Refraction Correction of the Acoustic Wave in Multibeam Systems

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Abstract. Dynamic surveys of the sea bottom that rely on determination of reflection points of
the acoustic wave transmitted by the echosounder use the wave field theory for determination
of the trajectories of the acoustic ray. Complex multibeam echosounder systems that use
diagonal beams to determine the coordinates of reflecting points on the sea bed, must take into
consideration the refraction phenomenon. Beam inflexion depends on the variability of sound’s
velocity in water. It is increasingly more important for beams most inflected from the plumb
line. It is a determinant of the angle zone of echosounder’s beam and swath width. The
efficiency of bathymetric surveys relies on the swath width. It is 3-5 times the water depth for
a multibeam echosounder and up to 12 times water depth for an interferometric one. High
value of swath width achieved for high beams inflexion decreases the reliability of the Digital
Sea Bottom Model built by data recorded during the bathymetric surveys. This article presents
results of correction of the phenomenon of non-linear propagation of the acoustic wave in
the multibeam echosounder calibration process in the area where the depth does not exceed 30m.
A calibration test was utilised on the perpendicular profiles to determine the variance of depths.
Depths measured by the diagonal beams were verified using a vertical beam during surveys on
perpendicular profile. Popular models for determining the trajectory of an acoustic wave were
used – one based on Snell’s law and another, a new one developed by TU Delft. The geospatial
data was sourced using R2Sonic multibeam echosounder during the preliminary stage of
bathymetric sounding.

1. Introduction
Accuracy in positioning sounding vessel and point of reflection of the acoustic wave, with its
nonlinear trajectory taken into consideration, make factors determining the accuracy of determining
seabed geospatial coordinates [1] in multibeam systems. Precise dynamic positioning of coastline with
geodesy (high accuracy) and navigation (dynamics) is possible thanks to modern geodetic systems [2-
4] in the dynamics [5-7]. They greatly exceed the required positioning accuracies in the littoral zone of
hydrographic measurements and in the area geodetic systems operate [8, 9].

The second element of the geospatial data acquisition process, executed in the lower hemisphere
(in water) is more complicated – due to acoustic characteristics of water. Non-linearity of the acoustic
wave propagation is one of the factors.

The refraction phenomenon, i.e. change of direction of the acoustic radius, has a significant
influence on positions of points of the acoustic wave reflection from the seabed. As a result, contrary
to a perfect linear trajectory of the acoustic wave, depending on the gradient of the water velocity in
water, the wave is subject to curvature [10-12]. This phenomenon is the most important for the beams the most deflected from vertical, resulting in a narrower angular sector of radiation and narrower swath [13, 14].

Field of acoustic wave emitted in water environment by the echosounder’s transducer and its changes in time-domain may be described mathematically by solving the wave equation [1, 15, 16], which in hydro-acoustics is a basis for descriptions of small amplitude waves. This solution does exist, however – only for simple or idealized cases. In general, a point source of the acoustic wave and horizontal stratification of water – in which the sound speed $c(x, y, H) = c(H)$ - are assumed.

Eiconal equation, describing the trajectory of the acoustic ray, is a partial linear differential equation which solutions provide tri-dimensional surfaces in a space $W(x, y, H) = \text{const}$. In respect to a field of acoustic interferences, these are waves’ surfaces, i.e. surfaces of the identical phase of the wave vibrations, and the wave front surface among them. Vector $dr$, perpendicular to the wave front, defines the direction of the propagating wave front limited to the section it is surrounded by, and its next positions in time-domain determine a path of this section – the trajectory of the acoustic wave ray.

These factors compound the accuracy [17-19] when building the Digital SeaBed Model [20-22] which is an essence of bathymetric measurements executed by means of the echosounder, in particular of the multibeam one.

2. Methodology
Geospatial data registered during roll calibration of MBES were used for assessment of the impact of acoustic wave refraction in water phenomenon on the accuracy of depth measurement. Distances between parallel profiles were set in the mid length of swath width. In general, the sea bed was covered by the data in 200%, i.e. that area was exposed to sounding twice. Neighbouring beams overlap within 50%-coverage. This means that vertical beam and the least deflected ones of one profile overlap with beams the most deviated from the neighbouring profile. It allows comparing the most deflected beams for which impact of the refraction phenomenon is the biggest with the beams enabling depth measurement with the highest accuracy.

![Figure 1. Area of the soundings](image-url)
MBES calibration, including HPR (heave, pitch, roll) corrections and latency, is executed in various dynamic conditions: various velocities, arrangement of profiles and seabed inclination. All the conducted tests were performed in a range of depths from 25m to 65m, but the roll offset was measured on a flat seabed at the depth of 63m (Figure 1).

3. Measurements

3.1. Sound speed in water
Measurement of sound speed in water is an important element of all hydrographic works conducted by means of hydroacoustic equipment and systems. Knowledge on the vertical distribution (profile) of the sound velocity in water enables more accurate measurements with a use of sonar and bathymetric equipment and systems. This is especially important in devices producing bias beams – MBES and USBL – Ultra Short Base Line underwater navigation systems.

Determination of sonic velocity is performed each time when it is necessary to apply hydroacoustic measuring equipment. Hydrography officer should plan places for the execution of measurements of the sound velocity in water precisely in the area of work delivery, in such a way so that obtained results allow the best possible reflecting of the real hydrological conditions present in the area where the hydrographical works have been executed. The measurements are always done prior to commencement of bathymetric measurements and after their completion [23].

Number and frequency of measurements both depend on the requirements for the echosounders’ equipment and on accepted criteria and quality standards describing the level of accuracy of the measurement data registered. The number and frequency of performing the measurements of the sound velocity in water are also determined by such elements as local hydrological conditions related to existence of inland waters’ inflows, operation of sea ports in which the inland waters’ inflows are present [23] and of areas with occasionally encountered areas of waters differing in temperature and salinity. Variations in the sound speed in water are of short-term (daily) and long-term (seasonal) nature [1, 15, 16]. The decision to increase the number of measurements is made by the hydrographer after analysis of gathered historical archives and measurement materials and each time if there are serious differences between the depth values under measurement and the assumed or already measured (Figure 2) ones there [23].

Figure 2. Measurement (left) and the vertical distribution (right) of the sound speed in the water
3.2. Bathymetric soundings

Geospatial data recorded during calibration of the multibeam echosounder for rolling correction (Figure 3) were used to verify the Digital Sea Bottom Model. The calibration preceded hydrographical soundings executed by hydrographic ship by means of R2Sonic 2022 multibeam echosounder, operating at 300 kHz frequency. The hydrographic system also consisted of: two-antenna Applanix POS MV precise positioning system, Applanix detector of roll and heave motions, Valeport Mini sound velocity profiler, DESO-30 singlebeam echosounder. They were all integrated by QPS QINSy hydrographic system. As a result of the performed MBES dynamic calibration, the parameters presented in Table 1 were obtained.

|                        | Pitch [°] | Roll [°] | Heading [°] | Starboard [m] | Forward [m] | Up [m] |
|------------------------|-----------|----------|-------------|---------------|-------------|--------|
| Sonic2022 Port         | -0.930    | 10.10    | 1.910       | -1.040        | 0.681       | 0.024  |
| Sonic2022 Starboard    | 0.250     | -10.170  | 1.510       | 1.051         | 0.686       | 0.028  |

Figure 3. Surface view with slice selection (left)

4. Results

Manual correction of the refraction phenomenon consists of introducing correction of the sound speed in water and in repeating determination of the sea bed’s geospatial coordinates. The corrected sound velocity value verifies distance (the bias one) to the bottom and determines coordinates of the acoustic wave’s reflection point (beam) at its nonlinear trajectory. It is to be assumed that – thanks to the measurements of the sound velocity in water distribution – the most approximated DSBM – Digital Sea Bottom Model should be obtained at the correction of 0 m/s (Figure 5). The section is presented in the swath of ±50 m – in order to achieve high resolution of the beams. The extreme outer beams (in purple and yellow colours), burdened with the most significant error, measure the depth varying even by 15 cm in respect to the vertical beams (green in colour) of the neighbouring profile.

The 5 m/s adjustment of sound velocity in water (Figure 4) results in lower value of the depth being measured by means of extreme outer beams, even by 1 m. Similar but opposite phenomenon may be observed when introducing positive correction of the sound velocity in water. For correction of +5 m/s (Figure 6), the extreme outer beams measure the depth increased by 1 m.
The sections presented on Figures 4 and 5 are given in colours of the profile – a separate colour shows the data registered with the beams on one profile. Figure 6 is given in colours of the beams – to observe the sea bed shape determined by means of particular beams.

**Figure 4.** Slice across the track – sound speed correction -5m/s

**Figure 5.** Slice across the track – no sound speed correction

**Figure 6.** Slice across the track – sound speed correction +5m/s
Mean deviations of the beams, obtained by applying the corrections from -5 m/s to +5 m/s, are given in Table 2.

**Table 2. Mean deviations of the beams with corrections from -5 m/s to +5 m/s**

| ∆c [m/s] | -5  | -4  | -3  | -2  | -1  | 0   | 1   | 2   | 3   | 4   | 5   |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| ∆h [m]   | 1.05| 0.90| 0.81| 0.62| 0.34| 0.18| 0.08| -0.20| -0.42| -0.56| -0.87|

| ∆c [m/s] | -1  | -0.8| -0.6| -0.4| -0.2| 0   | 0.2 | 0.4 | 0.6 | 0.8 | 1   |
| Δh [m]   | 0.34| 0.329| 0.22| 0.17| 0.16| 0.18| 0.09| 0.03| 0.5 | 0.06| 0.08|

TU Delft algorithm (Figure 7), implemented – among the others – in the QPS QINSy hydrographic system, is an alternative for the manual correction of the refraction phenomenon. The tool is based on an algorithm developed by researchers at the Technical University of Delft, The Netherlands [24-28]. It works by taking advantage of the overlap between survey lines and harnessing the power of redundancy of multiple observations. For a given set of pings, the algorithm simultaneously estimates sound speed corrections for the chosen pings and their neighbours by computing a best-fit solution that minimizes the mismatch in the areas of overlap between lines. This process is repeated across the entire spatial area, allowing for an adaptive solution that responds to changes in oceanographic conditions.

5. Conclusions
Vertical distribution of the sound velocity in water and the beam output angle, in respect to vertical, i.e. the vertical beam, are the factors determining the refraction phenomenon. The MRU sensors of 0.01 accuracy make Essentials element of the hydrographic system using MBES for the depth measurement. The sound speed in water, mainly of daily changes during the bathymetric sounding, is periodically measured in every water area. It highly minimizes the error (uncertainty) of the depth measurement. The smallest error in the depth measurement, in spite of the sound velocity distribution in water taken into consideration, is to be obtained after correcting (mainly by hand) the refraction phenomenon.

The most serious changes of the sound velocity distribution in water are observed in the summer when water – thanks to the sun - is the warmest at the surface. The water temperature, determining the sound speed in this medium, is of the least importance in winter. The presented results were obtained based on measurements taken in November; hence, the sound velocity in water impact should be
insignificant. In the depth of approx. 15 m, a decrease in the sound speed may be observed – as a thermocline effect. From the point of view of the acoustic wave propagation in water, the season from autumn to early spring is the best for the bathymetric measurements.

It can be determined from the DSBM observation whether the impact of the refraction phenomenon has a place and whether the correction is necessary. Based on the visualization of the 2D picture of the bottom, it may be indicated when the characteristic straps occur on the swath edge. The manual correction is performed on the vertical sections which overlap in some 10% of the swath width. The TU Delft algorithm of the refraction automatic correction sets the correction automatically, for every ping.

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