Burial depth determination of cables using acoustics

Requirements, issues and strategies

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Depth-of-burial (DOB) surveys are well-known in the oil and gas business to obtain the exact position and burial depth of pipelines or cables after dredging and for regular maintenance. With expanding offshore wind farming in the wake of the »Energiewende« site explorations, route and cable DOB surveys become increasingly important in this industry, too. Various geophysical methods like magnetic, electro-magnetic and acoustic sensors are used to detect and track buried cables. For best detection probability of buried cables to date mostly lines crossing the expected cable route are surveyed. Although this is suited to detect the cable and get its position with high accuracy, survey companies require more efficient technologies, accounting for both, operational and processing costs. Thus they are looking for easy to operate equipment that follows the cable along its actual route, works at different water depths, weather and seabed conditions and gives immediate and reliable results to produce deliverables with high accuracy of XYZ cable positions.

detection of buried objects | acoustic cable tracking | depth of burial – DOB | sub-bottom profiler – SBP

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1 DOB survey requirements

In shallow waters the cables are buried into the seabed to avoid damages by ships, waves, anchors or other impact. The burial depth depends on the cable location and is mostly between one and three metres for inter-array cables (connections within the wind farm) and power export cables (connections to shore). In areas with heavy fisheries or very dynamic seabed morphology burial up to ten metres or additional rock dumping may be needed.

Requirements for the cable position density along the cable route depend on the survey type. For surveys immediately after the cable was laid, positions of at least every metre are required while for maintenance surveys positions every 50 to 200 metres are sufficient. For cable-tracking systems a position density of up to 25 cm may be requested.

Horizontal (XY) cable position accuracy requirements are mainly based on the accuracy of the positioning system used (DGPS/RTK for surface vessels, USBL for subsea vehicles). Burial depth (vertical position Z) accuracy requirements vary from 5 % of slant range from sensor to 10 % of burial depth with limits of 5 to 10 cm RMS. For a sensor at two metres altitude and a cable buried two metres below seafloor these requirements translate into a vertical accuracy of 20 cm.

Operational costs mainly depend on the vessel costs, a vessel with ROV, crew, etc., often costs more than 50,000 € per day. Thus, survey time has to be as short as possible. If a high position density is required the cable detection system needs to go along the cable route and cover a wide across-track swath and should guide the helmsman along the cable to ensure the cable is not falling out of the survey corridor. If other sensors like multibeam echo sounders or electro-magnetic pipe/cable trackers shall be operated in parallel, there might be additional requirements like sensor distance above seafloor, which in turn affects the across-track swath requirements.

Data processing needs to be done offshore within 24 hours by the standard processing team aboard. Sometimes cable positions are needed immediately after trenching. For instance aluminium-cored cables are known to float in the slurry created by the trenching tool and end up rising behind the vehicle's depressor. So the contractor needs to have burial depth information quite fast to correct the target depth of burial if necessary. Thus for DOB surveys it is essential to have good online data visualisation for quality assurance and fast on-board post-processing with full position accuracy.

2 Cables as sonar targets

Active sonars used for acoustic cable detection emit sound pulses and register echoes of these pulses returning from objects or surfaces within the insonified volume. To estimate the acoustic performance the sonar equation (Lurton 2002; Urick 1983; Waite 2005) adapted for a buried target is used:

$$SE = \overbrace{(SL - 2\,PL - TL + TS)}^{\text{desired signal } (EL)} - \overbrace{(NL_R + RL)}^{\text{unwanted noise}} \\ - \underbrace{(5\log d - 10\log(BT) - 5\log n)}_{\text{signal processing } (DT)}$$

To detect the cable (target) the signal excess *(SE)* has to be positive. The desired echo signal (*EL*) depends on transmit source level (*SL*), the propagation loss ($PL = PL_W + PL_B$) in water

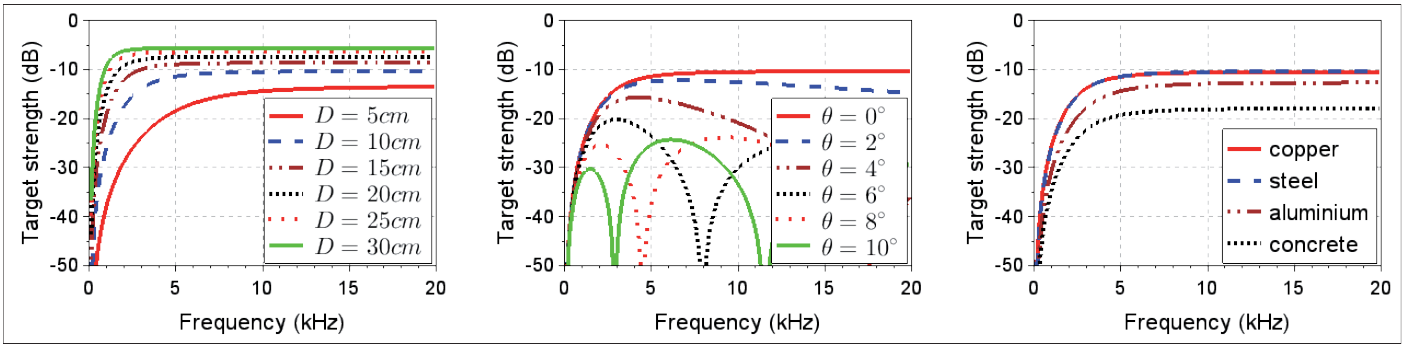

Fig. 1: Target strength depending on frequency of a cable modelled as infinite steel cylinder buried in sand (Stanton 1989) for different diameters D at normal incidence (left), for different incidence angles Θ with diameter $D = 10$ cm (centre) and for different cylinder materials at normal incidence (right)

and in the seabed (both depending on physical sound attenuation α and travelled distance R: $PL_{W,B} = 20 \log R_{W,B} + \alpha_{W,B} R_{W,B}$), the two-way transmission loss (TL) at the water-seabed interface and the relative amount of energy returned from the target (target strength TS). The received signal also contains unwanted noise and reverberation. The noise seen by the system ($NL_R = NL - DI_R + 10 \log B$) is mainly produced by the survey vehicle and depends on receiver directivity (DI_R) and sound pulse frequency bandwidth (B). The reverberation is caused by backscatter from random voids or objects within the insonified volume and the seafloor roughness. The reverberation level (RL $= RL_W + RL_B + RL_V$) depends on source level (SL), sediment type, the insonified seabed area and volume as well as the angle of incidence. The detection threshold (DT) depends on signal processing parameters to improve the signal-to-noise ratio ($SNR = EL/(NL_R + RL)$) like pulse length (T), pulse bandwidth (B), number of pings per processing ensemble (n) and detection index (d), which depends on detection probabilities as well as signal and noise characteristics (Waite 2005).

At fixed echo (EL), noise (NL) and reverberation (RL) levels the best signal-to-noise ratio will be achieved through a high receiver directivity (i.e. small beam width) and a high number of pings used per processing ensemble. The number of pings which can be used depends on beam width, vessel speed and ping rate. High survey speeds will require high ping rates to ensure pseudo-static conditions for the echo signal.

The reverberation level (RL) can be minimised by keeping beam width and pulse length as small as possible. For the low frequencies required for seabed penetration, narrow sound beams can be achieved by nonlinear (parametric) acoustics (Lurton 2002).

At fixed source level (SL) and propagation loss (PL) the echo level (EL) can be increased by reducing the transmission loss (TL), which strongly depends on the incidence angle (Fig. 1), and by increasing the target strength (TS). To estimate the target strength, a cable can be modelled as thin straight cylinder of infinite length. For simple shapes various simplified target strength models have been published (Lurton 2002; Stanton 1989; Urick 1983; Waite 2005).

The target strength depends on frequency, cable diameter, angle of incidence and material (Fig. 1). Typical diameters of wind farm cables range between 5 to 15 cm for inter-array cables and about 20 to 30 cm for power export cables going onshore. For cable diameters of 10 cm and more frequencies down to about 4 kHz can be used. For thinner (e.g. communications) cables higher frequencies are necessary. Especially for higher frequencies it is important to ensure the sound wave incidence perpendicular to the cable. This will be mostly the case at flat seafloors, but at slopes the sound beam direction needs to be adjusted either by tilting the vehicle (ROV/AUV) or by electronic beam steering.

The refraction at the water-sediment interface and at sediment layers is causing errors in the estimated cable position, depending on sediment type and incidence angle. This needs to be addressed during data processing. Sediment properties are mostly unknown and reducing the position error requires time-consuming optimisation algorithms, which will be faster if an educated guess on the sediment sound speed is available and the incidence angle is kept as small as possible (Fig. 2).

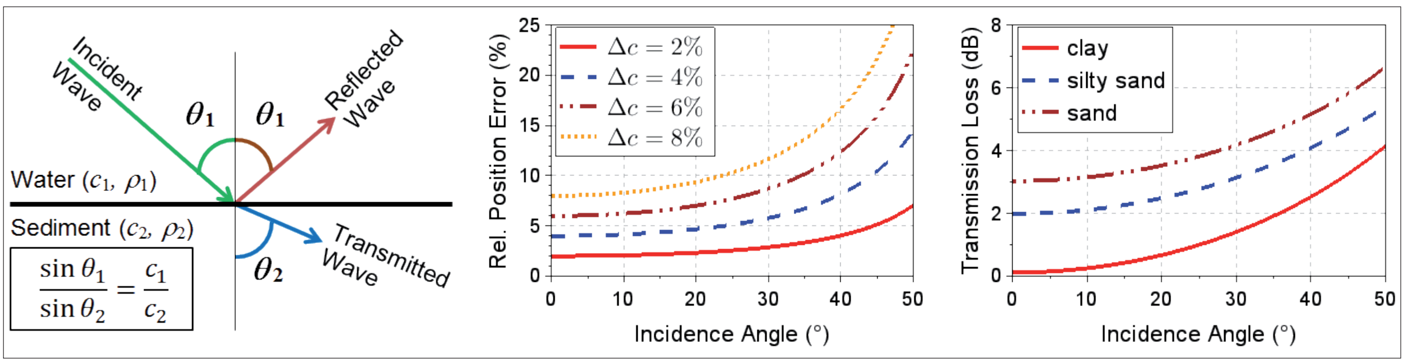

Fig. 2: Sound wave reflection and refraction at a flat water-sediment interface with incidence angle Θ_1, the same angle for the reflected wave front and angle Θ_2 of refracted wave front transferred into the seabed (left). Position error due to refraction (Euclidian distance between true and mapped cable position related to true burial depth) depending on incidence angle for sand at different sound speed estimation errors (centre). Two-way transmission loss TL (Sternlicht and de Moustier 2003) at a smooth water-seabed interface for different sediment types depending on incidence angle (right)

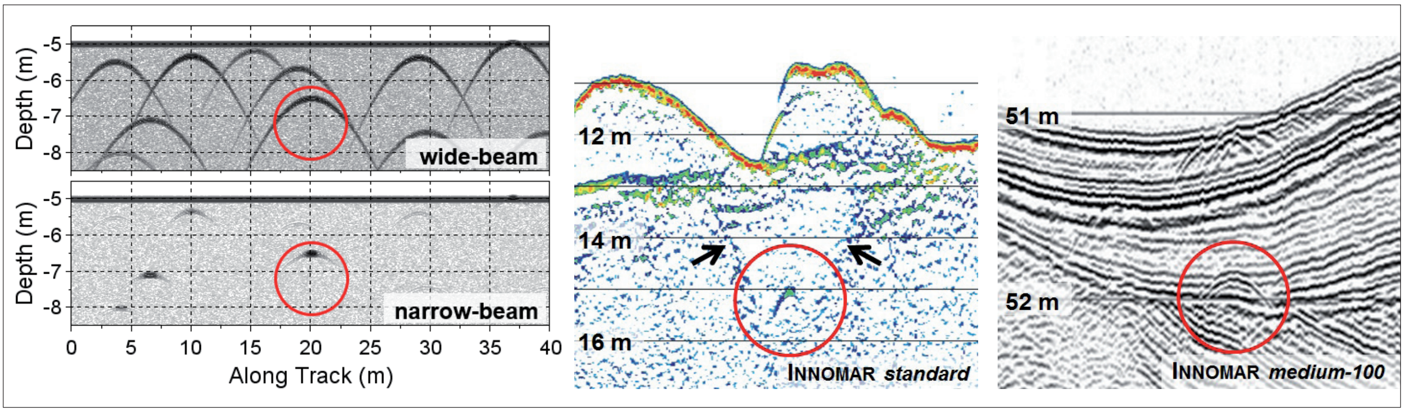

Fig. 3: Model echo prints from a cable (red marks) buried 1.5 m below seafloor surveyed across track and boulders spread in the seabed, for a linear wide-beam and a parametric narrow-beam system; boulders at the same locations for both data sets (left). Data example showing a pipeline approximately 4 m below sand, trench is visible (arrows), original seabed below sand waves (centre). Data example showing a 12 cm-cable buried about 1 m below seafloor at 51 m water depth surveyed shortly after dredging, diffraction hyperbolas visible at the seabed due to remaining trench banks (right)

3 Sonar track crossing the cable

Surveys using acoustics to map buried cables today mostly do survey lines crossing the expected cable route to get diffraction hyperbolas in the echo data, which gives a good detection probability. This method delivers cable positions at the cross points between cable route and survey track only. Thus the cable along-track position density depends on the line spacing. According to section 1 this may be sufficient for maintenance surveys, but higher requirements on position density will cause high operational costs due to the survey time needed. A time-consuming cable position picking in the survey profiles and distinguishing between hyperbolas originating from the cable or from random objects in the sediment, like boulders, result in high processing costs, too. Processing time can be reduced by using narrow-beam sub-bottom profilers (SBPs) instead of wide-beam systems. Narrow sound beams produce much less diffraction hyperbolas from boulders or other objects in the sediment and generate less reverberation (Fig. 3).

Survey tracks crossing the cable route have been successfully applied during DOB surveys for cables buried at water depths down to more than 50 metres using pole-mounted SBPs (Fig. 3). Also during surveys using electro-magnetic pipe/cable tracking equipment, SBP tracks across the cable route are utilised frequently for quality assurance.

4 Sonar track along the cable

This section shows possibilities to obtain the XYZ position of a buried cable while following the cable route. To get comparable results the same model is used for all configurations (Fig. 4):

- Flat sandy seabed 5 m below sensor with boulders spread in the sediment volume.
- Cable (diameter 10 cm) buried 1.5 m below seafloor (slightly dipping, angle ~0.6°).
- Survey vehicle moving not parallel to cable route (angle ~10°) to simulate the vehicle coming off-track.
- Linear wide-beam projector (beam width 50°) or parametric narrow-beam projector(s) (beam width 5°) of the same size.
- Linear hydrophones with same beam pattern as the linear projector.
- Sonar using CW pulses (centre frequency 10 kHz).

4.1 Projector and hydrophone at the same position

If an SBP follows a cable along track, the cable is seen like a sediment layer and there is no diffraction hyperbola. Burial depth and cable position can be determined assuming the SBP transducer was directly above the cable, but the error might be large depending on beam width and across-track position offset (Fig. 5). If the survey vehicle moves off the cable route, there is no helmsman guidance to correct this.

One idea to improve this situation is to use narrow sound beams pointing into different across-track directions (Schneider von Deimling et al. 2016; Wunderlich and Müller 2007; Wunderlich et al. 2005). Data from oblique beams can guide the helmsman to ensure the SBP stays roughly above the cable, but the localisation error will be still high.

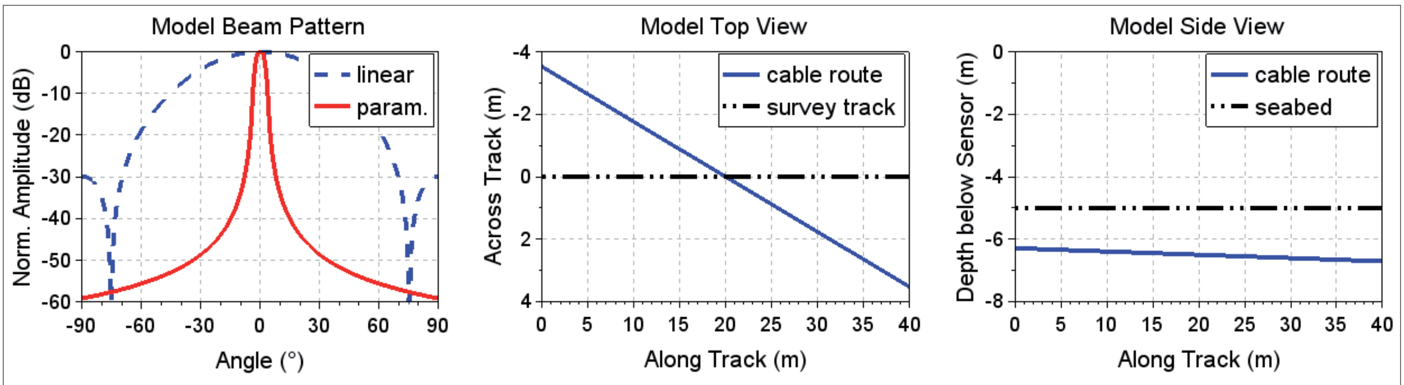

Fig. 4: Model used: linear (blue) and parametric (red) beam patterns, half-power beam width linear 50° and parametric 5° (left); model volume with cable (blue) and survey vehicle track (black) seen from top (centre); model volume with cable (blue) and seafloor (black) seen from the side (right)

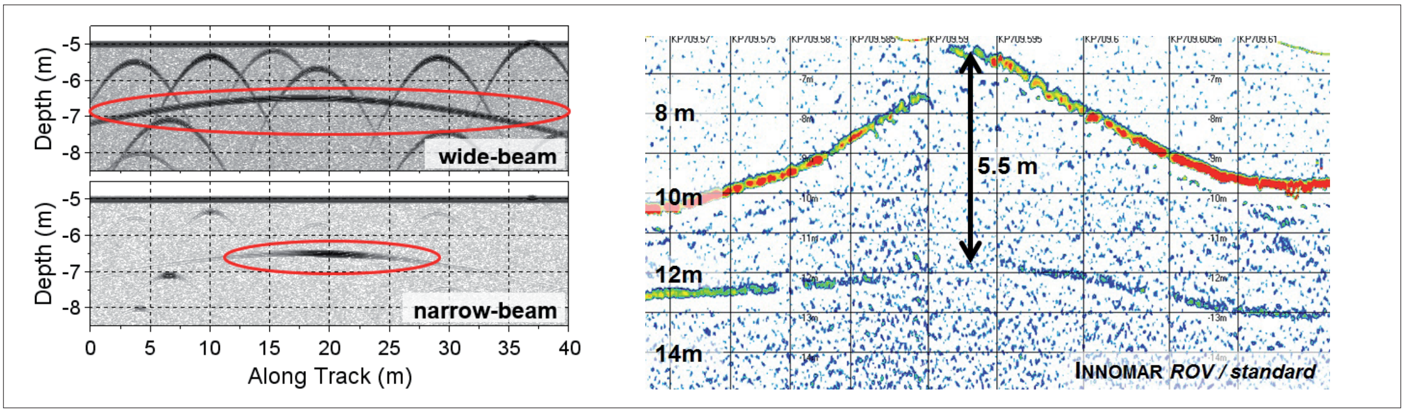

Fig. 5: Model echo prints from a cable (red marks) buried 1.5 m below seafloor surveyed along track according to the model shown in Fig. 4 (3.5 m off-track at start/end) and boulders spread in the seabed, for a linear wide-beam and a parametric narrow-beam system; boulders at the same locations for both data sets (left). Data example showing a pipeline followed along-track with burial depth up to 5+ m; pipeline echo level is decreased with increasing burial depth due to increasing sound attenuation; echo level reduction might be partly caused by the survey vehicle coming off-track, thus exact pipe position cannot be obtained (right)

4.2 Several hydrophones across track

At least two hydrophones at different positions across the cable track are needed to get the position of a buried cable. The receivers are ideally spread over the entire survey corridor. If only a few receivers are used with an across-track separation longer than half the wavelength, the target position can be obtained from the intersection of travel times from all receivers or by energy focusing of all receiver signals into the cells of a gridded volume. If a large number of receivers shorter than half the wavelength apart is used, phased array beam forming becomes possible and the receiver signals can be combined to a single echo print showing an across-track diffraction hyperbola at the target position. This can be used for online visualisation and quality assurance.

To fully insonify a wide survey corridor across track,

- one wide-beam projector at the swath centre pointing downwards or
- several narrow-beam projectors at the swath centre pointing into different directions or
- several narrow-beam projectors at different across-track positions pointing downwards

can be used.

As shown in section 2, wide sound beams will give higher reverberation levels decreasing the cable detection probability and lead to larger incidence angles resulting in larger position errors. Thus, narrow sound beams should be preferred. To avoid high transmission loss and large position errors at large incidence angles (cf. Fig. 2), these narrow-beam projectors are preferably spread across the survey corridor.

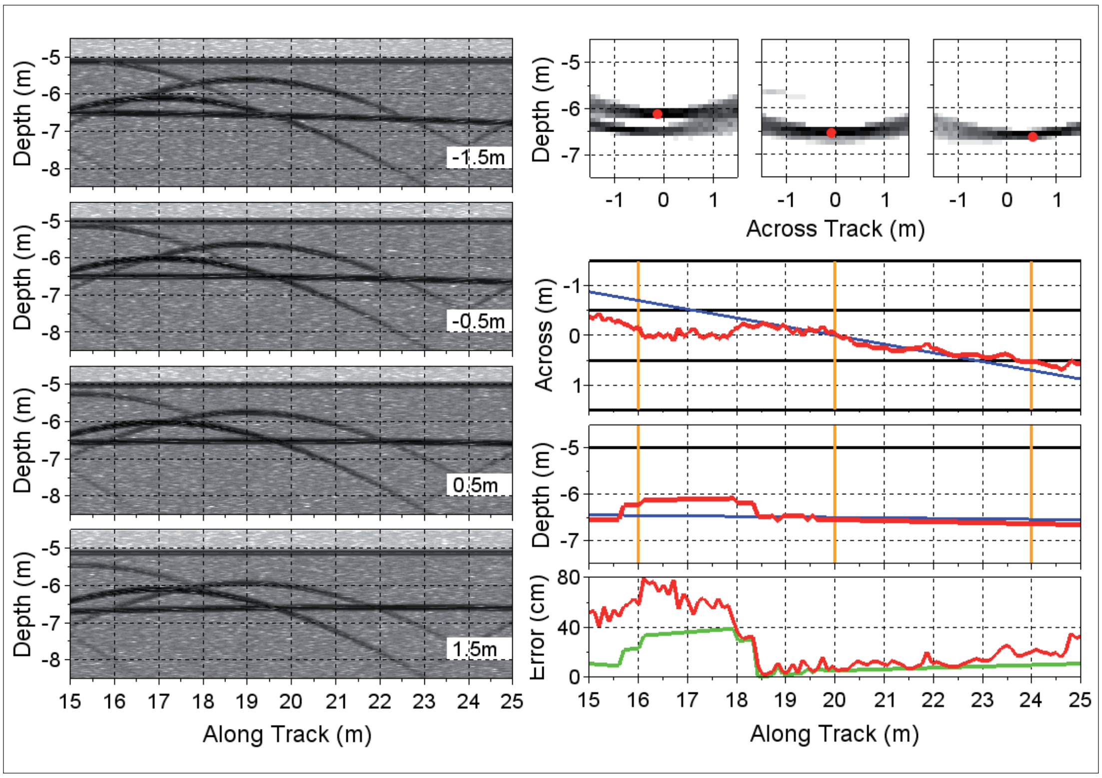

Fig. 6: One wide-beam projector covering the full swath and four hydrophones spread across-track 1 m apart following a cable according to the model shown in Fig. 4: echo prints of the four hydrophones (left); estimated (red) and true (blue) cable positions across track and burial depth; burial depth error (green) and total position error as Euclidian distance (red); receiver positions shown in black (right). Only the central ten metres of the model are shown. Cable position estimated from energy focusing. Large position errors due to boulders and refraction

The next two paragraphs show examples of different projector and receiver arrangements to illustrate advantages and drawbacks.

One wide-beam projector at the centre and several hydrophones across track

If one wide-beam projector at the swath centre is used together with hydrophones spread across the survey corridor, the full ping rate can be used and cable localisation will be possible at high position density and good accuracy (Fig. 6). To ensure the required accuracy across a full swath, extensive processing to reduce the refraction error (cf. Fig. 2) is necessary. This processing is not possible in real-time yet, so online results will be at much lower accuracy. Another issue is the high reverberation level due to the large insonified volume and seabed area. Reverberation can be reduced if two or more tilted narrow-beam projectors are combined to have a wider beam across- than along-track. The receiver signals are very similar and echo plots cannot be used to guide the helmsman to stay along the cable route.

Several narrow-beam projectors and several hydrophones across-track

To reduce reverberation and to avoid large localisation errors caused by oblique sound beams while still having the survey corridor fully insonified across track, several narrow-beam projectors can be used (Fig. 7). Compared to the wide-beam example shown in the previous paragraph, the reverberation level is much lower and much less boulder echoes interfere with the cable detection. Due to the smaller incidence angles the across-track cable position error is much lower and no time-consuming post-processing to reduce this error is necessary. The echo plots already show rough across-track cable position and can be used for helmsman guidance to stay above the cable.

5 Conclusions

Acoustic equipment is successfully used for cable DOB surveys. SBP survey tracks crossing the cable give the cable position at good accuracy, but position density along the cable track is limited. This position density is sufficient for maintenance DOB surveys and for quality assurance at surveys using electro-magnetic cable tracking equipment. Higher position density is either very costly due to increased survey and processing time or requires equipment following the cable along track. This needs an array of hydrophones spread across track and projector(s) to fully insonify the entire survey corridor. Best signal-to-noise ratio is achieved using narrow-beam projectors spread across track. This also reduces across-track position errors caused by (unknown) refraction at the water-seabed interface and avoids time-consuming post-processing to achieve full position accuracy. Online results can be used for quality assurance and to guide the helmsman. ⚓

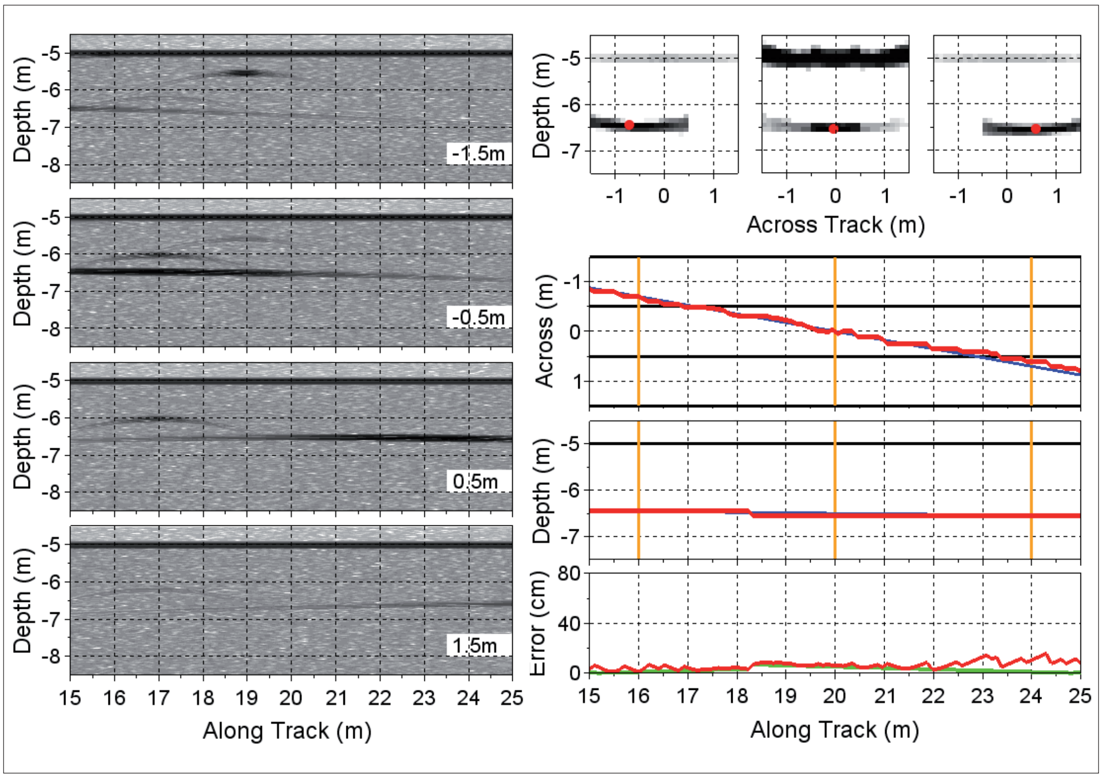

Fig. 7: Four narrow-beam projectors and four hydrophones spread across-track 1 m apart following a cable according to the model shown in Fig. 4: echo prints of the four hydrophones (left); estimated (red) and true (blue) cable positions across track and burial depth; burial depth error (green) and total position error as Euclidian distance (red); projector/receiver positions shown in black (right). Only the central ten metres of the model are shown. Cable position estimated from energy focusing. Much lower position errors compared to Fig. 6

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