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Comparison of different sub-bottom profiling systems to be used in very shallow and tide-influenced areas

A case study in the backbarrier tidal flat of Norderney, Germany

An article by CIGDEM ASKAR

Shallow waters are the transition zones between land and sea where human activities are dominant, such as building infrastructures and oil digging. Therefore, there is always a great interest in the stratigraphy of the sub-bottom in shallow waters. However, working in shallow waters is more complex than deep waters. Various seismic methods are used in subseafloor investigations, such as sparkers and air guns. Yet, these methods operate generally towed behind the vessel, which becomes challenging in very shallow waters. On the other hand, sub-bottom profilers operate mounted on the vessel; hence, more suitable for shallow waters. This article summarises findings from the Master Thesis that compared three sub-bottom profilers in very shallow and tide-influenced areas in the German Wadden Sea. The study was completed during an internship at the NLWKN Forschungsstelle Küste (FSK) Norderney.

sub-bottom profiler | shallow water | tidal flats | chirp SBP | parametric SBP
Sedimentecholot | Flachwasser | Watt | CHIRP-SBP | parametrisches Sedimentecholot

Flache Gewässer bilden die Übergangszone zwischen Land und Meer, wo menschliche Aktivitäten dominieren, wie z. B. der Bau von Infrastrukturen und Ölbohrungen. Daher besteht ein großes Interesse an der Stratigraphie in flachen Gewässern. Allerdings ist die Arbeit in flachen Gewässern komplexer als in tiefen Gewässern. Bei der Untersuchung des Bodenaufbaus werden verschiedene seismische Methoden eingesetzt, wie z. B. Sparker und Airguns. Diese Geräte werden jedoch in der Regel hinter dem Schiff geschleppt, was in sehr flachen Gewässern zu einer Herausforderung wird. Dahingegen arbeiten Sedimentecholote vom Schiff aus und sind daher für flache Gewässer besser geeignet. Dieser Artikel fasst die Ergebnisse einer Masterarbeit zusammen, in der drei Sedimentecholote in sehr flachen und tidebeeinflussten Gebieten im deutschen Wattenmeer verglichen wurden. Die Studie wurde während eines Praktikums beim NLWKN Forschungsstelle Küste (FSK) Norderney durchgeführt.

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Introduction

The challenge of shallow water surveys is their dynamic environment. Fierce wave actions, strong currents, shallow water depths, and a large tidal range are some factors that induce technological problems in shallow waters (Missiaen et al. 2018). The Wadden Sea is an example of such areas, an intertidal zone that extends along the south-eastern part of the North Sea and covers approximately 10,000 km^2 between the Frisian Islands and the coast of the Netherlands, the German Bight, and the Danish coast. The Wadden Sea system consists of large tidal flats, tidal gullies, inlets and sandy barrier islands (Hofstede 2005). Varying tidal ranges and meteorological circumstances work continuously on its geomorphology. While not all acoustic sub-bottom investigation methods are well suited for such environments, sub-bottom profiling works well.

Sub-bottom profiling is an acoustic technique used for investigating the characteristics of the seabed and the sub-surface layers and detecting buried objects, e.g. pipes or archaeological remnants. The method is similar to a single-beam echo sounder (SBES). An acoustic signal is vertically sent into water, then the echoes, which are reflected (not the backscattering) from the seabed and sub-surfaces, are recorded. Compared to SBESs, which operate at frequencies from 12 kHz up to 200 to 400 kHz, sub-bottom profilers (SBP) work at lower frequencies up to 10 kHz (Lurton 2010).

Parametric and chirp systems are commonly

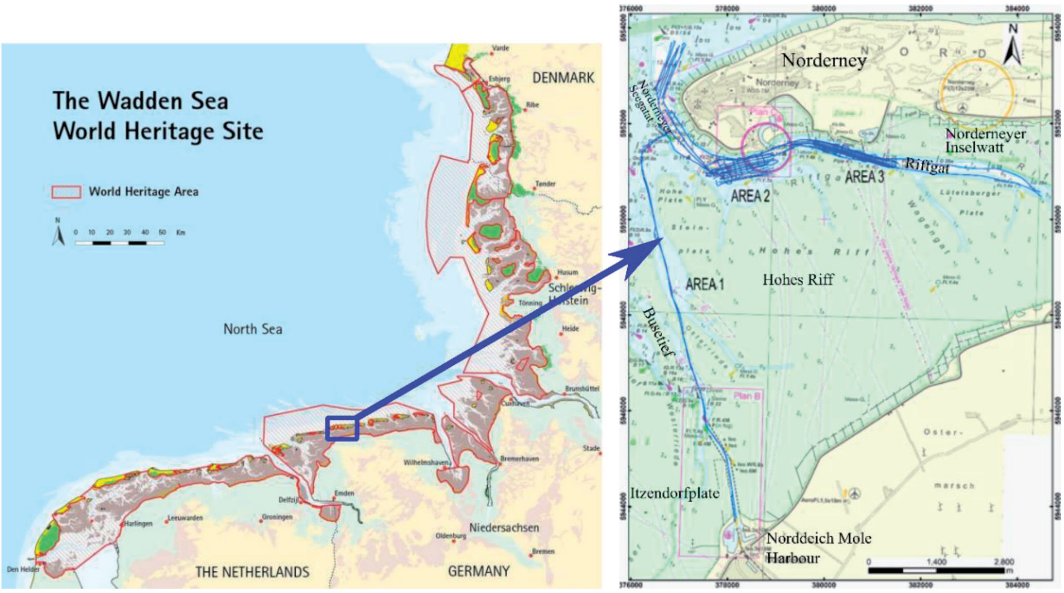

Fig. 1: Overview Wadden Sea (left), investigated areas and surveyed lines (right)

Source: Common Wadden Sea Secretariat, CWSS, 2017

used SBPs. The parametric SBP uses a nonlinear concept, the so-called parametric array, which produces the desired frequency using the nonlinearity in the medium. It sends two slightly different high frequencies (primary frequencies) into the water under high sound pressure. Due to the medium's nonlinearity, new frequencies (secondary frequencies) are generated, such as difference and sum. The difference is the low frequency used in parametric systems and can penetrate deeper into the seafloor while keeping the low horizontal resolution of the high primary frequencies. The chirp SBP transmits chirp signals, wide-band, frequency-modulated (FM) signals that sweep a wide range of frequencies, mostly varying from 2 to 20 kHz. Upon reception, chirp signals are correlated with a copy of the transmitted signal, and the envelope of the correlation's output is detected (Lurton 2010). This process is called pulse compression, which refers to producing a temporal response narrower than the received signal's duration by matched filtering (Abraham 2017). The vertical resolution depends on the output pulse width of this process rather than the received echo width.

This thesis compared three sub-bottom profilers, Echoes 10000 (iXblue), SES-2000 Quattro (Innomar) and Topas PS 120 (Kongsberg). Table 1 summarises specifications of each instrument.

Data acquisition and processing

The data was collected between March and May 2019 in cooperation with the FSK, which also provided this study with the supplementary data, like sediment cores, grab samples, bathymetric and backscatter data sets. The investigated region consisted of three different areas (Fig. 1) in the German Wadden Sea's Norderney tidal inlet. Area 1 had a very shallow water depth of less than 10 m. The seabed was covered mainly by coarser sediment or showed an irregular surface in parts due to some marine organisms. The sub-seabed here had alternating layers of marine and terrigenous sediments. The peat layers were one of the frequent deposits. Area 2 was located at the Riffgat channel entrance, close to the open sea and affected by strong tidal currents, waves and wind. Therefore, the sub-bottom consisted of a very compact glacial Pleistocene base under a very thin recently accumulated sediment, and coarser sediments covered the seabed. Area 3 had an irregular seabed due to the tide-induced ripples and high dunes along with coarse sediments. Also, the sub-bottom comprised a homogenous type of deposits in this area.

The instruments were not used simultaneously but on different dates due to the planning with other parties. The systems were pole mounted

Instrument	Manufacturer	System	Pulse form	Operating/secondary frequency	Primary frequencies	Vertical resolution
Echoes 10000	iXblue	Chirp	Chirp	5–15 kHz	–	8 cm
SES-2000 Quattro	Innomar	Parametric	Ricker, CW	4, 5, 6, 8, 10, 12 kHz	85–115 kHz	up to 5 cm
Topas PS 120	Kongsberg	Parametric	Ricker, Chirp, CW	2–30 kHz	70–10 kHz	less than 5 cm

Table 1: Instruments' specifications

on the port side of the vessel, MS *Burchana*. The same motion sensor and dual-antenna positioning system provided motion and navigation data. For a better comparison, the acquisition parameters were kept as constant as possible. Since the region experiences semi-diurnal tides, surveys were performed during both high tides and low tides. The wind mainly was strong on the survey days due to the season. As a result of the wind and tidal currents, the vessel speed changed from 5 knots to 7 to 7.5 knots, although the intention was to keep it less than 5 knots.

The data was post-processed with the Delph Seismic Interpretation software from iXblue. The sound velocity was applied as constant 1,500 m/s, and the tide was corrected. Furthermore, a matched filter was applied to the Echoes 10000 data while a bandpass filter was applied to the Topas PS 120 data. No filter was applied to the SES-2000 Quattro data. The absorption loss was balanced by applying some gain during processing. Lastly, the data was heave corrected, if not corrected during the acquisition, and backscatters from the water column were removed.

Each system's data was evaluated against the specialities of the surveyed areas concerning systems' technique by focusing on the penetration depths, visual quality of the plots and vertical resolution. The FSK mainly conducts surveys for geophysical investigations, which demands deeper penetration capacity with sufficient resolution. Therefore, penetration capability was an important criterion in comparison. On the other hand, the sub-bottom profiler data interpretation is not fully automated yet and demands quite a lot of time. Hence, the final image's visual quality is of importance for an effortless interpretation and was another essential criterion of the comparison. Besides, there is a constant sedimentation cycle and transport in the Wadden Sea, resulting in changes in the tidal channel and creeks. These events happen both in the noticeably short and long term. A good vertical resolution, therefore, is paramount to trace these events over time.

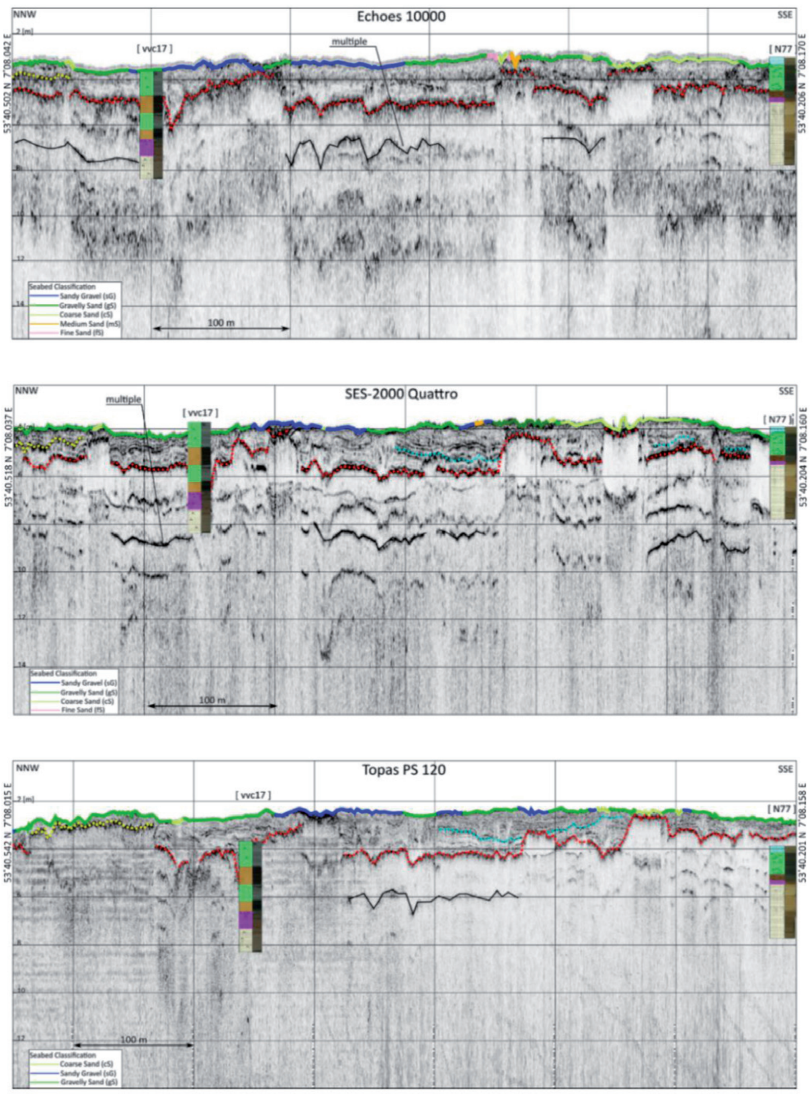

Fig. 2: Echograms of Area 1 acquired with a chirp frequency of 5 to 15 kHz and parametric low frequency of 8 kHz. The seabed is covered mainly by coarse sediments. The strong red reflector is interpreted as peat according to the core sample. The thinnest of laminated layers is 9 to 10 cm. The rest is acoustically blanked parts and multiple echoes. The same reflectors on each plot are interpreted with similar colours

Results

In Area 1 (< 10 m, coarse sediment), the systems achieved a maximum penetration of 2 to 4 m; yet, it was sometimes not exceeding 0.5 m (Fig. 2). Beneath these depths, there were transparent zones and multiples on the echo plots. Partly, there were laminated reflectors, the thinnest of which was measured as 9 to 10 cm. Visually, the echo plots from the parametric systems SES-2000 Quattro and Topas PS 120 demonstrated slightly better performance, especially in displaying thinly layered sediments.

In Area 2 (compact sub-bottom sediments topped by a thin layer of Holocene sediments), the average penetration depth was around 3 to 4 m in the deep channel for all systems (Fig. 3). In the shallow part, an old channel and fillings were visible on the plots. Here, the penetration was slightly deeper than in the channel centre, about 5 m, marking the old channel bed. SES-2000 Quattro penetrated slightly deeper, approximately 7 m below the seabed. The vertical resolution was 8 cm for each system. Visually, reflectors on the Echoes 10000 and Topas PS 120 were in parts weak that needed more effort to interpret. However, Echoes 10000 provided a good result in the very shallow tidal flat, considering it is a chirp system.

In Area 3 (homogeneous sediments, sand dunes and ripples), while the systems reached only down to 1 m from the seabed in the channel (Fig. 4), the penetration was around 3 m on the flanks. The Echoes 10000 and SES-2000 Quattro achieved similar penetrations along the longitudinal survey lines, while the Topas PS 120 displayed slightly fewer reflectors. However, the SES-2000 Quattro provided slightly better visualisation of the reflectors than the Echoes 10000. Also, the SES-2000 Quattro's performance along the transversal survey lines was moderately ahead of the Echoes 10000 and Topas PS 120 regarding penetration and visualisation of the reflectors. In Area 3, the ripples and the coarse sediment cover on the seabed blocked the systems' penetration of the seabed in the northern part of the channel.

Discussion

In Area 1, the systems were affected by the gaseous peat deposits, very shallow water depths and coarser sediments on the seabed. Peat is made of organic matters (such as mosses, grasses, shrubs), which do not entirely decompose due to water excess (Bozkurt et al. 2001). During the Wadden Sea region's transgression times, the barrier and tidal inlet system advanced landward, which resulted in flooding and subsiding of the peat areas due to the high-water content. Increased space of the inlet system led to an increase in the tidal prism, resulting in further subsiding of the peat areas due to the heavy deposits of clay brought by storms (Vos and Knol 2015). As a result of alternating transgressions and regressions, there are multiple peat layers in Area 1. In shallow water deposits, gas primarily results from the biogenic decomposition of organic matter (Floodgate and Judd 1992). The gaseous sediments are easily detected in the acoustic data because of their distinctive reflections. Higher acoustic and elastic contrast than the surrounding non-gaseous medium characterise gas-bearing deposits (Jaśniewicz et al. 2019). The gaseous sediments attenuate most acoustic energy and prevent further penetration; hence strong reflectors with a transparent zone underneath mark these sediments.

Besides the gaseous sediments, very shallow water depths affected the systems. Caused by the shallow water depths, multiples led to problems in interpreting the sub-bottom structures (Hung et al. 2010). Lastly, the seabed characterisation in Area 1 is attributed to another factor for limited penetration. On the echo plots, the first strong reflection represents the seabed where the acoustic impedance differs in the water-sediment border, and bottom sediments strongly affect the penetration depth (Hurtado et al. 2013). After most acoustic energy is reflected and scattered on the surface, the rest will penetrate the seabed. Jones et al. (2017) state that tens of metres of penetration in soft sediments will severely diminish within sand or rock in parametric systems. In chirp systems, the penetration might be as low as 3 m within coarse sediments. In contrast, it can be up to 200 m in soft sediments (Jones et al. 2017), depending on the water depth. Coarse sediments cause stronger scattering than the finer sediments due to their bigger grain size; hence, less signal penetrates through the medium. Some marine species, like Lanice conchilega in Area 1, increases seabed roughness, which results in higher scattering of the acoustic energy.

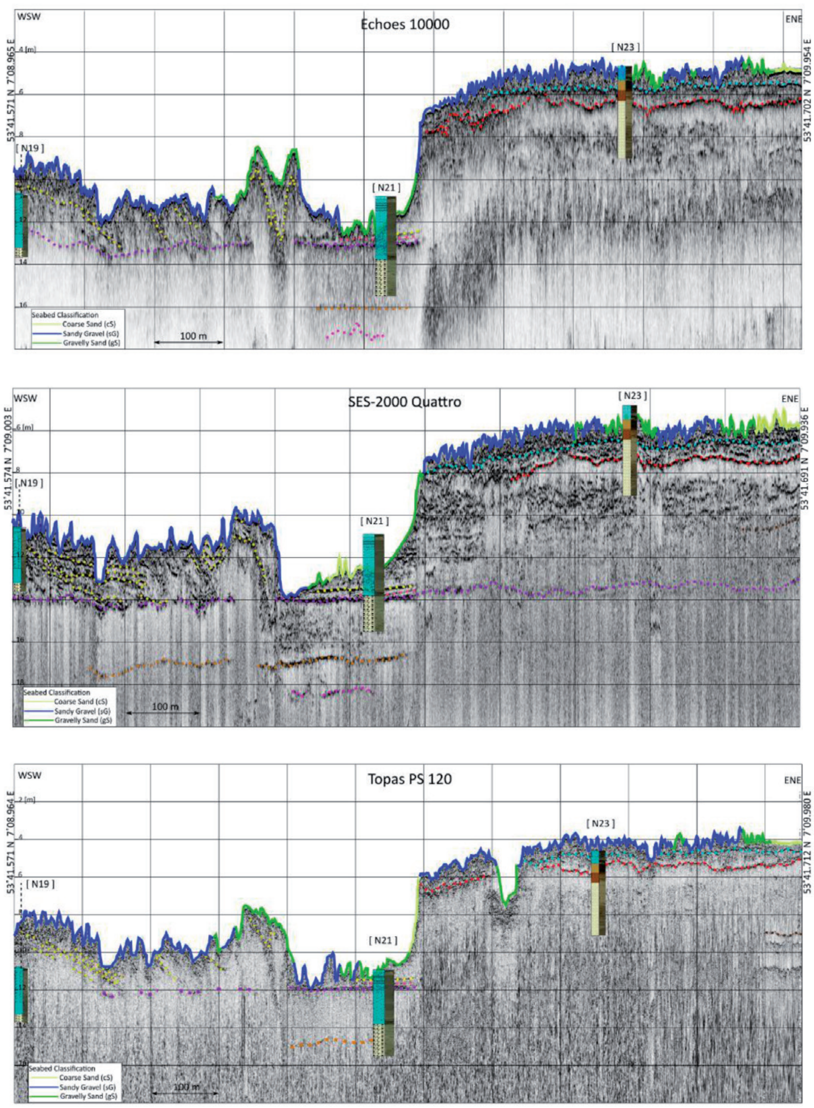

Fig. 3: Echogram showing the fillings of an old channel in the WSW edge in Area 2. Echoes 10000 and SES-2000 Quattro reached 5 m from the seabed in the trench, while Topas PS 120 reached only 3 m. In the ENE, SES-2000 Quattro achieves 7 m penetration. Same reflectors on each plot are interpreted with similar colours

In Area 2, the systems performed on a very compact seabed covered by coarse sediments in the channel and shallow water depths with peat deposits in the tidal flats. The Holocene deposits in the channel of Area 2 are scoured out due to the strong currents in the Riffgat channel's mouth. Hence, the sub-bottom layers are very compact. As stated in McGee (1995), consolidated sediments demonstrate strong scattering and lessen the seabed acoustic signal penetration. Besides the packed bottom, coarser sediments on the seabed also increased the scattering, and less energy is transmitted to the seabed. In the southern part of the area, where there was a thicker Holocene deposit, the systems performed better. However,

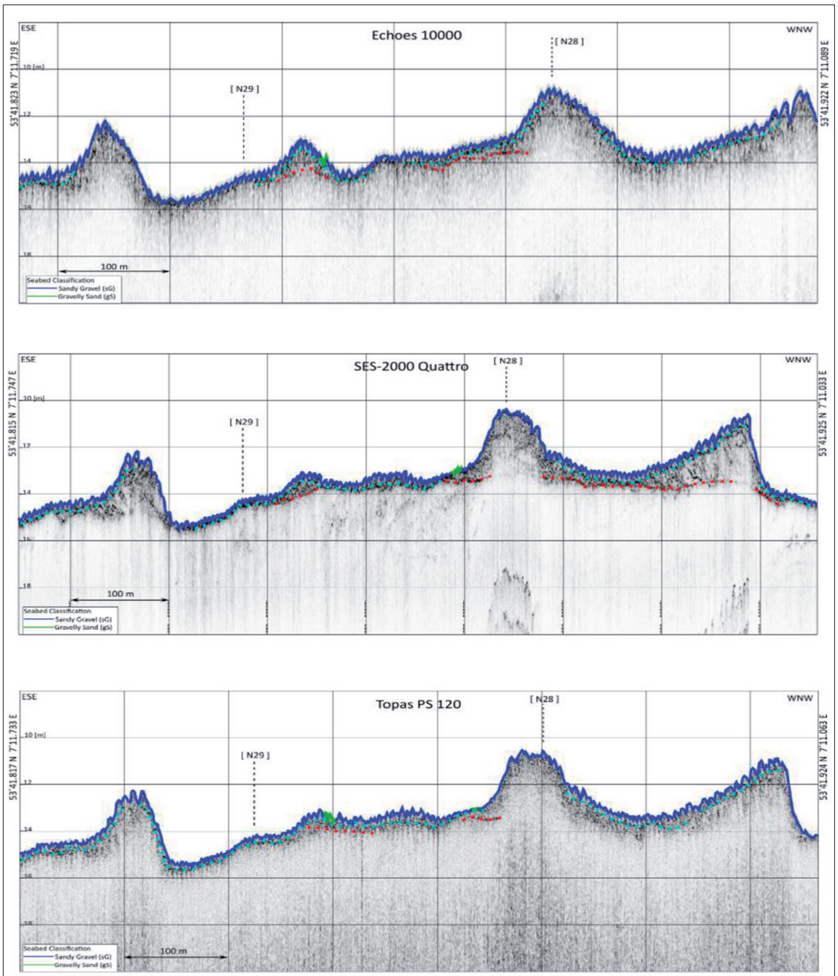

Fig. 4: Echogram of Area 3 showing ripples and dunes, acquired with a chirp frequency of 5 to 15 kHz and parametric low frequencies of 12 kHz (SES-Quattro) and 8 kHz Topas PS 120. Gravelly sandy sediments cover the seabed. There are only a few reflectors presented on each echo plot. The penetration is limited by the small ripples on the seabed, coarse sediment on the seabed and homogeneous sub-bottom sediment. The same reflectors on each plot are interpreted with similar colours

penetration was affected by the shallow waters in the tidal flats and the peat deposits.

In Area 3, irregular seabed with ripples and high dunes, the coarse sediment cover and the homogenous type of sub-bottom deposits impact the systems' performance. Rough surfaces spread the scattering in all directions while strongly attenuating the specular reflection (Lurton 2010). The increased scattering results in less energy transmitted into the sub-bottom. Besides that, the core samples suggest a homogenous type of sediment for the upper few metres, which means no change in the acoustic impedance. Therefore, no strong reflection is recorded until the signal encounters a border between mediums of different densities.

Conclusion

These results showed that shallow waters, especially areas under tide influence, are challenging to work with. Each system used in the study promised a reliable performance according to their specifications; although, they were affected by the surveyed areas' complex settings. The systems' capabilities in achieving deeper penetrations, visual representations of reflectors and the vertical resolution, performances in revealing thin layers of sediments were the main criteria in the comparison.

The parametric SES-2000 Quattro provided better penetration capability while maintaining a good resolution. The parametric Topas PS 120 and chirp system Echoes 10000 performed similarly in the penetration they achieved. The visual representation of reflectors on Echoes 10000 was weaker than on the parametric SES-2000 Quattro, whereas the parametric Topas PS 120 also provided a weak visualisation. This, for Echoes 10000, arose from the used power levels, which were preferred in order not to cause reverberation in the shallow environment of the study area. It operated at a lower transmission power level (1 to 3 ms pulses at 10 to 20 % power level) compared to its optimal configuration (~10 ms pulse at 50 to 70 % power level). For Topas PS 120, it is attributed to the higher vessel speed, which was higher than the suggested speed, 3 to 5 knots, as stated in the instrument manual. Regarding the vertical resolution, all systems performed well due to the narrow beam pattern of parametric systems and the chirp system's broad frequency range. The thinnest layers displayed by each profiler were as thin as 7 to 8 cm.

Besides their performances, the setup and the handling of the software during data acquisition/processing were straightforward for all systems. The user guides thoroughly explain the steps of installation, data collection and processing, and sub-bottom profiling technique. There was no interruption during the surveys that stemmed from system malfunctions. Also, the transducers' compact sizes make them handy for operating in shallow waters; however, one has to be careful in waters shallower than 3 m, especially in the presence of strong currents, not to run aground with the system on the pole. //

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