# SUBMERGED DUNES AND BREAKWATER EMBAYMENTS MAPPED USING WAVE INVERSIONS OF SHORE-MOUNTED MARINE X-BAND RADAR DATA

*Paul S. Bell*

Proudman Oceanographic Laboratory, Liverpool, United Kingdom

## 1. INTRODUCTION

Surveying very shallow coastal areas, particularly around coastal defences, can be a logistically difficult and time consuming process. A marine-radar based bathymetry mapping technique has been used to remotely map the embayments around a series of shore-parallel breakwaters at Sea Palling on the south east coast of England during the LEACOAST2 project. The duration of the deployment spanned over 2 years, with the aim of observing any evolution of bathymetric features over that timescale while providing a clear indication of the spatial variability of wave and current patterns contributing to such evolution. The embayments generated by the shore parallel breakwaters at that site are resolved and a field of subtidal dunes with a wavelength of the order of 200m and amplitude around 1m located in approximately 7m of water were within the radar field of view and are evident in the remotely sensed bathymetry. A comparison between bathymetric maps conducted using conventional survey techniques and the radar based technique is presented together with measurements of tidal currents mapped using the same remote sensing method and compared with ADCP data during a storm event.

## 2. BACKGROUND

During a major storm surge in 1953 seven people drowned when the sea overtopped the dunes at Sea Palling in East Anglia. Following that event, a sea wall was built to protect the village from further risk, but in recent years those sea defences began to be undercut by the sea, and a series of nine shore-parallel breakwaters (Figure 1.) were installed in conjunction with beach recharge in an attempt to protect the earlier defences.

These new breakwaters were designed to better retain the sand and hence continue the protection to that part of the coast, but the first four breakwaters performed better than expected at this site and the first breakwater on the northern updrift end of the structures now has a permanent tombolo linking the breakwater to the shore – something that was never intended in the original design. The subsequent set of five breakwaters installed during the second phase of construction were built to a different size and spacing and have performed closer to their design specification. Despite these efforts to protect the shoreline, beach recharge operations have been necessary every few years to maintain the beach at this vulnerable section of the coast.

In 2005 The UK Engineering and Physical Sciences Research Council (EPSRC) funded LEACOAST2, a collaborative research project to study the hydrodynamics and sediment processes around these breakwaters that followed on from the earlier LEACOAST project [1]. The aim was to improve the understanding of how such structures interact with their environment and hence improve future design guidelines, as well as provide a field scale dataset for sediment process model development and validation.

## 3. MEASUREMENTS

Teams from the Universities of East Anglia, Plymouth and Liverpool and from the Proudman Oceanographic Laboratory (POL) began work in 2006 with a wide range of equipment for monitoring waves, currents and sediment dynamics. In addition, an ARGUS video system was installed to study the nearshore processes and an X-band marine radar for looking over longer ranges of up to 4km. Surveys of the beaches and embayments were conducted at regular intervals both on foot and by boat using an RTK GPS system by the University of East Anglia team.

A Kelvin Hughes marine X-band (9.8GHz) radar with a 2.4m rotating antenna was deployed on the roof of the Sea Palling Inshore Lifeboat Station about 5m above beach level and overlooking the offshore breakwaters and associated embayments. This was coupled to a PC based digitisation system of in-house design, allowing image sequences of the sea surface to be recorded automatically every hour to ranges of 4km.

***Figure 1. The northernmost four shore-parallel breakwaters at Sea Palling in East Anglia, UK.***

Summary images of each record were produced and sent via a broadband link to the POL website so that the status of the system could be monitored via the internet, including radar snapshots of the sea surface and time-lapse images that show persistent sea surface roughness features very well. Waves tend to be visible on the radar images only when the wave height is larger than about 1m, so in contrast to more conventional surveying techniques this method of mapping is only appropriate during wave events. However, this would allow the bathymetry of an area to be monitored during storms when the largest changes might be expected.

Waves, tides and currents were monitored at various locations around the system of breakwaters and embayments using variety of in-situ instrument frames although none were located more than 500m offshore. Of particular interest is the upward looking Acoustic Doppler Current Profiler (ADCP) record from a frame located just seaward of the northernmost breakwater, as it was located in an area sufficiently clear of the breakwaters to allow clear tidal signals to be observed. During this time there was a significant storm and surge event during which all deployed current meters showed that the usual tidal reversal was overpowered by the storm induced currents such that the ebb tidal current continued to flow to the south east rather than reverse to flow north west as would be more usual.

The majority of these instrument frames included pressure sensors, but none were in place for the full duration of the radar deployment, so a continuous unbroken water level record could not be constructed easily. Instead, advantage was taken of the UK National Tide Gauge Network which operates a network of 44 tide gauges around the UK, the nearest of which being Cromer, 20km to the north of Sea Palling and Lowestoft 35km to the south. Tidal residuals from these gauges were combined with tide predictions for Sea Palling itself to provide a continuous estimate of water level at the Sea Palling site for the full 2 year radar deployment. This estimated water level record compared favourably with the shorter records from in-situ pressure sensors and provided a consistent water level reference for the full period of the radar deployment, allowing radar derived water depths to be related to a fixed datum.

## 4. DATA ANALYSIS

The extensive nature of the radar dataset and reliance on waves being present at any particular time for the data to be of use for bathymetry mapping has meant that attention has been focussed on specific hydrodynamic events. In particular a storm and surge event at the end of October 2006 occurred during one of the intensive measurement campaigns when all of the in-situ frames were deployed, and on which the project partners have focussed the majority of analysis and modelling efforts.

In terms of radar data analysis, four tidal cycles of hourly radar records during this event were processed for bathymetry and currents. Each individual radar record comprised a sequence of 256 images, each frame of which represents one 2.8 second rotation of the radar antenna, hence each image sequence spanned a period of around 12 minutes. The radar signal was digitised at 20MHz, giving radial samples at 7.5m intervals, and the ping rate was of the order of 3kHz. The antenna beam pattern was approximately 0.8 degrees in the horizontal, leading to the sample footprint at a distance of 1km from the radar being an arc with a radial dimension of 7.5m and a circumferential dimension of around 20m, going up to 80m at a range of 4km. The practical consequence of this is that the tangential resolution of the radar images degrades with range, precluding the ability to image shorter wavelength waves at longer ranges. The radial resolution does not degrade substantially with range, and at other sites it has been possible to resolve wave patterns and hence perform bathymetric inversions to a range of 7.5km when looking into the direction of incoming waves.

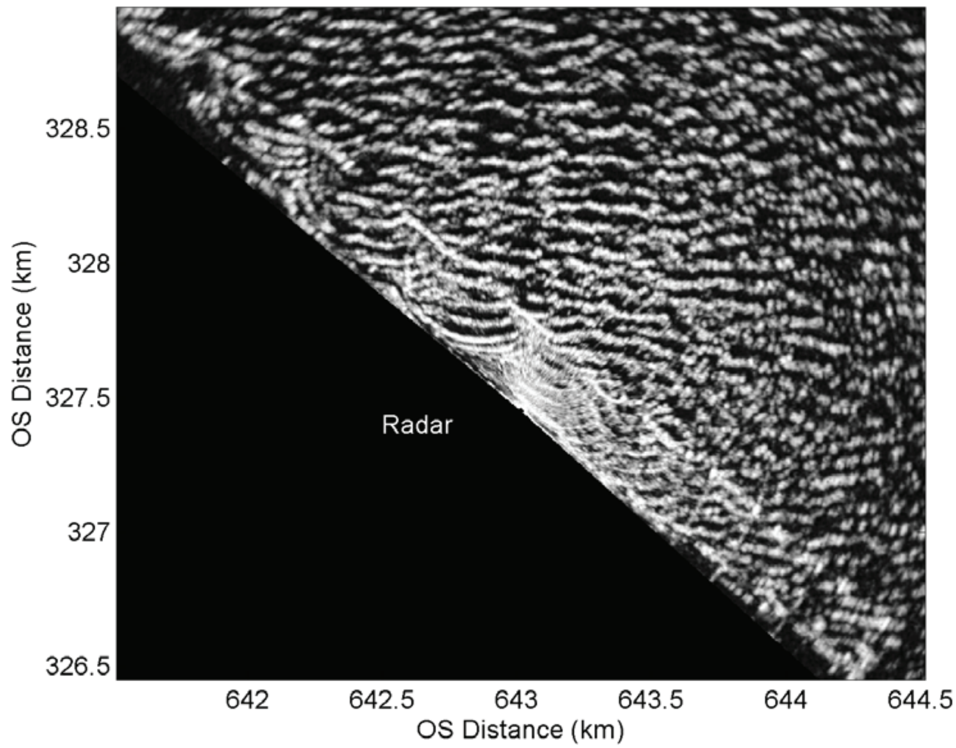


Figure 2. A radar snapshot of waves approaching the Sea Palling breakwaters. Brighter colours indicate stronger radar backscatter as on a conventional radar screen

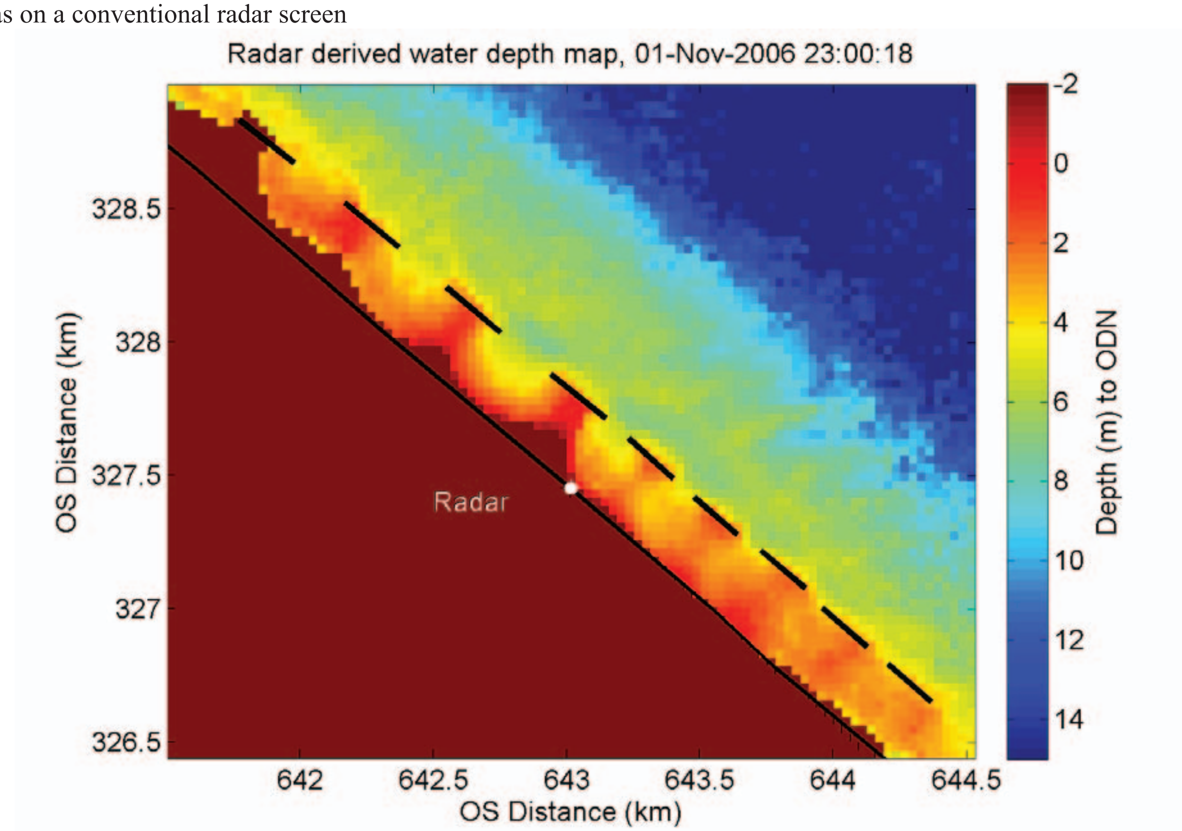


Figure 3. The radar derived bathymetric map for the area shown in Figure 2. Depths are referenced to Ordinance Datum Newlyn, the datum used by the UK Ordinance Survey System. The breakwaters are marked in black.

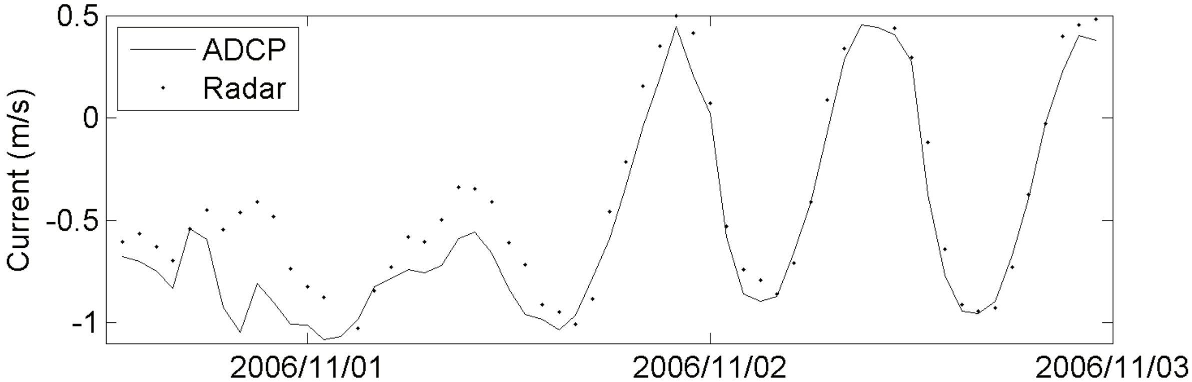


Figure 4. A comparison of long-shore currents measured using an ADCP (solid line) and radar (dotted line). +ve currents flow to the north west, -ve to the south east.

The principle of the radar analysis is that the behaviour of waves at a local scale is the result of water depth and current. If the wave behaviour, i.e. the frequency-wavenumber spectrum, can be mapped from an imaging system such as radar (or video) then it is simply a matter of finding the best fit of a wave dispersion relation to generate a water depth and current map that caused the observed wave behaviour. The wave dispersion relation used in this case approximates non-linear wave theory [2] [3] using a wave height correction to linear wave theory and has been modified to include the Doppler shift of the waves due to a mean current.

Radar data representing an area of 3km x 2km centred on the breakwater system, a snapshot of which is illustrated in Figure 2, were processed for bathymetry and currents at spatial intervals of 30m [4][5]. The bathymetric map derived from the radar data, shown in Figure 3, was compared with the echo sounder survey conducted by the University of East Anglia team [6]. The depth-mean currents measured by the ADCP seaward of the northern most breakwater were compared with the radar derived current closest to that location and are shown in Figure 4.

Comparisons of the radar derived bathymetry and currents will be presented showing that the radar analysis is able to reproduce both the water depths measured by conventional methods and the depth-mean current measured by an ADCP to within an accuracy that while not as good as the in-situ measurements, is more than made up for in spatial coverage and ease of use of the remote sensing. Results from a further wave event during 2008 will also be presented and compared with those obtained in 2006, showing changes to the subtidal dune field located seaward of the breakwaters. It is anticipated that this will show a net migration of the dune field to the south east, consistent with the direction of prevailing longshore drift, and representing a significant transport pathway for sediment on that part of the coast.

## 5. ACKNOWLEDGEMENTS

Thanks are due to the UK Engineering and Physical Sciences Research Council and Natural Environment Research Council for funding and to the Palling Volunteer Rescue Service for the radar site.

## 6. REFERENCES

[1] Dolphin, T.J., Taylor, J.A., Vincent, C.E., Bacon, J.B., Pan, S., O'Conner, B.A., "Storm-scale effects of shore-parallel breakwaters on beaches in a tidal setting (LEACOAST)", Proceedings of the 29th International Conference on Coastal Engineering, Lisbon (Portugal), Vol. 3 pp 2849–2861, 19–24 September 2004.

[2] Hedges, T.S., "An empirical modification to linear wave theory". *Proc. Inst. Civ. Eng.*, 61, 575-579, 1976.

[3] Booij, N., "Gravity waves on water with non-uniform depth and current". *Rep. No.81-1*, Dept. Civ. Eng., Delft university of Technology, 1981.

[4] Young, I.R., Rosenthal, W. and Ziemer, F., "A three-dimensional analysis of marine radar images for the determination of ocean wave directionality and surface currents". J. Geophysical Research, 90, C1, 1049–1059, 1985.

[5] Bell, P.S., Williams, J.J., Clark, S., Morris, B.D., Vila-Concejo, A., "Nested radar systems for remote coastal observations", Journal of Coastal Research, SI39 (Proceedings of the $8^{th}$ International Coastal Symposium, Itajaí, SC (Brazil)), pp 483–487, 14–19 March 2004.

[6] Bell, P.S., "Remote bathymetry and current mapping around shore-parallel breakwaters", Proceedings of 33rd International Association of Hydraulic Engineering & Research (IAHR) Biennial Congress, Vancouver, Canada, August 9-14, 2009.