AN EFFICIENT METHOD FOR REDUCING THE SOUND SPEED INDUCED ERRORS IN MULTIBEAM ECHOSOUNDER BATHYMETRIC MEASUREMENTS

Mirjam Snellen, Kerstin Siemes, Dick G. Simons

Acoustic Remote Sensing Group, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS, Delft, The Netherlands

Email: m.snellen@tudelft.nl, Tel: +31 15 2788144, Fax: +31 15 2783711

Abstract: *Nowadays extensive use is made of multibeam echosounders (MBES) for mapping the bathymetry of sea- and river-floors. The MBES is capable of covering large areas in limited time by emitting an acoustic pulse along a wide swathe perpendicular to the sailing direction. The angle and the corresponding two-way travel-time of the received signals are determined through beamsteering at reception. Water depths along the swathe can be derived from this angle and travel-time combination. In general, two sets of sound speed measurements are taken when conducting MBES measurements. The first set is used for the beamsteering and consists of the sound speeds at the MBES transducer. The second set is used for determining the propagation of the sound through the water column, needed for correctly converting the measured travel times to a depth. In general, this set of sound speed measurements consist of the complete sound speed profiles (SSPs). The quality of the sound speed measurements at the transducer position sometimes gets degraded, resulting in beam steering angles that differ from those aimed for. Also sometimes the SSPs used for converting the beam travel times to depths deviate from the true prevailing SSPs due to the, in general, limited amount of SSP measurements taken during a survey. Both above mentioned effects result in an erroneous bathymetry. Here, we present a method for eliminating these errors, without the need for additional sound speed information.*

Keywords: *Multibeam echosounder, sound speed profile, optimization*

1. INTRODUCTION

Multibeam echosounder (MBES) systems are nowadays extensively used for mapping the bathymetry of sea- and river-floors. The MBES sends out an acoustic pulse along a wide swathe perpendicular to the sailing direction, thereby covering a large area of the seafloor at once. Beamsteering at reception allows for determining the (two-way) travel-time of the received signals as a function of angle. Water depths along the swathe can be derived from the combination of travel-time and angle, provided that the local sound speed profile in the water column is known [1]. However, in environments with large variations in the water column sound speeds (both temporally and spatially) this is not always the case, preventing a reliable conversion from the measured travel-times to bathymetry. Situations where information regarding the prevailing sound speeds is insufficient occur, for example, in estuaries where fresh river water mixes with seawater.

Also for the beamsteering, sound speeds need to be known accurately. Hereto, often a sound speed measurement device is placed close to the MBES transducer. However, due to e.g. algae growth on the sensor, the quality of these sound speed measurements can get degraded. As a result of this, the actual beamsteering angles deviate from the angles aimed for, and are not known.

Both effects, i.e., employing an erroneous sound speed profile for converting travel- times to water depths, and using an erroneous sound speed value for the beamsteering result in errors in the derived bathymetry. These errors can be such that surveys need to be repeated, which is very undesirable due to the high costs involved.

MBES surveys are normally carried out such that neighboring swathes partly overlap. This overlap allows for detecting the sound speed induced errors, since the water depths, as determined at the overlapping swathe points, will be different for each of the swathes. However, the overlap does not only allow for detection of the errors, it also allows for eliminating them. The method described here fully exploits the redundancy in the MBES measurements obtained from the overlap of adjacent swathes. Since temporal variations of the seafloor during the survey (several hours) are negligible, differences in bathymetry at overlapping parts of the swathes are the result of measurement errors. The method presented assumes errors due to erroneous sound speeds to be dominant. The prevailing water column sound speeds and thus the bathymetry are then estimated by inversion, requiring the derived bathymetry along overlapping regions to coincide, i.e., it searches for those water column sound speeds that result in a maximum agreement in the bathymetry along the overlapping swathes. The Gauss-Newton method is employed for the optimization. In [2] use is made of simulations to demonstrate the method's applicability. The configuration considered in [2] represents a typical MBES survey geometry. The results demonstrate that the method allows for correctly estimating the true bathymetry and the true sound speeds. In [3] the method is applied to real MBES data and it is shown that it allows for efficiently eliminating sound speed induced errors in the bathymetry.

The redundancy in the measurements is due to the overlap in adjacent swathes. This redundancy increases with increasing overlap. However, increasing the overlap requires the adjacent tracks to be sailed closer together, decreasing the MBES survey efficiency. In this paper the effects of overlap on the method's performance is assessed.

Section 2 provides a description of the approach. In Section 3 the results of applying the method for different overlaps are presented. The data considered are synthetic simulated data. The paper ends with the conclusions in Section 4.

2. DESCRIPTION OF THE APPROACH

Multibeam echosounders (MBES) emit acoustic pulses in an opening angle of 1 to 2 degrees in along-track direction, and in an opening angle of about 120–150 degrees in the across-track direction. Beamforming in across-track direction is applied to determine the corresponding two-way travel-times for a selected number of arrival angles. Water depths along the swathe spanned by the across-track opening angles are determined from the combinations of two-way travel-time and angle. Hereto, either propagation along straight sound rays is assumed for shallow water environments, or in case the curvature of the sound rays can not be neglected, ray-trace calculations are carried out.

Inaccurate knowledge about the water column sound speeds result in an erroneous bathymetry in two ways:

1. Errors in the beamsteering process. In case the actual sound deviates from the measured sound speed, the actual beamsteering angles differ from the beamsteering angles aimed for and are unknown.
2. Errors in the conversion from the angle and travel-time combinations to water depths along the swathe.

Fig. 1 shows the geometry of a typical MBES survey, consisting of a series of tracks sailed parallel to each other. Track distances are such that a certain overlap exists between adjacent swathes.

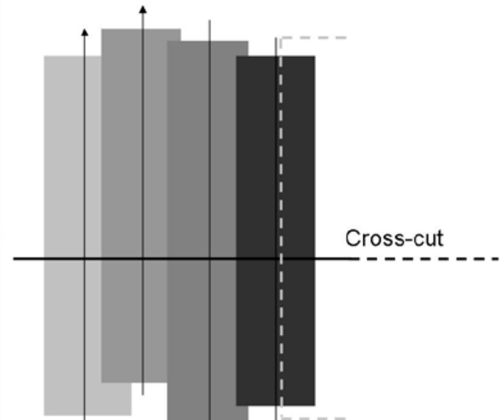

Fig.1: Schematic overview of MBES survey geometry. The arrows indicate the sailing direction. The rectangles indicate the area as measured per track.

Fig. 2 shows an example of the typical bathymetric behavior along a cross-cut such as indicated in Fig. 1 in case erroneous sound speeds are used. The area in which these MBES were taken is located close to the entrance of the Rotterdam harbor, where mixing of fresh and salt water occurs. The number of parallel tracks amounted to 12. The bathymetry was estimated from the measured travel-times, employing all sound speed information available, i.e., sound speeds measured at the transducer head for the beamsteering and a single sound speed profile for calculating the sound propagation through the water column. The colors indicate the bathymetry as estimated for each of the tracks. Differences in water depths along the overlapping parts of adjacent swathes range to almost 0.5 m.

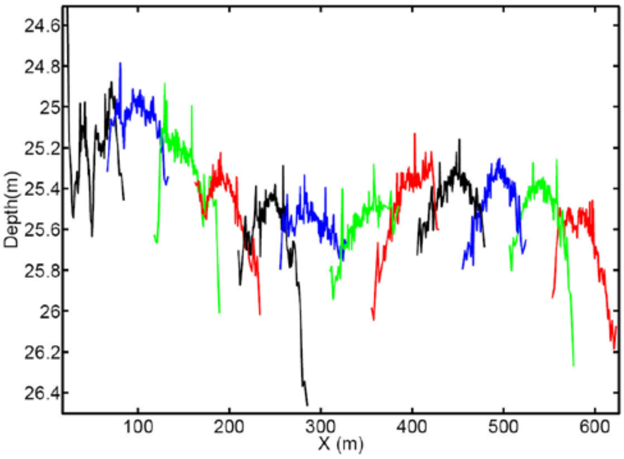

Fig.2: Example of 'droopy' effects. The MBES measurements were carried out near the entrance to the harbor of Rotterdam.

The method proposed for eliminating these effects fully exploits the redundancy of measurements in the overlap region between two adjacent swathes. Assuming that the seafloor does not change during a survey, the depth measurements in the overlap regions should be the same.

The measurements are the two-way travel-times. We aim to minimize the function:

$$E = \sum_{k=1}^{S} \sum_{j=1}^{N} \left(t_{k,j} - T_{k,j} \right)^2 \tag{1}$$

where N and S are the total numbers of MBES beams and swathes, respectively. The modeled two-way travel-times are denoted by $t_{k,j}$ and the measured two-way travel-times are denoted by $T_{k,j}$. The model that calculates $t_{k,j}$, accounts for both the effect of sound speed on the beamsteering and on the propagation through the water column. The unknowns are the sound speed profiles for each of the swathes and the bathymetry. These unknowns should be selected such that E becomes minimal.

Hereto the seafloor is modeled with an interpolated grid function. The water depths at the grid positions are the unknowns that are obtained through the minimization of E. Assuming a shallow water situation, we approximate the sound speed profile by a constant sound speed. This results in one unknown sound speed for each of the tracks. The unknowns to be optimized are thus the depths at the grid positions and the sound speeds for each of the swathes.

For minimizing E use is made of the Gauss-Newton method. The optimization procedure is as follows: For the seafloor, we use a fixed grid of horizontal positions, denoted X_n in the across-track direction. At every position X_n, Z_n denotes the corresponding water depth. Between the grid points the depth is interpolated linearly. For every beam j at angle $\theta_{k,j}$, the point where the acoustic beam impinges on the model seafloor is denoted as $(x_{k,j}, z_{k,j})$. Fig. 3 shows a schematic overview of this model. The MBES is located at $(X_{k,MBES}, Z_{k,MBES})$.

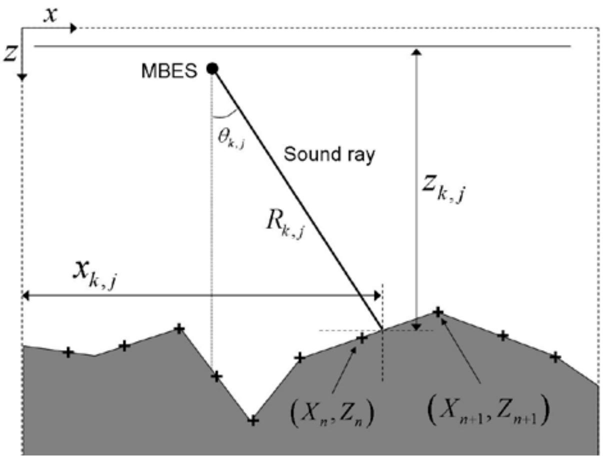

Fig. 3. Schematic overview of the MBES measurements.

Mathematically, the function for $t_{k,j}$ can be derived by calculating the intersection between two lines: the sound ray and the line between the grid points in Fig. 3. The position at which these two lines intersect is given by:

$$x_{k,j} = \frac{\dfrac{X_{k,MBES}}{\tan\theta_{k,j}} + Z_n - Z_{k,MBES} - X_n \dfrac{Z_{n+1} - Z_n}{X_{n+1} - X_n}}{\dfrac{1}{\tan\theta_{k,j}} - \dfrac{Z_{n+1} - Z_n}{X_{n+1} - X_n}} \tag{2}$$

and

$$z_{k,j} = \frac{x_{k,j} - X_{k,MBES}}{\tan\theta_{k,j}} + Z_{k,MBES} \tag{3}$$

Values for $t_{k,j}$ are calculated employing the water column sound speed c_k as

$$t_{k,j} = \frac{2\left(x_{k,j} - X_{k,MBES}\right)}{c_k \sin\theta_{k,j}} \tag{4}$$

where c_k is the sound speed in swathe k.

We can write

$$\mathbf{y} = A(\mathbf{x}) \tag{5}$$

with **y** the vector containing the measured travel-times, and **x** the vector containing all unknowns.

Solving for **x** in a least-squares sense requires the iterative Gauss-Newton approach. Hereto the expressions for the derivatives of A to all unknowns have been determined.

3. RESULTS

The situation considered is that of 8 parallel tracks. The overlap between two adjacent swathes amounts to half the swathe. In practice, overlaps will in general be smaller. The grey area in the upper plot of Fig. 4 shows the bathymetry. True and “measured” sound speeds are given in Table 1. The bathymetry obtained when using the wrong “measured” sound speeds is also shown in the upper plot of Fig. 4. The resulting errors in the derived bathymetry are clearly visible.

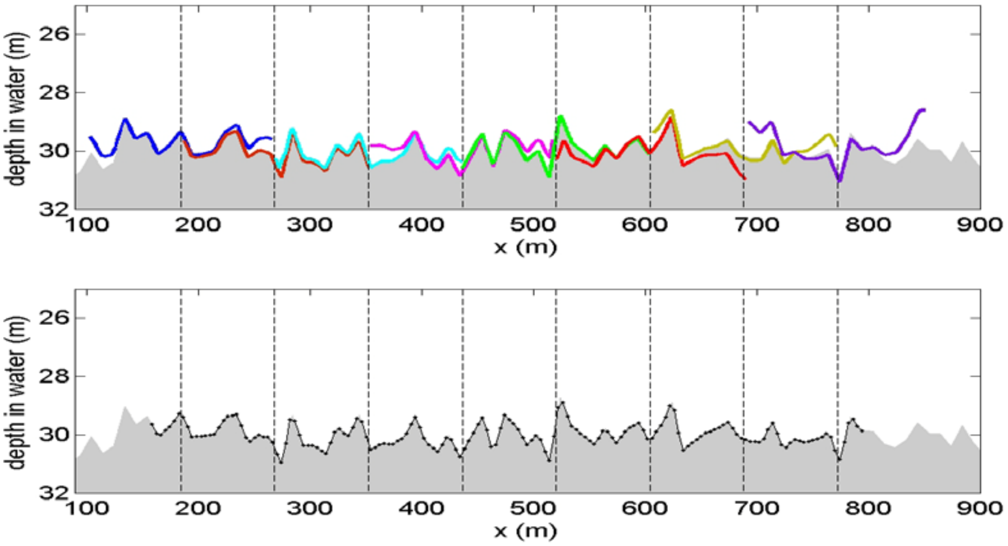

Fig. 4. MBES measurement configuration consisting of 8 parallel tracks. The positions of the MBES are indicated by the vertical black dashed lines. The true bathymetry is indicated by the grey surface. The upper plot presents the estimates for the bathymetry along the swathes where use is made of erroneous sound speeds. The lower plot presents the optimized bathymetry.

Swathe	True sound speed (m/s)	Measured sound speed (m/s)	Optimized sound speed (m/s)
1	1499.9	1505.6	1499.9
2	1504.3	1508.1	1504.3
3	1507.8	1496.7	1507.9
4	1504.0	1494.0	1504.1
5	1490.6	1504.9	1490.6
6	1500.0	1499.6	1499.8
7	1508.1	1502.2	1508.2
8	1502.4	1507.2	1502.4

Table 1: True, measured and optimized sound speeds for the 8 swathes.

The lower plot of Fig. 4 shows the optimized bathymetry. Clearly the optimized bathymetry almost coincides with the true bathymetry as indicated by the grey filled area. Furthermore, the optimized sound speeds almost coincide with the true sound speeds, as seen from Table 1. Fig. 5 shows the sound speed estimates obtained from 100 independent optimizations. From this plot it is clear that the method is capable of retrieving the true sound speeds. This off course also holds for the bathymetry.

In general, the overlap between adjacent swathes will be smaller. In addition, the measured travel-times will be subject to noise. To assess these effects, simulated data have been generated for measurement configurations with different overlaps and with noise added to the travel times. The left plot of Fig. 6 indicates the deviations of the optimized sound speeds from the true sound speeds as a function of the overlap. The right plot indicates the mean errors in the estimated bathymetry. The black lines indicate noiseless measurements. The red and cyan lines have been obtained by adding Gaussian noise to the measured travel times with standard deviations of 0.2 and 0.4 msec, respectively.

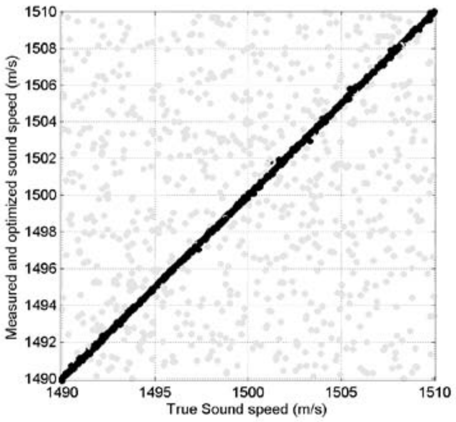

Fig. 5. Sound speed estimates obtained from 100 independent optimizations. The situation considered is that of 8 parallel tracks. The black circles denote the sound speed estimates, plotted versus the true sound speeds. The grey circles indicate the measured sound speed values, also plotted versus the true sound speed.

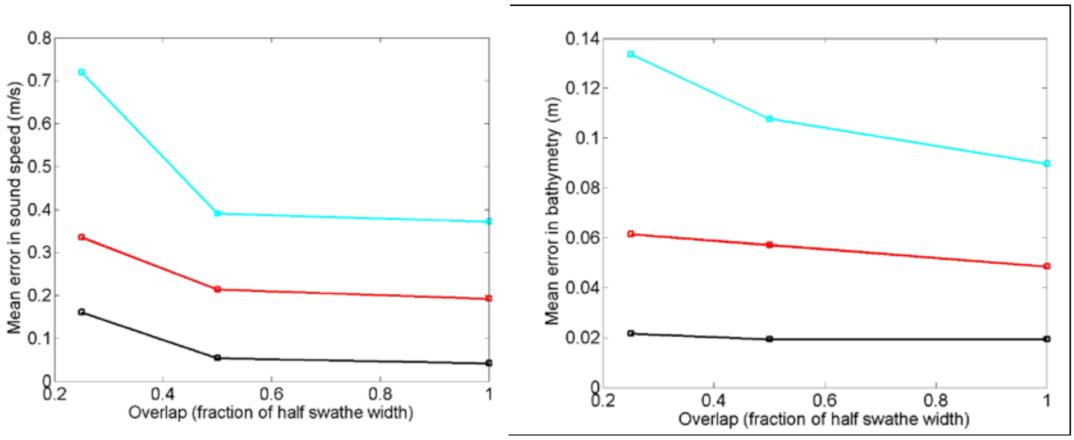

Fig. 6. Mean error of the estimated sound speed as a function of the overlap (left plot) and the mean error in the estimated bathymetry (right plot). The black lines indicate noiseless measurements. The red and cyan lines have been obtained by adding Gaussian noise to the measured travel times with standard deviations of 0.2 and 0.4 msec.

It can be concluded that both an increasing noise level and a decreasing overlap result in increased deviations of the estimations from the true bathymetry and sound speeds, but that still the deviation is limited. This is further illustrated in Fig. 7, showing the estimated bathymetry (lower plot) for the situation with noise superimposed on the measured travel times (standard deviation of 0.4 msec), and an overlap amounting to 1/8th of the total swathe width only.

4. SUMMARY AND CONCLUSIONS

In this paper it is demonstrated that by employing the overlap between adjacent MBES swathes, errors in the bathymetry due to erroneous sound speed information, can be eliminated. In principle, this method allows for MBES surveys where no information regarding the prevailing sound speeds is acquired. The only requirement is that sufficient overlap exists between the neighboring swathes. Simulations such as presented in the current contribution allow for a quantification of the required overlap.

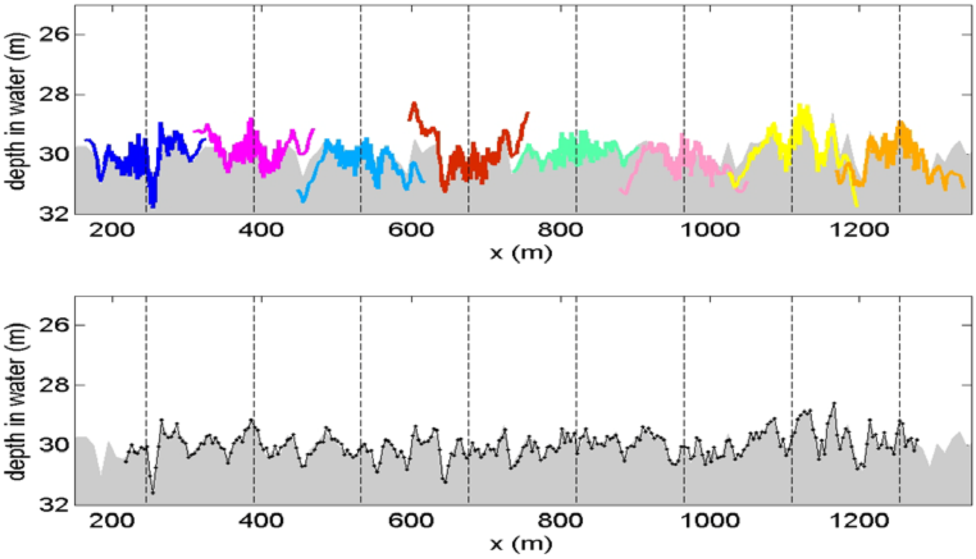

Fig. 7. Similar to Fig. 4. However, now noise is imposed on the travel time measurements and the overlap is limited.

5. ACKNOWLEDGEMENTS

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