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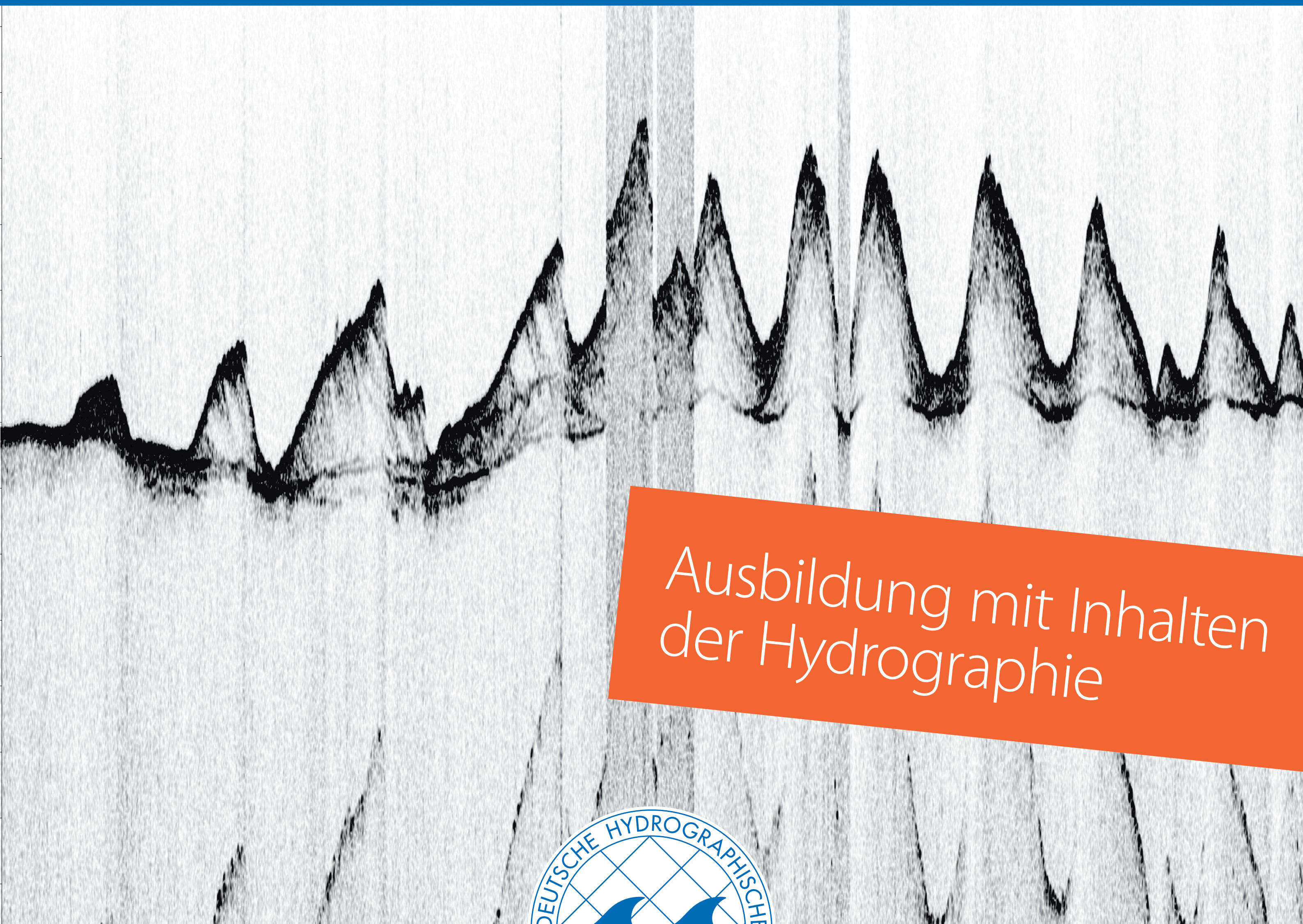

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Enhancing MBES surveying by multi-frequency technology

Checking the feasibility of the multi-frequency functionality of the EM2040P MKII MBES for shallow water investigation

An article by TONY SEBASTIAN

By using the multi-frequency mode of the EM2040P MKII echo sounder, the riverbed of the Elbe River near Hamburg Port was analysed. By conducting a single survey run utilising multi-frequency mode with three different frequencies, the system demonstrated its capability to detect soft sediment layers with improved clarity. Bathymetric analysis revealed significant variations in the volume between bathymetric surface levels of each frequency dataset, with differences amounting to approximately 3,310 m³ across an area of 78,995 m². Additionally, backscatter intensity distribution of the different frequencies in the same areas were analysed. Individual backscatter mosaics corresponding to each frequency were generated and analysed separately. These mosaics were then combined to create a multi-spectral image, effectively illustrating the differing sediment penetration capabilities of each frequency over the same riverbed area within a single survey run. The results highlight the value of multi-frequency surveys in enhancing the interpretation of riverbed composition and morphology within a single data acquisition effort.

multibeam echo sounder | multi-frequency survey | backscatter intensity
Fächerecholot | Mehrfrequenzmessung | Rückstreuintensität

Mit Hilfe des Multifrequenzmodus des Fächerecholots EM2040P MKII wurde das Flussbett der Elbe in der Nähe des Hamburger Hafens analysiert. Durch die Durchführung einer einzigen Vermessungsfahrt im Multifrequenzmodus mit drei verschiedenen Frequenzen ermöglicht das System, weiche Sedimentschichten klarer zu erkennen. Die bathymetrische Analyse zeigte signifikante Unterschiede im Volumen zwischen den bathymetrischen Oberflächenebenen der einzelnen Frequenzdatensätze, mit Unterschieden in Höhe von ca. 3310 m³ auf einer Fläche von 78 995 m². Zusätzlich wurde die Verteilung der Rückstreuintensität der verschiedenen Frequenzen in denselben Gebieten analysiert. Für jede Frequenz wurden individuelle Rückstreumosaike erstellt und separat analysiert. Diese Mosaike wurden kombiniert, um ein multispektrales Bild zu erstellen, welches die unterschiedlichen Sedimentdurchdringungsfähigkeiten der einzelnen Frequenzen effektiv veranschaulicht. Die Ergebnisse verdeutlichen den Wert von Mehrfrequenzmessungen zur Verbesserung der Interpretation der Zusammensetzung und Morphologie des Flussbettes innerhalb einer einzelnen Messfahrt.

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Background

The development of multibeam echo sounders (MBES) has significantly advanced the field of hydrography, offering a wide range of applications for both bathymetric and backscatter analysis. While research improves their functionality, challenges persist in survey parameters and time efficiency. This remains a complex issue in the field. Recent advancements in hydrography have focused on reducing data acquisition time, which in turn helps lower the associated costs.

The Elbe River near Hamburg has highly variable sediments (sand, clay, rock, fluid mud), complicating depth measurements. These conditions can lead to inaccuracies in depth determination. The accuracy of both depth and backscatter intensity measurements is highly influenced by the frequency of the acoustic signal, as different frequencies interact differently with sediments. Higher frequencies, for instance, may fail to penetrate fluid mud layers, leading to misleading bathymetric results.

With innovations in the hydrographic field, Kongsberg has developed a new MBES system with a new multi-frequency feature. Instead of using a single frequency for one survey, now it is possible to use up to five different frequencies in a single-pass MBES survey. The introduction of broadband MBES allows each operating central frequency to be on each ping. The operating frequency can be modified on a ping-by-ping basis (Fig. 1). The main advantage of this feature is that it can collect different datasets of different frequencies in a single survey run. Eventually, it reduces the time for data acquisition, which is one of the main constraints of the hydrographic surveys, along with the mentioned frequency-based problems.

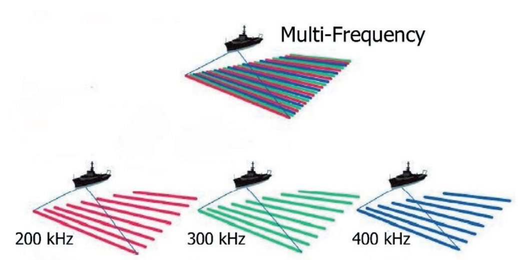

Fig. 1: Multi-frequency data acquisition (edited image from Brown et al. 2019)

Survey location and data acquisition

The Elbe River is one of the major rivers in Central Europe, with the Port of Hamburg – a key economic hub and one of Europe's most significant ports – located along its banks. The riverbed primarily consists of fine to coarse gravel and sand, with grain sizes ranging from 0.5 mm to 30 mm. However, ongoing dredging operations between the port and the North Sea have altered the river's natural geomorphology and sediment distribution (Scholten et al. 2003).

This study aims to enhance the understanding of the multi-frequency capabilities of the Kongsberg EM2040P MKII multibeam echo sounder by analysing frequency-dependent variations in bathymetry and backscatter data along the riverbed of the Elbe River. The research focused on three strategically selected survey sites within the Port of Hamburg area, each chosen for its distinct riverbed characteristics and sediment composition.

The selected survey sites included Hansahafen, a historic cargo harbour near HafenCity University (HCU) established in 1893, where a 140 × 50 m area of the southern channel – characterised by infrequent dredging and traditional ship piers – was surveyed to examine soft sediment and floating mud responses at 200, 300 and 400 kHz. The Köhlfleet channel near Finkenwerder, featuring a heterogeneous riverbed of stone walls, sand and fluid mud, was chosen to investigate multi-spectral backscatter responses and suspended sediment layering, with particular focus on the entrance and berthing area. Finally, the Strom Barrage (Billwerder Bucht) was surveyed due to its concrete bedding beneath the gate structure, which provided a highly reflective surface ideal for evaluating frequency-dependent interactions (200, 300 and 400 kHz) with hard substrates. Fig. 2 presents the geographic distribution of the selected survey sites within the Hamburg Port area.

The survey was conducted aboard HCU University's *DVocean* vessel, equipped with a pole-mounted Kongsberg EM2040p MKII MBES system operating at 200 to 700 kHz with 512 beams per swath. The setup included an AML-3 LGR sound velocity profiler for water column corrections, a Septentrio AsteRx-U3 GNSS receiver with RTK positioning, an iXblue Hydrins G4 inertial navigation system and an Innomar SES-2000 sub-bottom profiler. This set of instrumentation enabled detailed evaluation of the MBES's multi-frequency performance across different survey conditions while ensuring high-quality data collection through precise positioning and environmental compensation.

Data processing and analysis

The bathymetric data collected in Qinsy's DB format were processed in Qimera, with additional KMALL files from SIS 5 used to handle the multi-frequency datasets more effectively. These files were separated into individual frequency-specific versions using Kongsberg's KMALL Datagram Splitter before being processed separately in QPS Qimera (v2.5.0) under a WGS 84 (ETRS89/UTM Zone 32N) horizontal coordinate system and German Combined Quasi-geoid 2016 vertical datum. Following patch tests and offset calibration, the data underwent swath editing, CUBE-based automated cleaning and cross-check validation, with all final surfaces meeting IHO S-44 Special Order standards. This systematic approach ensured high-quality results across all three survey locations.

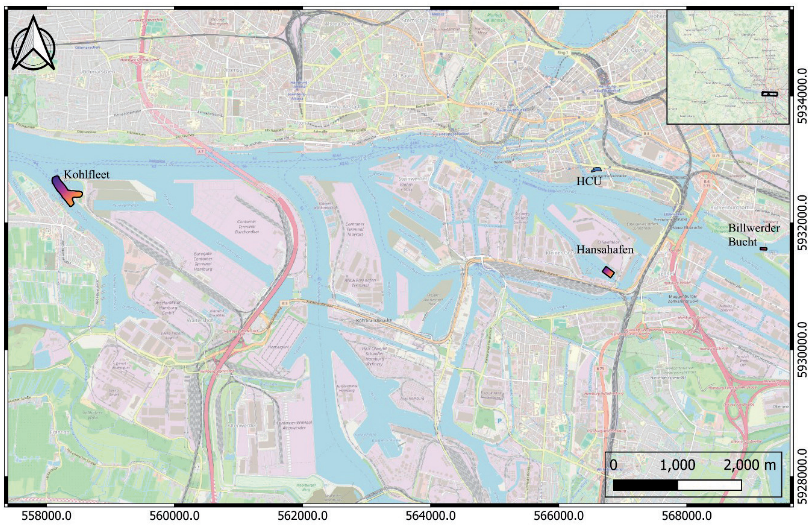

Fig. 2: Survey areas in the Port of Hamburg (created using QGIS, EPSG 25832)

After validation and quality checks, frequency-based DTMs were exported as XYZ files for further analysis. These DTMs, representing riverbed topography, were analysed in Civil 3D software to determine various riverbed levels. Alongside bathymetric data, the survey also captured backscatter intensity, which provides insights into the composition of riverbed materials such as sand, gravel or rock (Brown et al. 2019).

The processed and cleaned bathymetry data from QPS Qimera was exported as GSF files and imported into FM Geocoder Toolbox (FMGT) for backscatter processing. The latest version of FMGT (7.10.2) allows separation of frequency-based pings directly from the MBES datagram, enabling the creation of frequency-specific mosaics without the need to import individually split files (QPS 2022). Radiometrically corrected backscatter files were imported with georeferencing, and separate mosaics were generated for each frequency. Additional with the individual mosaics a multispectral image (RGB) was build for each survey location using the software, with the new option in the software (QPS 2022). The three channels for the RGB image are correspondingly 200 kHz, 300 kHz and 400 kHz.

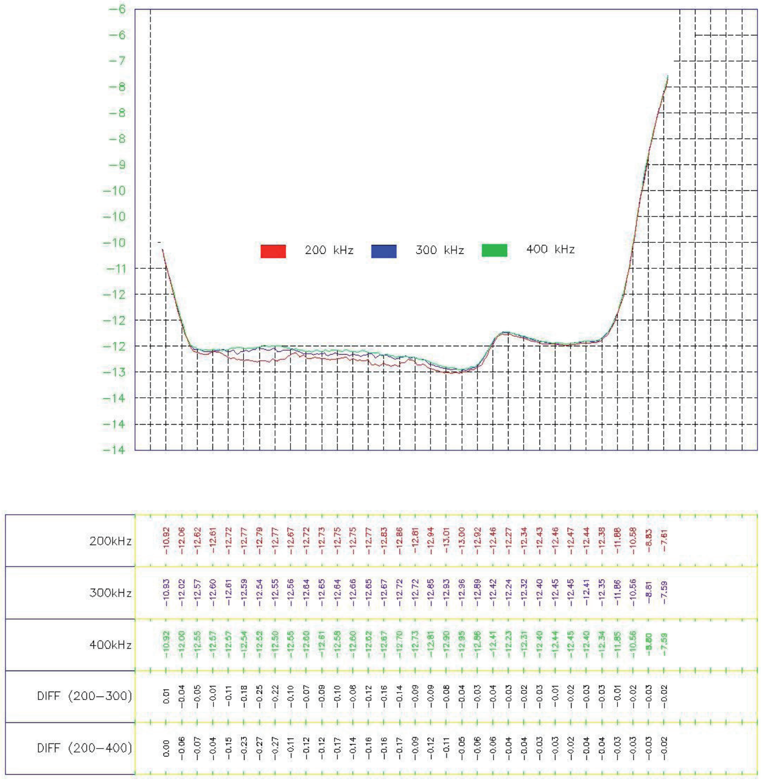

Fig. 3: Section drawing the determination of different riverbed levels – Köhlfleet

Volume Summary

Name	Type	Cut Factor	Fill Factor	2d Area (sq.m)	Cut (Cu. M.)	Fill (Cu. M.)	Net (Cu. M.)
200-300	full	1.000	1.000	78961.10	56.64	2320.64	2264.01<Fill>
200-400	full	1.000	1.000	78995.14	43.30	3309.13	3265.83<Fill>

Fig. 4: Cut-and-fill calculation – Köhlfleet

Results

Bathymetric analysis

Autodesk Civil 3D compared multi-frequency bathymetric surfaces (200/300/400 kHz) from Köhlfleet and Hansahafen. Cleaned DTM data (XYZ format) were converted to TIN surfaces and analysed using cross-sections, colour-coded by frequency (red = 200 kHz, blue = 300 kHz, green = 400 kHz). Quantitative analysis revealed frequency-dependent depth variations, with 200 kHz detecting surfaces up to 30 cm deeper than 400 kHz (Fig. 3), demonstrating superior sediment penetration. Conversely, 400 kHz resolved shallower layers more precisely, confirming frequency selection critically impacts riverbed characterisation.

At Hansahafen, the maximum variation between bathymetric surfaces from the 200 kHz and 400 kHz frequencies was 14 cm, and 12 cm between 200 kHz and 300 kHz, with the largest difference observed at chainage 120 m along the survey alignment. In some areas, all three frequency surfaces aligned perfectly, resulting in no difference. In contrast, the Köhlfleet area showed greater variation – up to 30 cm between 200 kHz and 400 kHz, and 25 cm between 200 kHz and 300 kHz, with the highest difference found at chainage 60 m along the west-east alignment.

Beyond depth comparisons at each section, the study also assessed overall volume differences across the survey areas. Using the 200 kHz surface – typically the deepest – as a base, surfaces from the 300 kHz and 400 kHz frequencies were compared to measure the impact of frequency on total surveyed volume. Cut-and-fill reports were generated for each site (Fig. 4), providing a clear view of volume differences. »Fill« areas indicated additional volume detected by the lower 200 kHz frequency, representing deeper regions not captured by higher frequencies. These reports offer valuable insight into how frequency selection influences both depth and volume calculations.

Backscatter analysis

The bathymetric analysis reveals that lower frequencies achieve greater penetration depth at Hansahafen and Köhlfleet compared to higher frequencies. While backscatter intensity typically increases with frequency when surveying identical riverbed compositions, the observed penetration differences suggest each frequency may interact with distinct sediment layers. This creates variations in both bathymetric surfaces and backscatter intensity measurements. To examine these effects, backscatter mosaics produced in FMGT software were analysed.

The distribution of backscatter intensity across the survey area is compared using mosaics generated for each frequency. A multi-spectral image is also produced by combining the individual mosaics from 200 kHz, 300 kHz and 400 kHz. Fig. 5 and Fig. 6 show the results of the comparison from Hansahafen and Köhlfleet, respectively.

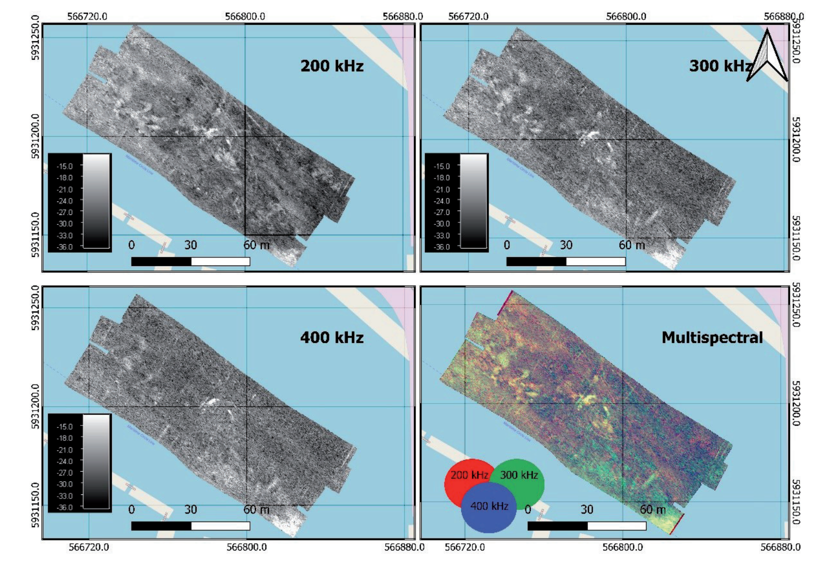

Fig. 5: Visual analysis of single mosaics with multi-spectral image – Hansahafen

Discussion

Bathymetric analysis of multi-frequency mode

The results showed that different frequencies produced distinct bathymetric surfaces, with soft sediments and fluid mud significantly affecting depth measurements. Depth differences reached 30 cm in Köhlfleet and 14 cm in Hansahafen, highlighting sediment-related inaccuracies. In Hansahafen, 90 % of the area had multiple surfaces, as the 200-kHz signal penetrated deeper into soft sediments. Fig. 7 also shows increasing depth differences from north to south in the channel.

Soil samples from the northern (VV3) and southern (VV2) survey areas supported the findings. The northern sample had higher sand content (12 %), resulting in smaller bathymetric differences, as the 200-kHz signal penetrated less due to denser sediment. In contrast, the southern part showed greater penetration, indicating softer sediments.

At Köhlfleet, fluid mud was detected, with the largest bathymetric discrepancy (30 cm) at the centre (Fig. 8). Sub-bottom profiler (SBP) data confirmed a fluid mud layer of 60 to 70 cm, deeper than the 25 cm difference observed between 200 kHz and 400 kHz measurements. The SBP's low-frequency (10 kHz) parametric effect enabled deeper penetration. Turbidity measurements near the riverbed (11 m depth) showed a rise from 12.91 to 17.54 NTU, indicating increasing suspended particles toward the bottom. This gradient suggests higher sediment concentration near the riverbed.

The findings from the Hansahafen and Köhlfleet regions show that different bathymetric surfaces created using three different frequencies showed differences of up to 30 cm in some locations. These variations indicated the presence of soft material or fluid mud in those areas. To validate this detection method, a multi-frequency survey was conducted at Billwerder Bucht, where the riverbed is composed of concrete. Since the bed material is hard, it was anticipated that the bathymetric surfaces generated by different frequencies would show similar depths.

As expected, the bathymetric surfaces produced using all three frequencies are almost identical in depth, as illustrated in Fig. 9. Even along the edges of the concrete bed, the bathymetry remained consistent. This could be attributed to the fact that

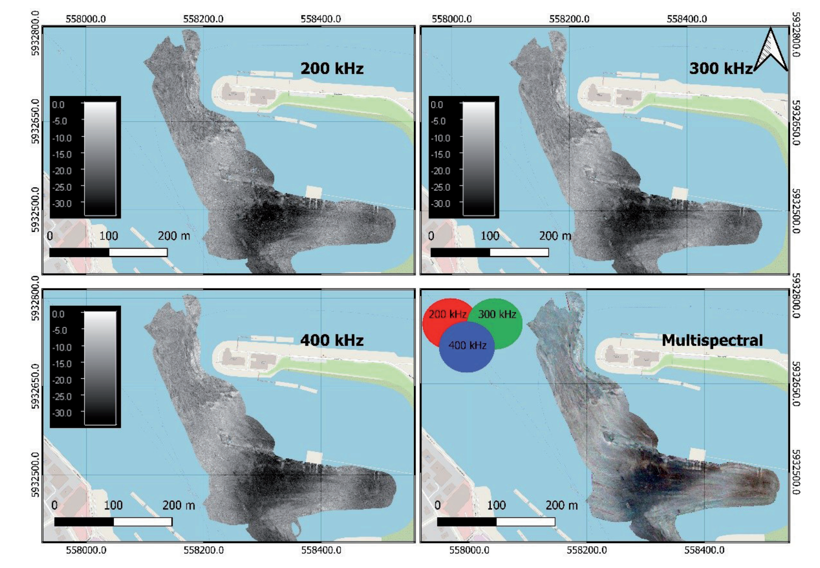

Fig. 6: Visual analysis of single mosaics with multi-spectral image – Köhlfleet

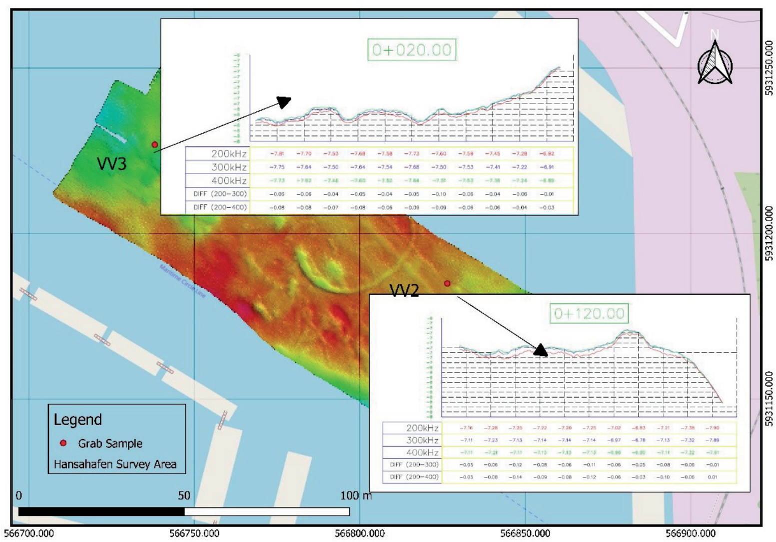

Fig. 7: Map with section drawing showing the different bathymetric surface setection – Hansahafen

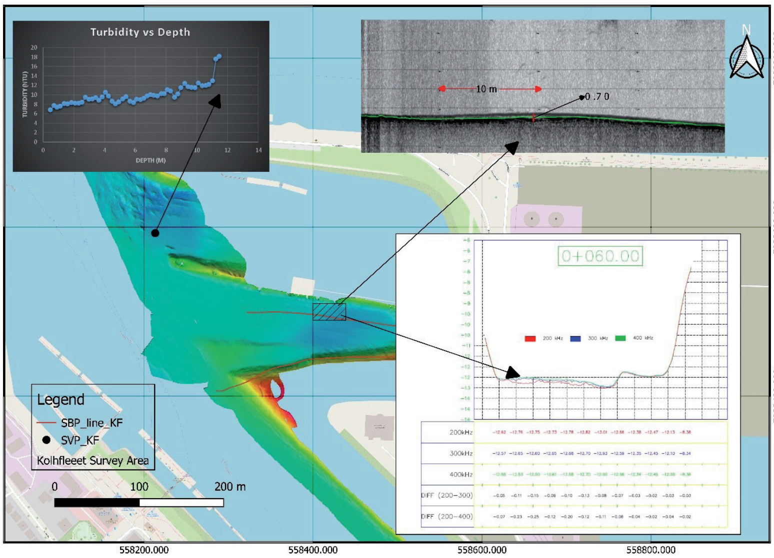

Fig. 8: Map with section drawing showing the different bathymetric surface setection – Köhlfleet

any soft material near the concrete bed had likely been eroded away by scouring, thereby exposing the harder riverbed material underneath.

This validation shows that multi-frequency bathymetric surveys can effectively differentiate between hard and soft riverbed materials. The consistent results at Billwerder Bucht support the idea that differences in bathymetric surfaces, like those observed in Hansahafen and Köhlfleet, can surely be indicative of the presence of soft or fluid materials.

Backscatter analysis

Following the promising results of the multi-frequency bathymetric analysis, this section focuses on the findings from the backscatter data. The locations Köhlfleet and Hansahafen selected for image-based analysis due to the noticeable penetration differences between low and high frequencies. In these areas, mosaics revealed clear variations in backscatter intensity, making them ideal for further investigation.

At Hansahafen, two sediment samples were collected along the survey boundary. The northern sample (VV3) was identified as clay with 12 % sand, while the southern sample was pure clay. As shown in Fig. 5, the 200 kHz backscatter mosaic displayed higher intensity in the northern area compared to the 300 kHz and 400 kHz mosaics. This suggests that higher frequencies mainly reflected off the surface clay, a soft, low-reflectivity material, whereas the lower-frequency 200 kHz signal penetrated deeper, reaching and reflecting off more compact, sandy layers beneath. Fig. 7 supports this, showing greater bathymetric depth for the 200-kHz signal, confirming its ability to reach deeper layers.

Each frequency in multi-spectral backscatter provides unique insights. Combining 200 kHz (red), 300 kHz (green) and 400 kHz (blue) into a pseudo-coloured GeoTIFF enhances sediment visualisation. In Hansahafen (Fig. 10), white areas show uniform returns, while green/blue zones in the southeast suggest harder sediments due to stronger high-frequency responses. Red-dominated regions in the north/centre indicate deeper 200-kHz penetration, revealing subsurface layers missed by higher frequencies. Integrated multispectral backscatter and bathymetric data reveal distinct sediment characteristics across the study area. Southern regions with thick clay exhibit uniformly low backscatter intensity, while northern areas with thin clay over sandy sediments show enhanced reflections, particularly at 200 kHz. This lower frequency demonstrates superior performance, with both deeper penetration and stronger returns in sandy substrates.

Quantitative analysis (Fig. 11) confirms these observations: 200 kHz displays the broadest intensity range (–12 to –35 dB) and highest median (24.34 dB), reflecting its sensitivity to varied sediments. Higher frequencies show progressively

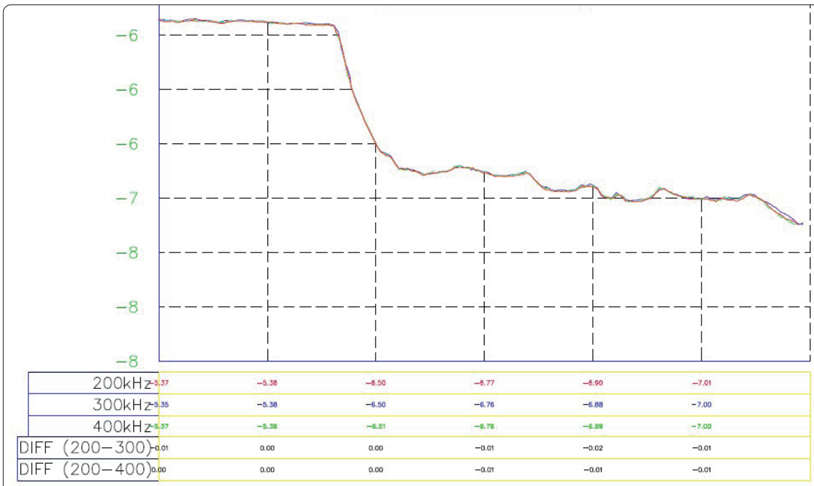

Fig. 9: Cross section drawing showing the different bathymetric surfaces – Billwerder Bucht

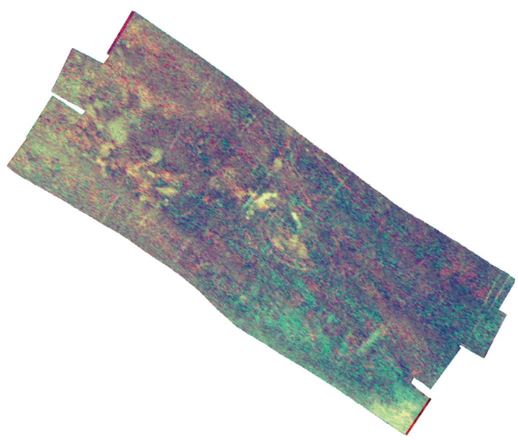

Fig. 10: Multi-spectral image – Hansahafen

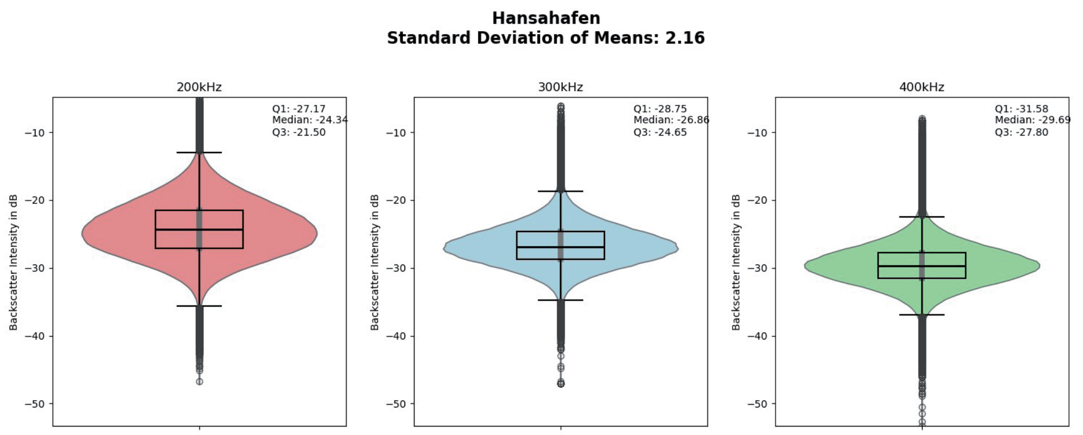

Fig. 11: Violin plot of intensity distribution – Hansahafen

narrower ranges (300 kHz: –18 to –36 dB, median 26.84 dB; 400 kHz: –22 to –37 dB, mean 29.69 dB), indicating more constrained sediment responses.

The 200-kHz channel's broader intensity variability and higher median values demonstrate its superior performance at Hansahafen, consistently yielding stronger returns than higher frequencies. This hierarchical pattern is particularly evident in the 5.39-dB-median value difference between 200-kHz and 400-kHz data. These findings underscore the effectiveness of lower-frequency channels like 200 kHz in penetrating soft sediment layers, such as fluid mud, and detecting harder, more reflective sediments located below the riverbed. This capability is particularly valuable for detailed sediment profiling, as it provides insights into both surface and subsurface material characteristics.

A similar pattern to Hansahafen appears at Köhlfleet. Bathymetry shows soft sediments in the central and eastern areas, where lower frequencies penetrate deeper. The northern section shows limited penetration, indicating harder material. In the RGB image (Fig. 12), the east appears red – strong 200-kHz returns – while the north has a bluish tint, reflecting dominance of 400 kHz. Consistent backscatter across all frequencies in the north suggests uniform reflections from a hard surface. This supports the idea that higher frequencies dominate in hard sediments due to shallow penetration.

Fig. 12: Multi-spectral image – Hansahafen

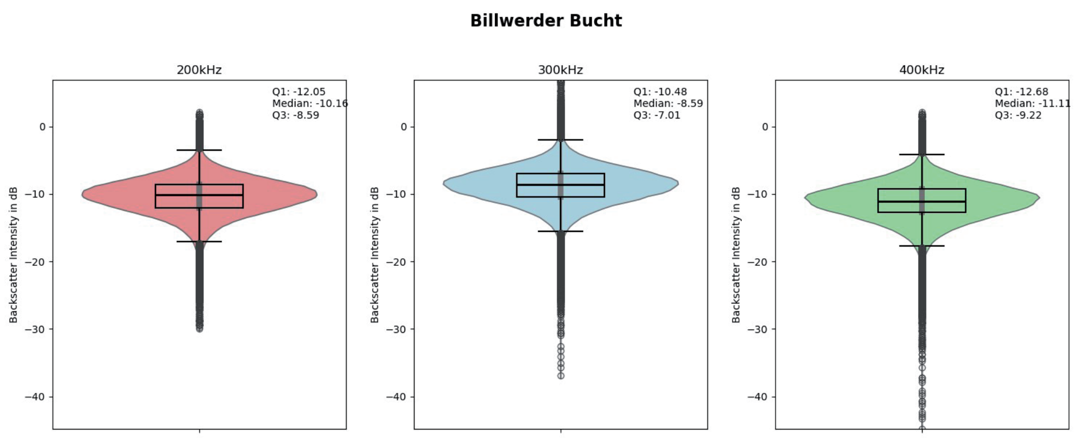

Fig. 13: Violin plot of intensity distribution – Billwerder Bucht

To compare with areas lacking soft sediments, a violin plot was created for Billwerder Bucht, known for its concrete riverbed. As shown in Fig. 13, no clear intensity hierarchy is observed across frequencies. All three range from –3 to –19 dB, with just a 1-dB-median difference between 200 kHz and 400 kHz – much smaller than the 5.3-dB difference at Hansahafen. This indicates that all three frequencies reflected off the same concrete bed at Billwerder Bucht, resulting in similar intensity values. In contrast, the intensity differences at Hansahafen and Köhlfleet are due to each frequency interacting with different sediment types at the same location. Interestingly, 300 kHz yields slightly stronger returns at Billwerder Bucht, possibly due to lower acoustic absorption in the water column. These findings suggest that in stable, hard-bottom environments, 300 kHz may offer the best performance.

Conclusion

The research targeted two locations, Hansahafen and Köhlfleet, where fluid mud and soft sediments were anticipated. The results were satisfying, demonstrating that different bathymetric layers could be effectively detected in a single pass using various frequencies (200 kHz, 300 kHz and 400 kHz) on the Kongsberg EM 2040P MKII echo sounder. Notably, the lower frequency (i.e., 200 kHz) penetrated to greater depths – up to 30 cm in Köhlfleet, where fluid mud was confirmed by sub-bottom profiling (SBP) and turbidity measurements, and up to 14 cm in Hansahafen, where soft sediments such as clay were verified through grab samples. The findings are valuable for port and dredging operations. Dredging activities, which often rely on single-frequency systems, can face challenges in accurately determining riverbed levels and sediment types. Misjudgments in riverbed detection can result in errors in material volume estimations. This study revealed that volume differences between bathymetric surfaces measured by different frequencies reached up to 575.43 m^3 over a 7,815 m^2 area in Hansahafen and up to 3,309.13 m^3 across 78,995 m^2 in Köhlfleet. Additionally, the varied penetration depths achieved with different frequencies can help inform the selection of appropriate dredging techniques, contributing to more efficient and accurate sediment removal.

The backscatter results from Hansahafen and Köhlfleet indicate that multi-spectral imaging provides a clearer visual interpretation, allowing for a better understanding of how each frequency performs across various locations within the same survey area. This enhanced interpretative capability supports more accurate sediment classification along the surveyed riverbed. Additionally, the varying penetration depths, particularly those achieved by lower frequencies with higher backscatter intensity, revealed the presence of buried hard materials beneath the surface sediment layer. Such insights would not be achievable using a single-frequency MBES, highlighting the significant advantages of the multi-frequency approach in identifying sediment characteristics and underlying materials.

The combination of bathymetric differences observed with the multi-frequency MBES and the enhanced multi-spectral images effectively addresses a key limitation of traditional bathymetric surveys: the trade-off between range and resolution. This approach allows for high-resolution riverbed data capture using higher frequencies while also achieving longer-range penetration with lower frequencies. This dual capability is highly valuable for the dredging industry and soil characterisation, as it enables accurate distinction between soft and hard sediments, thereby facilitating more precise sediment removal operations and habitat mapping. This implementation ultimately aids in the planning and execution of sediment management tasks, improving efficiency and environmental outcomes. //

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