Mapping Shallow Water Coastal Areas Using a Standard Marine X-Band Radar

Dr Paul S. Bell *Proudman Oceanographic Laboratory, Liverpool, United Kingdom*

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Abstract

The bathymetry and currents in a 4km radius area of the Dee Estuary in Liverpool Bay have been mapped using a wave inversion of marine radar data without the need for any prior bathymetric data. The radar is mounted 30m above sea level on an island in the estuary and 10 minute sequences of radar images of the sea surface are recorded automatically each hour giving 360 degree coverage of the area. Several such records taken around high tide during a moderate wave event have been processed to produce the map using a wave inversion that accounts for currents, frequency and amplitude dispersion. The results are compared to a combined LiDAR and Multibeam echosounder survey carried out in 2003, clearly identifying migrating sand banks within the estuary. The strength of this technique is in its ability to map large areas of bathymetrically complex shallow coastal waters rapidly, remotely and under storm conditions, with vertical accuracies generally better than +/-1m of survey data.

Introduction

The monitoring of bathymetry and currents in estuaries can be a difficult problem to overcome due to difficulty of instrument deployment and access over shallow waters and muddy areas. The use of marine radar has been demonstrated several times as a tool for remote mapping of bathymetry [1] [2] [3] in a variety of locations on open coastlines. The principle of the technique is to digitally record sequences of radar images of the sea surface – the radar sea clutter signal. These animations of the sea surface are then post processed using Fourier based methods to determine the spatial distribution of the wave lengths at a range of wave periods. Waves slow down and hence reduce their wavelength as the water depth becomes shallower (shoaling), and any currents present introduce a Doppler shift to the propagating waves. The spatially varying properties of the waves are then fitted to a wave dispersion equation to determine the water depth and current maps that caused the observed wave behaviour.

Once a water depth map has been derived, it is straightforward to subtract the tide level such that the map is then referenced to chart datum. If a sequence of records is processed, the resulting maps can be averaged to reduce noise.

Since the technique is dependent on recording the sea clutter signal, there must be sufficient wave action present for the technique to operate. In practice it has been found that a significant waveheight (Hs) of at least 1m is necessary, and preferably higher. Higher quality data are generally collected if the radar antenna is mounted some 10s of meters above sea level, although in the absence of alternatives the author has regularly used a 2m high scaffold tower erected by hand at the back of a beach.

In 2005 a marine radar was deployed on the remote island of Hilbre in the Dee estuary on a tower at a height of around 30m above mean sea level. The radar overlooks a topographically complex area comprising intertidal sandbanks and deep subtidal channels. The Dee Estuary (Figures 1 & 2) is located about 10km west of Liverpool in the United Kingdom on the south side of Liverpool Bay. Waves are fetch limited and generally do not exceed 8 seconds in period, while the tidal range at peak springs exceeds 10m.

These factors combine to provide a difficult test for extracting bathymetry and currents from marine radar data and provide a useful illustration of the strengths and weaknesses of the technique. It is hoped that by establishing a long time series of radar records the gradually evolving bathymetry of the estuary will be better understood and also provide the ground truth needed for numerical model development.
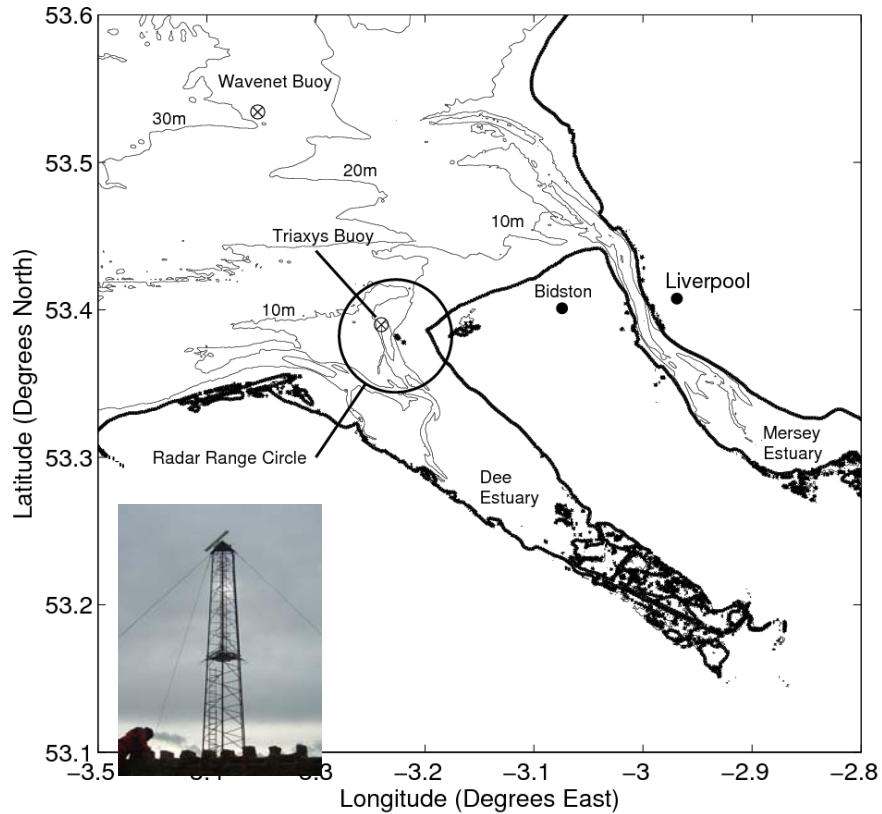

Figure 1. A map showing the location of the test site in the Dee Estuary. The 4km range of the data recorded from the marine radar is shown as a circle centred on Hilbre Island. The photo insert shows the radar tower.

Figure 2. Photograph taken from a light aircraft looking south east into the Dee Estuary and showing the extensive intertidal sand banks and deep tidal channels.

Data Collection

A sequence of 256 radar images at 2.4 second intervals spanning about 10 minutes are recorded on an hourly basis using a Wamos radar digitization system [6] with a radial sampling interval of 7.5m or smaller. The radar is a Kelvin Hughes 10kW X-band radar operating at 9.8GHz with a 2.4m rotating antenna transmitting 60ns pulses at a rate of 3000Hz and is mounted on a 15m high tower (Figure 2), the base of which is approximately 15m above mean water level. Until the middle of 2007 the data were recorded to a range of just under 4km, and subsequently have been recorded to a range of 7.5km. The beam pattern generated by such an antenna is approximately 22° in the vertical – deliberately wide to allow for pitch and roll of the ships on which they are intended to be mounted – and 1° in the horizontal, giving very good angular resolution. The length of the sector traced out by the horizontal beam width increases with range being approximately 50m at a range of 2km and about 100m at a range of about 4km. The practical consequence of this is that short waves traveling perpendicular to the radar beam will not be resolved at the longer ranges. An example of a raw radar image recorded in the Dee Estuary is shown in Figure 3, clearly showing the wave patterns within the sea clutter signal.
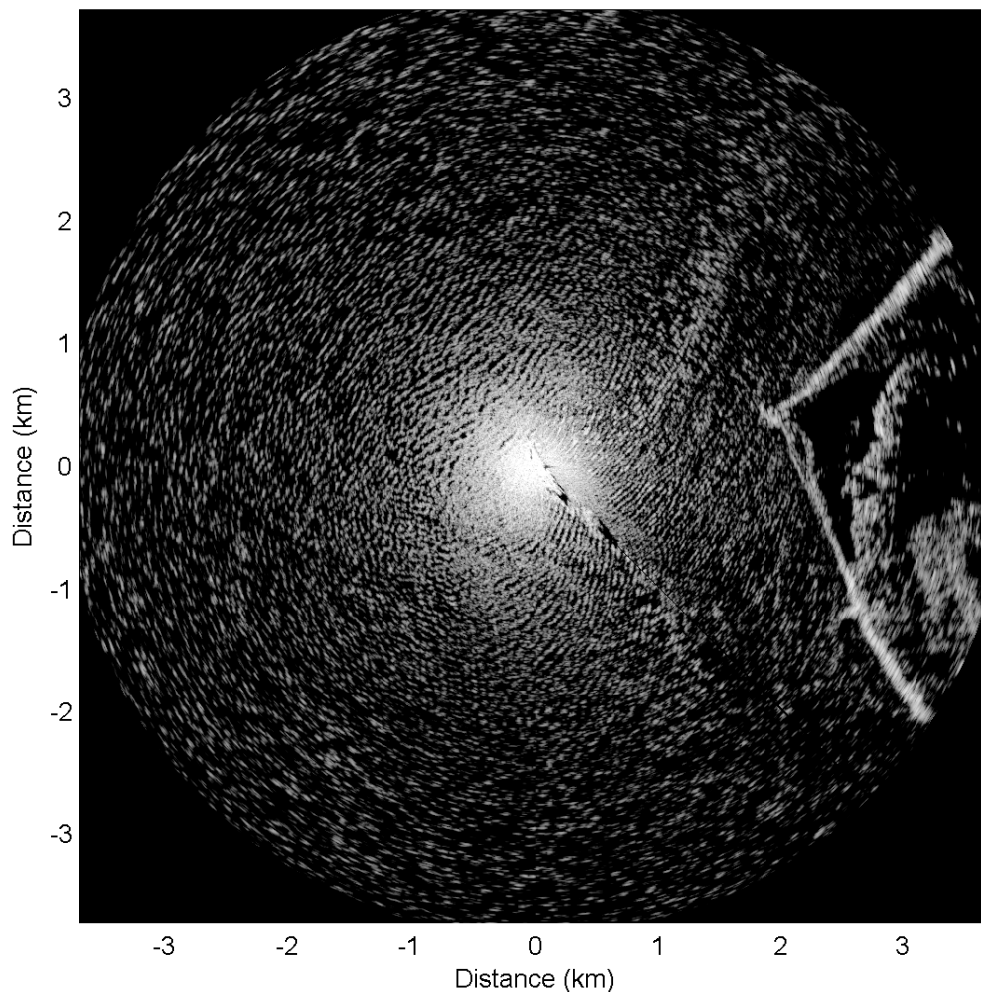
Figure 3. A raw digitized image from the X-band radar showing the eastern side of the mouth of the Dee Estuary at high water during a wave event. The image is oriented to true north. Clearly defined wave patterns are visible over much of the image, and the coastline of West Kirby and Hoylake on the Wirral peninsular is evident in the east of the image.

A tide gauge operated by the Mersey Docks & Harbour Company was located on the northern tip of Hilbre Island and a wave buoy was located about 15km offshore, operated by the UK Centre for Environment, Fisheries & Aquaculture Science (CEFAS) as part of the UK Wavenet system, while a Triaxys wave buoy was located inside the estuary just off Hilbre Island. The relevant data from these systems is illustrated in Figure 4.
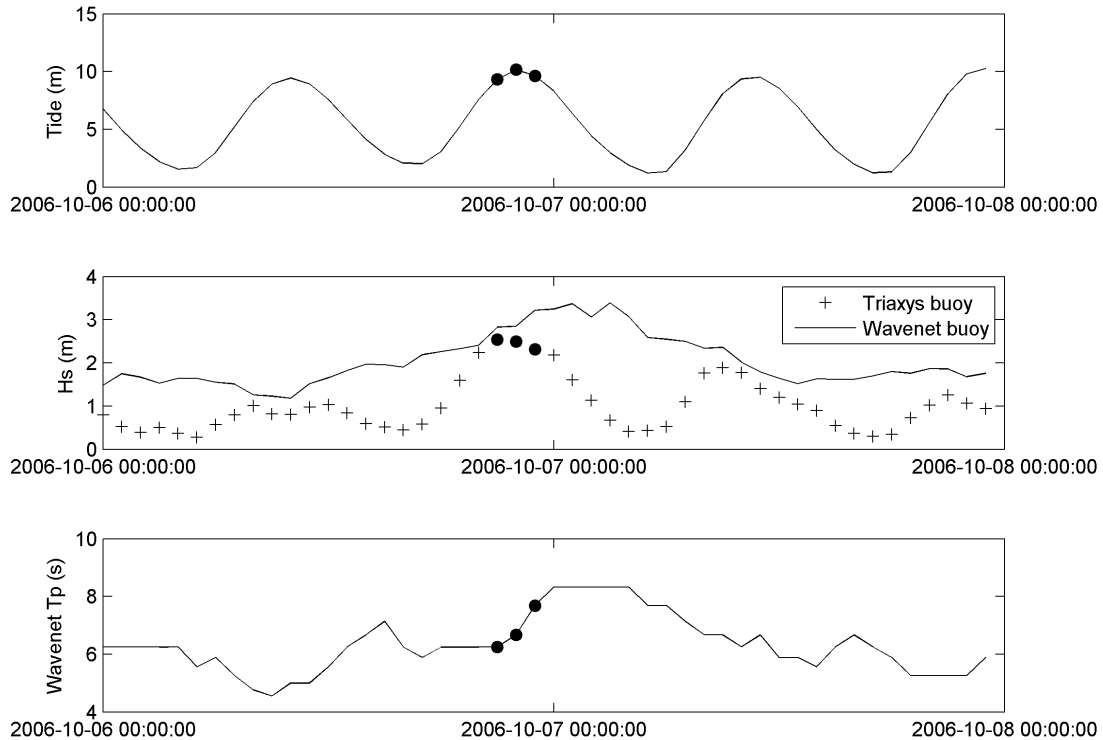

Figure 4. Water level data from the Hilbre Island tide gauge and wave measurements from the two wave buoys. The black circles denote the time of the three radar records used here.

The significant waveheight measured inside the estuary by the Triaxys buoy shows considerable modulation by the tide compared with the offshore Wavenet buoy due to the shielding effect of the sand banks in the mouth of the estuary as the tide drops. Since much of the area viewed by the radar will also be experiencing this modulated waveheight that is the value used in the wave inversion equation shown in the next section.

Analysis

A 240m analysis window - a size chosen to include at least 2 wavelengths (*L*) of the dominant waves - is translated in 2D across the area viewed by the radar. At each point the window of data is processed using Fourier methods to produce a three dimensional wavenumber (*k*) spectrum [7]. A wave dispersion equation is then fitted to the observed wavenumber spectrum to determine the water depth (*d*) and 2D current vector (*U*) that caused that wave behavior. The dispersion equation is based on linear theory with a correction for amplitude dispersion, i.e. the non-linear behaviour of large waves in shallow water which travel faster than the predictions of linear theory [5]. There is also a correction for currents to account for the Doppler shift the waves traveling on a mean current:

Water depth $d = \dfrac{1}{k}\left(\tanh^{-1}\dfrac{(\omega - k.U)^2}{gk}\right) - Z$

where wavenumber $k = \dfrac{2\pi}{L}$, angular frequency $\omega = 2\pi f$

and $Z = 0.5H$ for monochromatic waves [4], or $Z = 0.35H_S$ for spectral waves.

Results

At this particular site the sandbanks and sand flats are only fully submerged around spring high water and so only data recorded at these times allow the full area to be mapped. Three such records around a single spring high water during a wave event have been analysed using these algorithms.

Radar-Derived Bathymetry Results

The bathymetric map derived from these data has been corrected to chart datum and is shown in Figure 5. The overall features correspond well with a LIDAR and Multibeam survey carried out in 2003 and shown in Figure 6, despite being 3 years out of date. A more recent LIDAR survey from 2006 was available and is shown in Figure 7. Survey Data for the northern part of the study area was not available in either year, and so has had to be filled in with depths digitised from Admiralty Charts in the plot of the 2003 survey and left blank in the plot of the 2006 survey.
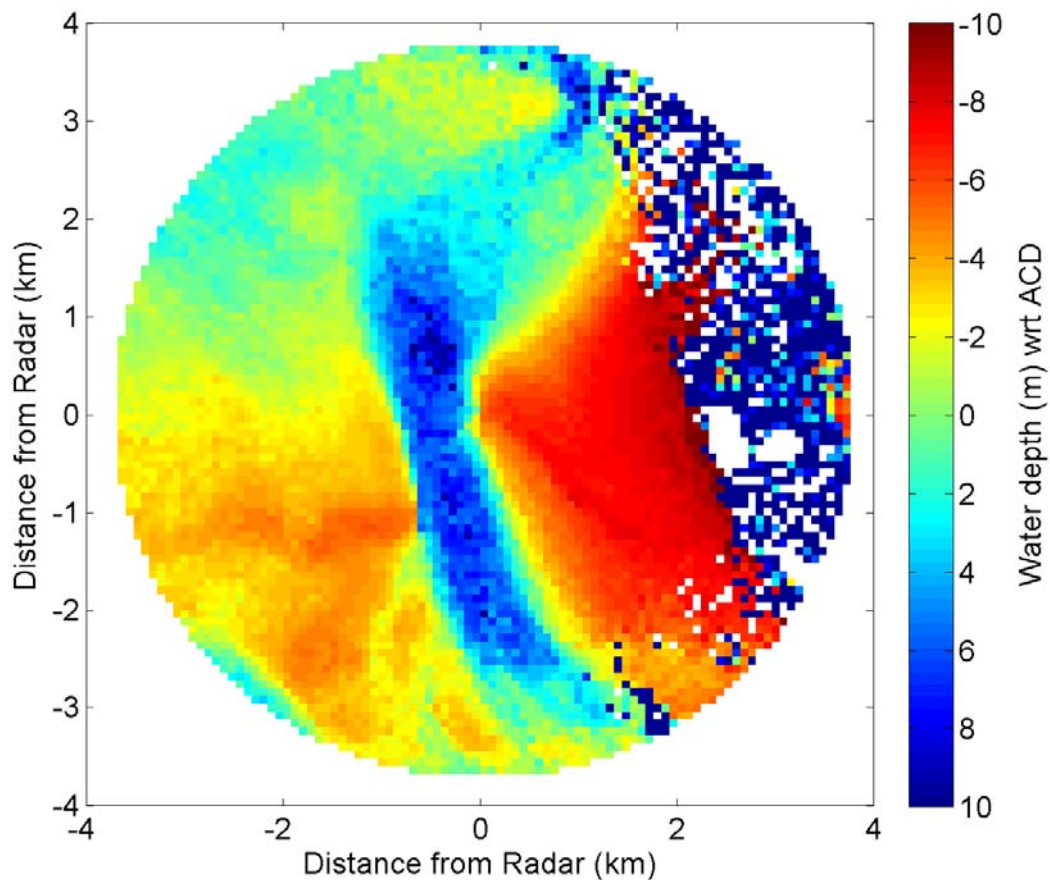

Figure 5. The bathymetry derived from three radar records over one spring high water
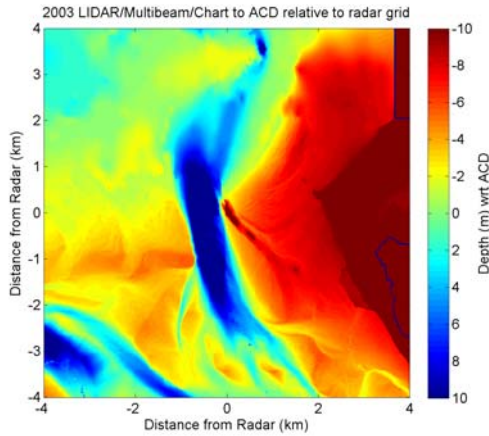.

Figure 6. The combined LIDAR, Multibeam echosounder and Admiralty Chart survey of the Hilbre Island area from 2003.
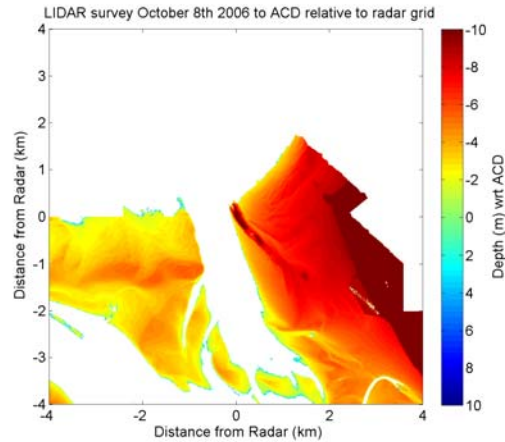

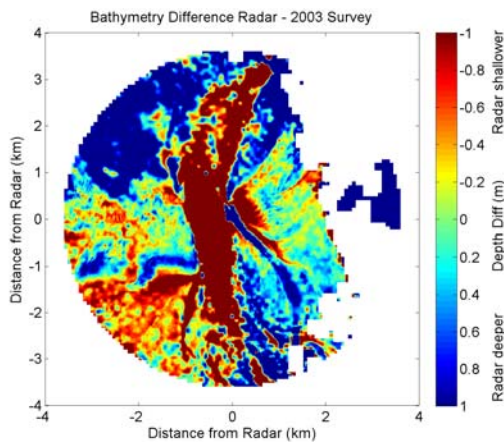Figure 7 The 2006 LIDAR survey of the Hilbre Island area. Surveys of the deeper areas were not available.

Figure 8. The Difference between the radar derived bathymetry and the 2003 survey data. Red colours indicate that the radar is reading shallower depths than the survey.
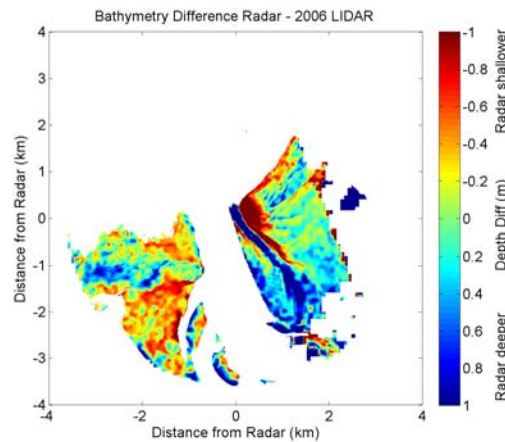

Figure 9. The Difference between the radar derived bathymetry and the 2006 LIDAR survey Red colours indicate that the radar is reading shallower depths than the survey.

The combined 2003 LIDAR-multibeam-chart bathymetric map of the area is shown in Figure 6 and the 2006 LIDAR survey is shown in Figure 7. By subtracting the survey data from the radar derived bathymetry it is straightforward to illustrate the distribution of errors in the radar derived bathymetry. Figures 8 and 9 illustrate the errors relative to the 2003 and 2006 surveys. In Figure 8 a marked deterioration in agreement with the survey data in the northern half of the area in Figure 7 can be explained by the sparsity and age of soundings used in the Admiralty Charts, hence this area of the data is not considered particularly useful for comparisons other than in general form. The underestimate in depth by around 0.5m in the south west corner of the study area is thought to be an artifact of the use of a single Hs value for the entire region. One could expect that the waveheight behind the sandbanks located 1km south of the radar and to the west would be substantially lower than to the north of these sand banks, which would lead to an over correction for the effect of wave height in the depth inversion equation.

It is pleasing to note that the radar derived bathymetry show better overall agreement with the 2006 survey than the 2003 survey. In particular the complex of sandbanks located to the west and 1km south of the radar have been resolved with no significant offset in position in Figure 9, while the comparison with the 2003 survey in Figure 8 shows that the sandbanks have migrated

approximately 200m to the south in the intervening three years. Independent verification of the migration of this system of sand banks can be found in the fact that the navigation buoy marking the southern edge of these sand banks has had to repeatedly moved southwards by the local harbour authority over the past few years.

The area with the most significant errors in radar derived depth is the deep channel running through the centre of the study area. This is not unexpected since wave periods at this site rarely exceed 8 seconds and hence the waves being used to image the sea bed are barely interacting with the bottom in the deep (25-30m at high water) channel.

Radar-Derived Current Results

Currents are derived simultaneously with the water depths and can give a broad view of current patterns in the same region as the water depths. The analysis has been tuned to pick up the current that the waves are feeling, which can be interpreted as an integral of the current profile with depth, but with a bias towards the surface values. No comparisons with independent current measurements have yet been performed, but the correction they introduce to the water depths has proven sufficiently accurate to remove errors in derived water depths due to the Doppler shift of waves, lending confidence to the results. Two examples of the radar-derived water depth and current fields are shown in Figures 10 & 11, the first being during the flood half of the tide one hour prior to slack water and the second during the ebb, one hour after slack water.
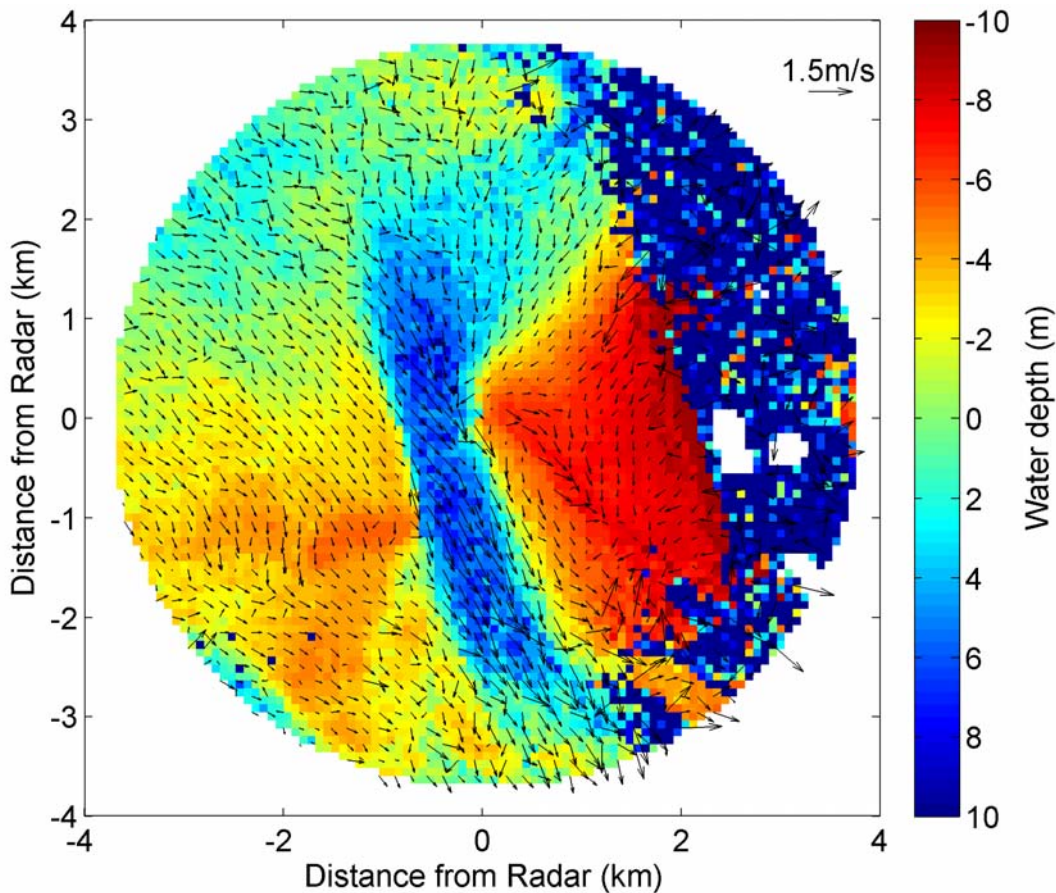

Figure 10. The radar-derived bathymetry (referenced to chart datum) and current maps corresponding to the flood tide one hour prior to slack water.
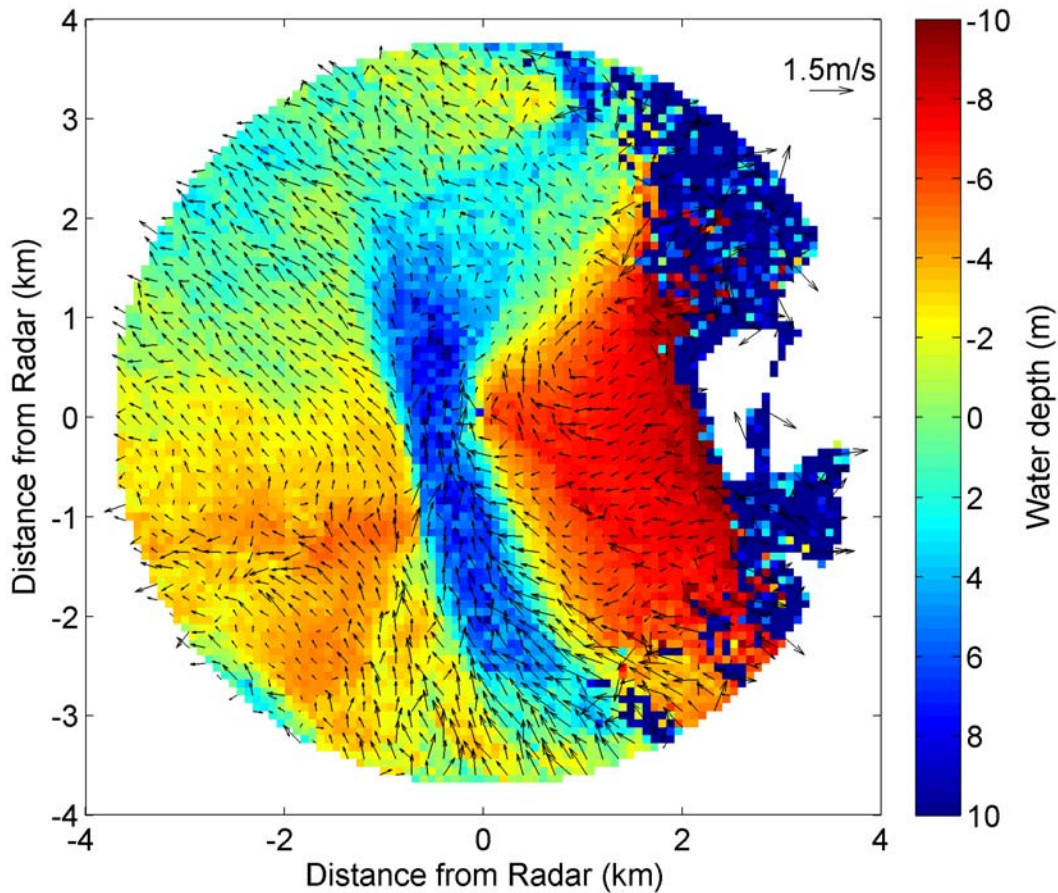
Figure 10. The radar-derived bathymetry (referenced to chart datum) and current maps corresponding to the ebb tide one hour after slack water.

Although no comparisons with current meter data have been performed, the magnitude and direction of the currents on the flood and ebb are consistent with those that might be expected for this area. The currents have largely reversed from flood to ebb as expected, and follow realistic paths for the measured bathymetry. Further work will investigate the exact correspondence of these radar derived currents with ADCP data that are available from deployments in the deep channel to the west of Hilbre Island.

Conclusions

Marine radar image sequences of waves have been processed to determine water depth and current vectors at ~100m intervals. The water depth derived from these data have been adjusted to chart datum using tide gauge data and compared with two sets of survey data from 2003 and 2006. The results demonstrate that the radar derived water depths are generally within +/-1m of the survey data in areas where the waves are feeling the bottom. Further work is needed to establish the quality of the derived current data, although they appear qualitatively reasonable for the area and tidal conditions and accurately compensate the derived depths for the errors caused by current induced Doppler shifts.

References

1. Bell, P.S., 1999. Shallow water bathymetry derived from an analysis of X-band marine radar images of waves. Coastal Engineering, 37(3-4): 513-527.

2. Bell, P.S., 2001. Determination of bathymetry using marine radar images of waves, Waves 2001: 4th International Symposium on Ocean Wave Measurement & Analysis, San Francisco, USA, pp. 251-257.

3. Bell, P.S., Williams, J.J., Clark, S., Morris, B.D. and Vila-Concejo, A., 2006. Nested Radar Systems for Remote Coastal Observations. Journal of Coastal Research, SI39 (Proceedings of the 8th International Coastal Symposium, Itajaí, SC, Brazil, 14-19 March 2004): 483-487.

4. Booij, N., 1981. Gravity waves on water with non-uniform depth and current. Rep. No.81-1, Dept. Civ. Eng., Delft University of Technology.

5. Hedges, T.S., 1976. Empirical modification to linear wave theory. Proceedings of the Institution of Civil Engineers Part 2-Research and Theory, 61(SEP): 575-579.

6. Hessner, K.G., Nieto-Borge, J.C. and Bell, P.S., 2008. Nautical Radar Measurements in Europe - Applications of WaMoS II as sea state, current and bathymetry sensor. In: V. Barale and M. Gade (Editors), Remote Sensing of the European Seas. Springer, Geosciences, Dordrecht, The Netherlands, pp. 435-446.

7. Young, I.R., Rosenthal, W. and Ziemer, F., 1985. A 3-dimensional analysis of marine radar images for the determination of ocean wave directionality and surface currents. Journal of Geophysical Research-Oceans, 90(NC1): 1049-1059.

Biography

Paul Bell graduated from St Andrews University in Scotland in 1992 with an honours degree in Physics and Electronics. Following a few months as a stagiaire tinkering with X-ray detectors at the European Synchrotron Radiation Facility in Grenoble, he took up post in the Technology Group at the Proudman Oceanographic Laboratory (POL) working with high performance sonar and radar systems. Whilst working full-time he completed a part-time PhD in determining bathymetric changes using ground based radars with the University of Bangor, Wales, in 2006.

He has taken part in a number of large collaborative field experiments including the EU-funded COAST3D (1998 and 1999), INDIA (1999) and Deltaflume (1997 and 2001) as well as other nationally funded field experiments such as the Holderness experiments (1994 and 1995) and LEACOAST2 (2006-2008).

In recent years he became more interested in the science within the data than in the instruments themselves, transferred to the Marine Physics Group at POL, and now concentrates on developing and validating algorithms for determining oceanographic data from radar and sonar systems in order to measure and explain large scale bathymetric changes in coastal areas.

psb@pol.ac.uk