Remote Detection of Sea Surface Roughness Signatures Related to Subsurface Bathymetry, Structures and Tidal Stream Turbine Wakes

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***Abstract*— Tidal flow over shallow bathymetry is known to create an identifiable sea surface signature in satellite synthetic aperture radar. Here we present results investigating a similar effect visible on ground based marine radar data recorded at a tidal energy test site. Sea surface roughness signatures generated by strong flow over uneven bathymetry create patches of tidally modulated radar backscatter that may be identified and quantified in an uncalibrated form. Further, we investigate whether tidal stream turbines and their support structures might also create such tidally modulated sea surface signatures related to their turbulent wakes. Initial analyses have identified tidally modulated areas of roughness that are centred on the locations of turbine foundation structures. These however, are dwarfed by the naturally occurring tidally modulated sea surface roughness signatures associated with steep gradients in the bathymetry and shear zones around headlands.**

***Keywords*— Marine radar, turbine wakes, sea surface roughness, bathymetry**

I. INTRODUCTION

The need for low-carbon sources of energy is now widely accepted globally, and the search for such forms of energy includes the oceans. The development of wave and tidal energy harvesting technologies has received considerable investment in recent years, recognising that the technological challenges of developing robust and cost effective energy harvesting devices are formidable, though almost certainly solvable.

In parallel, there has been the need to rapidly develop a better understanding of, and better ways of measuring, the high energy environments in which such devices are likely to be placed. Oceanographic researchers have traditionally shied away from trying to take measurements in tidal races in particular, on the basis that the likelihood of successfully deploying and recovering their expensive instruments in such difficult environments is somewhat less than optimal and can be very costly.

Here we present a method of remotely observing sea surface roughness features using a marine X-band radar. Further, we are able to draw out a significant level of understanding about the overall marine environment from some relatively straightforward analysis of the radar imagery.

An X-band marine radar was deployed at the Fall of Warness tidal energy test site of the European Marine Energy Centre (EMEC) in Orkney as part of the NERC & DEFRA funded FLOW and Benthic ECology 4D (FLOWBEC 4D) project. The FLOWBEC 4D project [1] aimed to develop a better understanding of the interactions of marine renewable energy devices with their operating environment. Although the focus of the work was on understanding the effects the devices might have on their environment, the results of the research methods are also highlighting potential effects of the environment on the devices.

Radar image sequences were recorded at least every half hour to a range of almost 5km. The scanned area encompassed all tidal energy test berths at the site. The system began recording in 2011 and was still recording data at the time of writing. Thus there is a substantial library of data spanning the testing phases of a number of foundation structures and tidal stream turbines that have been deployed at the site over a three year period.

Marine radar uses a simple form of echo-location, whereby a short (50-60ns) pulse of electromagnetic (EM) energy is transmitted from an antenna, and any suitable targets reflect or backscatter the pulse back to the antenna. The time of flight (at the speed of light in air) of the reflected signals provides the range from the radar to the targets. Marine radars use a rotating antenna, and so are able to build up a 360 degree view of the environment around them. As well as visualising hard targets such as ships and coastlines, marine radar receives (usually) weak backscattered signals from the sea surface – known as ‘sea clutter’. This means that a marine radar sited on the coast is able to provide a plan view image of a variety of sea surface features (including waves) and anything on or above the sea surface every time the antenna rotates.

The radar was deployed at EMEC with the aim of using the wave patterns recorded by the radar in a wave inversion analysis to determine water depth and current patterns at the site. The principle behind this is that the depth of the water directly affects the ocean wave propagation (wave length and wave speed) in shallow water, and any mean current introduces a Doppler shift to the waves. Thus the wave inversion analysis derives maps of the water depth and current vector patterns that best explain the observed wave behaviour.

One of the strengths of marine radar is that there are a variety of ways of analysing the raw data depending on what one is looking for. Here we describe a relatively simple method of analysing the raw radar data to provide long-exposure images of the sea surface. These long-exposure images smooth out the transient wave patterns, allowing more persistent spatial differences in sea clutter to be mapped. It has been found that areas with strong tidal currents often exhibit regions of tidally modulated sea clutter that correlate with the underlying sea bed as well as highlighting regions of strong current shear associated with headlands.

Maps of the tidally modulated sea surface roughness signatures (sea clutter) extracted from the marine radar data were compared with maps of the gradient of the seabed derived from multibeam survey data. These clearly show patterns associated with the distinctive seabed rock strata that make up the Fall of Warness, with most areas being between 30-50m in depth.

The fact that the signatures are clearly associated with variations in seabed topography indicates that the sea surface roughness being detected by the radar must have its origins at the seabed. Since EM radar energy does not penetrate through sea water there must be a hydrodynamic mechanism that transports that 'information' to the surface.

A study of bird behaviour at the site by Waggitt et al. [2] as part of the FLOWBEC 4D project showed that different types of hydrodynamics such as flow speed, turbulent features and convergences, were potentially being used by sea birds as a cue to influence behaviour. It was also clear that regions with fast flows were affecting the detectability of birds by shore based observers. This finding is also highlighted in EMEC's independent wildlife data collection programme that has been ongoing at the site since 2005 [3][4].

Alpers & Hennings [5] suggested that similar signatures observed in a range of types of radar imagery with a range of electromagnetic wavelengths from cm to tens of cm were associated with regions of convergence and divergence of flow over the seabed undulations. These zones of convergence and divergence were then modulating the Bragg resonant scattering that is the primary imaging mechanism of such radars. Regions of convergence would reduce sea surface roughness and hence reduce radar backscatter, while regions of divergence would lead to an increase in sea surface roughness and increase radar backscatter. They also commented that this theory was almost certainly an over simplification and that additional factors such as turbulence would be likely to have additional effects.

Visual observations at such sites suggests that high current flow areas are often characterised by persistent regions of turbulent 'kolk' boils, and it is likely that sharp changes in seabed topography relative to a strong current are acting as a source of these turbulent boils. These are then propagating up to the surface a short distance downstream of the bathymetric features, where they manifest as patches of smoother water creating a measurable change in the small scale sea surface roughness visualised by the radar.

In addition, there is consistent anecdotal evidence that acoustic surveys of tidal straits encounter significant interference from entrained bubble clouds – which must need significant downwelling from the water surface to get to any significant depth – downwelling that could be associated with the turbulent kolk boils.

What is clear is that variations in sea surface radar backscatter are associated with sharp changes in seabed topography, and manifest during periods of strong currents.

It is suggested that regions where strong, tidally modulated sea surface roughness features are evident in radar data, could have turbulent characteristics that may not be optimal for the placement of tidal turbines, due to the possibility of locally increased levels of turbulence. Such areas within the data from the Fall of Warness site are highly localised, and it would be relatively straightforward in future to avoid installing devices in areas where the effects are most significant, if this suggestion is further supported in future studies.

II. MEASUREMENTS

A Kelvin Hughes 10kW marine X-band (9.4GHz) radar with high speed (1.3 second rotation time) horizontally polarised 2.4m long antenna was installed overlooking the EMEC Fall of Warness tidal energy test site in 2011 (Fig. 1). The 2.4m antenna provides a horizontal beamwidth of 0.8 degrees, and has an approximately 20 degree vertical beamwidth to allow for mounting on vessels that experience significant pitch and roll.

Sequences of 256 radar images were recorded automatically at regular intervals using an OceanWaves GmbH (now Rutter Inc.) Wamos II radar digitiser. The sequences of 256 images were averaged to generate the equivalent of long-exposure images in photography, smoothing the signatures of waves and other transient features but emphasising persistent spatial variations in radar backscatter across the images. Each long-exposure image represents approximately five minutes of radar imagery.

An example of a raw marine radar image is shown in Fig. 2. A number of features are visible in this image that go beyond those normally associated with marine radar, such as vessels, buoys and coastlines. Wave patterns are clearly visible in the data – known as sea clutter, and other oceanographic effects can also create a measureable signature to radar.

Wave signatures within sea clutter may be used to derive current vector maps [6][7][8][9][10] and, since summer 2014, these have been generated automatically twice per hour following each record. Examples of these at peak flood and ebb are shown in Figs. 3 and 4. The currents within the main channel can flow at 4m/s or more during peak spring tides and are funnelled between the islands, generating a very defined current jet [11]. It is within this jet that a number of tidal turbine test areas have been implemented, and a range of tidal turbine designs have been tested at the site in recent years.

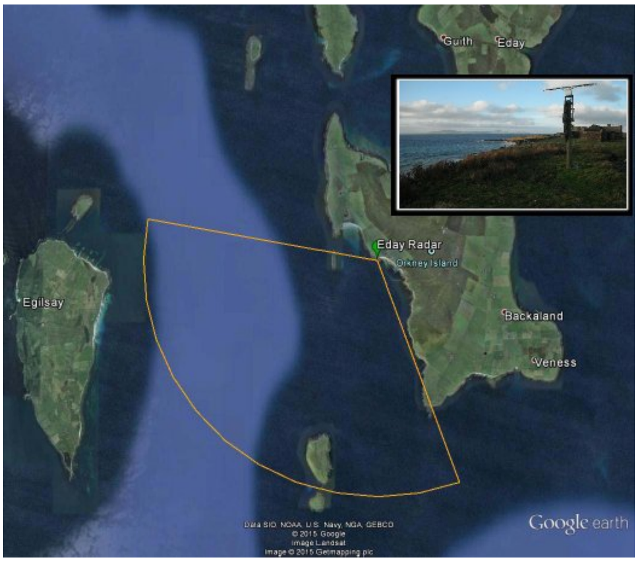

Fig. 1 Main: An approximate outline of the radar scan area overlaid on Google Earth Imagery. Insert: The marine radar located at the EMEC substation on the island of Eday, overlooking the Fall of Warness tidal energy test site. Map data: SIO, NOAA, U.S.Navy, NGA, GEBCO, Google, Landsat, Getmapping plc.

Although some variations in sea clutter intensity are evident in the image in Fig. 2, it requires a degree of averaging to smooth out the transient wave signatures to reveal the more subtle features hidden within the imagery.

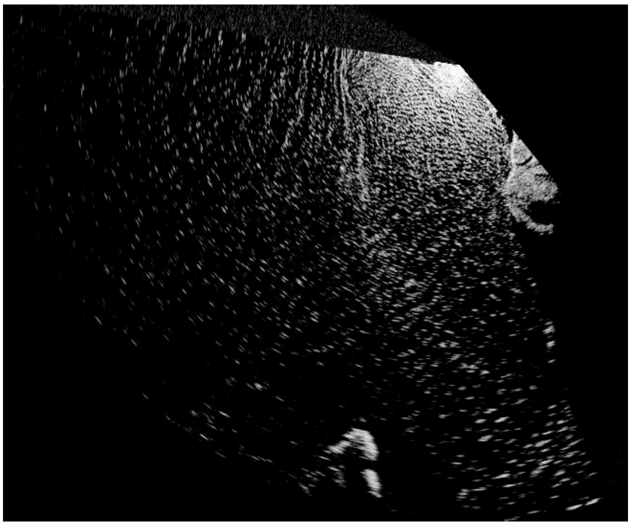

Fig. 2 A single raw marine radar image recorded at the EMEC tidal energy site on the 9th March 2015 at 22:30GMT. Significant levels of sea clutter (bright areas correspond to stronger radar backscatter) are present during a wave event, with wave patterns visible propagating into the site from both the north west and south east. The radar was located on the island of Eday in the north eastern corner of the image, while the feature in the bottom centre of the image is the small island of Muckle Green Holm.

Averaging of a single five minute image sequence can reveal the most significant variations in sea clutter, such as the shear zones around the headlands in the south of the site. However, individual radar time-lapse images are extremely variable in intensity and quality, dependent on ocean and weather conditions. During calm conditions there is very little radar sea clutter, while in higher sea states the average signal increases. In order to obtain a stable and relatively representative impression of these features, the long-exposure images were phase binned into 13 phase intervals according to the phase of the 12.42 hour principal lunar M_2 tidal component.

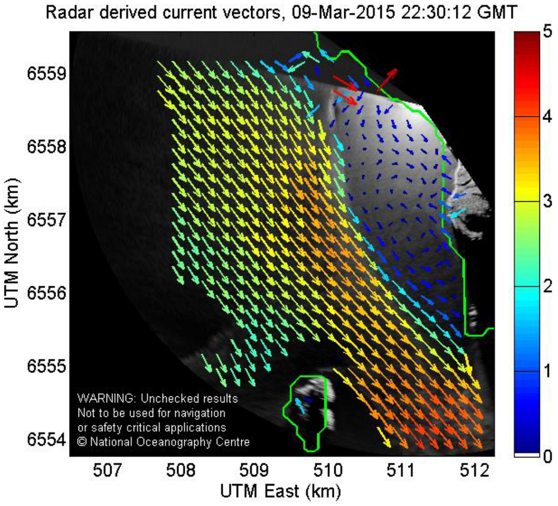

Fig. 3 A tidal current vector map of the EMEC Fall of Warness tidal test site corresponding to the flood tide and derived using a wave inversion. The current vectors are overlaid on the average (long-exposure) radar image of the corresponding image sequence. The colour scale of the arrows refers to the current speed in m/s. This corresponds to the same record as the snapshot of raw radar data shown in Fig. 2.

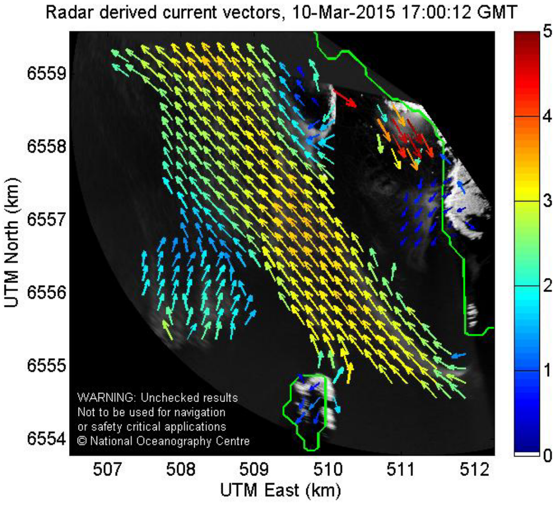

Fig. 4 A tidal current vector map of the EMEC Fall of Warness tidal test site corresponding to the ebb tide and derived using a wave inversion. The current vectors are overlaid on the average (time-lapse) radar image of the corresponding image sequence. The colour scale of the arrows refers to the current speed in m/s.

III. RESULTS

Examples of these phase-binned images are shown in Fig. 5 and Fig. 6, corresponding to peak flood and peak ebb flow respectively. A transect through the site is marked in yellow and the average radar backscatter profile along that transect through each of the 13 phase intervals is shown in Fig. 7. The circles mark the locations of a number of turbine foundation structures.

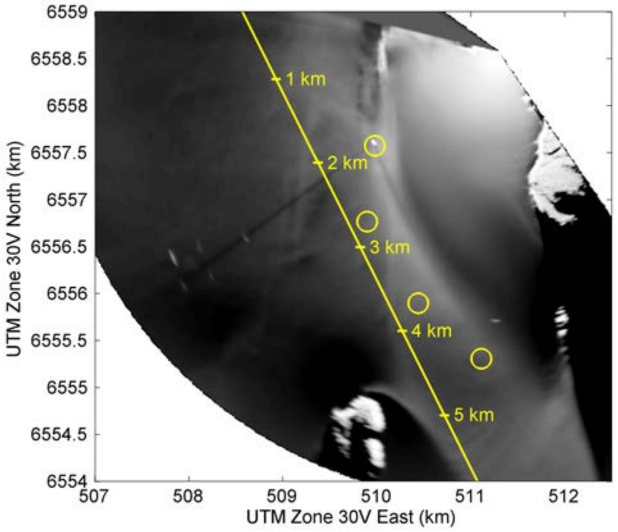

Fig. 5 A phase binned image of the EMEC Fall of Warness tidal test site corresponding to the flood tide. Increased radar backscatter corresponding to a shear zone around the island (Muckle Green Holm) at the bottom of the image can be seen. The yellow line marks the transect in Fig.7, and the circles mark the location of turbine foundation structures.

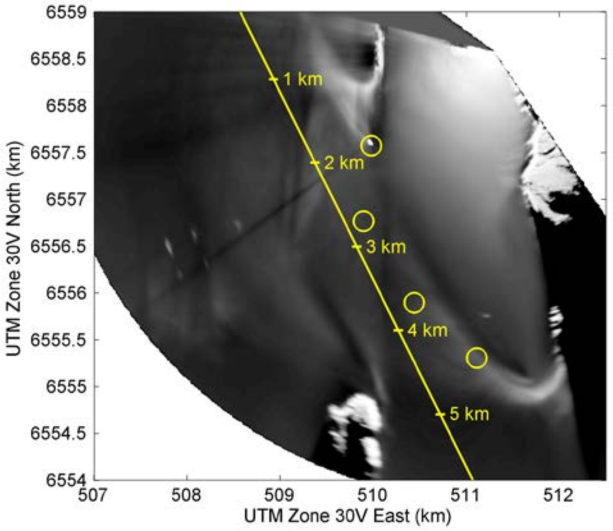

Fig. 6 A phase binned image of the EMEC Fall of Warness tidal test site corresponding to the ebb tide. Shear zones from the flow around the headlands of the southern part of the Islands of Muckle Green Holm (middle bottom) and Eday (Right) can be seen. There is also a clear signal from a bathymetric feature to the north west of the site. The yellow line marks the transect in Fig.7, and the circles mark the location of turbine foundation structures.

The different shear zones associated with different flow directions are clear around the headland and island to the south, while the mid-channel signatures are also evident in the peak flow images.

It was observed that the presence or absence of these signatures was controlled by the tide, with the most significant signatures present at peak flow, with no evident signatures in low current conditions around the turn of the tide.

Inspection of the variation in backscatter through the tide in Fig. 7 shows a strong tidal modulation, both of large kilometre scale features, but also of finer details.

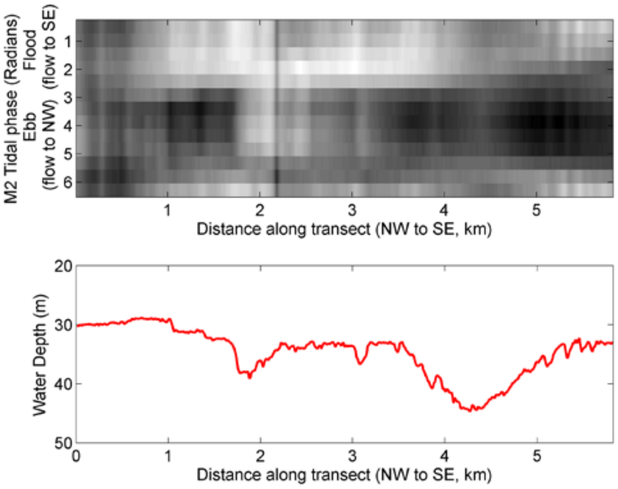

Fig. 7 Upper plot: A transect run through the main channel and shown in Figs. 5 and 6 showing the variation in mean radar backscatter through a tidal cycle. There is a clear tidal modulation to the mean backscatter which is likely to be related to the interaction of the flow with the bathymetry. The line of low radar returns at position 2.2km corresponds to the shadow cast by the surface-piercing OpenHydro Platform. Lower plot: The water depth along the transect.

While there are features evident in these simple phase binned images that are clearly associated with the tidal flow, the finer details are obscured by the larger variations in signal across the site. By taking the first derivative of these images before phase binning, one can preserve the information on spatial variability while removing the wider area gross signal variations across the images.

Figs. 8 (peak flood current) and 9 (peak ebb current) show examples of backscatter gradient images made up by phase-binning 59 days of images. It is possible to obtain these images from much shorter image sequences, but the signals from the turbine structures are extremely small and a long period of averaging was necessary to be certain that the signatures were consistent above the background noise.

The major features of the rock strata of the seabed at the Fall of Warness are clearly identifiable when compared with a similar gradient plot of the Maritime Coastguard Agency's multibeam survey of the area, shown in Fig. 10. The presence of these easily recognisable signatures of natural origin serves to illustrate that man-made structures should also be expected to generate analogous sea surface roughness signatures. One clear example of this is the OpenHydro test platform at the site – comprising two pilings and a platform above the water. The pilings from this structure, marked with the northern most yellow circle in Figs. 8 and 9 appear to create a persistent wake of approximately 1km in length on the flood tide, although this merges into alignment with other flow features of natural origin, so it is extremely difficult to identify where the structure’s wake finishes and natural flow features dominate. It should be noted that the OpenHydro platform is a test facility and production versions of their turbines would not have surface piercing elements. Thus, being fully submerged with no near-surface structures, they would have a significantly smaller sea surface wake than the one at EMEC.

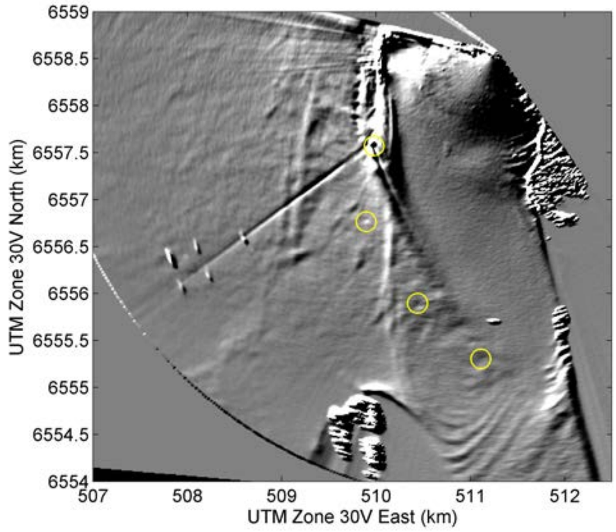

Fig. 8 The gradients in the radar sea surface roughness signatures during peak flood current showing a range of features that are linked to both bathymetry variations and horizontal shear zones around the headlands. The locations of turbine foundation structures are marked by yellow circles. The radial streaks at the top of the image are caused by shadowing from a rocky outcrop known locally as ‘Seal Skerries’, and the large radial line is a shadow cast by the OpenHydro platform.

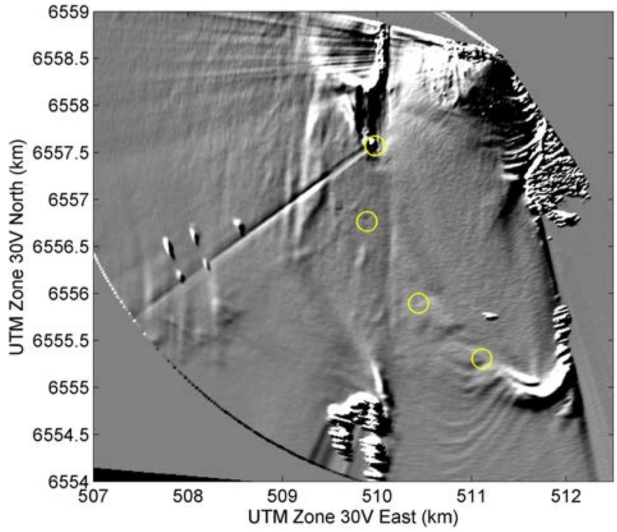

Fig. 9 The gradients in the radar sea surface roughness signatures during peak ebb current showing a range of features that are linked to both bathymetry variations and horizontal shear zones around the headlands. The locations of turbine foundation structures are marked by yellow circles. The radial streaks at the top of the image are caused by shadowing from a rocky outcrop known locally as ‘Seal Skerries’, and the large radial line is a shadow cast by the OpenHydro platform.

Wakes similar to this have been observed by one of the authors at another radar installation, caused by natural outcrops of rock close to the sea surface. The wake flow structures in that instance extended for several kilometres from the point of origin on the radar imagery.

A number of floating marker buoys are visible as relatively strong targets – a cluster of five in the west of the images, and a single one marking the test site of a floating turbine system in the south east of the images. These buoys provide a much more significant target than most of the natural features in the imagery.

Further, at peak flood flow in particular, there are small signatures associated with the locations of two other test turbine foundations – marked by the middle two yellow circles in Figs. 8 and 9. Information regarding the operational state of the turbines and foundations is not available to the authors. However, it well understood that any form of structure placed in such a high current environment will generate turbulence during the flow of the tide and passage of waves, so it is likely that this turbulence is what is appearing as a signature in these data.

The southernmost circle marks the position of a further turbine and support structure, but there is no discernible sea surface signature. This may be because it is in slightly deeper water, and is also located on a major headland shear zone that significantly raises the overall radar backscatter at that location, particularly on the ebb tide, making the detection of more subtle signatures problematic. Another possibility is that the naturally higher levels of turbulence in that area are breaking up turbulent features originating from the turbine structures more rapidly than would otherwise be the case.

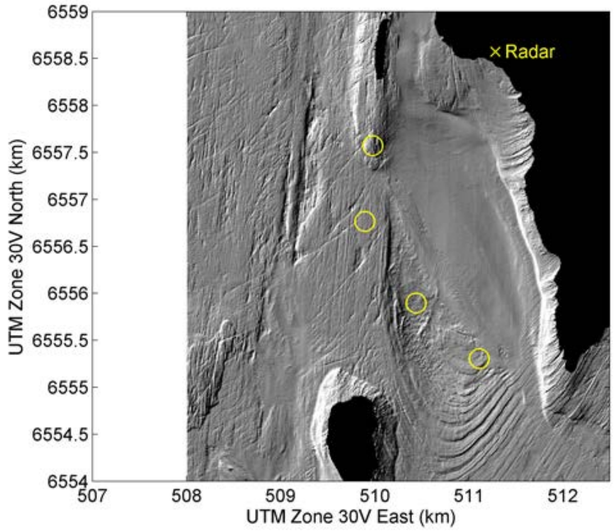

Fig. 10 A plot of the gradients in the Maritime Coastguard Agency’s multibeam echosounder survey of the EMEC Fall of Warness tidal energy test site. The rock strata of the sea bed are clear in this image and bear a striking resemblance to many of the features visible in the radar derived plots in Figs. 8 and 9. The locations of turbine foundation structures are marked by yellow circles.

IV. CONCLUSIONS

Initial analyses of long-exposure radar image sequences have identified tidally modulated areas of roughness that are centred on the locations of turbine foundation structures. These however, are dwarfed by the naturally occurring tidally modulated sea surface roughness signatures associated with steep gradients in the bathymetry and shear zones around headlands. We suggest that in order for the signatures of sea bed rock strata to be apparent in imagery of the sea surface, there must be a hydrodynamic mechanism propagating this information from the seabed to the surface, and that if this involves the generation of kolk boils – features known to be generated at such sites, then an analysis such as this might be used to highlight both regions of strong seabed generated turbulence, and also regions of high horizontal shear around headlands and other submerged rocky outcrops. It may be that areas of particularly high turbulence are best avoided for turbine placement in order to reduce turbulent loadings and fatigue and thus potentially increase operating lifespans of energy extraction devices, and the techniques reported here may be useful in determining such areas.

ACKNOWLEDGMENTS

This work was funded by NERC/DEFRA grant NE/J004332/1 – FLOw and Benthic ECology 4D (FLOWBEC 4D) with additional support from the EU FP7-INFRASTRUCTURES “MARINET” project. Thanks are due to James Waggitt for his helpful comments on the bird observations conducted under the FLOWBEC 4D project.

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