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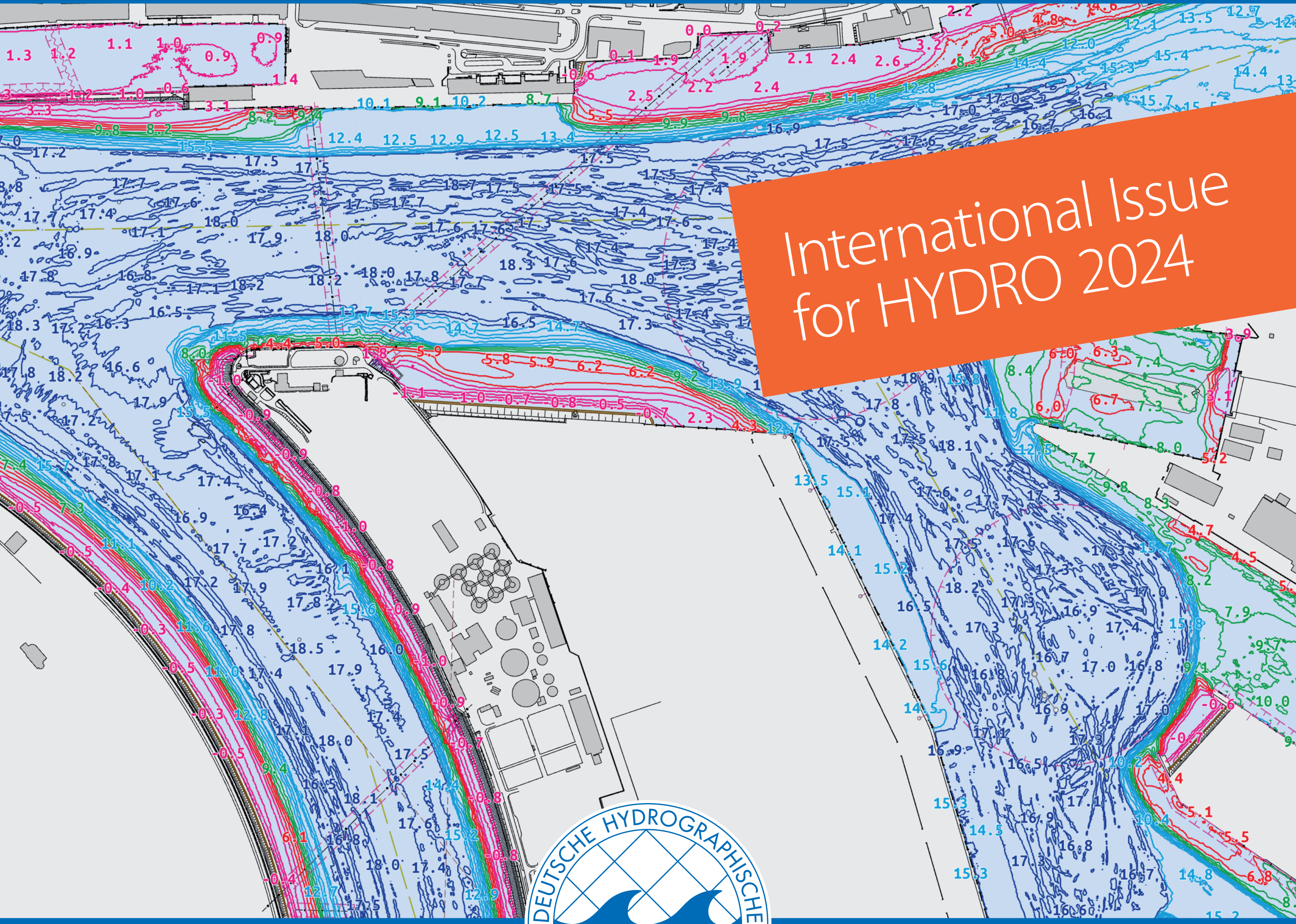

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Bathymetry estimation using airborne remote sensing RGB image data of the tidal flats of the North Sea

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Reliable bathymetric data are essential for safe navigation, as inaccuracies can pose risks for vessels dependent on precise depth information. This study investigates whether a combined approach using colour-based remote sensing systems and wave kinematic methods can improve the temporal resolution of bathymetric information in the Wadden Sea of the North Sea and provide a cost-efficient method for targeting regions with highly variable bathymetry for acoustic measurement techniques.

optical hydrography | remote sensing | optical bathymetry estimation | image-based water wave detection
optische Hydrographie | Fernerkundung | optische Bathymetrieabschätzung | bildbasierte Wasserwellenerkennung

Verlässliche bathymetrische Daten sind für eine sichere Schifffahrt unerlässlich, da Ungenauigkeiten für Schiffe, die auf genaue Tiefeninformationen angewiesen sind, ein Risiko darstellen können. In dieser Studie wird untersucht, ob ein kombinierter Ansatz aus farbbasierten Fernerkundungssystemen und wellenkinematischen Methoden die zeitliche Auflösung bathymetrischer Informationen im Wattenmeer der Nordsee verbessern und eine kosteneffiziente Methode bieten kann, um Regionen mit stark veränderlicher Bathymetrie für akustische Messverfahren zu erschließen.

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Introduction

The mapping of bathymetric changes is a critical component in a variety of applications, including navigation, research and monitoring (Caballero and Stumpf 2021). In highly variable natural environments such as the German Wadden Sea, the detection of bathymetric changes with a high temporal resolution is particularly important. Reliable bathymetric data are essential for safe navigation, as inaccuracies can pose risks for vessels dependent on precise depth information. Additionally, bathymetric data are indispensable for models that estimate sea level rise (Wachler et al. 2020).

This study investigates whether a combined approach using colour-based remote sensing systems and wave kinematic methods can improve the temporal resolution of bathymetric information in the Wadden Sea of the North Sea and provide a cost-efficient method for targeting regions with highly variable bathymetry for acoustic measurement techniques.

State of the art

Traditionally, monitoring water depths has been primarily achieved using acoustic multibeam echo sounder systems. These systems provide accurate measurements of water depth along transects by emitting sound waves and measuring the time taken for the echo to return from the seabed to the sensor (Gao 2009). However, these systems come with certain disadvantages, including high costs and limited accessibility in coastal and intertidal waters, which are often characterised by obstacles such as sandbanks or shoals (Tronvig 2005). As a result, the sampling rate in these areas is often once in 20 years or more (Grabbert 2022).

Remote sensing has the potential to improve the spatial coverage and temporal resolution of bathymetric data in shallow waters. Airborne remote sensing offers the advantage of more flexible spatial and temporal deployment, allowing data collection to be adapted to weather and tidal conditions. Additionally, airborne remote sensing can achieve a higher ground sample distance (Klemas 2013).

One method for determining water depth through airborne remote sensing is the use of LiDAR (Light Detection and Ranging) systems. These systems use green lasers with a wavelength of 532 nm to achieve sufficient penetration into the water column. A laser with a wavelength of 1064 nm is also used, which reflects off the water surface. The difference between the distance measurements of both wavelengths is used to determine the water depth. With this system, water depths can be measured up to three times the Secchi depth (Szafarczyk and Toś 2022). However, the use of LiDAR systems is limited in optically complex coastal waters (Case 2 waters), such as those found in the Wadden Sea of the North Sea (Holland 2001).

Satellite-derived bathymetry (SDB) is another method for optically determining bathymetry. The quality of the data obtained using this method is highly dependent on water turbidity, seabed reflectance and the wave-dominated structure of the water surface. Colour-based remote sensing systems are capable of detecting small-scale bathymetric features (Al Najar et al. 2022). However, with this method, water depths can only be measured up to the Secchi depth (Véronique Jégat et al. 2016).

Another method for estimating bathymetry is based on wave kinematics. This approach is more suitable for deeper waters than optical methods but relies on surface waves and has a greater margin of error when applied globally (Al Najar et al. 2022). This method is based on the influence of water depth on the structure of shallow water waves. The dispersion relationship describes the connection between wavelength and frequency. Additionally, »wave shoaling« describes the change in wave shape with water depth, while refraction is another effect related to water depth (Bryan et al. 2020).

Technical background

To extract information on bathymetry from the properties of shallow water waves, the relationships between various wave parameters and water depth are considered. The dispersion relationship for shallow water waves approximates the phase velocity as a function of the gravitational constant and the water depth. A wave with a defined period has a single wavelength for the depth (Holland 2001). In addition to wavelength, wave shape is also influenced by water depth, and the change in wave shape in shallow water is described as the shoaling effect. Another parameter that changes with decreasing water depth is the orientation of the wave fronts, which is described by refraction. This phenomenon aligns the wave crest with the bathymetric contours due to the dependency of propagation speed on water depth. Different sections of a wave are in different water depths, causing those in deeper water to move faster than those in shallower depths (Bryan et al. 2020).

In addition to wave characteristics, the colour values from the aerial image data provide additional information about the seabed, as long as it is visible due to the diffuse attenuation of the water body. When the seabed is not visible, the colour information mainly indicates sediment transport due to strong tidal currents. The relationship between tidal currents and bathymetry (Guerra et al. 2021) can also provide insights into the bathymetric profile.

Data collection

To address the research question, aerial imagery was collected from areas in the East Frisian Wadden Sea, near the island of Spiekeroog, using the research aircraft »Jade One« from Jade University. The data was acquired using the MARS (multispectral aerial remote sensor) system of Jade University, mounted in an external pod beneath a wing of »Jade One«. This system is equipped with RGB, NIR, SWIR and IR cameras. For this project, the RGB camera with a resolution of 9504 × 6336 pixels and a field of view of 54° × 37° is used. The image data is triggered by the position together with a high-resolution inertial measurement unit (IMU), controlled by the Pixhawk autopilot system. The research aircraft »Jade One« from Jade University – a Touring Motor Glider of type Diamond Aircraft HK36-TTC-ECO, that can be equipped for remote sensing tasks in an extremely flexible way – is shown in Fig. 1.

The RGB image data represent the reflectance of the water surface across three wavelengths. The light field produced by reflection from the water surface is related to the gradient of the sea surface elevation (Bondur and Murynin 2021). Capturing the reflected light field with an area sensor produces an image showing the sea surface gradients as intensity, depending on the light field incident on the water surface.

Method

To extract information on the structure and changes in surface waves, analysing spatial and temporal frequencies is a suitable method (Collard et al. 2008). Spectral analysis of aerial imagery is

Fig. 1: The Jade University research aircraft »Jade One« with two external sensor containers

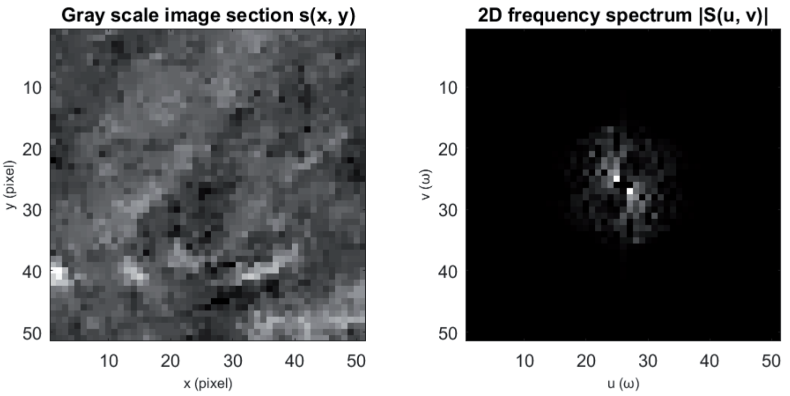

Fig. 2: Section of an aerial image showing the North Sea surface (left) and its frequency spectrum in spatial representation (right)

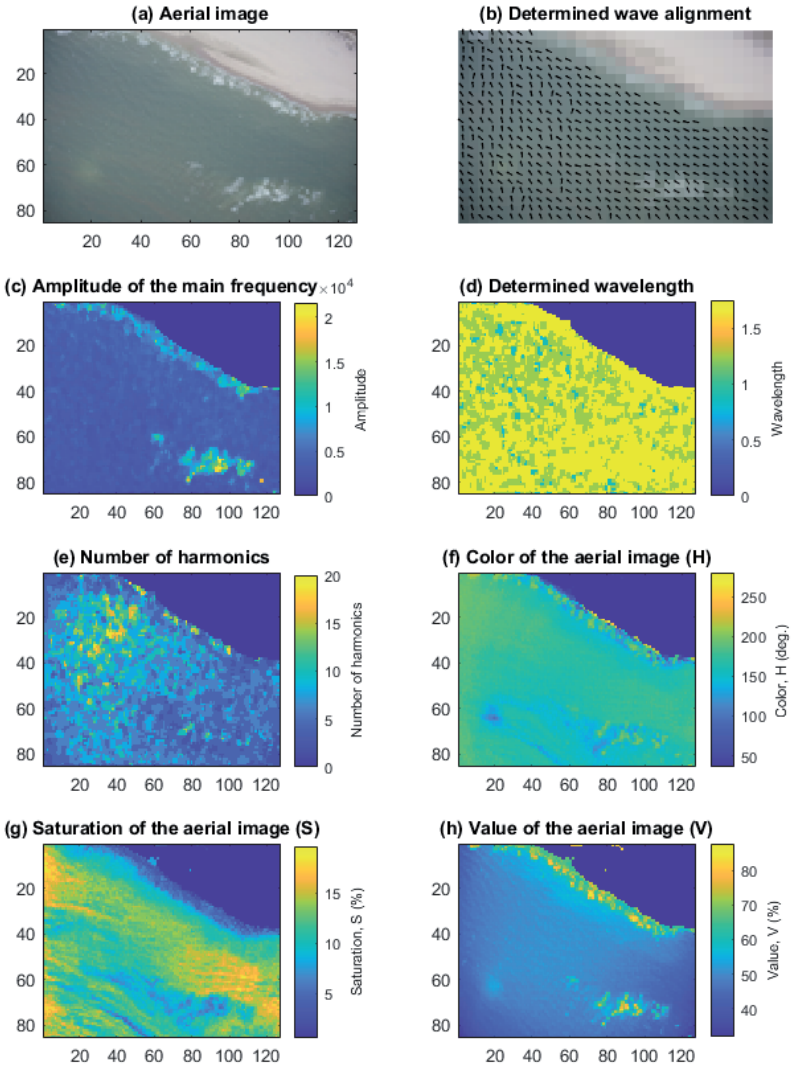

Fig. 3: (a) Partial section of an aerial image of the northern coast of the barrier island of Spiekeroog, (b) alignment of the waves determined from the frequency spectrum, (c) amplitude of the main frequencies, (d) wavelengths determined from the frequency spectrum, (e) number of harmonics, (f) colour from the HSV space of the aerial image, (g) saturation from the HSV space of the aerial image, (h) value from the HSV space of the aerial image

an appropriate technique for analysing these frequencies. Bondur and Murynin (2021) developed a method for obtaining spatial wave spectra based on the brightness field of the water surface using aerial image data. The collected images were divided into segments of 50 × 50 pixels for data analysis. These segments were transformed into the frequency domain F(u,v) using the 2D Fourier Transform.

$$F(u,v) = \sum_{x=0}^{X-1} \sum_{y=0}^{Y-1} f(x,y) e^{-j2\pi\left(\frac{ux}{X} + \frac{vy}{Y}\right)}$$

Subsequently, key parameters such as the primary frequency, wave propagation direction, and the number of harmonics were derived from the resulting 2D amplitude spectrum. Fig. 2 shows an example of an image segment along with its corresponding frequency spectrum.

In the frequency spectrum, the main frequency is clearly identifiable, along with several secondary maxima that describe the non-sinusoidal components of the wave. The primary frequency of the image segment reflects the spatial variation of the light field reflected from the water surface, which is related to the gradients of the sea surface (see section »Data collection«). Therefore, the primary frequency of the image represents the spatial frequency of the sea surface's vertical displacement and, consequently, that of the waves. The dispersion relationship provides a connection between the primary frequency of the wave image and the water depth. However, this relationship only holds for shallow water waves.

It is also known that waves begin to build up and break as water depth decreases (see section »Technical background«). This aspect can be used to identify shallow areas. The wave shape can also be determined from the 2D frequency spectrum of the water surface by extracting the number of harmonics with an amplitude of 0.3 times the primary frequency. This value is useful for distinguishing signal noise.

Another feature considered is the orientation of the wave fronts. Due to refraction, the alignment of the wave crests conforms to the bathymetric contours (see section »Technical background«). This can also be derived from the frequency spectrum of the image data.

In addition to the features obtained from surface waves, features based on the water body's colour impression are also used. For this, the RGB data are transformed into the HSV (hue-saturation-value) colour space. In the HSV space, the image data are represented by hue as an angle, saturation and an intensity value.

Fig. 3 (a) shows an aerial image of the northern coast of Spiekeroog, along with the described features from the frequency spectra of the image segments. Fig. 3 (b) illustrates the alignment of the main frequencies and wave crests derived from the frequency spectrum. A clear alignment of the waves is observed in the surf zone. In the lower right area of the image, the wave alignment in the surf zone also indicates a possible change in bathymetry.

The other image data obtained from the frequency spectrum were spatially resolved using pixel coordinates and filtered with a 2D median filter over 3 × 3 pixels. The amplitude (c) of the reflectance shows a significant local increase at the breaking zones, at the water's edge, and at the lower left side of the image. This observation can be explained by »wave shoaling« (the build-up of a wave) in shallower areas. The wavelength (d) derived from the main frequency shows only minor differences across the examined water surfaces. The comparison between the wavelength and the number of harmonics (e) reveals slight local minima of the wavelength in areas with a high number of harmonics.

The hue (f) remains relatively constant across the water surface, with small deviations caused by foam crests at the breaking zones. The saturation (g) shows local differences of about 10 % to 15 %. It is lower in areas along the surf zone at the beach and in the offshore breaking zone compared to other water surfaces, suggesting shallower zones. The value component of the HSV space (h) exhibits a characteristic increase due to the high reflectance of foam crests at the breaking zones.

Results

A k-means classification was performed for each pixel based on the features described above. Pixels were classified into ten categories, with areas of the same class having similar properties influenced by water depth. It is assumed that areas of the same class have approximately the same water depth. The spatial distribution of the classes is shown in Fig. 4 (left image). The data shows a high degree of scatter due to the influence of waves from additional non-linear forces, different wave-driving forces or irregularities in the light field. However, spatial clustering of certain classes is evident. By applying a mean filter, the matrix is smoothed, and gradients are generated, as shown in Fig. 4 (right image). The figure shows a shallower area on the right side of the image, which coincides with a surf zone in the original image. The decreasing bathymetry from the coastline to the sea also represents a plausible bathymetric profile.

Validation using BSH reference data

To validate the data, reference data from the Federal Maritime and Hydrographic Agency (BSH) of the »Exclusive Economic Zone of Germany« were used (BSH 2018). The aerial image data were collected in 2022. For comparison with the BSH

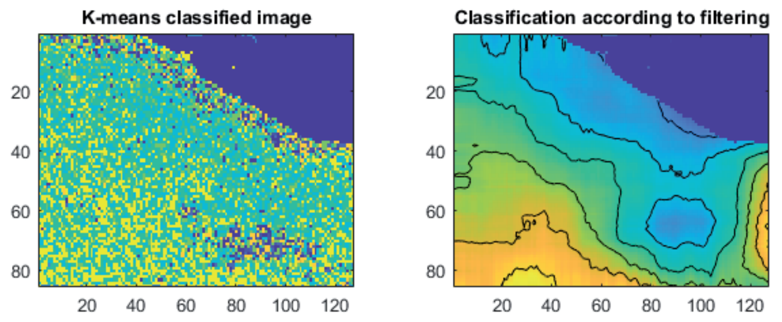

Fig. 4: Spatial distribution of classes from k-means classification based on wave parameters: amplitude, primary frequency, number of harmonics and wave crest orientation (left image), and filtered spatial distribution of the classes (right image)

dataset, the processed data were geo-referenced. The gradient profile was scaled to the maximum depth from the reference data. Subsequently, a difference matrix was calculated from the reference data and the estimated bathymetric profile. Fig. 5 shows the geo-referenced estimated bathymetric profile, the BSH reference data and their difference map. The image data are oriented to the north. Both the estimated bathymetric profile and the BSH reference data show a slope to the north, with a local maximum depth at the northern boundary. However, unlike the estimated bathymetric profile, the reference data reveal a depression in the centre of the image. The difference map indicates that the greatest deviation occurs on the western side, where the estimated bathymetry drops significantly more. The tidal currents present in the Wadden Sea influence the wave field in this region, causing waves to become increasingly nonlinear due to countercurrents (Dodet et al. 2013). Additionally, the lower resolution of the reference data and the different survey periods of the two datasets are further reasons for discrepancies in the data.

Conclusion and outlook

This study has demonstrated that RGB aerial imagery can efficiently provide defined wave parameters over large water surfaces. It was also shown

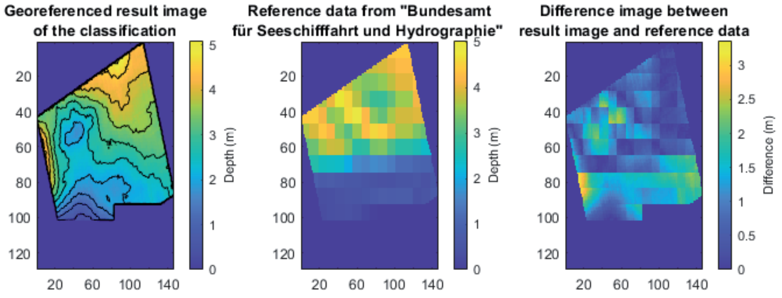

Fig. 5: Geo-referenced results matrix for bathymetry estimation (left image), BSH reference data (middle image) and difference matrix between the results matrix and the reference data

that it is possible to estimate bathymetric conditions based on wave properties, although this method does not provide absolute depth measurements but rather describes the bathymetric profile. In the Wadden Sea areas of the North Sea, tidal currents significantly affect surface wave properties in addition to bathymetry. To improve methods for determining bathymetric conditions, it is essential to separate these signals. The next step should involve estimating the influence of tidal currents on the wave fields. Another potential approach to mitigate this issue is to conduct measurements during slack water.

In conclusion, the examined method offers the capability to detect bathymetric changes but does not provide quantitative information on water depths. Remote sensing can be used to identify potential shallow areas and regions with interesting bathymetric developments over large areas. This allows subsequent collection of bathymetric data using conventional methods to be spatially focused on areas of interest. //

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