11-2001

Field Evaluation of Sounding Accuracy in Deep Water Multibeam Swath Bathymetry

Christian de Moustier
University of California - San Diego

Recommended Citation

C. de Moustier, "Field evaluation of sounding accuracy in deep water multibeam swath bathymetry," MTS/IEEE Oceans 2001. An Ocean Odyssey. Conference Proceedings (IEEE Cat. No.01CH37295).

Field Evaluation of Sounding Accuracy in Deep Water Multibeam Swath Bathymetry

Christian de Moustier
Scripps Institution of Oceanography
9500 Gilman Drive, La Jolla, CA 92093-0205, USA

***Abstract*- A new Kongsberg-Simrad EM120 multibeam echo-sounder has been installed aboard Scripps Institution of Oceanography's Research Vessel Roger Revelle in January 2001. This system can map reliably a 20 km swath of seafloor in 4000 m water depth with 191 soundings per ping. Such a wide swath width demands highly accurate (<0.05° RMS) roll information from a motion sensor, and makes estimating sounding accuracy across the swath an interesting challenge. It is shown that good accuracy estimates can be obtained by collecting data on station under control of the GPS-aided dynamic positioning system usually available on most modern long-range oceanographic vessels. A number of motion sensors, with RMS roll accuracy specifications ranging from 0.05° to 0.01°, were tested with the EM120 sonar on station in 3800 m to 4000 m water depths. Unexpectedly, they yielded roughly the same depth uncertainty as a function of receive beam angle. This result might be explained by synchronization errors between the attitude data and the sonar data leading to beam pointing errors, other types of beam pointing errors, a range of roll accuracy narrower than specified for the motion sensors, or a combination of these factors.**

I. INTRODUCTION

In January 2001, the Scripps Institution of Oceanography installed a Kongsberg-Simrad Inc (KSI) EM120 multibeam echo-sounder aboard the newest ship in its fleet, the Research Vessel (R/V) Roger Revelle owned by the US Navy and commissioned in 1996 (AGOR 24).

This sonar system operates at a nominal frequency of 12 kHz, with a 1°x150° overall transmit sector (fore-aft x athwartships) and up to 191 receive beams steered athwartships at regular angular steps across the swath, or at gradually narrower angular steps to achieve uniform horizontal offset between soundings athwartships, or a combination of both. Its flat hydrophone array configuration yields nominal receive beam widths of $2°/\cos(\theta)$ from broadside ($\theta=0°$) to the outer steering angles ($\theta=\pm75°$). Most importantly, the sonar achieves broad swath widths in deep water (e.g. 20 km at 4km depth) by steering the transmit beam in 9 discrete sectors athwartships, while compensating for the ship's yaw, pitch, and roll. However, it is necessary to know the ship's roll and pitch to better than 0.05° RMS to achieve KSI's specification for sounding accuracy of 0.2% of water depth across the swath. In fact, since the sea trials at the end of January 2001, an apparent roll artifact has ruffled along-track the outer edges of the bathymetric swath collected aboard R/V R. Revelle. Several tests have been conducted with various motion sensors to try and identify its cause.

With swath widths in excess of 20 km it is difficult to find a seafloor area, with suitably little relief along and across track, on which to conduct sounding accuracy tests. Options include survey techniques developed to resolve biases in swath bathymetry data, such as running a patch test over a known seafloor area [1], or creating a reference surface from a highly redundant set of soundings obtained by running tightly spaced parallel tracks with up to 90% swath overlap between adjacent tracks. Sounding accuracy is then estimated by comparing individual soundings to the reference surface [3]. In all cases, a deep water reference surface is very costly in data acquisition and processing time.

Provided the ship has good dynamic positioning capabilities, a simpler and much cheaper alternative consists in maintaining the ship on station at a constant heading over a relatively flat seafloor area. Ping after ping, the same patch of seafloor is sampled in a given beam direction and changes in bottom relief along and across track become nearly negligible.

The purpose of this paper is to highlight the effectiveness and potential pitfalls of estimating sounding accuracy from multibeam swath bathymetry data gathered while the ship holds station. EM120 swath bathymetry and associated navigation data collected aboard R/V Roger Revelle are used to illustrate the ship's station keeping requirements in Section II, and the sounding statistics in Section III. In Section IV, a comparison is made between results obtained on station, in 3800m to 4000 m of water depth, with four different motion sensors providing attitude data to the EM120 sonar. Their unexpected similarity is discussed and potential causes are analyzed.

II. SHIP STATION KEEPING REQUIREMENTS

A. Position

At average oceanic depths (4 km), the along and across track extents of the footprint of a 1°x2° specular beam are roughly 70m and 140m, respectively. Adjacent beams on either side athwartships are within 1°, but the angular beam spacing becomes progressively narrower from nadir out when using the sonar's mode that provides equidistant soundings across-track, which is true for all the data presented here. Therefore one needs to maintain the ship's position within a watch circle 10 m in diameter for a given beam direction to sound the same patch of seafloor repeatedly.

Aboard R/V Roger Revelle, the dynamic positioning system controls two stern Z-drive azimuthal thrusters and a bow thruster. It can maintain the ship's position in a P-Code GPS reference frame in a circle less than 10 m in diameter for the 40 min required to collect 100 pings in 3800 m of water depth, as shown in Fig. 1.

B. Heading

The 1° fore-aft beamwidth of the transmit beams imposes restrictions on the ship's heading variability during a test, before relief variations along and across track can no longer be neglected. As illustrated in Figs. 1-2, experience with R/V R.Revelle shows that the ship can hold station and heading to 0.6° RMS (Fig. 3) in sea states 4 or below. In the foregoing analysis, data with heading variations up to 0.75° RMS have been used, but they start showing the limitations of the negligible relief assumptions.

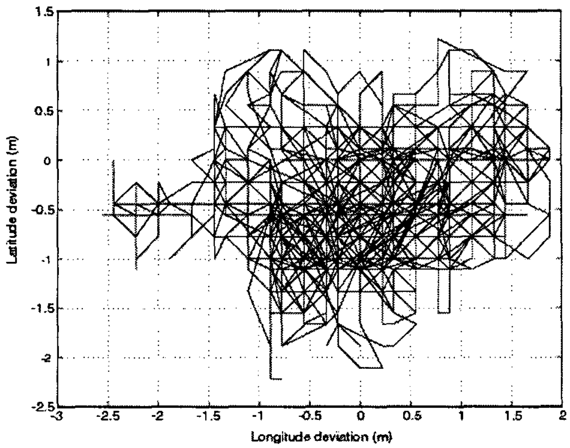

Fig. 1. Variations in the ship's position while on station.

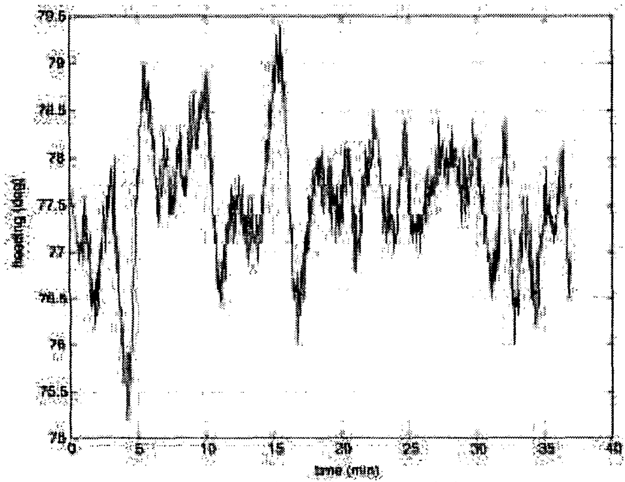

Fig.2 Variation in the ship's heading while on station.

Likewise, the noise in the heading data supplied to the EM120 sonar should remain a small fraction of the fore-aft beam width. As a first order verification, Fig. 3 shows a noise histogram drawn from the residuals of detrending and low-pass filtering performed on the heading data of Fig. 2. Although not strictly speaking a noise sequence, the residuals have a mean of zero and a standard deviation of 0.12°, which is within 20% of the 0.1° specified RMS accuracy of the Meridian Gyro used in these tests, and of the accuracy required by the EM120 sonar.

Control of heading variations during a test is achieved by setting a maximum heading deviation in the dynamic positioning system. However, local weather conditions might make such settings moot and it becomes necessary to collect enough pings to be able to select a subset of pings that fall within the desired heading bounds.

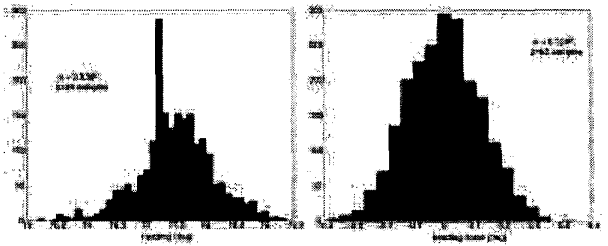

Fig. 3. Histograms of variation in the ship's heading (left) and heading noise (right) while on station.

III. SOUNDING STATISTICS

A. Depth Profiles

Given proper control of the ship's heading and position during data collection on station, it is straightforward to compile statistics of the soundings as a function of receive beam angles referenced to nadir, hence corrected for the ship's roll and for refraction effects at the face of the array. Here, beam angles are considered in 0.1° increments, but only beam directions reporting data for more than half the total number of pings in the set are used in the statistics.

Stacked profiles of depth vs. received beam angle are shown in Fig. 4, with details in Fig. 5 showing the mean depth (solid line) and the scatter of soundings about the mean. The scatter increases with steering angle, and tighter angular spacing of beams at increasing athwartships angles to achieve equidistant soundings can be seen also in these plots.

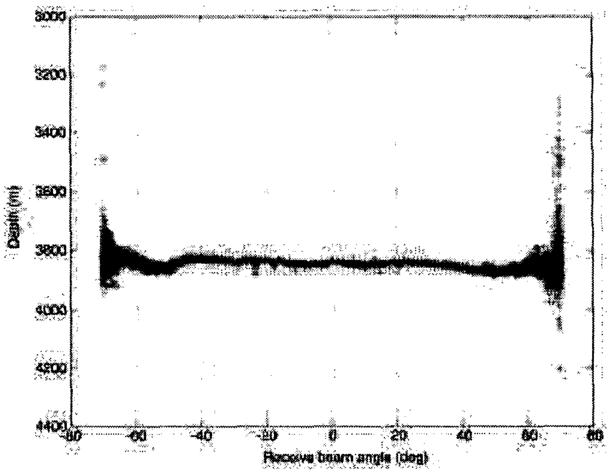

Fig. 4. Stacked instantaneous bottom profiles of depth vs. receive beam angles (port <0, starboard >0) for about 100 pings recorded with the ship on station.

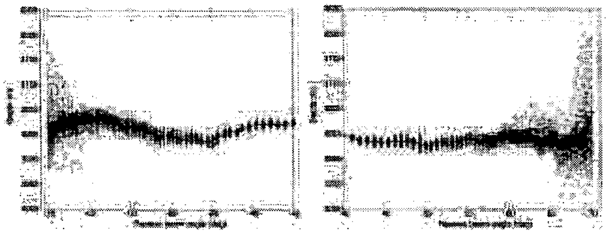

Fig. 5. Details of the port and starboard beam soundings (+) from Fig. 4 with the mean profile drawn as a solid line.

Closer inspection of the outer beams from Figs. 4-5 reveals two interesting clues illustrated in Fig. 6, where soundings at ±65° from nadir are plotted as sequences of depth vs. consecutive ping numbers (equivalent to time at ~20 s/ ping). These two sequences contain frequent spikes that are for the most part "180° out of phase" between port and starboard, indicating that the athwartships profile rolls with the ship. Second, there is a long term oscillation with a period of about 60 pings (~20 min) that does not seem to be correlated with anything obvious at this point.

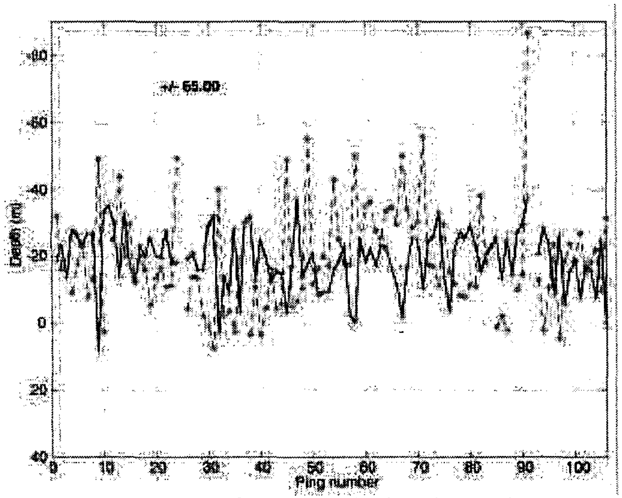

Fig. 6. Evolution of soundings in time for two beams at ±65° from vertical for the data shown in Figs. 4-5. Solid line port, dashed line starboard.

B. Depth Uncertainty

The depth accuracy for each sounding is estimated from the data in Figs 4-5, by forming the ratio of the standard deviation of the soundings in each angular bin to their mean. This yields a depth uncertainty in percent of mean water depth.

As shown in Fig. 7-8, uncertainties remain below 0.2% from nadir to about ±60° and climb rapidly thereafter to values in excess of 2% at ±70°.

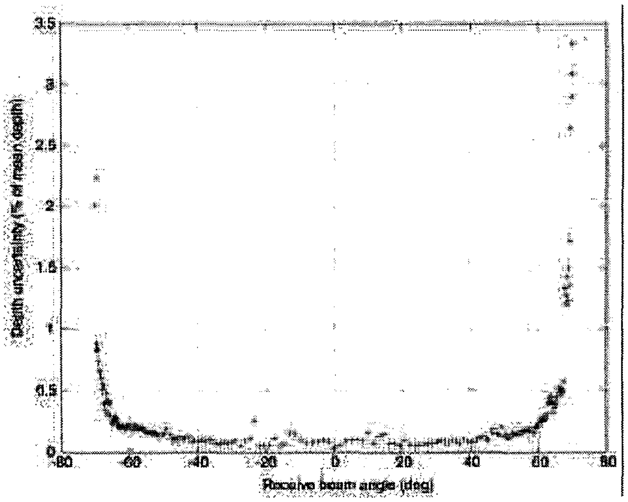

Fig. 7 Depth uncertainty (standard deviation/mean) of soundings in Figs 4-5 for each beam direction referenced to vertical.

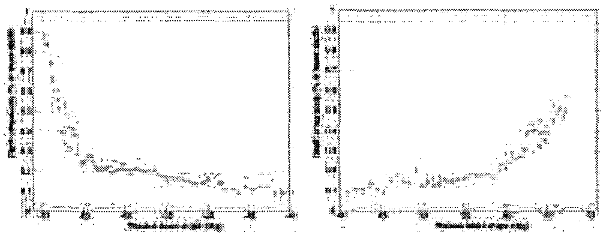

Fig. 8. Details of the depth uncertainty (Fig. 7) measured on the outer beams for soundings in Figs. 4-5.

C. Angular Variations

To first order, the depth uncertainties ΔD vs. receive beam angles θ can be converted to an apparent angular error in beam pointing $\Delta\theta$. This is done by differentiating the conversion of straight path slant-range R to depth D ($D=R\cos\theta$), yielding:

$$\Delta D / D = \Delta R / R - \Delta\theta \tan\theta . \qquad (1)$$

The range uncertainty ΔR of the EM120 is on the order of 37 cm in the deep water mode, hence the ratio of ranges on the right side of (1) is of order 10^{-4} and is negligible relative to the angular term. The apparent angular error is then:

$$\Delta\theta = -\Delta D / (D \tan\theta) . \qquad (2)$$

The apparent angular error associated with the data in Figs. 5-8 is plotted in Fig. 9, along with its mean (zero) and standard deviation (solid line). The standard deviation line remains roughly constant and below 0.08° until ±60° and increases to over 0.2° at ±70°. All else being equal, one would expect the apparent angular error to remain essentially constant across the swath, and the fact that it increases beyond ±60° indicates that beams in the outermost sectors of the 9 sector transmit pattern behave differently than the rest. Their higher sensitivity to roll error could be one factor, so could beam pointing errors due to insufficiently accurate sound speed information at the face of the array to correct for refraction effects. The latter is less likely because the ship was on station and sound speed continuously measured at the depth of the array agreed to within 1m/s with the corresponding sound speed in the measured sound speed vs. depth profile entered in the EM120.

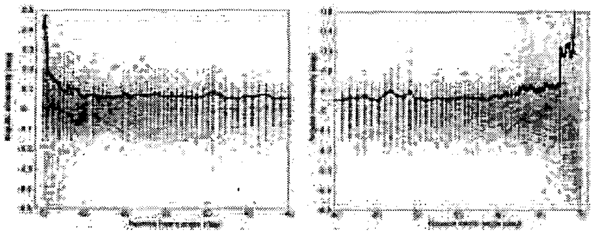

Fig. 9. Apparent angular error (2) associated with the depth uncertainties in Fig. 7-8, showing the scatter of individual points, their standard deviation (solid line), and their mean (zero center line).

IV. COMPARISON OF MOTION SENSORS

The data collection technique described in previous sections was used to test 4 different motion sensors with the EM120 sonar, in an effort to verify whether inaccuracies in roll were mainly responsible for the apparent roll artifact mentioned earlier. The four sensors are a TSS DMS05[4], a Seatex MRU5, a Seatex Seapath200[5], and an Applanix POS-MV320[6], whose relevant characteristics are listed in Table 1.

TABLE 1. MOTION SENSORS ACCURACY SPECIFICATIONS

SENSORS	RMS Roll/Pitch Accuracy (deg)	Heave accuracy (cm)
DMS05	0.05	5
MRU5	0.03	5
Seapath200	0.03	5
POS-MV320	0.01	5

All the tests reported here were conducted in sea state 3. Tests with the DMS05 and the MRU5 were conducted at the same location in 3800 m of water depth within one hour of each other, hence conditions can be deemed identical. Tests with the Seapath200 were conducted in 4000 m of water depth, and tests with the POS-MV320 were conducted on a gentle slope (3750 m to 3900 m over 21 km) with the swath parallel to the slope. A summary of the test conditions is given in Table 2.

Results of the four tests are compared by plotting the respective depth uncertainties on the same graph (Figs. 10-11). Fig. 10 provides the comparison results, and Fig 11 illustrates the limitation of the method as will be explained shortly. In spite of a factor of 5 in specified RMS roll accuracy between the POS-MV320 and the DMS05, there are surprisingly small differences in Fig. 10 between the depth uncertainties obtained with the four motion sensors from nadir to ±60°. As expected, data gathered with the POS-MV320 has a somewhat lower depth uncertainty overall, but the improvement is not commensurate with the specified RMS roll accuracy.

Results with the Seapath200 were obtained after the ship's roll compensation tank had been emptied to provide a nearly sinusoidal roll motion. With the roll tank in operation, the ship's roll departs noticeably from a simple harmonic modulation, and results with the Seapath200 were noisier than those shown here.

The smaller than expected differences in depth uncertainties between motion sensors could be explained by a narrower range of RMS roll accuracy than specified in Table 1. Nonetheless, the apparent roll artifact is present at the edges of the swath with all four sensors, indicating that factors other than inaccuracies in roll are involved as well.

TABLE 2. TEST CONDITIONS

	Heading Standard Deviation (deg)	Position Variations (m x m)	Bottom Slope (deg)
DMS05	0.64	3x4.5	0.11
MRU5	0.57	5x5	0.11
SEAPATH200	0.750	8x6	0.13
POS-MV320	0.71	9x4	0.4

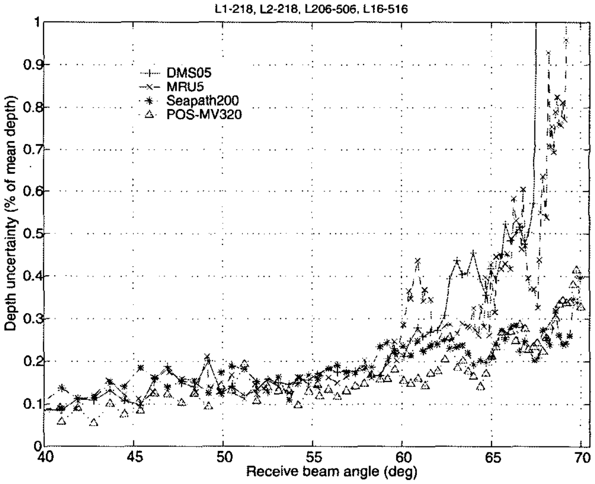

Fig. 10. Depth uncertainties vs. starboard beam angles referenced to vertical for 4 different motion sensors.

Except for data obtained with the POS-MV320, depth uncertainties exceed 0.2% of water depth beyond 60°, and climb above 1% by 70° for the MRU5 and the DMS05. These much larger uncertainties are most likely due to bottom detection errors on the outerbeams causing a few outliers to skew the results. Ping by ping outlier removal will probably be necessary to obtain a picture of depth uncertainty vs. receive beam angle that remains consistent over several tests, and from which more definitive depth accuracy estimates can be derived.

The requirement for careful data editing prior to assessing depth accuracies is illustrated in Fig. 11 where results obtained with the POS-MV320 have larger uncertainties than with the other sensors. Yet this plot corresponds to the port half of the data shown in Fig. 10. In this case, the higher depth uncertainties are due to larger bottom detection scatter upslope, which is most likely caused by local relief and the somewhat higher standard deviation of the ship's heading (0.71°). Once again, careful data editing will be required to obtain a consistent picture because the uncertainties reported for POS-MV320 data are not representative of the actual depth accuracy capabilities of the sonar system. The other curves are more consistent and therefore closer to the actual accuracy.

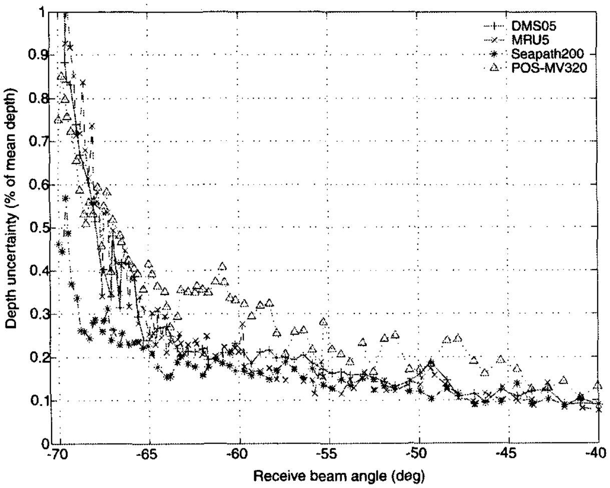

Fig. 11. Depth uncertainties vs. port beam angles referenced to vertical for 4 different motion sensors.

III. CONCLUSIONS

The sounding accuracy of a deep water multibeam swath bathymetry sonar can be assessed from data collected while the ship holds station, maintaining position and heading to tolerances set by the fore-aft beam width of the transmit beam, and by the nominal footprint of the intersection of the transmit beam and the narrowest receive beam. However examples provided in previous sections show that careful data editing is required to obtain reliable estimates.

Comparisons of sounding accuracies obtained with 4 different motion sensors yielded smaller than expected differences given the factor of 5 in RMS roll accuracy among the sensors. Likely explanations include incorrect specification of RMS roll accuracy for the motion sensors, beam steering errors on the outermost sectors (beyond ±58°) of the EM120 sonar, and misregistration between the roll time series and the sonar data. The last two explanations are the most probable given the evidence of apparent roll errors found at the edges of the swath (Fig.6).

ACKNOWLEDGMENTS

This work would not have been possible without the generous contributions of Duane Fotheringham (KSI), Michael Mathewson (Seatex), Peter Stewart (Applanix) who loaned us the various vertical reference units used in the tests described here. Many thanks are due to the captain and the crew of R/V Roger Revelle who provided the necessary precision ship handling, and to John Chatwood, Jim Charters and Dan Jacobson who helped with EM120 data acquisition. Purchase and installation of the EM120 system were funded in part by the US Navy under a DURIP grant, by the National Science Foundation and by UC ship funds.

REFERENCES

[1] Kongsberg-Simrad Inc, EM120 product description, 27-4-1999
[2] D.R. Herlihy, B.F. Hillard, and T.D. Rolon, "NOAA Sea Beam system patch test," Int. Hydr. Rev., vol. 66, 119-139, 1989.
[3] J.A. Hammack, D.H. Fabre, J.E. Hughes Clarke, and B. Reed, "Hydrographic multibeam processing system (HMPS) swath alignment tool," Proc. Canadian Hydrographic Conf., 157-167, 1998.
[4] TSS, www.tss-realworld.com
[5] Seatex, www.seatex.no
[6] Applanix, www.applanix.com