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Improving MBES Measurements

In dynamic water environments such as the Maasgeul waterway off the Dutch coast at the Port of Rotterdam, tides and a varying presence of salt and freshwater from river run-off can cause considerable variation of the water column sound speed profile (SSP). It is important to adequately correct bathymetric data for sound refraction effects in the face of limited SSP information. A new approach, described here by case study, requires and exploits the multi-beam echo sounder (MBES) in surveying adjoining swathes with overlap.

To maintain safe passage of ships along the waterways leading to the Port of Rotterdam, water depth needs to be monitored by regular survey. Dredging operations are carried out if the depth is found to be too shallow. To properly derive water depths from measured multi-beam echo sounder (MBES) acoustic travel times sound-refraction effects need to be accounted for. In practice, however, refraction correction can be hampered by insufficient knowledge of the water-column sound speed profile (SSP) at the time and place of MBES measurement.

Sound Refraction

With each ping the MBES emits an acoustic pulse and measures the time to reception of the acoustic bottom-return signal in directions across a wide fan or swathe perpendicular to the shipâ€™s heading. Because sound speed varies with water depth the sound emitted in oblique directions is subject to refraction, resulting in sound propagation along paths no longer straight. This is a manifestation of the well-known Snellâ€™s Law of refraction. In order to correctly convert acoustic travel-time measurements to water depth, account must be taken of sound-refraction effects.

Water Column

In principle, (towed) systems are available for continual SSP measurement, so providing sufficient information. These systems are not, however, widely applied and often use is made of a conductivity-temperature-depth (CTD) device. Whilst performing CTD measurement the ship needs to be stationary, making it a time-consuming process. Thus in practice only a limited volume of SSPs are measured during a survey. While this plays a minor role in environments showing little SSP variation it may cause considerable errors in measurements of water depth in dynamic environments such as the Maasgeul.

Reducing Error

It is standard practice to carry out MBES surveys with (at least a small) overlap between adjacent swathes (see Figure 3, top). In this way partial redundancy in water-depth measurement is introduced. Bottom features like the sand waves in the Maasgeul area are known to vary considerably only over several days to weeks. Thus bottom features can be expected to remain unchanged in the time taken to survey two overlapping swathes and water depth measured along the overlap will be the same at equal points of the seafloor (after applying tide correction). If, however, the SSP used for converting measured travel times to water depths differs from the prevailing SSP at the time and place of the MBES measurement, water depths along the overlap will generally differ between the two swathes. The new approach proposed here is to exploit the measurement redundancy resulting from the overlap by searching for those SSPs that minimise water-depth differences between overlapping paths of adjacent swathes.

SSP Inversion

In contrast to many existing post-processing methods used to obtain a consistent estimate of water depth in overlapping areas of a swathe, the new approach works on measured travel times and not on derived depth estimates. The steps taken are as follows: assume new SSPs, one for each swathe; SSPs are modelled according to a certain parameters. Then determine from measured travel times and new assumed SSPs (using Snellâ€™s Law) updated water depths along swathes. Finally, determine differences between updated water depths along overlapping parts of adjoining swathes; a cost function is introduced for quantifying these differences. This three-step process is iterated until the cost function is minimal. We will now consider these steps in more detail.

Parameterisation

A straightforward SSP parameterisation consists of sound-speed value at, for example, every metre of water depth. For a water depth of 25 metres, however, this would result in 25 parameters describing the SSP, implying a search for 25 unknowns per SSP when minimising the cost function. To limit the number of unknowns a simple linear parameterisation is taken with two unknowns, transducer sound speed and linear sound-speed gradient. Another option would be parameterisation based on empirical basis functions determined from an area representative SSP dataset.

Recalculating Depth

The MBES measures acoustic travel times in a discrete number of directions along the swathe: beam departure angles. Crucial here is precise steering of beams in the direction of departure angles, but this requires accurate knowledge of transducer sound speed at the time of measurement. Since in practice this sound-speed value can be highly accurately continuously measured it is assumed that no errors occur in the beam-steering process. Based on beam departure angles and measured travel times, water depths are recalculated according to the assumed SSP for every swathe. This is done using acoustic-ray tracing based on Snellâ€™s Law of refraction.

Minimising Cost

A cost function is introduced in quantifying resulting depth differences along overlapping parts of adjoining swathes. The cost function is taken to be the sum of squared overlap differences. The objective now is to minimise this function by searching for those SSP parameterisation values that minimise depth differences. Considering the number of unknown parameters and the fact that problems like these typically carry multiple local minima, a global search algorithm is required. Here we use the method of Differential Evolution, a variant of the Genetic Algorithm, nowadays relatively standard as a global search algorithm for inverse problems.

Assessing Performance

The performance of the method is assessed by simulation. As a first step, three adjoining swathes are considered with an overlap of almost 100%. A true situation is first defined for the simulations: true bottom and for each swathe a true sound-speed profile. From these follow the true travel times. A â€˜measuredâ€™ SSP is then defined and using this SSP the measured bottom profiles are calculated from true travel times. The SSP-inversion method is applied to the resulting measured bottom profiles for the three swathes. The method employs a Monte Carlo search implying statistical behaviour of the solution. Thus multiple independent solutions need to be generated to assess how well the true bottom and the true SSPs are retrieved.

Simulation Set-up

A bottom with typical bottom features is considered at a depth of 60 metres. Two cases are defined. In the first, the true SSPs are taken to be linear and the measured SSP piece-wise linear. The errors resulting from the use of the measured SSP are clearly visible and amount to more than one metre. In the second case the true SSPs and the measured SSP are constructed from an SSP dataset. The resulting errors in bathymetry are now at decimetre level. The SSP-inversion method is applied to the measured bottom profiles; SSPs are parameterised according to the linear method. This means that in the second case the true SSPs cannot be constructed according to parameterisation; that is to say, there is a mismatch.

Performance Results

It was confirmed that in the first case application of the SSP-inversion method resulted in virtually complete recovery of true linear SSPs for all three bottom profiles. Both transducer sound speed and sound-speed gradient were very well determined. Further, in both the first and second cases all independent solutions resulted in an absolute difference between optimised and true bathymetry of less than 5 centimetres. This means that, in terms of bottom recovery, the more realistic case of a mismatch between modelled and true SSP performs at the same level as the case without mismatch. This is quite a remarkable result.

Concluding Remarks

The SSP-inversion approach proves promising for correcting MBES bathymetry for refraction errors. In principle the method completely eliminates the need to measure SSPs during a survey. Interesting further research lies in investigation of the necessary overlap between adjacent swathes, use of other, more suitable SSP parameterisations, and application to (and verification against) real MBES and SSP survey data.

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