High-resolution 3D sub-bottom profiling

Principles and case study

An article by FRITJOF BASAN

With sub-bottom profilers it is possible to investigate the subseafloor. However, common sub-bottom profilers are only providing two-dimensional depth slices of the subseafloor, that are difficult to interpret and that cannot display the complex three-dimensional reality of the subseafloor. Therefore there is a high demand for systems, capable of mapping the sediment three-dimensionally. The article describes what is possible with the SES-2000 sixpack from Innomar.

sub-bottom profiler | subseafloor | parametric effect | penetration depth | resolving capacity

Sub-bottom profilers are special echo sounders that are widely used for the investigation of the subseafloor. Among other fields of applications it is commonly used in the field of marine archaeology. Since most archaeological artefacts are concentrated in the top metres of the sediment these instruments enable the user to easily survey these layers. Sub-bottom profiling, in this context, is posing an effective, undisturbing alternative to excavations. For archaeological applications the resolution is more important than the penetration depth (Vandiver 2002). However, common sub-bottom profilers are only providing two-dimensional depth slices of the subseafloor, that are difficult to interpret and that cannot display the complex three-dimensional reality of the subseafloor. Therefore there is a high demand for systems, capable of mapping the sediment three-dimensionally (Vardy et al. 2008).

The SES-2000 sixpack is the most recent development of the Innomar Technologie GmbH from Rostock. This multitransducer system combines six parametric sub-bottom profilers (of the type SES-2000 smart), that can be arranged in different setups. These setups enable the user to record closely meshed survey lines at a time that can easily be transformed to three-dimensional representations of the survey area. Within the scope of this work this system was used to map the subseafloor at a historic pile structure, which was discovered off the coast of Markgrafenheide near Rostock. Three data sets with different array configurations and different signal frequencies were acquired.

This work aims to answer the questions how these settings affect the resolving capacity and the sediment penetration. The resolving capacity indicates how small a feature can be to still be detected. Besides that it will be shown whether the derived data is convenient for 3D modelling and the reconstruction of detected features. To investigate these questions self-conceived methods were applied, that will be discussed later in this article.

All systems by Innomar rely on the benefits of the parametric effect. Non-linear, parametric sub-bottom profilers are known for delivering high-resolution images due to the very short pulse lengths and small aperture angles. Compared to conventional sub-bottom profilers the size of the transducers can remain relatively small (Lowag et al. 2010). The theoretical principles of parametric sub-bottom profiling are described in detail in Wunderlich and Müller (2003) and in Wille (2005). It can be recapped to the procedure of the simultaneous transmission of two high-intensity sound pulses of slightly different frequency ($f_2/f_1 \approx 1$). Within the water column both waves interfere, leading to constructive as well as destructive superposition. Among the newly created frequencies, the difference frequency ($F = f_2 - f_1$) is of particular interest in the context of sub-bottom profiling, because it is able to penetrate the seafloor significantly. While the indispensable low frequencies can be created by this method, still narrow beamwidths and large bandwidths can be maintained. The narrow beamwidth allows the acoustic footprints on the seafloor to be rather small and guarantees a good lateral resolution (Hampton 1974). The large bandwidth enables the generation of very short pulses, that, besides the utilised frequency, are decisive for a good vertical resolution (Wille 2005).

The SES-2000 sixpack uses two primary frequencies near 100 kHz. The resulting difference frequencies can range from 5 kHz to 15 kHz. Because of the characteristic narrow sound beams it is possible to configure line arrays of individual parametric transducers with overlapping footprints. Obviously this is a method to create higher data density in across ship direction, which for single-transducer systems is only determined by the vessel's line spacing. By this, small archaeological artefacts or structures can be resolved (Missiaen et al. 2017). Working with the SES-2000 sixpack makes it possible to choose among five different operating modes. During the presented surveys the Hexa Beam Mode (HBM) and the Penta Beam Mode (PBM) were utilised. In both cases all six transducers are arranged next to each other in the bracket at the bow of the survey boat, creating a line of transducers perpendicular to the vessel's direction of motion. Utilising the HBM all six transducers are operated one after the other, thus six survey lines are created with one

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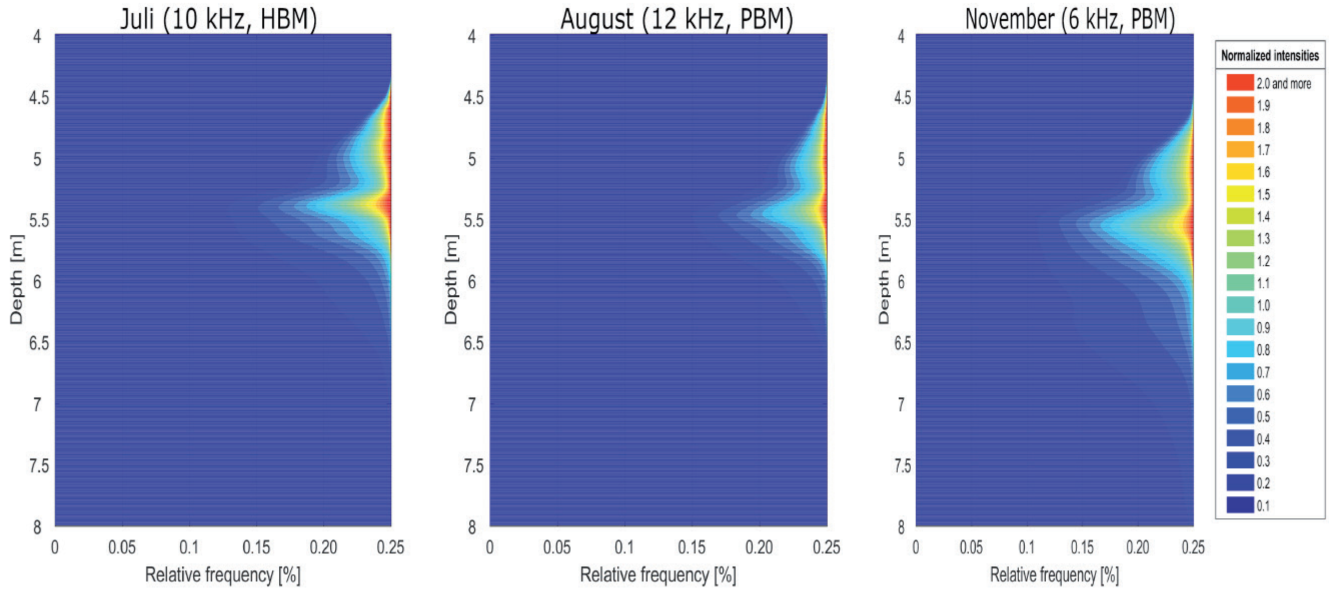

Fig. 1: Vertical normalised amplitude distribution throughout the survey area

run. The PBM uses two transducers at a time, thus resulting in five individual survey lines. In both cases the distance between the transducers, respectively between the virtual transducers is given to be 25 cm. In the course of the year 2017 three surveys with different settings could be conducted. Two surveys were conducted with the PBM (with 6 kHz and 12 kHz) and one with the HBM (10 kHz).

It was one aim to investigate the penetration depth. It proved to be convenient to investigate the energy, that penetrates the seafloor. Therefore the measured amplitudes per depth were sorted according to their intensity. The results for all three measurements are displayed in Fig. 1. The amplitudes are normalised to the mean intensity of the reflections from the seafloor, which is supposed to be the strongest reflector. This is done to compensate for different source levels, gain settings and for the different operating modes.

Investigating the whole survey area and several subareas has led to results, that eventually show, that the used frequency is primarily determining the penetration depth and thus the lowest frequency (6 kHz) penetrates the deepest. This meets the expectations as high-frequency waves experience more attenuation in water and even more in denser materials like sediments. However, comparing the rather high frequencies (10 kHz and 12 kHz) not much of a difference can be seen, which is supposed to be due to the different operating modes. It is consequently assumed, that the utilisation of the HBM – and thus of several transducers at a time, can increase the penetration depth by increasing the source level.

Furthermore the resolving capacity in all three spatial directions was investigated. Therefore three different methods were conceived and applied for all three spatial directions. Two methods focussed on the investigation of one-dimensional samples. Here, the autocorrelation functions and the differences of neighbouring cells were investigated for varied grid sizes. It is assumed, that for a resolution, that is higher than the resolving capacity the gridding software (SES-Gridder 64) will inter-

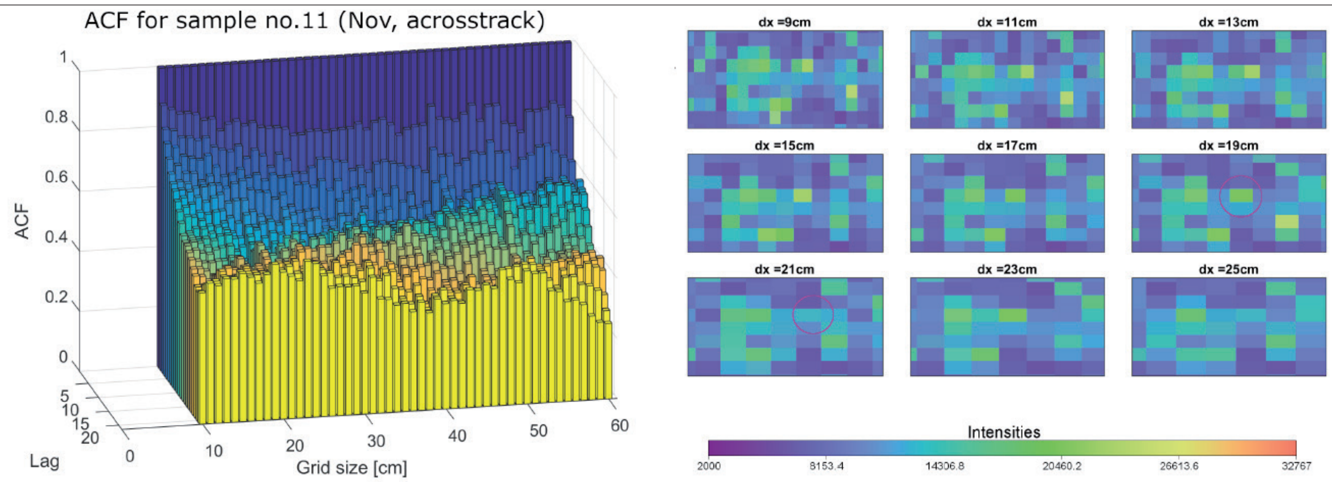

Fig. 2: Autocorrelation method (left) and direct investigation of depth slices to investigate the resolving capacity (right)

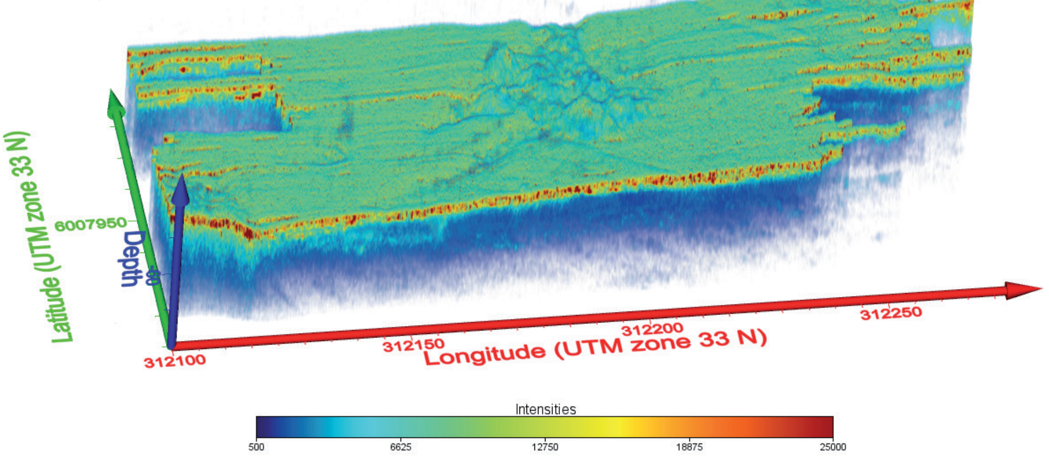

Fig. 3: Three-dimensional visualisation of the subseabed at the survey area near Markgrafenheide

polate between distinguishable features. As soon as the gridder interpolates between the cells, the autocorrelation should increase and the difference of neighbouring cells should decrease. In several samples for all spatial directions it was searched for such behaviour. The idea of the third and most straightforward method was to look at depth slices and search for neighbouring, distinguishable features. In the following the grid size was gradually increased until it was not possible anymore to distinguish between the two features. In Fig. 2 two examples for the investigation using the autocorrelation function and one example for the direct investigation of depth slices is shown. Both images only serve as examples for a much broader empirical study. In both cases a threshold for the resolving capacity of 21 cm was determined.

All three methods were qualitatively confirming the expected outcomes. In across-track direction the applied methods came to a result of 25 cm for all conducted surveys which corresponds with the transducer-, respectively the virtual transducer spacing. Although the results in along-track direction showed rather broad scattering the expected resolving capacities were met quite well. Depending on the boat speed at the different survey dates and the ping rates resolving capacities ranging from 17 cm to 24 cm could be achieved. Regarding the vertical resolving capacity it could be shown, that the used frequency and the corresponding effective pulse lengths are the defining factors. Hence, the low-frequent measurements (November) have the worst resolving capacity (9.0 cm in average). The measurements from August on the other hand were reaching better vertical resolving capacities (7.3 cm in average). It needs to be stated, that the applied methods for the resolving capacity were only yielding to subjective results for a confined number of samples. To obtain comprehensive results, that can quantify the exact resolving capacity these methods need to be elaborated in future research.

The whole survey area was mapped in 3D by using the software package Voxler 3D. One result, of the measurement from November (6 kHz and PBM) is displayed in Fig. 3. With the help of a number of other software packages it was possible to distinguish and identify several features in the seabed. Among them were at least two wrecks, of which one was already known to be there, presumed wooden boxes, wooden poles and boulders. At the example of one wreck it was tried to model features in the subseafloor. The qualitative results can be seen in Fig. 4. To draw a conclusion it can be stated, that the results, obtained with the SES-2000 sixpack sub-bottom profiler can be used for detailed visualisation and reconstruction of the marine subseafloor, and by this prove to be especially useful for the field of marine archaeology. Regarding the research questions it could be shown, that the simultaneous utilisation of transducers (thus of the special operating modes) can lead to compensation of higher frequencies in terms of penetration depths. Further the factors, influencing the resolving capacity could be identified to be the transducer spacing, ping rate and range in lateral direction and the frequency and the effective pulse length in vertical direction. //

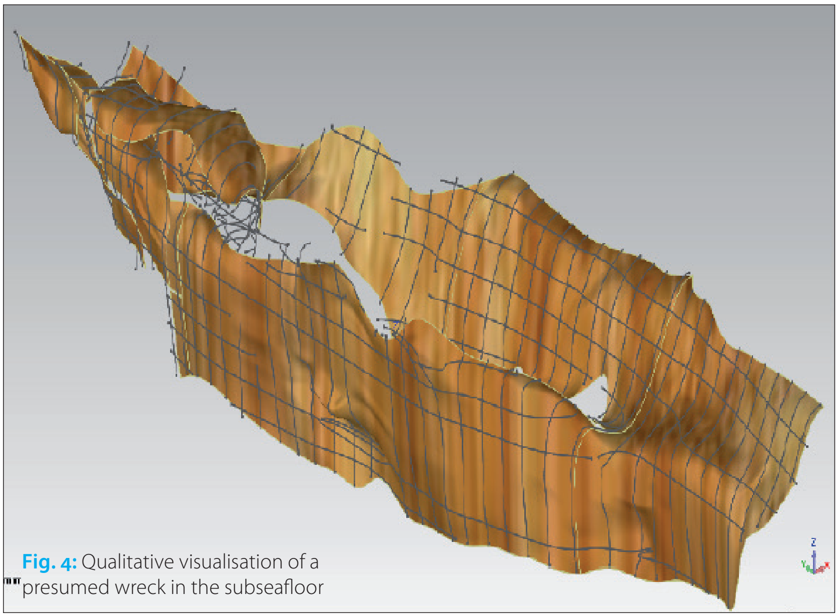

Fig. 4: Qualitative visualisation of a presumed wreck in the subseafloor

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