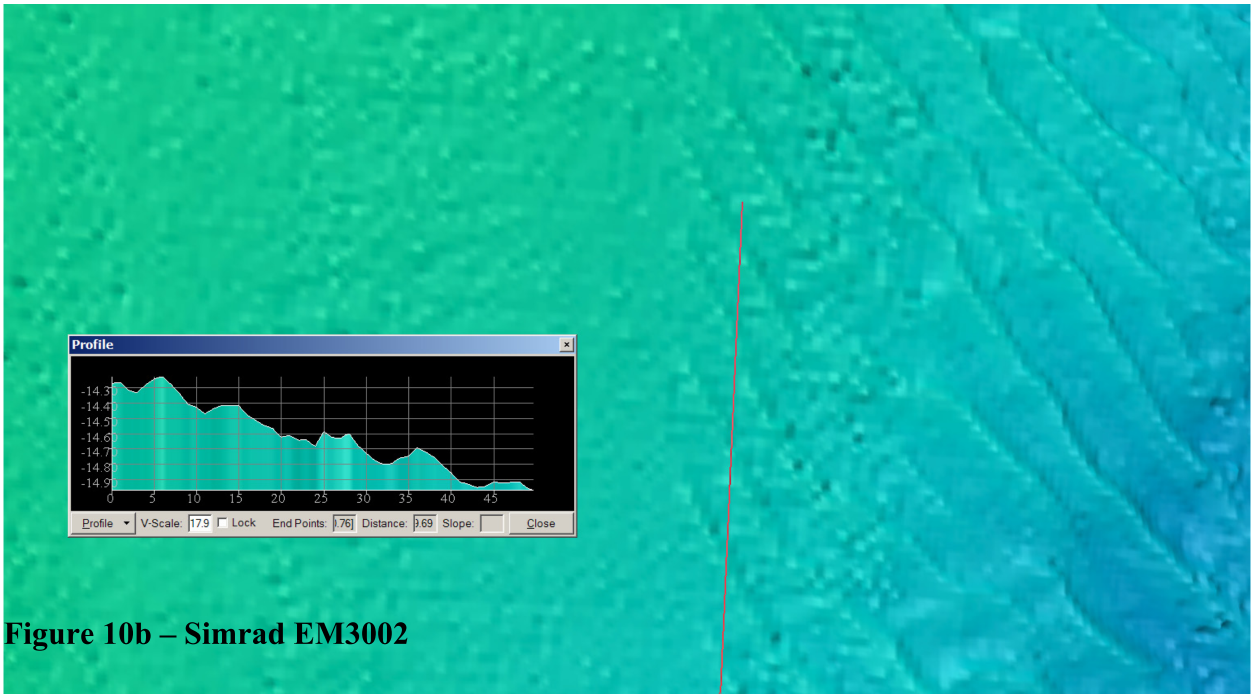
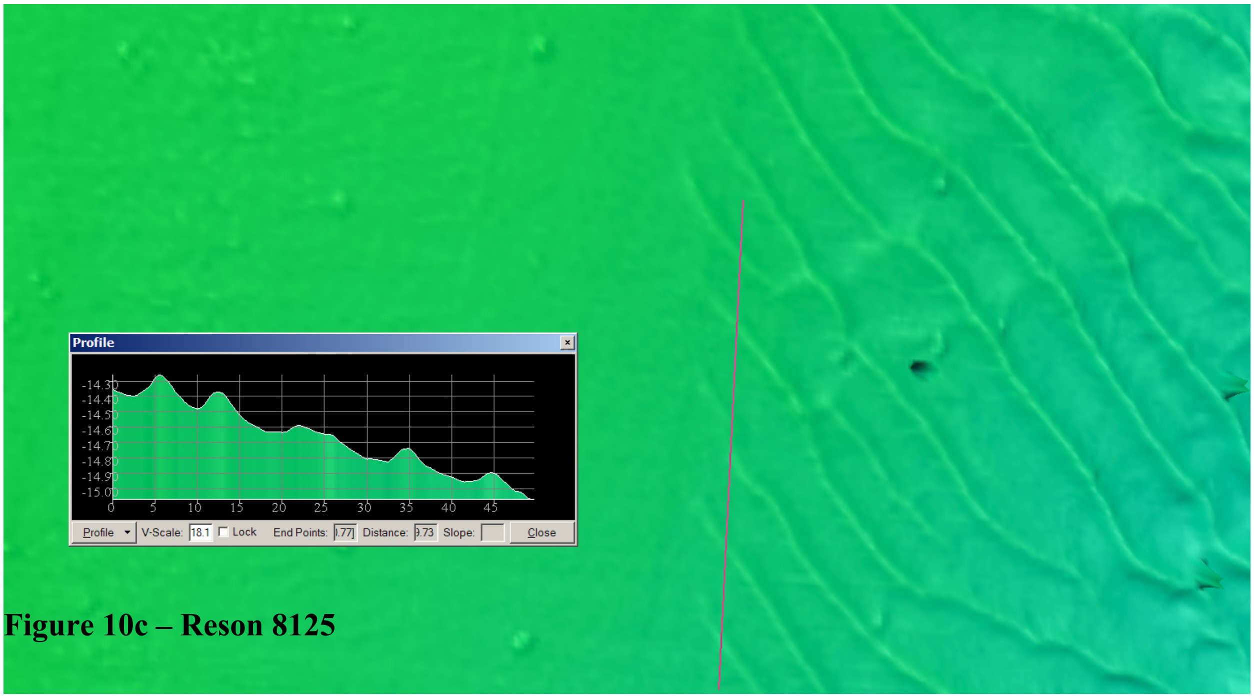


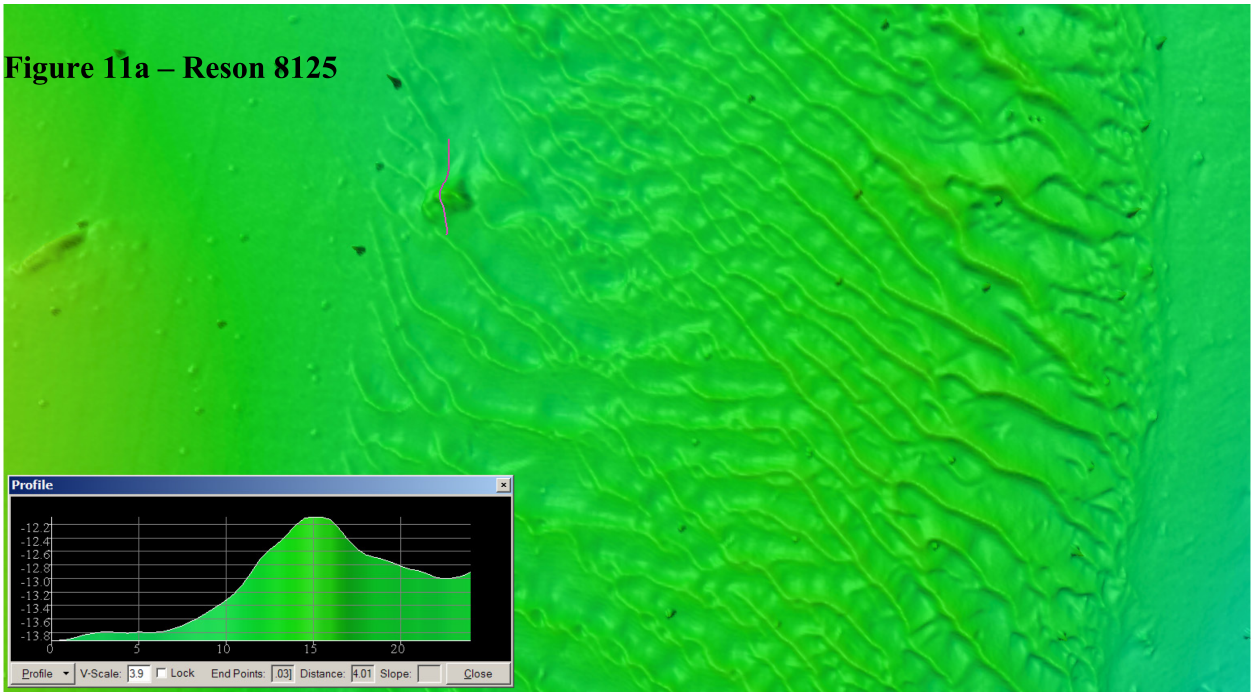
Figure 10b – Simrad EM3002



V-Scale: 18.1 ☐ Lock End Points: .77] Distance: .73 Slope:

Figure 10c – Reson 8125

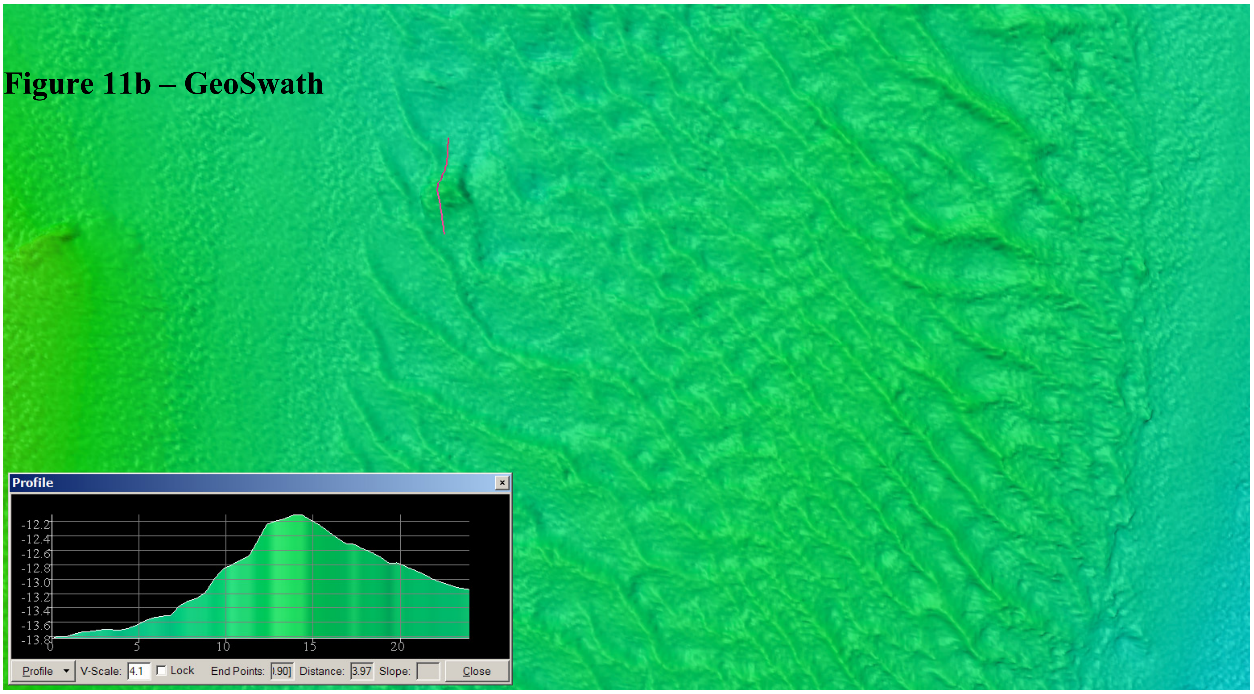
Figure 10 – GeoSwath (a), Simrad (b), and Reson (c) data at the southwestern edge of the sand wave field in Portsmouth Harbor. Note the similarity in sand wave geomorphology and amplitude between the three datasets. GeoSwath and Simrad datasets acquired within a few weeks of each other while the Reson data were acquired more than two-years previous. Profile lines were drawn with the same endpoints and scale lines on profile represent 0.1m increments.



V-Scale: 3.9 ☐ Lock End Points: .03] Distance: 4.01 Slope:

Figure 11a – Reson 8125

Figure 11b – GeoSwath

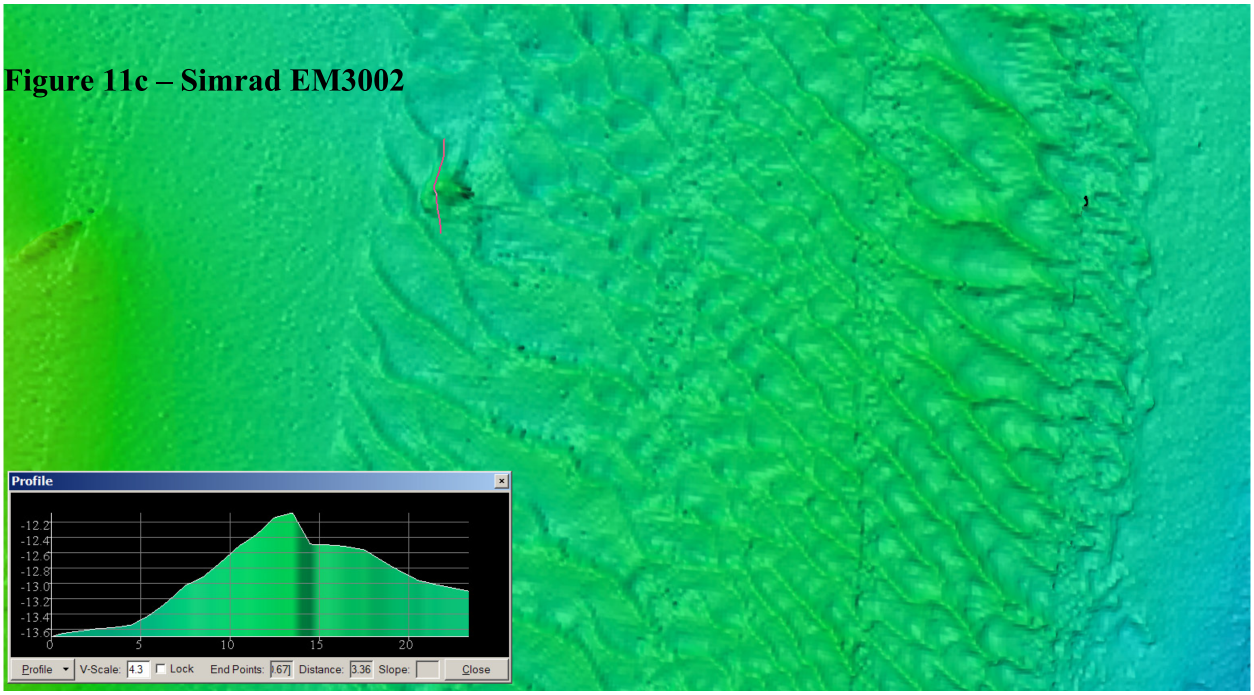


V-Scale: 4.1

End Points: .90]

Distance: 3.97

Figure 11c – Simrad EM3002



V-Scale: 4.3

End Points: .67]

Distance: 3.36

Figure 11 – Reson (a), GeoSwath (b), and Simrad (c) data over the central portion of the sand wave field in Portsmouth Harbor. Note the similarity in sand wave geomorphology and amplitude between the GeoSwath and Simrad datasets. The GeoSwath and Simrad datasets were acquired within a few weeks of each other while the Reson data were acquired more than two-years previous making differences in sandwave configuration between the Reson data and other data unsurprising. For this reason, the GeoSwath and Simrad images have been kept on the same page. Profile over 1.8m object to left of sandwave field. Profile lines were drawn with the same beginning point and length but endpoint was shifted to capture the shoalest point atop the feature. Scale lines on profile represent 0.2m increments.

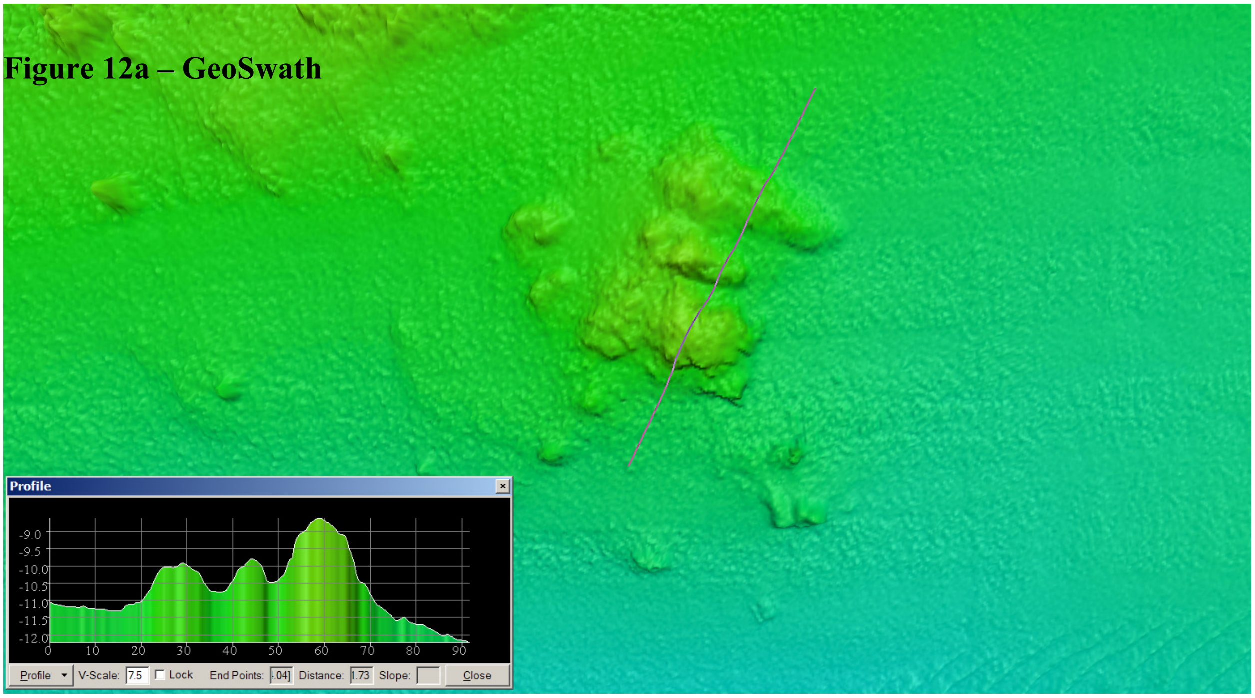


Figure 12a – GeoSwath

V-Scale: 7.5

End Points: .04]

Distance: 1.73

Slope:

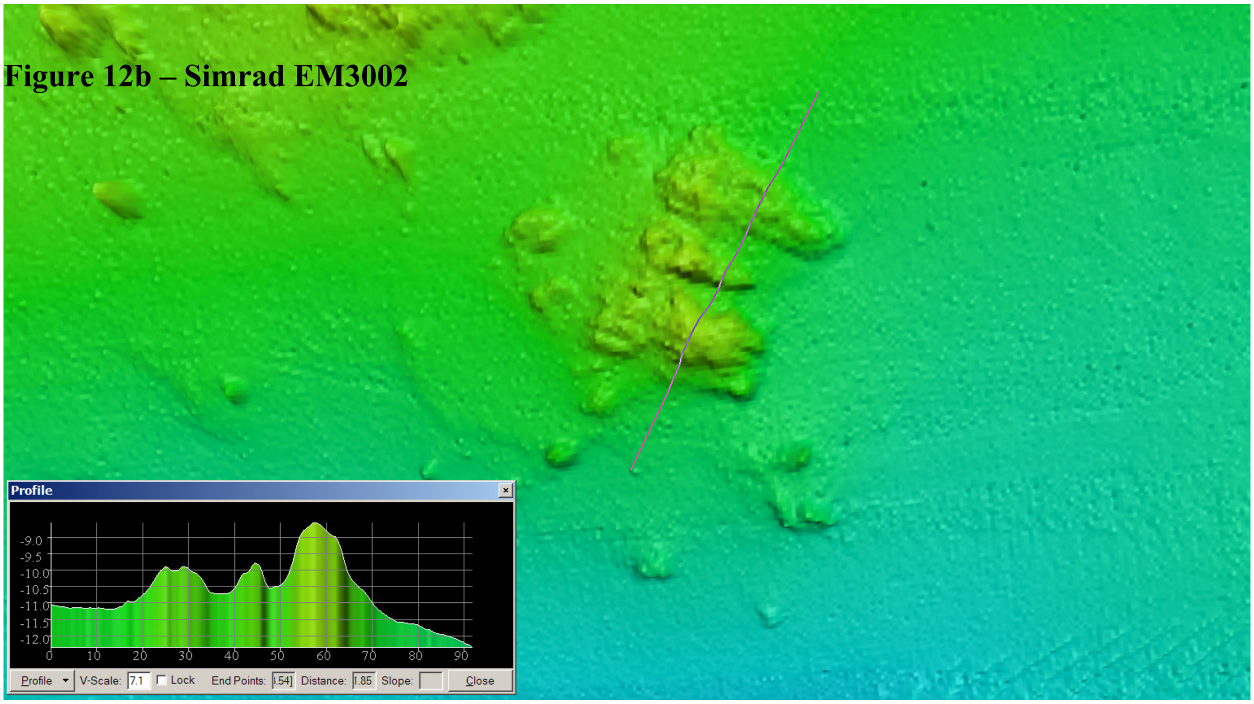


Figure 12b – Simrad EM3002

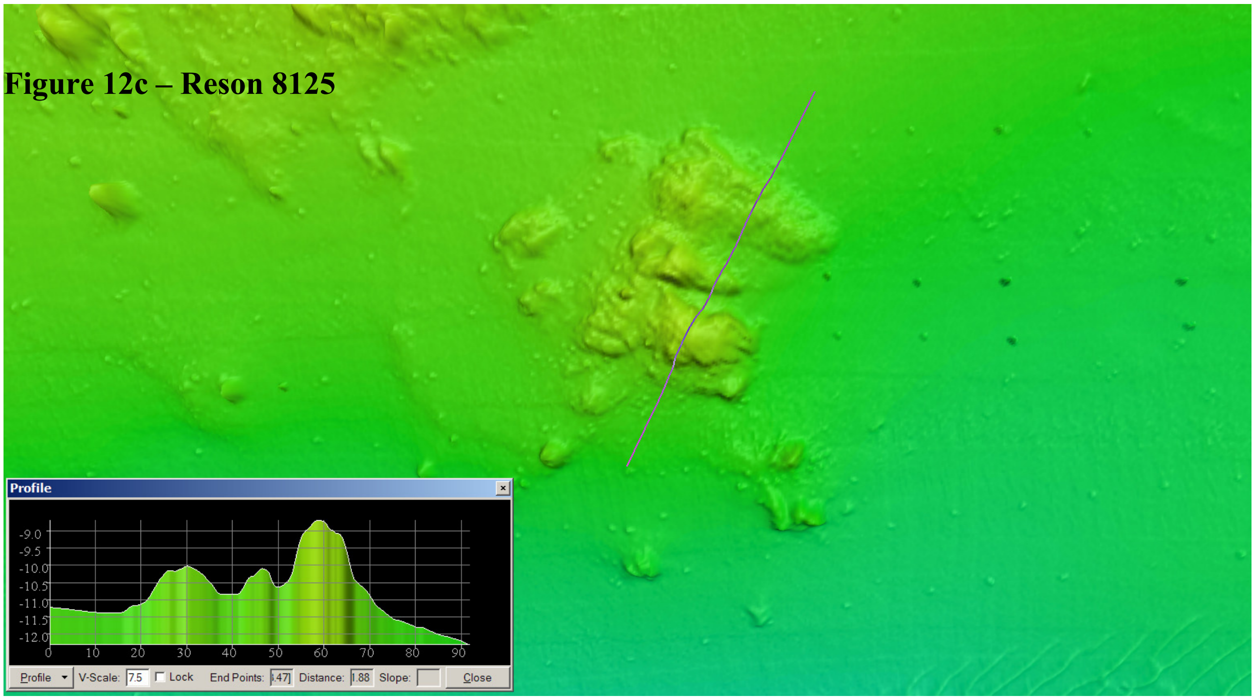
V-Scale: 7.1

End Points: .54]

Distance: 1.85

Slope:

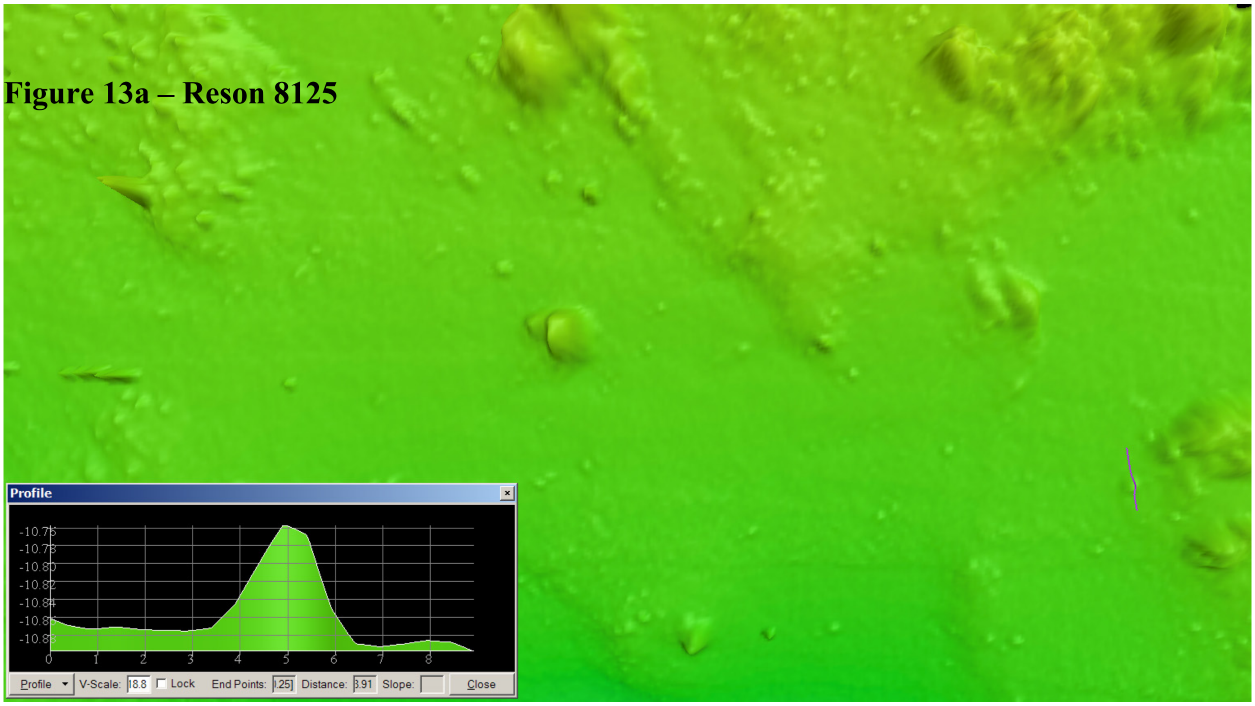
Figure 12c – Reson 8125



V-Scale: 7.5 ☐ Lock End Points: .47] Distance: 1.88 Slope:

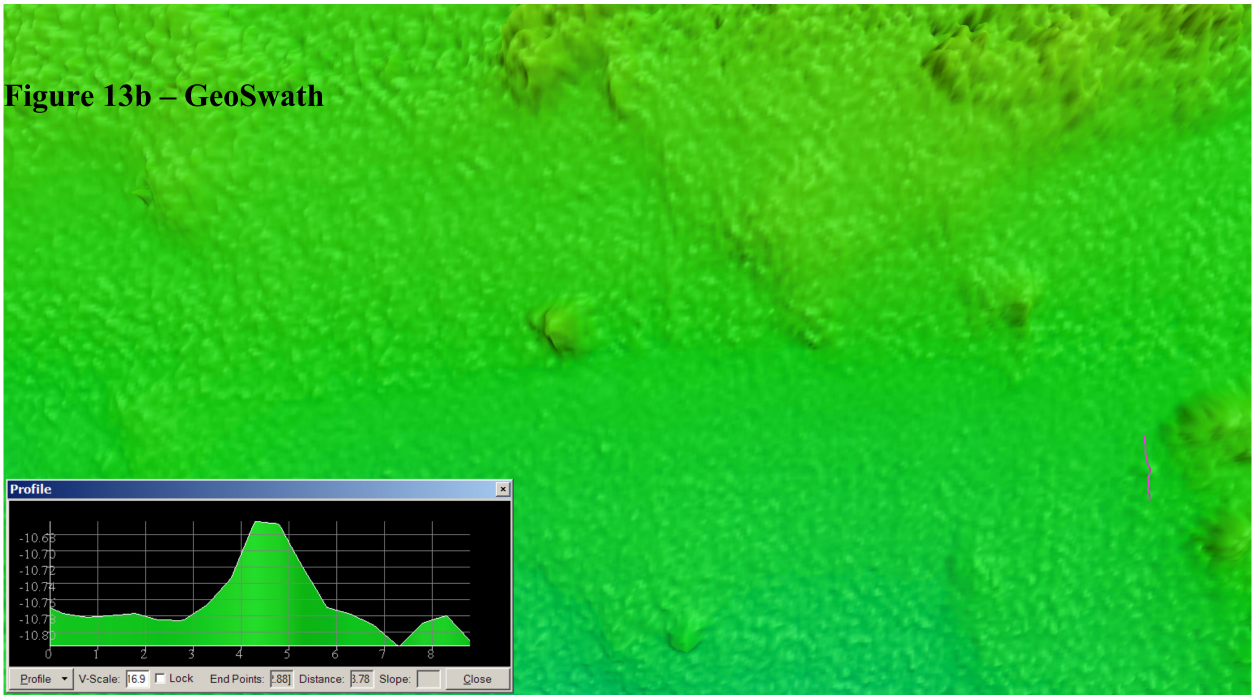
Figure 12 – GeoSwath (a), Simrad (b), and Reson (c) data over the outcropping at the southwest corner of the survey area in Portsmouth Harbor; data rotated 90° to the right to better fit the page. Note the similarity in geomorphology and depth profiles between all three datasets and edge of sandwave field in bottom right corner. Profile lines were drawn with the same endpoints. Scale lines on profile inset represent 0.5m increments.

Figure 13a – Reson 8125



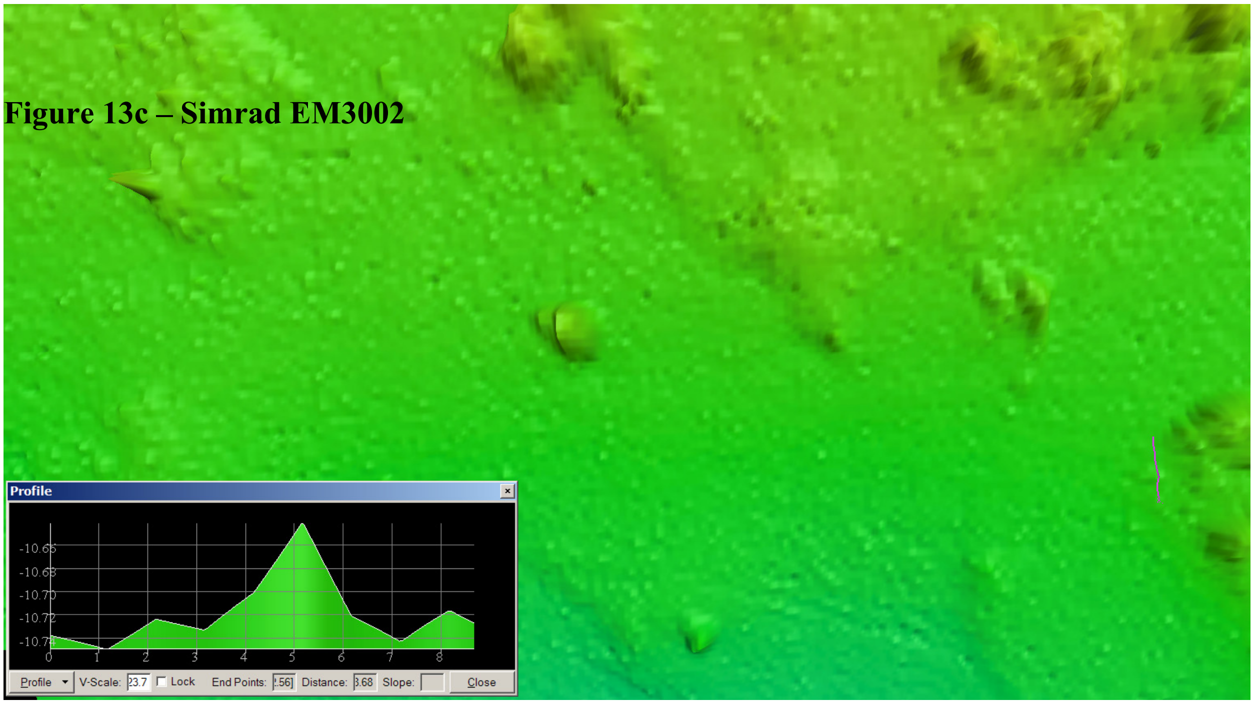
V-Scale: 18.8 ☐ Lock End Points: .25] Distance: 3.91 Slope:

Figure 13b – GeoSwath



V-Scale: 16.9
End Points: :.88]
Distance: 3.78

Figure 13c – Simrad EM3002



V-Scale: 23.7
End Points: :.56]
Distance: 3.68

Figure 13 – Reson (a), GeoSwath (b), and Simrad (c) data near the outcropping at the southwest corner of the survey area in Portsmouth Harbor; data rotated 90° to the right to better fit the page. Profile over a 2m wide 0.1m high object visible in all three datasets. GeoSwath and Simrad profile lines were drawn with the same endpoints while the Reson profile was slightly shifted to traverse the object. Scale lines on inset represent 2cm increments.

Discussion:

- **Standard Deviations –**

The standard deviations given by examining $5m^2$ regions of point data over relatively flat sections of seafloor tended to be 3 to 5 times higher for the GeoSwath than for the beamforming multibeam systems yet the GeoSwath and Simrad grids generated from the points were quite similar to each other. The reason for the high standard deviation of the interferometric data is attributed to the fact that it is a much denser dataset and there is no bottom detect algorithm applied during acquisition as there is with a multibeam system (Hiller and Lewis 2004). All data are retained, creating the possibility for later analysis by the user. Because the data tends to have a normal distribution about the true surface a grid generated from the data will be representative of the true surface.

This seems to hold true overall as the point to surface comparisons showed. Averaged over a variety of scales the GeoSwath point data was 3.1cm above the Reson surface and 0.9cm below the Simrad surface while the Simrad data was 1.9cm below the Reson surface and 0.5cm below the GeoSwath surface. It was unfortunate that the Reson point data were not available in smaller file sizes to enable their comparison to the other two surfaces. The Reson is recognized as a higher resolution system, however, the GeoSwath and Simrad data appear quite similar.

Because the datasets were independently collected different survey lines were run for each dataset. This meant that it was not possible to compare data points from a similar across-swath region covering the same small section of seafloor. As all the results were averaged this should have had a minimal effect but this is something that may need to be addressed in a future study.

- **Surface Difference –**

The surface differences, while broadly general, do give an idea as to how closely the different surfaces bathymetry match. The slight horizontal shifts of features due to positioning errors tend to create offsetting deviations from the surface which will cancel each other out. This makes the resulting average difference of the surfaces a measure of bathymetric depth difference as opposed to horizontal positioning error. That said, the difference between the GeoSwath and Simrad surfaces was small, with the GeoSwath surface being on average 5cm above the Simrad surface, which in turn was 4cm on average above the Reson surface.

This test may have been better conducted using many small regions for comparison as opposed to the entire survey area, however, that was not feasible with the time constraint involved. The results are seen to be a good indicator of similarity both because of the low average difference values and a visual inspection of the difference surfaces. In examining the GeoSwath-Simrad difference surface the majority of the variance occurred in the dynamic sandwave field. When looking at large features, like the rock outcrops pictured in Figure 12, the difference surfaces appear nearly flat with the majority of the variation occurring at the edges of the features, as would be expected from positioning errors. Maximum difference in that region was ≈ 0.5m and the average difference was less than a decimeter.

- **Visual Analysis –**

The visual analysis showed that the GeoSwath was capable of resolving sandwaves as small as 0.1m in amplitude. The comparisons between the GeoSwath and Simrad data over the sandwave field were remarkably similar; individual sandwaves can be concurrently traced in both datasets. There is no question that in this instance the Reson data is superior to both the GeoSwath and Simrad but for many applications the resolution achievable with the other systems would be acceptable. The difference may largely be due to the Reson's higher operating frequency of 455kHz, half again the Simrad's 300kHz, and nearly double the GeoSwath's 250kHz. The GeoSwath and Simrad data appear to be of similar resolutions probably because of their similar operating frequencies. The lower resolution in many cases is an acceptable tradeoff for the substantially lower cost of the system and the ease of installation and operation.

Unfortunately, there were no $1m^3$ features on the seafloor for comparison between the three datasets. Objects on the seafloor tended to be slumped and broader than they were tall meaning that most $1m^2$ features in the Reson data were only a few centimeters high. Because of the vertical noise present at the 0.5m grid resolution in both the GeoSwath and Simrad systems these types of features were difficult to identify. The 500kHz GeoSwath may be capable of resolving these types of features but that will have to be assessed at a later date. Because of the accurate detection of sandwaves ranging from 0.1m to 0.8m in amplitude with several meter wavelengths it seems a safe assumption that the GeoSwath would have been capable of detecting the ubiquitous one-meter-cube. Testing with sonar targets will need to be performed to fully assess the object detection threshold for the system.

- **Object Detection and Data Filtering –**

There has been some concern voiced related to the use of the proprietary automated cleaning techniques used with the Swath32 software package. Users, both experienced and inexperienced, have been known to manually delete navigationally significant objects from multibeam data so this is not a problem unique to interferometers. Interferometric sonars do provide the added benefit of co-located sidescan sonar imagery with their bathymetry making it feasible to easily perform quality control after cleaning a dataset. If working in an area where $1m^3$ objects are considered significant to the safety of navigation and there is reason to believe they may have been filtered out, the sidescan imagery can be reviewed while draped over the bathymetry to ensure all significant features are present (Figure 1).

Interferometric datasets are orders of magnitude larger than their multibeam counterparts due to increased data density. They are also inherently noisy making them difficult to manually clean, however, the sophisticated moving average box filtering algorithms seem to work well when applied correctly. Generally, an entire day’s interferometric data can be automatically cleaned with only a few minutes of user interaction. It has traditionally taken one to two times as long to clean multibeam data as to collect it, meaning that it has required approximately 12-hours of user interface to clean 8-hours worth of survey data. With the advent of the Combined Uncertainty Bathymetric Estimation (CUBE) and Bathymetry Associated with Statistical Error (BASE)-Surface this has become less of an issue but it should be noted that automated data cleaning is a benefit also available with interferometric systems.

- **Recommendations for future studies –**

Many aspects of this study were successful, however, several changes should be made in future examinations to make the results more robust. The use of the same survey vessel and ancillary equipment removed many variables from the equation. In future research it may be better to retain the same positioning system for acquisition with all sonar systems to reduce slight horizontal positioning shifts between datasets. The survey area selected for this study was optimal, containing myriad features for comparison, as well as a sand wave field, flat regions, and slopes ending at shoreline. A similar site is recommended for additional studies. The closer in time the datasets can be collected the better; optimal would be concurrent acquisition to remove any possible changes in geomorphology that may occur over time. While it appears that some regions of the survey area were quite static even over a period of two-years, other areas and features were more dynamic and appeared to change over a matter of weeks.

Without ground truth data it is difficult to definitively state what size objects are detectable. While the Reson and Simrad were treated as true representations of the seafloor in this study, the use of sonar targets of varying size and shape would be advisable for use in future studies. Additionally, running the same lines with all involved sonar systems to compare achievable swath width and analyze vertical sounding variance on the same region of seafloor with the same across track distance would be beneficial. The inclusion of bridge abutments or piers in the survey area would allow the testing of the ability of the sonar to survey vertical features. All survey lines run with the GeoSwath in this survey were conducted at 40m range scale. It would be interesting to increase the swath width to maximum when running near shore to ascertain the true capability of the system to obtain bathymetry up to the shoreline.

If interferometers are shown to provide data of adequate quality for near shore nautical charting work, an efficiency test should be conducted to determine the actual time and cost savings as well as coverage advantages that may be attained through their use. It is estimated that working in very shallow water (i.e., less than 8m) survey time could be cut by a factor of four with better near shore coverage. This would result in larger area coverage in less time for less money freeing up personnel and resources to survey additional critical areas.

Conclusion:

Interferometric sonar systems are capable of providing improved efficiency over shallow water multibeam sonar systems in shoal areas. The technology has not been formally evaluated by NOAA following significant improvements in electronics, phase differencing techniques, and filtering algorithms. This was a preliminary evaluation aimed at determining whether an official study should be undertaken. A 250kHz GeoSwath interferometric sonar was used to acquire data in Portsmouth Harbor, New Hampshire for analysis. The GeoSwath data was compared to Reson 8125 and Simrad EM3002 data which were used as virtual ground truth surfaces. Statistical analysis showed that the GeoSwath data tended to have a higher standard deviation but that grids created from that data were similar to the surfaces generated from multibeam data. Visual evaluation showed that the system was able to reproduce fine scale and discrete features with fidelity. Sandwaves as small as 0.1m in amplitude were visible as were solitary objects ≈

2m across. The GeoSwath is seen as one of several viable candidate systems for use in a formal follow-up evaluation. While a significant amount of work remains to be done to determine whether interferometric technology is ready for use in the nautical charting hydrographic survey industry, that work will be worthwhile. A formal re-examination is recommended.

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Appendix A: Equipment and Software Information

Equipment Used*

Applanix POS/MV 320, Model# PCS08 (Jan 2002), Ser# 548
C&C Technologies C-Nav 2000RM GPS Receiver Unit, Ser# Unknown
C&C Technologies C-Nav CnC DU Interface Unit, Ser# Unknown
GeoSwath PC, Stock# 5342, Ser# 221
GeoSwath Transducers Ser# 12248 and 12255
Odom Hydrographic Systems, Inc. Digibar Pro, Model# DB1200, Ser# 98139
Tritech PA500 Precision Altimeter, Ser# 2125-80597
Valeport Mini Sound Velocity Sensor, Ser# 19944(6430)

Tide Station Level Accomplished Using the Following Survey Equipment –
  Carl Zeiss Ni2 T-100548 Level Ser# 362311
  Wild GST 20 Tripod Ser# JHC00045
  Maine Technical Source SVR 5.0m Philly Rods

*See page A3 for manufacturers specs on GeoSwath system

Software Used

Applanix POS/MV Controller Version 1.3
CARIS HIPS/SIPS data processing software Version 5.4 Service Pack 1
IVS Fledermaus visualization software suite Version 6.1.0 Professional
GeoSwath32 Version 2.07BE
MapInfo Professional Version 7.5 Build 21
Mathworks MATLAB Version 6.5.0.180913a Release 13
Microsoft Excel 2002 Version 10.6501.6714 Service Pack 3
Nobeltec Visual Navigation Software Suite
Odom Hydrographic Systems, Inc. Digibar Pro Log Version 2.3
Simrad Seafloor Information System Version 1.0.0 Build 88

Number of Data Points	Number of points tested for which a reference height was found.
Data Mean	Average height of the source data files.
Reference Mean	Average height of the matching sample reference points.
Difference Mean	Average value of the (ref-source) difference.
Difference Median	The median difference height (50% above, 50% below).
Difference Std. Deviation	The standard deviation calculation of the height differences.
Data Z–Range	The overall Z(height) range of the source data.
Reference Z-Range	The overall Z(height) range of the matching reference data.
Difference Z-Range	The overall range of the difference data.
Order 1 Error Limit	The IHO Order 1 error limit for the average data depth.
Order 2 Error Limit	The IHO Order 2 error limit for the average data depth.
Order 1 P-Statistic	The Order 1 P-Statistic (percentage confidence)
Order 2 P-Statistic	The Order 2 P-Statistic (percentage confidence)
Order 1 - # Rejected	Number of soundings rejected in the target population.
Order 2 - # Rejected	Number of soundings rejected in the target population.
IHO Order 1 Test Status	Pass/Fail for an IHO Order 1 Survey Quality
IHO Order 2 Test Status	Pass/Fail for an IHO Order 2 Survey Quality

Table A1 – Description of statistics calculated using Crosscheck software package (Fledermaus 2004).

GeoSwath Plus Specifications

GeoSwath is available in three frequency versions, 125 kHz, 250 kHz and 500kHz. The system accuracy of all versions exceed the Special Order specifications, as set out in *IHO Standards for Hydrographic Surveys, Special Publication 44, 4th Edition, April 1998.*

Sonar Frequency	125 kHz	250 kHz	500 kHz
Maximum Operating Depth Below Transducers	200 metres	100 metres	50 metres
Maximum Swath Width	600 metres	300 metres	150 metres
Range	Up to 12 x depth	Up to 12 x depth	Up to 12 x depth
Resolution (pulse width and bandwidth limited)	24mm	12mm	6mm
Slant range resolution	6mm	3mm	1.5mm
Spacing between across track data samples	12mm	12mm	12mm
Two Way Beam Width	0.9° Azimuth	0.5° Azimuth	0.3° Azimuth
Transmit Pulse Length	16 µS to 1mS	8 µS to 1mS	4 µS to 500uS
Swath Update Rate			
50m Swath Width	30 swaths per second	30 swaths per second	30 swaths per second
150m Swath Width	10 swaths per second	10 swaths per second	10 swaths per second
300m Swath Width	5 swaths per second	5 swaths per second	
600m Swath Width	2.5 swaths per second		

Table A2 – GeoSwath technical specifications as provided by GeoAcoustics in March 2004 (current version viewable at http://www.geoacoustics.com).