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The Application of X-Band Radar for Characterization of Nearshore Dynamics on a Mixed Sand and Gravel Beach

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ABSTRACT

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Remote sensing using X-band radar allows the estimation of wave parameters, near surface currents and the underlying bathymetry. This paper explores the use of radar to derive nearshore bathymetry at a complex site, at Thorpeness in Suffolk, UK. The site has a history of sporadic and focused erosion events along the beach frontage and as part of the X-Com project (*X-band Radar and Evidence-Based Coastal Management Decisions*) a radar system was deployed with the aim of further understanding the complex nearshore sediment processes influencing erosion. Initially, the bathymetric variation at the site is quantified through analysis of current and historic multibeam surveys. These indicate depth changes approaching 3 m. Subsequently, validation of the radar data against concurrent multibeam survey data has been undertaken. Results show that the radar derived bathymetry has a precision of ±1m at the site, with the largest errors being associated with areas of more complex bathymetry and where wave data quality was less suitable for analysis by the X-band radar bathymetry algorithms. It is concluded that although the accuracy of radar-derived bathymetry is lower than traditional multibeam survey, the low cost for high temporal coverage can be utilised for long-term monitoring of coastal sites where a cost-effective means of quantifying large-scale bathymetric changes is required.

ADDITIONAL INDEX WORDS: *Remote sensing, mixed sand and gravel beach, radar.*

INTRODUCTION

The interactions between the shoreline and the nearshore are complex and understanding the dynamics and sediment exchange is essential to fully characterise a coastal system and to define the drivers of significant coastal change. Although extensive and prolonged measurement campaigns allow monitoring of changes at elevations above the low water level at high-temporal and spatial resolution, monitoring changes below the water line is difficult, expensive and rarely attempted. Further, surveying in the nearshore is particularly challenging during high-energy conditions, when significant morphological changes are most frequent.

Remote sensing technologies offer a viable alternative for longer-term, high-temporal resolution coastal monitoring; X-band radar systems have been employed to derive wave parameters (Young, 1985), near-surface currents (Reichert *et al*., 1999), bathymetry (Bell, 1999) and inter-tidal topography (Bell *et al*., 2016). As part of the X-Com project (*X-band Radar and Evidence-Based Coastal Management Decisions*) an X-band radar was installed at Thorpeness, Suffolk, UK from August 2015 to April 2017.

This paper presents preliminary results and discussion from investigations to test the viability of X-band radar technology as a coastal monitoring tool and its ability to support evidence-based coastal management decisions. The methods employed to quantify nearshore changes at the study site are described and results from validation of radar derived-depth are presented. The advantages and disadvantages of using X-band radar in coastal monitoring and management applications is then discussed.

Figure 1. Aerial image of the field site (Photo by Mike Page), showing the Ness at the top right feature to the north and radar position (red star, left panel) and location in the UK (right panel, Digimap, 2017).

Field Site

Thorpeness beach (Figure 1, 52.1823°N, 1.6130° E) is a mixed sand and gravel beach (MSGB) on the east coast of Suffolk, UK. The beach is a composite type (Carter & Orford,

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1993; Jennings & Shulmeister, 2002) comprising an intertidal area (of approximately 65% gravel and 35% sand by mass) with pure gravel ridges present above the high-water line which are shaped and infilled by swash processes. The present study area extends 2km south from the Ness (a cuspate shingle foreland) in the north to the end of Thorpeness village.

The underlying bathymetry is complex (Figure 2). To the north of the Ness, the Sizewell bank acts as a sink for fine and medium sand delivered by tidal currents and wave action from the north and the south (Carr, 1979). This in turn is influenced by the underlining Pliocene geology of the Coralline Crag formation (cemented fine sands and silts rich in bryozoan and bivalve shells formed in a shallow shelf environment). These form an underwater ridge of around 12 km long and 2 km wide which outcrops in the Aldeburgh area, just south of Thorpeness and extends SW-NE offshore from Thorpeness (Figure 2).

The wave climate is bi-modal, dominated by SE and NE wave direction, which varies in both occurrence and power year to year. The tidal regime is semi-diurnal mesotidal (peak astronomical range ~2.5 m) and the area is prone to large winter storm surges (observed to exceed 3.50 m in Aldeburgh, Lamb & Frydendahl, 2005). These metocean conditions and complex nearshore bathymetry have been attributed to two recent erosion events (2010 and 2013), which caused focused erosion and threats to properties along a small stretch of the frontage (*c.* 300m) and have required coastal protection measures. Prior to further investment, the local authority requires to better understand the complex interactions between on- and offshore sediment movement and the associated shoreline change at site. This project seeks to gain a holistic understanding of the system through remote sensing (outlined in this paper) and traditional beach survey techniques.

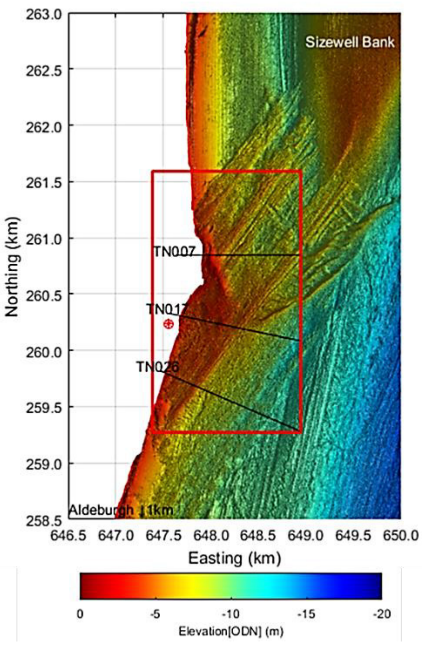

Figure 2. Multibeam survey bathymetry (January 2017) with the red box and circle indicating radar coverage and position and black lines indicating the cross-shore transects used during radar data validation.

METHODS

To better understand the magnitude and spatial variability of changes in bathymetry at the study area, differences between two multibeam surveys (July 2014 and January 2017) were analysed. The surveys data were resampled to comparable 0.5 m resolution grids and differences were calculated for each grid cell. Negative values from this analysis reflect an increase in depth between 2014 and 2017 (erosion) and positive values reflect a reduction in depth (accretion).

The multibeam survey of January 2017 (conducted over 4 weeks as part of a regional monitoring campaign and due to metocean constraints) was used to determine the accuracy of radar-derived bathymetry. These survey data were resampled at the same spatial resolution as the radar (40 x 40m cells) and included the full spatial coverage of the radar. For each grid cell, the minimum, maximum, mean, standard deviation and range of depth values were calculated. The highest linear correlation coefficient (R^2) with the depth estimated from radar data was then used in the validation process. As part of the validation, a comparative analysis was also performed along three shore-normal transects defined by established long-term monitoring profiles (TN007, TN017 and TN026, Table 1).

Table 1. *Profiles coordinates (OSGB36) and azimuth used in validation analysis.*

Profile	Starting Northing (m)	Starting Easting (m)	Azimuth (°N)
TN007	260845	647631	90
TN017	260315	647635	100
TN026	259827	647444	110

X-Band Radar

X-band radar is defined by IEEE (Institute of Electrical and Electronics Engineers) as microwave energy within the frequency of 8 and 12 GHz and wavelength of 2.50 to 3.75 cm. It has been traditionally used for nautical navigation and collision avoidance. Through Bragg scattering (Bragg & Bragg, 1913), this wavelength allows resolution of relatively small surface ripples (caused by wind speeds >3 m s^{-1}) on the water surface. The reflection of radar pulses causes constructive interference which is received by the radar and the signal strength can be used to understand the size and shape of the ocean surface. The radar system deployed at Thorpeness consisted of a Kelvin Hughes 10kW, 9.8 GHz, horizontally polarized antenna, rotating every 2.8 s, equipped with OceanWaveS GmbH WaMoS II analogue to digital converter providing ~0.8-degree horizontal resolution.

A bathymetric inversion (Bell & Osler, 2011) was used to calculate the water depth at 40x40 m cells within the radar view utilizing digitized images through the WaMoS II system, before being referenced to Ordnance Datum Newlyn (ODN) through calibration against tidal level. It is known that the accuracy of the bathymetric inversion algorithm is dependent upon wave conditions: specifically, the wave length and period of the waves, and so, the bathymetry was derived on 13-Jan-2017 during a sustained period of high quality data conditions due to significant wave height >1.5 m and peak period >10 s from the north-east. The inversion algorithm applies the dispersion relation between wave frequency (σ), wave number (k) and mean water depth (h). Within a region defined by σ, the mean water depth directly affects k. To calculate these wave parameters, analysis of a finite area of water surface (large enough to cover at least one wavelength in all directions) is undertaken with the assumption that the area is homogenous for both k and frequency spectra. This technique is further explained in Bell (2009a; 2009b). To reduce computing time, data processing was focused on an area of 3.3 km^2 (1500 m by 2200 m, Figure 2).

RESULTS

Change between 2014 and 2017 is spatially variable over the field site (Figure 3), the areas coinciding with the Coralline Crag ridges aligned SW/NE (Figure 2) show little or no change over the period. In fact, areas showing no or little change in bathymetry dominate across the entire study area, except in the areas closest to the shore and in the central sector of the radar view. The data show a dominance of accretion around the Ness and at the centre of the study area. The largest changes, reflecting erosion of 2-3 m, are observed closer to the shore to the north and south of the Ness (northing 260.6 km), and include the frontage along Thorpeness.

Alternating bands of deposition and erosion are visible offshore of the central sector (most prominently between TN007 and TN017). While these features appear to be large migrating bedforms associated with the dominant wave direction between surveys, the evidence is inconclusive. The northern position of these large bedforms appears to be controlled by the underlying geology, as evidenced by a band of accretion < 1 m aligned with the Coralline Crag ridges. Bands of erosion (< 0.5 m) aligned approximately north-south in the south sector are believed to be artefacts of the surveying method.

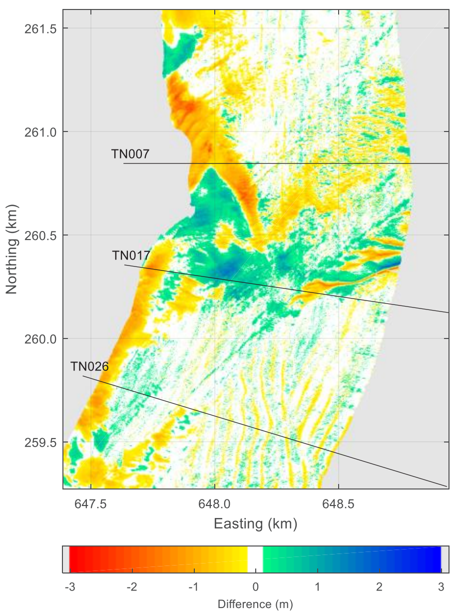

Figure 3. Change at site between July 2014 and January 2017 (0.5 m cell size) within the radar view.

Radar Validation

Gridding the multibeam data to 40 m resolution (Figure 4) removes much of the small-scale features observed in Figure 2. The standard deviation within each grid cell is indicative of the complexity of the bathymetry, high standard deviation values indicate the cells showing the largest bathymetric variance (up to 3 m), which reflect steeper slopes and/or the edge of features, such as the Coralline Crag ridges or large bedforms (sand waves).

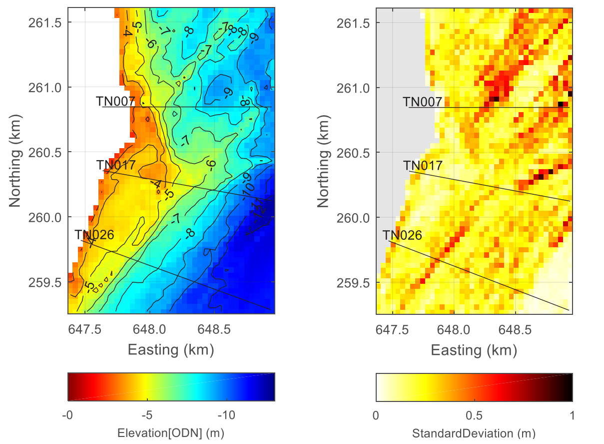

Figure 4. Gridded multibeam data and contour lines (left panel) and standard deviation of multibeam points within each grid cell (right panel).

The resulting radar derived bathymetric map (Figure 5) indicates south of the radar view, depths are underestimated, whilst in the north, the error is related to overestimation, this suggests the differences between measured and radar-derived bathymetry cannot be accounted for simply by bias. Some of the largest errors are observed in regions where the bathymetry is more variable within the grid cells (identified by high standard deviation values in Figure 4). These areas are found at the edges of the Coralline Crag ridges and where large bedforms seem to be present. Other area of high error are found at the extremes of the radar view; to the north and south east.

Results indicate that for about 90% of grid cells, the depth derived from radar data is within ±1 m of the measured bathymetry and for about 60% of grid cells the difference is within ±0.5 m (Figure 6). The scatter plot and linear regression analysis shows a high R^2 correlation coefficient (0.93) with a general over-estimation of depth in shallow water and an under-estimation in deep water.

The three offshore profiles (TN007, TN017 and TN026) presented in Figure 7 show the radar reproduces the general shape of the profile (with no errors exceeding 1 m). However, the more complex morphological features along the profile are not well resolved. This is shown in TN017 where the undulation between E 647.8 and 648.2 km is smoothed and not captured by the radar.

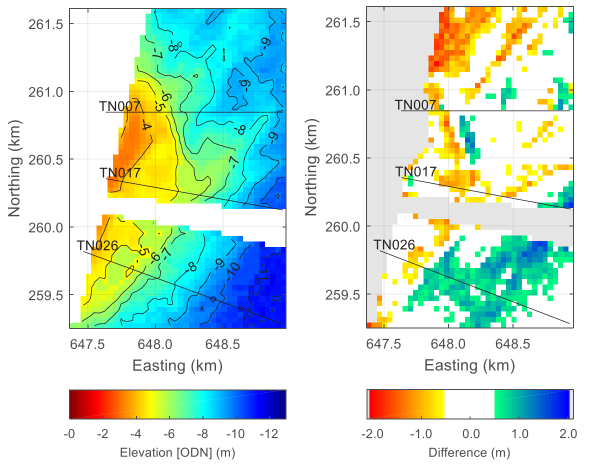

Figure 5. The radar derived bathymetric map and contour lines (left panel) and resulting differences between radar and multibeam survey (right panel). The band of missing data through the centre of the radar view were removed due to a mechanical rotation error in the radar.

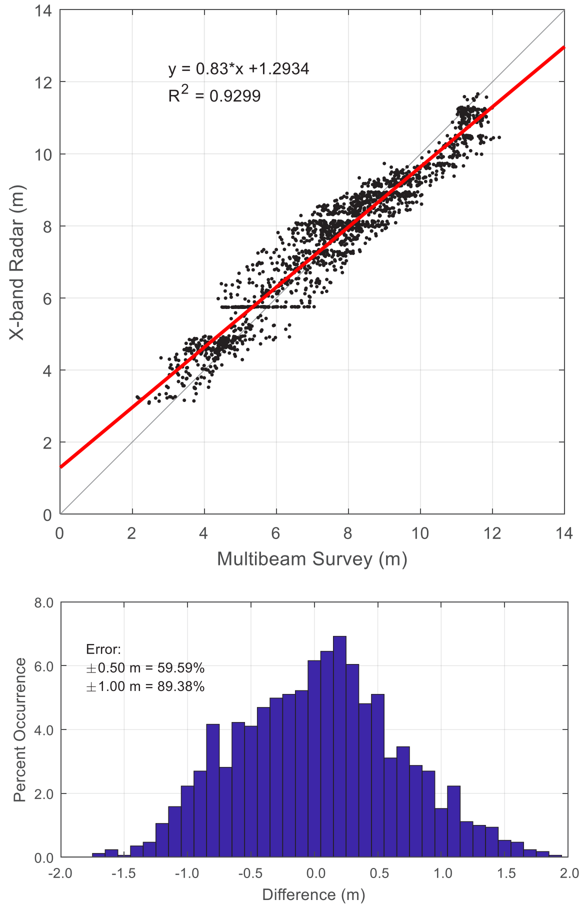

Figure 6. Scatter plot with regression analysis (R^2 and line equation, top panel) and resulting histogram of differences between multibeam and radar derived depths (0.1 m bins).

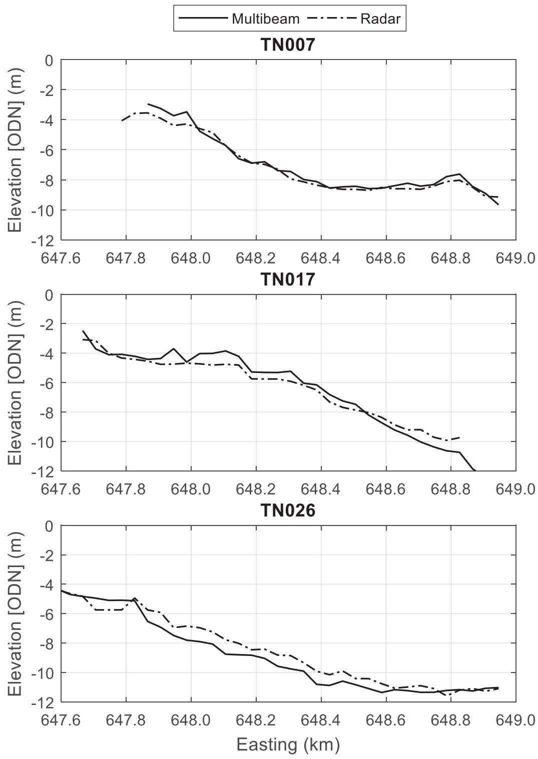

Figure 7. Cross-shore transects showing depth values obtained from the resampled multibeam data and radar data.

DISCUSSION

The validation of the radar-derived bathymetry has shown the radar to have a precision of ±1 m for ~90% of the radar field-of-view during optimum conditions coinciding with a concurrent bathymetry survey. While this limits the use of the radar for some applications requiring greater precision (e.g. for detailed sediment budget calculations), the high-temporal resolution monitoring provided by the radar allows resolution of large-scale features such as sand banks and large sand waves, as well as a means of recording the large seasonal changes that characterise many coastal environments.

The largest errors in radar-derived bathymetry are related to two controlling factors: (1) the distance from the radar and the wave direction; and (2) the complexity of the underlying bathymetry. The effect of distance from the radar is compounded by two factors: (a) the decrease in radar resolution with distance from the instrument (universal for any deployment); and (b) the effect of wave direction at the site. For example, January 2017 (when the radar derived map was calculated) was dominated by northerly waves, which upon investigation, resulted in a higher-quality signal in the northeast sector. However, results indicate that even during the best wave conditions (high energy), the strength of the signal return is variable across the radar view. Consequently, waves approaching from the northeast sector improve the accuracy of radar-derived depth in the north sector but lower accuracy in the southern sector. This is clearly demonstrated in the northern extract profile (TN007) which shows strong agreement and low errors throughout the profile, whereas the southern profile (TN026) shows large errors (approaching 1m). Although the effect of multi-modal wave climates has been explored in relation to wave height estimates (Al-Habashneh *et al*. 2015) an investigation into reducing uncertainty during wave inversions for depth calculations has not been attempted.

The effect of underlying bathymetry can be seen in regions of high standard deviation along crag lines and sand waves. This is attributed to each radar cell assuming homogeneity of the wave field. However, in areas of bathymetric complexity this assumption is not necessarily valid since the changes in seabed elevation are reflected by the non-linear behaviour of the wave field. In deeper water, linear wave theory is usually adequate to model wave propagation. However, in shallow water, wave transformations are non-linear and more complex. Non-linear wave fields have been explored in X-band and remote sensing applications (Catalan & Haller, 2007, Wu *et al*. 2008), though further testing and development needs to be continued to assess whether the incorporation of non-linear wave analysis reduces error in shallow depth areas (Ludeno *et al.*, 2015).

Another, harder to quantify source of uncertainty within the validation methodology is the effect of changing bathymetry during the multibeam survey period. The survey took 30 days as part of a larger monitoring campaign and was impacted by unworkable wind and wave conditions. These conditions will have also impacted the nearshore bathymetry, particularly close to the shoreline and may explain some of the nearshore differences, however the previously outlined issues are considered to have the largest impact.

CONCLUSIONS

X-band radar has been used to derive a relatively good quality bathymetric map at a dynamic and complex site. The resulting radar-derived map was found to have a statistically significant correlation with multibeam survey data ($R^2 = 0.93$) with ~90% of all returned radar depths within ±1m of the depths measured by the multibeam. Although this precision limits the utility of the radar for detailed sediment budget volume calculations, the radar nevertheless has utility to assist with acquisition of data to quantify the changes occurring to large-scale features at a higher temporal resolution than is feasible with traditional survey techniques. It provides a remote and relatively cost-effective means of studying a dynamic site and provides new information that can contribute to better understand the near-shore and offshore behaviour of coastal sites at wide range of temporal scales.

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