General enquiries on this form should be made to:
Defra, Science Directorate, Management Support and Finance Team,
Telephone No. 020 7238 1612
E-mail: research.competitions@defra.gsi.gov.uk

SID 5 Research Project Final Report

- **Note**

  In line with the Freedom of Information Act 2000, Defra aims to place the results of its completed research projects in the public domain wherever possible. The SID 5 (Research Project Final Report) is designed to capture the information on the results and outputs of Defra-funded research in a format that is easily publishable through the Defra website. A SID 5 must be completed for all projects.

  A SID 5A form must be completed where a project is paid on a monthly basis or against quarterly invoices. No SID 5A is required where payments are made at milestone points. When a SID 5A is required, no SID 5 form will be accepted without the accompanying SID 5A.

- This form is in Word format and the boxes may be expanded or reduced, as appropriate.

- **ACCESS TO INFORMATION**

  The information collected on this form will be stored electronically and may be sent to any part of Defra, or to individual researchers or organisations outside Defra for the purposes of reviewing the project. Defra may also disclose the information to any outside organisation acting as an agent authorised by Defra to process final research reports on its behalf. Defra intends to publish this form on its website, unless there are strong reasons not to, which fully comply with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

  Defra may be required to release information, including personal data and commercial information, on request under the Environmental Information Regulations or the Freedom of Information Act 2000. However, Defra will not permit any unwarranted breach of confidentiality or act in contravention of its obligations under the Data Protection Act 1998. Defra or its appointed agents may use the name, address or other details on your form to contact you in connection with occasional customer research aimed at improving the processes through which Defra works with its contractors.

Project identification

1. Defra Project code: A1227
2. Project title: Assessment of the Significance of Changes to the Inshore Wave Regime as a consequence of an Offshore Wind Array
3. Contractor organisation(s): CEFAS
4. Total Defra project costs: £ 123,563
5. Project: start date .... 01 April 2003

   end date .... 30 September 2005

6. It is Defra’s intention to publish this form.
Please confirm your agreement to do so...**YES** ☒ **NO** ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.

Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.

In all cases, reasons for withholding information must be fully in line with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Objectives

Offshore windfarm (OWF) development within the UK is presently in the Second Round of licensing by Defra through FEPA (1985). Many of the Round One licences have already been granted, and of these, the development on Scroby Sands was one of the first. More significantly, Scroby Sands is amongst the few OWFs situated in a dynamic sedimentary environment. It is also close to a coastline which is vulnerable to erosion and which has seen numerous different coastal protection schemes in recent years. Development of the OWF at this site was started in autumn 2003, and electricity production commenced in December 2004.

As part of the licensing process, Cefas provides specialist “coastal process” advice to Defra to enable a Government View to be provided. As a result of the review of the associated Environmental Statement (ES), Cefas was commissioned by Defra to carry out research on the Scroby Sands development to include investigation and assessment of the significance of changes to the inshore wave regime as a consequence of development of the wind turbine array. The resulting contract (AE1227) was performed in conjunction with research on changes to sediment transport pathways and sandbank geomorphology (contract AE0262 – www.cefas.co.uk/renewables).

This report details work undertaken only under contract AE1227. It was anticipated that this work would provide evidence-based research from which to refine any requirements for monitoring of waves that have been included within licence conditions of Round One developments, and that could be included within those conditions for Round Two developments.

Methods

In order to assess the extent to which wave interference and diffraction patterns would develop following transmission through an array of monopile structures, this work has made use of measurements of waves and sea-surface roughness, numerical modelling techniques and a review of relevant literature. The modelling undertaken by Halcrow was further development of their work for the Environmental Impact Assessment (EIA). The modelling comprised specific scenarios that encompassed a range of incident wave direction, wavelength, and wave height, over both a flat and realistic bathymetry, and considered the proposed location of the individual monopiles. In doing so, it aimed to provide a theoretical (quantitative) prediction of the wave patterns in the region between the sandbanks of Scroby Sands, and the coastline between Great Yarmouth and Caister. An X-band radar was located on Britannia Pier (Great Yarmouth) during the consecutive winter seasons of 2002/2003 and 2003/2004. The radar covered the pre- and post-development periods of the monopile construction and enabled wave patterns during these times to be qualitatively assessed, so that the role of the structures could be investigated. Whilst the limited range of the radar meant that any wave patterns close to the monopile array were not measured, those patterns that might contribute significantly to enhance coastal erosion at the coastline were observed. Simultaneous measurements of waves were made using wave-gauges, providing an opportunity to calibrate the radar data and quantifying changes in wave height.

Main Findings

The sensitivity analysis enabled by the modelling showed that for a simplistic flat seabed, wave interference patterns were most pronounced for waves approaching the monopile array obliquely, at an angle of 35 degrees. For more realistic bathymetry, this angle was decreased, but more significant was the maximum reduction in wave height from 5% (flat seabed) to 2% (realistic bathymetry). Thus, effects of wave refraction in shallow water are greater than those of monopile-related wave diffraction and interference. Wave refraction in shallow water acts to reduce any effect of the monopiles upon waves.

The quantitative value of predicted change to wave height as a result of monopile arrays, of 2%, is in agreement with those estimates presented as part of the Environmental Statements for other more recent windfarms. It has not been possible to detect this small change using the presently available measurement and analysis techniques afforded by X-band radar. It is therefore concluded that wave diffraction and interference effects arising from monopile arrays are negligible. By inference, any effect on coastal erosion is therefore also likely to be negligible.

Significance

Regarding the Scroby Sands OWF, there is no further requirement to investigate and quantify the effect of the Scroby Sands development on coastal erosion.

Whilst for future developments, the rotor blades and the foundation structures that support them are likely to increase in size, the controlling parameter for determining inter-turbine spacing is likely to remain that of maximising the efficiency of wind flow over the rotors. Thus the present spacing for monopile foundations of 6-8 rotor diameters is unlikely to be significantly different to that used in this study and it is therefore very unlikely that wave diffraction and interference would require further investigation.

Regarding the broader picture, Defra's Marine Consents and Environment Unit (MCEU) are advised **not** to require developers of OWFs to monitor waves for diffraction/interference effects under a FEPA licence.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

1. Scientific Objectives

This research will primarily aid licensing decisions and UK policy and advice on offshore windfarm development under current legislation (i.e. the Coast Protection Act (CPA) 1936, Food & Environment Protection Act (FEPA) 1985). The aim of this research was to assess the significance of changes to the nearshore wave regime as a result of the construction of offshore windfarms, based primarily on unique field measurements, but including scenario-testing using numerical modelling techniques. The research is concentrated at a specific site (i.e. Scroby Sands, offshore from Caister, Norfolk), which was identified as the "*worst-case scenario*" for impact on coastal processes, from the first round of applicants for windfarm development to the Crown Estate (hereafter referred to as "Round 1") in Cooper and Beiboer (2002). In support of the various Environmental Impact Assessments of these Round 1 developments, there has understandably been a lack of field evidence to validate numerical modelling predictions, but more notably a lack of consensus between models that have been used by the various consultants involved with each development. As a consequence, judgements of the stability of the adjacent coastline to erosion may, until now, have been inadequately informed. This study thereby supports DEFRA's remit to promote the sustainable development of the marine and coastal environment, and provides evidence to improve coastal defence. As a result, it is anticipated that this work will assist in ensuring that the sustainable development of offshore wind energy is maintained.

Scientific Objectives as set out in the CSG7 and the signed contract with Defra:

1. To provide detailed field measurements of waves relating to an offshore windfarm at Scroby Sands.
2. To carry out sensitivity analysis on a numerical model for the Scroby Sands "*wind array*" and "*wave regime*" parameters that control wave diffraction.
3. To use the results of (1) in comparison with those from the numerical model, and assess the extent of agreement.
4. To extend the results of (1) and (2) for a more broad application of wave diffraction effects, to generic future windfarm developments.
5. To assess the significance of changes to the nearshore wave regime as a result of the construction.
6. To provide timely and quantitative results to enable the provision of sound generic scientific advice for the second round of windfarm developments.

Notes accompanying the above Scientific Objectives:

Note 1: *It is anticipated that the sensitivity analysis will test the importance of various parameters (e.g. wave height, wave period, wave direction, water depth) associated with the wave climate, in relation to wave diffraction effects. Thus although the study is site-specific, it is anticipated that it will identify any significant wave diffraction effects as they relate to windfarm arrays, and, as importantly, will identify the extent of variation of these effects. In this way, interpretation of the results of this site-specific study will be used directly to highlight developments under which more thorough investigation of wave diffraction effects may need to be undertaken. Thus guidance on the importance of the various parameters (above) will be included within this research.*

Note 2: *The present level of funding being made available for this research prohibits the inclusion of data from other sites. However, the present timetable for Scroby Sands (i.e. construction in Autumn 2003 - Spring 2004) is along similar timescales to other developments for which the ES have been reviewed, and therefore, at present there is no reason to change the proposed field site. For reasons of dynamic sediments, proximity to shore, shallow water depth, vulnerable coastline, etc, the Scroby Sands site has been preferred (and indeed acknowledged as the "worst-case scenario" for impact on changes to coastal processes in a recent study by ABPMer, and funded by ETSU). However, should the construction timetable again be changed, then several other alternative sites could be utilised (e.g. second choice Gunfleet Sands, although the ES has only recently been submitted; third choice Lynn/Inner Dowsing). The sites are largely limited by the low range (i.e. approx. 2 km) of the X-band radar, and the use of other sites would necessitate the use of 2 X-band radars (one land-based, the other in close proximity to the OWF) during each deployment. It should be noted that within the licensing conditions for each OWF, is presently being included a potential requirement for monitoring of wave diffraction effects, dependent upon the outcome of AE1227 project. However, pre-construction deployment of the X-band radar would have to be ensured for these measurements to be most effective.*

Note 3: *Validation and consensus on a range of industry-standard numerical models in relation to wave diffraction and focussing effects is only to be provided through subsequent research contracts (e.g. Phase 2 submitted previously to Defra as a Pre-CSG7.)*

2. Summary of Success [Against Scientific Objectives]

OBJ. NO.	ACHIEVEMENT	OUTPUT
1	X-Band radar data: 16/04/03 to 04/06/03 (i.e. 7 weeks; Pre-construction) ADCP “with waves” data:9/04/03 to 06/06/03 (i.e. 8 weeks; Pre-construction) ESM2 data: 09/04/03 to 08/06/04 (i.e. 8 weeks; Pre-construction) X-Band radar data: 19/01/04 to 09/03/04 (i.e. 7 weeks; Post-construction) AquaDopp Profiler data: 05/02/04 to 27/02/04 (i.e. 3 weeks; Post-construction) ESM2 data: 05/02/04 to 18/03/04 (i.e. 6 weeks; Post-construction)	Figures (Report & CD) Cefas Data archive Cefas Data archive Figures (Report & CD) Cefas Data archive Cefas Data archive
2	Halcrow MWAV_LOC model: Flat bathymetry: 28 model runs (wave direction, 19 runs over range N to E; wavelength, 3 runs over range 1:10 to 1:50 year storm; wave height, 3 runs over range 1:10 to 1:50 year storm; water depth, 3 runs over range 2–10 m) Real bathymetry: 22 model runs (wave direction, 13 runs over range 030 to E; wavelength, 3 runs over range 1:10 to 1:50 year storm; wave height, 3 runs over range 1:10 to 1:50 year storm; water depth, 3 runs over range 0-2.9 m CD)	Figures (Report & CD) Figures (Report & CD)
3	The wave interference & diffraction patterns predicted by modelling techniques were not detected in any of the radar images. It was therefore not possible to assess the extent of agreement nor to undertake the comparison.	None
4	Discussion of (3) above concluded that where the foundation type was of the monopile form, then wave interference & diffraction effects required no further consideration for future windfarm developments. However, assessment of different foundation types was beyond the scope of this study.	None
5	The sensitivity analysis undertaken in this study has given results that are in agreement with and have enhanced understanding of modelling carried out for other Round 1 sites. Based on results in (2), and the lack of interference/diffraction patterns observed in (1), that meant it has not been possible to validate the modelling predictions, this study concludes that there is no reason to believe that realistic changes were significantly different to those predicted, and therefore that changes in the wave regime were unlikely to be significant.	None
6	Round 2 developments are presently in various stages of progress, and there have to date been few technical enquiries. A sensitivity analysis (see (2) above) has quantified the importance of specific factors that control the interference/diffraction effects. This study has therefore reported in a timely manner to feed into Cefas/Defra advice to Round 2 applicants.	Advice to Cefas Regulatory Assessments Team at Burnham-on-Crouch

3. Methods

a. The Consortium

A consortium comprising The Centre for Environment, Fisheries & Aquaculture Science (Cefas), Proudman Oceanographic Laboratory (POL), Halcrow Group Limited (Halcrow), and Terry Oakes Associates (TOA) was set up to achieve the various scientific objectives and milestones. Responsibilities were broadly assigned as follows:

- Model sensitivity analysis - Halcrow
- X-band (wave) radar deployment, data processing, and analysis - POL
- Assessment of the significance of changes to the wave regime to local coastal defence – TOA
- Moored instrument deployment, data processing and analysis – Cefas
- Updates on licensing and industry developments – Cefas
- Project co-ordination and management - Cefas

b. Site Location

The site for development of the offshore windfarm at Scroby Sands was on the Middle Scroby sandbank, off Caister on the East Anglian coast (Fig. 1).

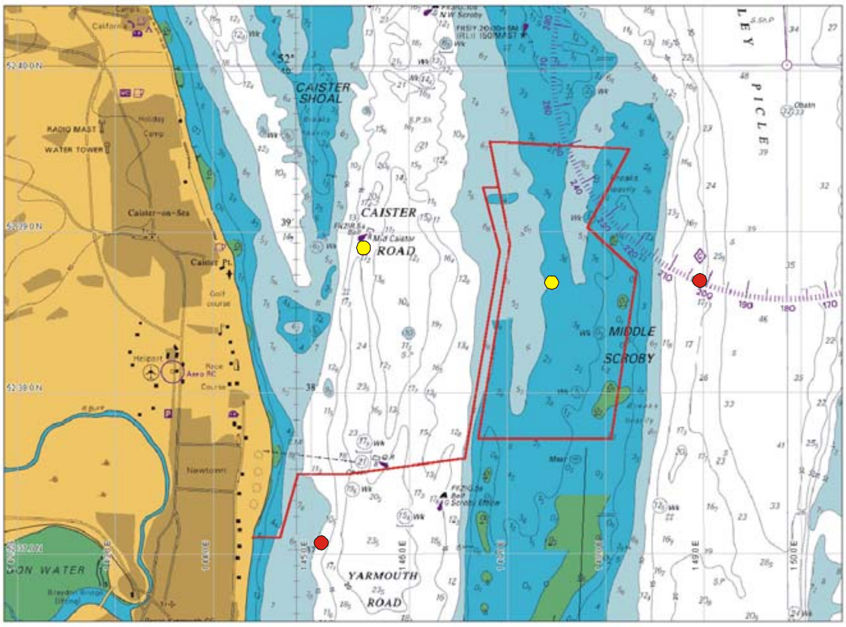


Figure 1 – Instrument mooring locations at Scroby Sands, as part of this contract (red circles; for instrumentation see Table 4), and Defra contract AE0262 (yellow circles). Also shown is the extent of the wind array (red box), and the location of the cable to shore (red line).

In this region, dominant waves during winter are from the North to the North-East. The choice of location of the X-band radar ground station was controlled by various constraints - the data coverage (of the radar), logistical, incident wave direction, complexity of nearshore bathymetry, and the security of hardware. Britannia Pier (Great Yarmouth) was selected for the following reasons:

- As this project had identified a potential impact on the wave regime “downstream” of a windfarm, this could have an effect on alongshore sediment transport and hence the coastline. Thus the nearshore zone was an important area in which to understand the spatial distribution of waves (rather than any changes to sandbank morphology and the adjacent seabed, which was specifically covered under Defra project AE0262). Radar range was a maximum of around 1.5 km (i.e. about ½ - 2/3 the distance from the coast to the turbine array of 2.3 km – nearest Wind turbine to the coast is number 01 directly across Yarmouth Roads). This enabled measurement over either the near-field (the coast) or the far-field (the sandbank region of Middle Scroby).

- All changes in wave height (c. 2-5%), complex nearshore bathymetry (e.g. bars and sandbanks, which are particularly prevalent around the Caister region due West of Middle Scroby sandbank) would have complicated any wave patterns by enhancing wave refraction and energy loss through friction with the seabed, and reduced the likelihood of measuring this change.

- Availability and logistical constraints meant that was only one radar was available.
- A further driver was to measure impacts on the dominant NE waves, which approach the wind array at an oblique angle. The likelihood of measuring any resulting wave pattern was thus to the SW of Middle Scroby (i.e. on the straight coastline immediately to the N of Great Yarmouth). This had the disadvantage of increasing the distance over which any wave pattern generated immediately inshore of the wind array would have to remain resolvable by the radar.
- A secure location with radar sited at 10 m above water level was required. Piers have successfully been used in previous studies of coastal wave regimes (e.g. Teignmouth Pier as part of the Future Coast project).

c. Sensitivity Analysis

i. The Wave Model

The wave diffraction caused by the offshore wind array was studied using Halcrow's numerical wave model, MWAV_LOC, which enabled a number of alternative wave regime scenarios to be investigated. The MWAV_LOC model development is based on an evolution equation solution to the mild slope equation for water waves. The evolution equation is a time dependent parabolic equation and its solutions will approach the results of the elliptic mild-slope equation as time increases. A perturbation method was used to derive the evolution equation. The equation takes into account the combined effects of refraction, diffraction, wave reflections and wave breaking. The mild-slope equation is derived from the exact linearised governing equations of irrotational flow in the three dimensional domain under the assumption that the bottom elevation changes little over one wavelength. It reduces to the Helmholtz diffraction solution for constant water depth on the one hand and to the long wave equation for shallow water on the other. The accuracy of the equation remains satisfactory, even for a bottom slope of the order of unity (Chandrasekera and Cheung, 2001). The model is designed for modelling impacts over large areas, of the order a few square kilometres, and has been used frequently in commercial applications by Halcrow, largely in the assessment of environmental impacts of a range of coastal engineering schemes. In this case, the model was used to investigate the local influence of the monopiles on the wave climate and was set up to determine the wave propagation pattern over the sandbank and inshore to 1.2 km off the coast, using a monopile diameter of 4 m. The MWAV_LOC wave model has been used in numerous EIA studies.

ii. Model Scenarios

Two series of model runs were undertaken: 1) "*Flat Seabed*", to provide a baseline from which to assess subsequent wave patterns, which described a simplistic and theoretical situation, and 2) "*Real Bathymetry*", to provide a more realistic representation of the Scroby Sands wind turbine array and environmental setting, from which comparisons with the baseline could be made. The offshore wave conditions used were waves of annual, 10-yr and 50-yr return periods (Table 1).

Table 1 - Extreme offshore wave conditions used in the model, which match those used by Halcrow (1996) for the original Environmental Statement.

Return period (years)	Wave height (metres)	Wave period (seconds)
1	3.77	6.6
10	4.96	7.6
50	5.36	7.9

"Flat Seabed"

The flat seabed bathymetry used represented no shore-perpendicular change in water depth. The model grid comprised a 3.9 km length of coastline to a distance offshore of 2.4 km, with a grid spacing of 3.0 m (from which 1300 by 800 grid points were generated) thus capable of representing the size of individual monopiles (4.2 m). The monopile array was arranged as a regular grid (i.e. N-S straight lines with regular inter-turbine spacing of 250 m). A total of 28 model runs were performed, that described a range of dominant conditions for wave direction, incident wave length, incident wave height and water depth (Table 2). Water depths of 2, 6 and 10 m at the windfarm were chosen because they represent the actual spread of depths at the windfarm array (2 m in the south of the array increasing to 10 m in the north).

Table 2 - Wave conditions and water depths used for the "Flat Seabed" model scenarios.

Run No.	Effect studied	Return period (year)	Wave direction (degrees) (from north)	Wave period (seconds)	Water depth (metres)
1	Effect of wave direction	50	90	7.9	10.0
2		50	85	7.9	10.0
3		50	80	7.9	10.0
4		50	75	7.9	10.0
5		50	70	7.9	10.0
6		50	65	7.9	10.0
7		50	60	7.9	10.0
8		50	55	7.9	10.0
9		50	50	7.9	10.0
10		50	45	7.9	10.0
11		50	40	7.9	10.0
12		50	35	7.9	10.0
13		50	30	7.9	10.0
14		50	25	7.9	10.0
15		50	20	7.9	10.0
16		50	15	7.9	10.0
17		50	10	7.9	10.0
18		50	5	7.9	10.0
19		50	0	7.9	10.0
20	Effect of wave length	1	90	6.6	10.0
21		10	90	7.6	10.0
22		50	90	7.9	10.0
23	Effect of wave height	1	90	6.6	10.0
24		10	90	7.6	10.0
25		50	90	7.9	10.0
26	Effect of water depth	50	90	7.9	2.0
27		50	90	7.9	6.0
28		50	90	7.9	10.0

"Real Bathymetry"

The waves, water depths, and bathymetry describe wave propagation over the site at Scroby Sands. Bathymetry was generated from Admiralty Chart 1536. The water levels of HAT (2.9m), MSL (1.6m) and LAT (0.0m) are from the Admiralty Tide Tables for Gorleston-on-Sea, which is the closest tidal station to the windfarm (Table 3). The model grid comprised a 4.47 km length of coastline to a distance offshore of 3.6 km, with a grid spacing of 3.0 metres (from which 1490 by 1200 grid points were generated). The monopile array locations were provided by Powergen plc (Steve Gopsill, Powergen plc, *pers. comm.*). The bathymetry was significantly smoothed at the incident wave boundary in order to minimise the numerical noise within the model. This smoothing should not significantly affect the results because the most important wave conditions would be affected by gross bathymetric changes rather than small perturbations due to sand waves. A total of 22 model runs were performed, that described a range of dominant conditions for wave direction, incident wave length, incident wave height and water depth (Table 3).

Table 3 - Wave conditions and water depths used for the “Real Bathymetry” model scenarios.

Run No.	Effect studied	Return period (years)	Wave direction (degrees) (from north)	Wave period (seconds)	Water level (metres CD)
29	Effect of wave direction	50	90	7.9	2.9
30		50	85	7.9	2.9
31		50	80	7.9	2.9
32		50	75	7.9	2.9
33		50	70	7.9	2.9
34		50	65	7.9	2.9
35		50	60	7.9	2.9
36		50	55	7.9	2.9
37		50	50	7.9	2.9
38		50	45	7.9	2.9
39		50	40	7.9	2.9
40		50	35	7.9	2.9
41		50	30	7.9	2.9
42	Effect of wave length	1	90	6.6	2.9
43		10	90	7.6	2.9
44		50	90	7.9	2.9
45	Effect of wave height	1	90	6.6	2.9
46		10	90	7.6	2.9
47		50	90	7.9	2.9
48	Effect of water depth	50	90	7.9	0.0
49		1:50	90	7.9	1.6
50		1:50	90	7.9	2.9

d. Wave Radar

i. Locating the Radar

An X-band radar system was deployed from a small scaffolding tower placed on Britannia Pier in Great Yarmouth. The view to Scroby Sands in the NE was unobstructed, with the only obstruction being a small angle to the E (<5°) which was blocked by some of the pier superstructure.

ii. How the Radar Works

The X-band radar is a standard Racal-Decca marine radar, in which backscatter echoes of a transmitted pulse are received by the radar. The main source of backscatter is from sea-spikes associated with steep and breaking waves, and to a lesser degree from the capillary waves on the crests of gravity waves (Bragg Scattering). Gravity waves themselves provide no backscatter signal.

Images of the sea surface were recorded as sequences of 64 images at a nominal separation of 2.4 seconds, and therefore spanning approximately 2.5 minutes. Data were recorded at burst intervals of 30 minutes for the duration of the radar deployment (see section 2, Obj. 1). The radial range resolution was 7.5 m, independent of range. The angular resolution was 1.2 degrees and thus the resolution perpendicular to the radar beam decreased with increasing range (i.e. 10 m at 500 m; 20 m at 1 km; 40 m at 2 km). The consequence is that short waves travelling perpendicular to the radar beam will not be resolved at the larger ranges. Data were recorded to a radial range of 2 km from the radar and have been referenced to WGS84 UTM grid UDU31. The minimum wave conditions usually visible on the system are approximately H_s=0.5 m. Weather conditions were over the period of the deployments were unfortunately quiet with significant wave heights at the Radar calibrator location of less than 1m.

iii. Data Presentation

In order to enable any wave interference patterns to be observed within the data, data was analysed to produce several different types of plot:

- A "**raw**" radar image with no processing other than rectification to a geo-referenced grid. This includes data of all waves, at all frequencies;
- A "**mean**" radar image, with all 64 images averaged to give a single image. This technique tends to remove individual waves, but emphasises the location of any consistent sea surface features, and enables identification of regions of wave breaking and the calibration buoy;
- A "**peak-frequency**" radar image, which filters and isolates the strongest wave frequency and removes all other waves from the image, consequently providing a more regular image of sea-state. This was achieved by running a Fast Fourier Transform (FFT) over the 64-image sequence. This type of image was used most to qualitatively investigate the presence of wave interference patterns;
- 1-D and 2-D directional wave spectra were also estimated from radar data. This was undertaken when wave interference patterns were observed, in order to compare the radar-derived wave characteristics with data from standard directional wave gauges.

iv. Calibration of the Radar

Under normal circumstances, the X-band radar would be calibrated with single point data collected from either surface Waverider Buoys or bottom-mounted seabed pressure transducer/acoustic wave sensors. In this project no calibration of the radar was undertaken as waves from the pre-construction the post-construction deployments were of insufficient height to enable a worthwhile calibration to be made. However, in the absence of any wave interference patterns in either the raw or directional wave spectra plots (see Section 4), an absolute calibration is not required.

e. Moored Instrumentation

Oceanographic instruments were deployed on fixed moorings at two locations off Britannia Pier, Great Yarmouth: to enable calibration of the X-band radar, in the region inshore of Scroby Sands sandbank on the 10 m bathymetric contour; and to enable model validation to be undertaken as part of future studies, in the region offshore of Scroby Sands sandbank (Figure 1).

Instruments were deployed on the standard Cefas MiniLander, in a variety of configurations and to record data at a variety of sampling rates (Table 4), in order to provide directional wave data at each site.

Table 4 – Instruments used on fixed moorings at Scroby Sands.

Site	Deployment	Instrument	Sampling rate
Inshore	Pre-construction	▪ RDI Sentinel 1200 KHz "Waves" (ADCP with Directional waves) ▪ Cefas ESM2 with pressure sensor ▪ Optical Backscatter Sensor	▪ *Currents*: ½ hourly; 45 pings @1 Hz ▪ *Waves*: 1 hourly; 2400 pings @ 2 Hz ▪ 1 hourly; 1200 pings @ 1 Hz ▪
Inshore	Post-construction	▪ Nortek Aquadopp Profiler (ADCP) ▪ Cefas ESM2 with pressure sensor ▪ Optical Backscatter Sensor	▪ 1 Hourly, profile interval 900 seconds average every minute ▪ 1 hourly; 1200 pings @ 1 Hz ▪
Offshore	Pre-construction	▪ Cefas ESM2 with pressure sensor ▪ Optical Backscatter Sensor	▪ 1 hourly; 1200 pings @ 1 Hz
Offshore	Post-construction	▪ Cefas ESM2 with pressure sensor ▪ Optical Backscatter Sensor	▪ 1 hourly; 1200 pings @ 1 Hz

To coincide with data measured by the wave radar, that recorded by the moored instruments was at burst intervals of 1 hour for the duration of the radar deployment (see section 2, Obj. 1).

4. Results

a. Sensitivity Analysis

Wave interference and diffraction patterns are evident in each of the scenario results (Figures 1-51 of Li, 2003), but their intensity changes in response to the different wave directions, different incident wavelengths and different water depths. The wave model is based on the mild-slope equation so that these factors do not change for different incident wave heights. Full results are given in Li (2003), but here we highlight only the significant results.

Flat Bathymetry

With the wave model applied to the theoretical flat bathymetry, at the monopole array there are no wave refraction and shoaling effects. Inshore of the monopile array, wave refraction is the only mechanism altering wave patterns. Incident waves approaching from the East are reduced in height less than those approaching from the North, and wave interference and diffraction patterns are most apparent for waves approaching the array obliquely from the NE (angle of 045, Figure 2). The impact zones show reduction in wave height of up to 5 % and extending to the edge of the model domain, typically 5-6 turbine spacings.

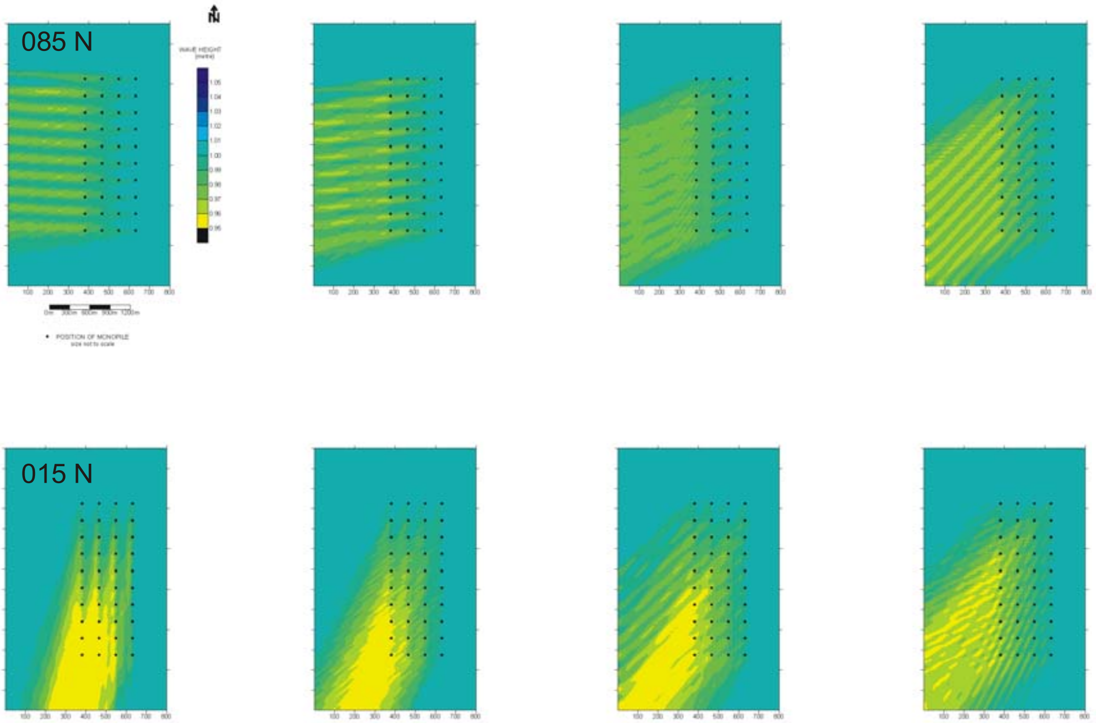


Figure 2 – For a theoretical “flat seabed”, the effect of incident wave direction on the wave interference/diffraction pattern (clockwise from top left, from: 085 ° N, 075 °, 065 °, 055 °, 045 °, 035 °, 025 °, 015 ° N). Scale shown in Fig. 3. All panels at same scale.

Real Bathymetry

With real bathymetry applied to the wave model, the strong wave refraction and shoaling effects revealed from the modelling results will be compared with the wave diffraction patterns caused by the offshore wind array. This is outside the scope of this project and will be undertaken by E.ON UK, the operators of the Scroby Sands OWF under a Food and Environmental Protection Act (FEPA) licence condition.

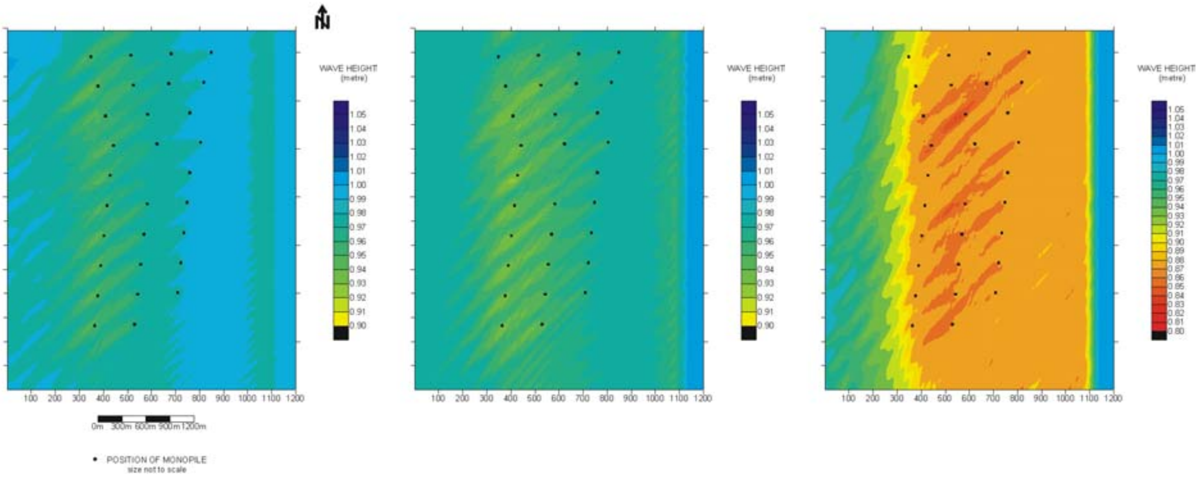
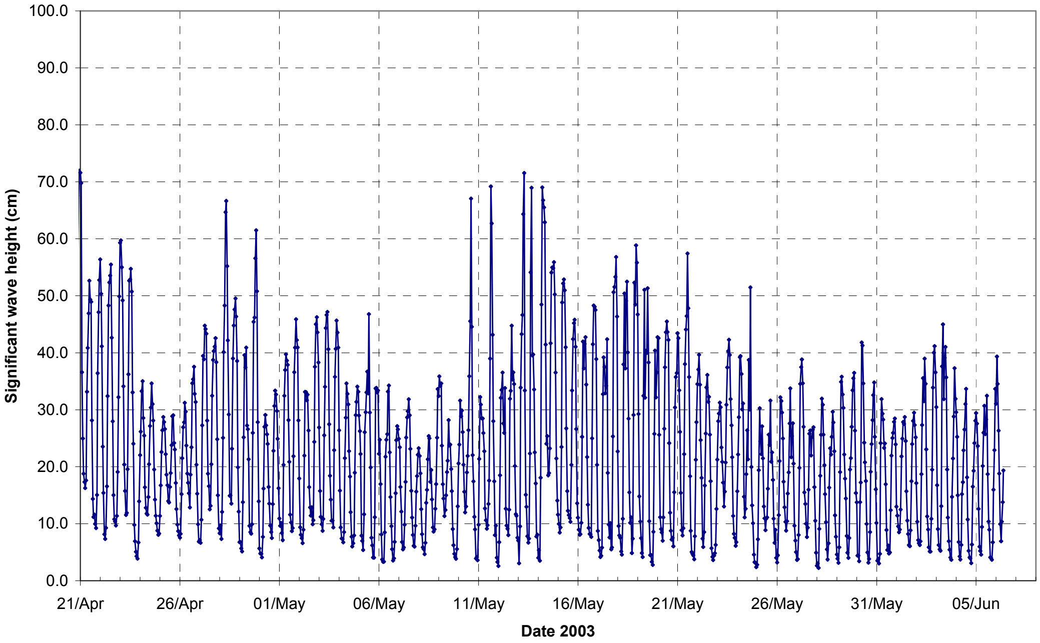


Figure 3 – For a "real bathymetry" for Scroby Sands and adjacent regions, the effect of incident wave direction on the wave interference/diffraction pattern (from left, from: 055 ° N, 050 °, 035 ° N).

b. Moored Instrumentation

Results from the moored seabed instrumentation show the wave conditions at the calibration point for both the X-band radar deployments (see Figure 4). The first deployment shows relatively small waves with a maximum of 0.7 m with a large tidal modulation.



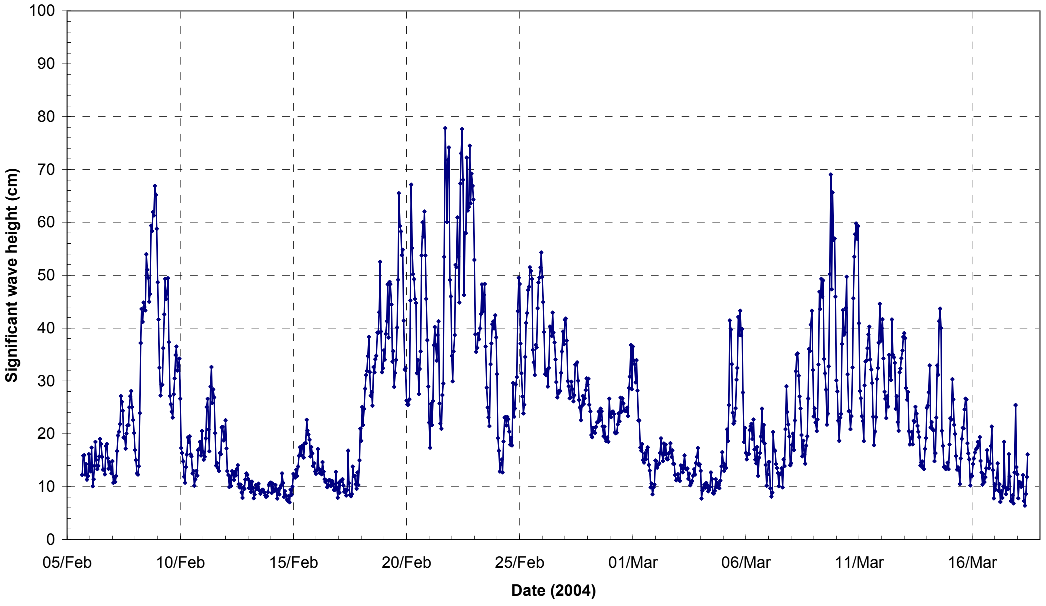


Figure 4 – Significant wave height recorded at the Britannia Pier monitoring site for the first (upper panel) and second (lower panel) corresponding to the pre construction and post construction X-Band radar deployments

The second deployment shows three small wave events on the 8th/9th, 20-25th Feb and around the 10-11th March when wave heights reached a maximum of just under 0.8 m.

c. Wave Radar

The wave-model and wave-sensitivity testing has shown that if any diffraction effect is present that this will be expressed as a series of "constructive" peaks and "deconstructive" troughs in a line perpendicular to the wave direction and downstream of the "disturber"; in this case the windfarm. Thus, with the predominant NE winds and with the wave radar placed SW of the windfarm any effect will be observed in the region between the windfarm and Britannia Pier.

The HF wave radar results (Figs. 5, 6, 7) show:

1) that the minimum significant wave heights that can be recorded are 0.5 m;

2) Waves propagating southwards on the prevailing NE winds;

3) There is a small sector of the coverage (at approximately 95 degrees), that is masked by structures on the end of the Britannia Pier;

4) That the raw and processed images can be misleading as wave propagating towards the radar transmitter are emphasised over those travelling perpendicular to the radar beams. These raw data files can be processed using Fourier analysis (Bell, 1995) to produce directional wave spectra. These 1-D and 2-D directional wave power plots are therefore more significant and can be used to interpret the wave radar data without bias.

5) During the period of HF radar deployments the maximum wave height recorded was only 1.0 m.

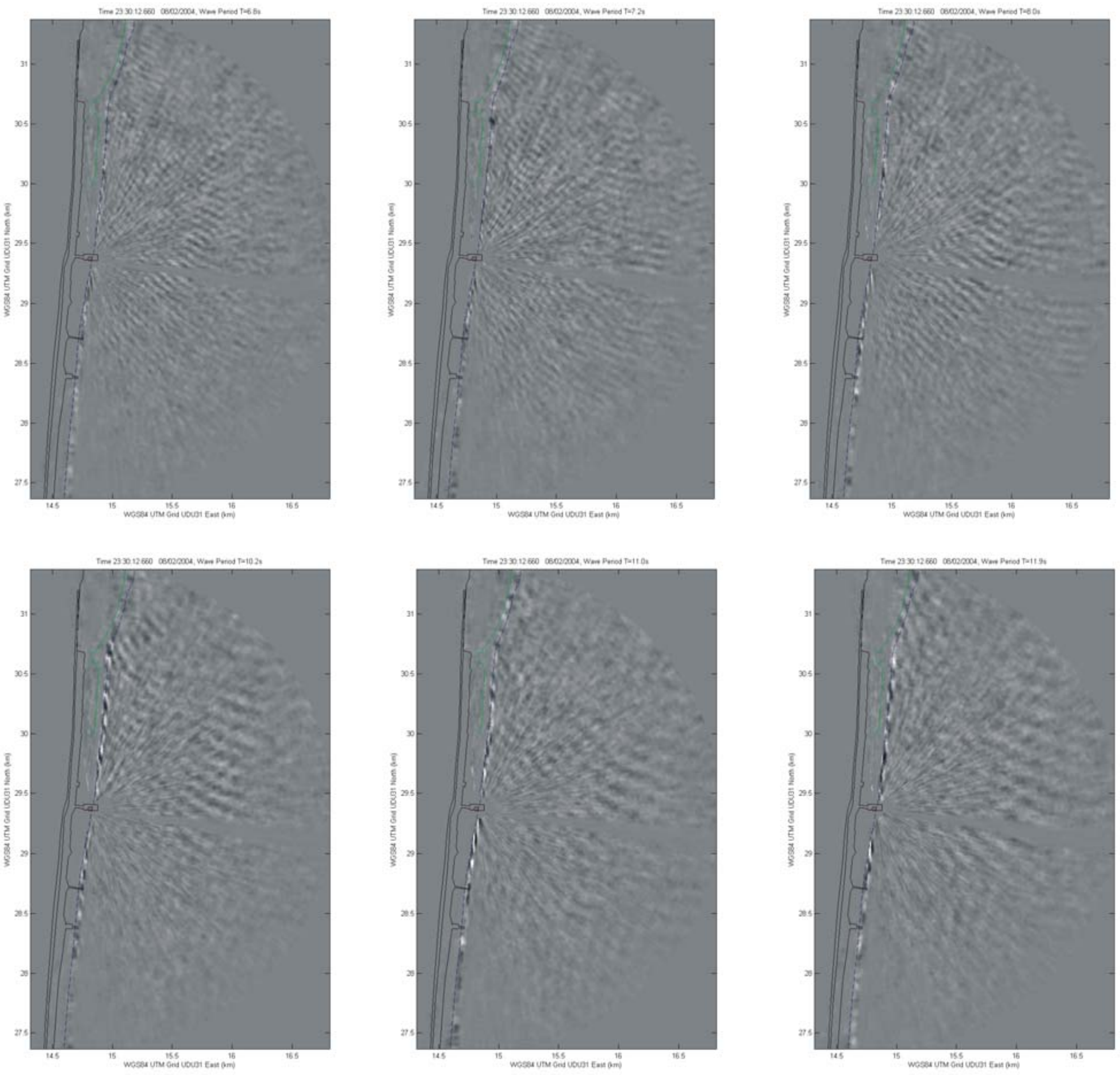


Figure 5 – X-band radar data, showing waves from the NE at the peak of storm activity (08/02/04 23:30 GMT), when the peak wave period was ~11 s. The wave crescents are shown as black banding and wave troughs as white banding. Also shown is the bathymetry along the Gt. Yarmouth frontage and the location of Britannia Pier.

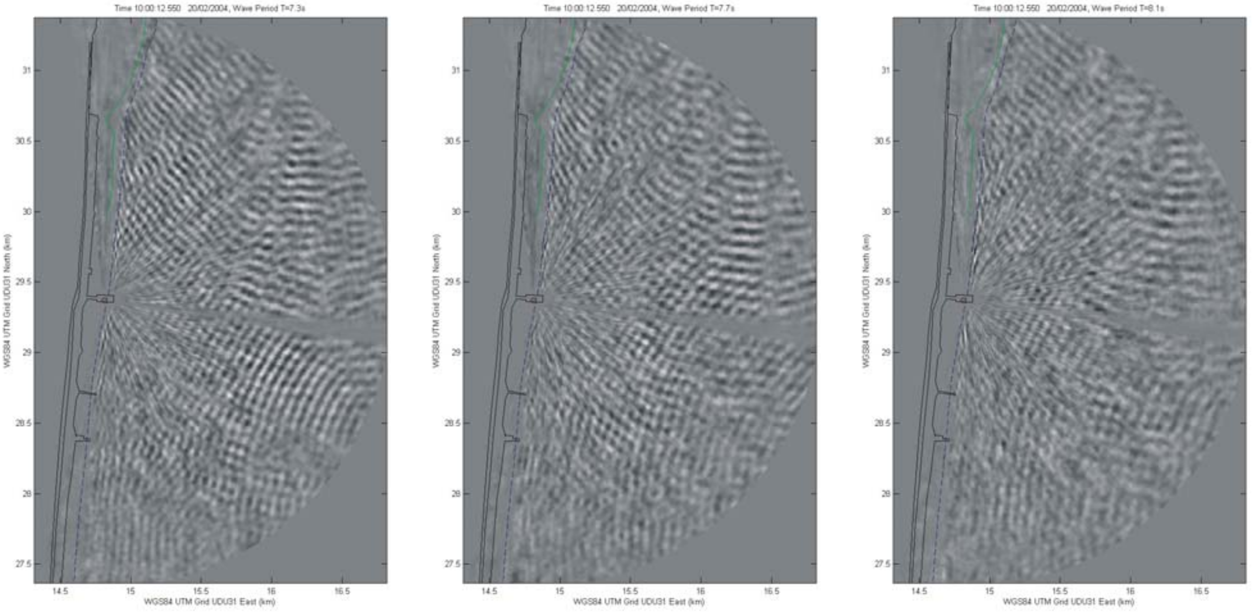


Figure 6 – X-band radar data as Figure 5 but showing waves from the NE at the peak of storm activity (20/02/04 10:00 GMT), when the peak wave period was ~7 s.

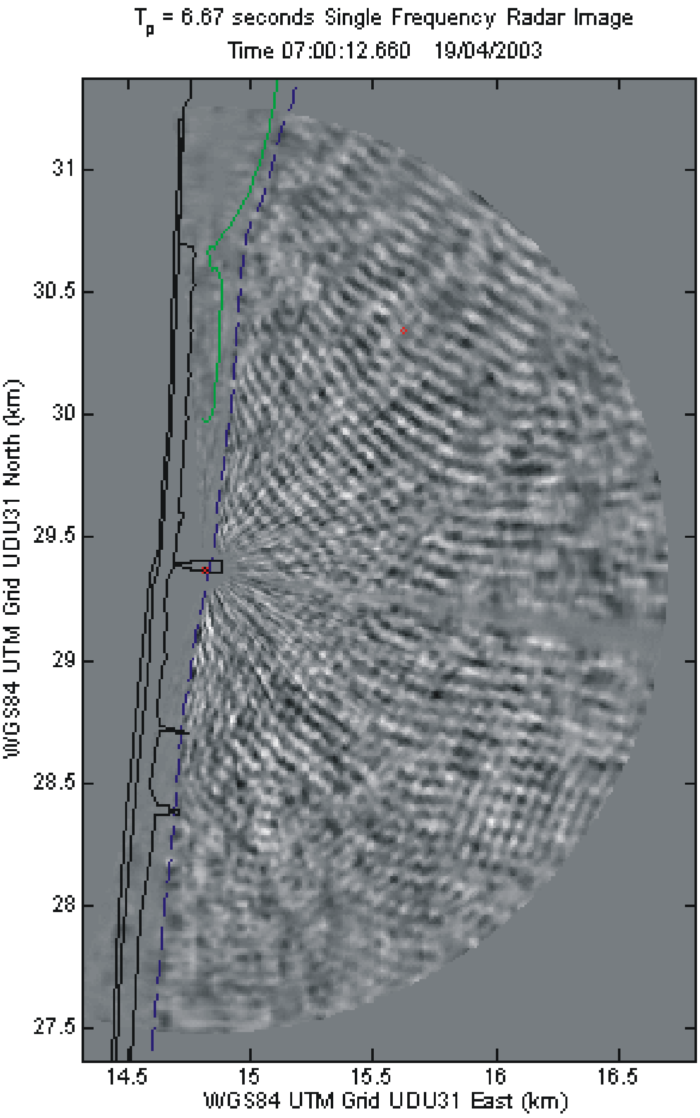


Figure 7 – X-band radar data as Figure 6, showing waves from the NE at the peak of storm activity (19/04/03 07:00 GMT), when the peak wave period was ~7 s.

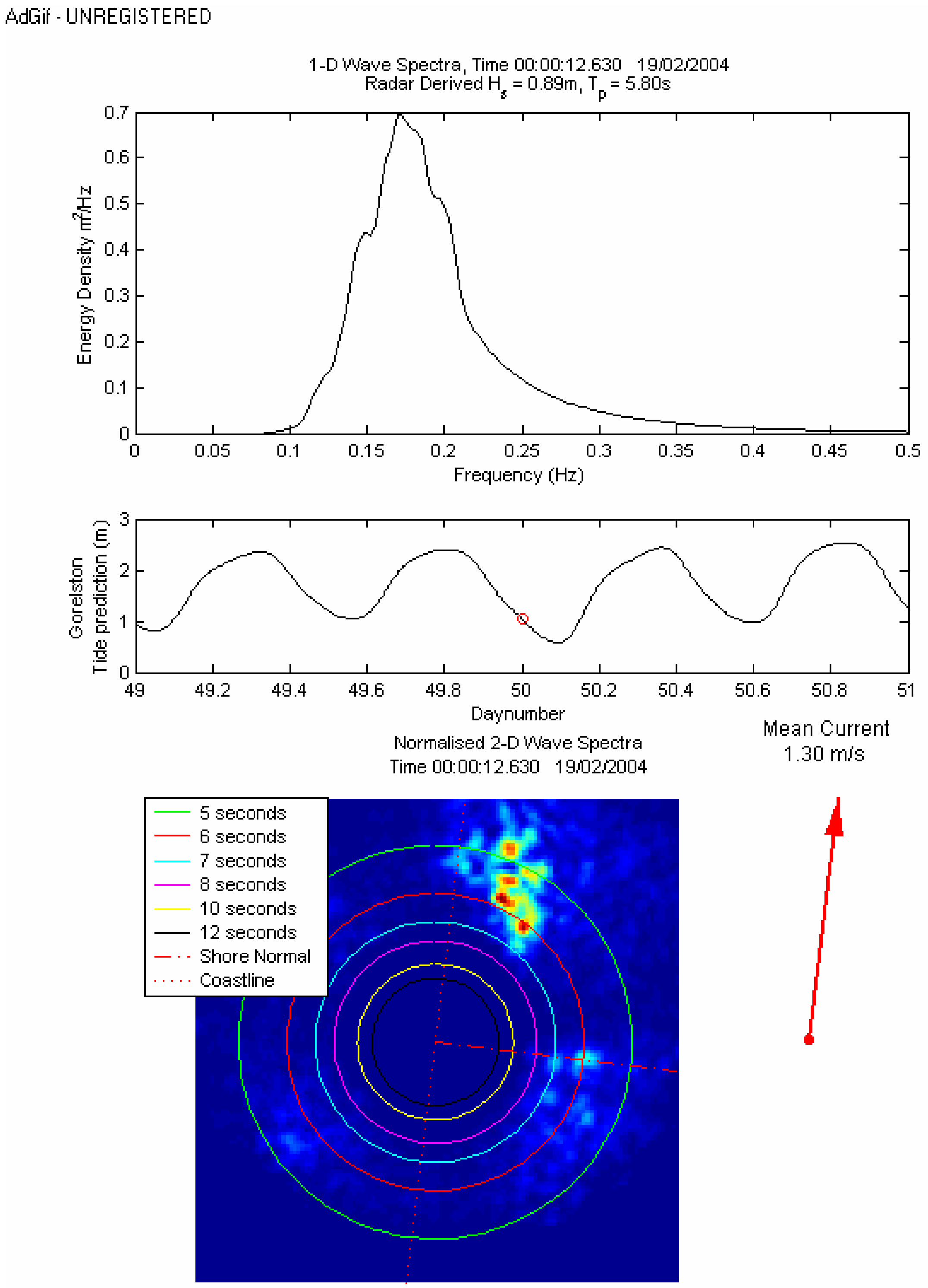


Figure 8 – 1-D and 2-D wave spectra from the X-band radar system showing the upper panel the 1-D wave spectra, the middle panel the tidal curve for the period around the wave observation and the 2-D wave spectra. The rings show the wave period and direction of waves whilst the colours show higher wave energy. Thus, in this example waves are from the NE, have a period of 6-7 s. The red arrow on the lower left panel indicates the direction and strength of the surface mean current. (This is also available as a time-series of images, i.e. an animation).

The X-band results expressed as a series of directional wave spectra plots (as shown in Figure 8) can used to identify if any constructive or destructive waves exists. If present, these would be expressed as a series of high and low energy spots or bands probably at a constant wave period, i.e. on a circle line of the 2-D directional wave energy plots. All the periods of wave with larger waves, of significant wave height up to 1 m, have been reviewed and no occurrence of a series of high and low spots or banding has been identified.

5. Discussion

5.1 X-Band Radar

The X-band radar has shown that with the wave conditions experienced during the second post-construction deployment, no constructive or destructive waves were measurable in the lee of the windfarm. It should be noted that the wave conditions during this post-construction x-band radar survey were small when compared when compared with longer-term regional data (waves of over 2.5 m significant wave height were observed at the Caister Bank MiniLander site during the third lander campaign of the companion AE0262 project). The deployment was extended as much as possible to capture larger wave events but was unsuccessful. If larger wave were present, it would have been easier to differentiate between the constructive and destructive waves and thus the results would be more robust.

5.2 Modelling

The MWAV_LOC wave model used in this project has been used extensively in the marine engineering and consultancy markets. Specifically, it was used in this project as the Environmental Impact Statement (EIS) used this model and as the model had been setup for this area, efficiency savings could be made. Comparison with the EIS could also be undertaken.

Results from the model are directly comparable with other findings from other researchers and consultancies. Cooper (2002) also shows only small reductions in wave height due to wave diffraction.

5.3 General

The wave models have shown reductions in significant wave height of 5% in a “flat” bathymetric case and of 3% in a more realistic case. The impact zone of these reductions is relatively small (typically within background levels within of 2-3 turbine spacings) and the majority is within the licence boundary of the windfarm. The MWAV_LOC wave model has been used in a number of applications and thus is a tried and trusted. Although, the wave conditions during the post-construction survey were small, no direct evidence was found to show either interference patterns in wave crests/troughs or energy banding in the 2-d directional wave spectra.

The results shown here are broadly applicable as the spacing between turbines is controlled by the length of the blade (a “rule of thumb” of 6-10 blade lengths (currently maximum of 61.5 m) is often used) and this is significantly larger than the wavelength of the waves which in the North Sea is typically of the order 50-100 m. Round 2 windfarms will tend to produced more electricity than 5 MW and thus will have longer blades and thus greater turbine spacings.

Other foundation types such as gravity based structures or hybrid/tripod structures generally have more total cross-sectional area, but tend to have cross-sectional areas similar to monopiles near the surface. Thus, as wave orbital motions are largest at the surface, these novel structures will tend to have similar impacts if the cross-sectional area is similar at the surface.

6. Conclusions

This project has shown that field observations and results from wave models over flat and “real” bathymetry have both shown insignificant impacts on the wave regime due to diffraction from a monopile-based offshore windfarm. Impacts of changed waves on sediment transport are thus also insignificant and the likely impact is a small reduction in sediment transport.

The key results from the numerical modelling are:

Modelled Flat Seabed:

- Waves from direction 035° have maximum effect on wave diffraction patterns (significant wave height reduced by 5%).

- 1:50 year wave conditions have maximum effect on wave diffraction patterns (significant wave height reduced by 3%).
- 10 m water depth has greater effect on wave diffraction patterns than lower depths (significant wave height reduced by 3%).

Modelled Real Bathymetry:

- Waves from direction 055° have maximum effect on wave diffraction patterns (significant wave height reduced by 2%).
- For many wave directions, the extent of wave refraction eliminates wave diffraction effects beyond the sandbank region.
- Decrease in significant wave height change due to diffraction is 5% for a flat seabed, but only 2% for realistic bathymetry (wave refraction and shoaling are more important than diffraction).

No direct impact was observed in the X-radar data, so that comparison with models was not undertaken.

7. Implications & Significance

As well as the Defra MCEU unit who license construction of windfarms or structures under the FEPA and CPA acts, responsibility for the management of the coastlines also rests with Local Authorities, English Nature and the Environment Agency. These Operating Authorities are concerned that the construction of offshore windfarms may influence the natural processes along the coast with a consequent impact on the condition of flood and coastal defences. The primary impact will effect which the support structure for the wind turbines has on the local wave and current regimes. The concerns will be two-fold: the way in which waves directly impact on cliffs and defence structures including natural beaches; and the impact which variations on wave energy will have on nearshore sediment transport.

In general, the small reduction of wave impact predicted by this study is expected to be a welcome finding to the Operating Authorities. Any reduction in wave energy is likely to be beneficial with respect to direct erosion at the coast. The changes brought about in the sediment flux is expected to vary from site to site but are likely to be slight. The implications are that wave diffraction effects from a monopile-based windfarm reduce the wave climate in the direct vicinity of the windfarm by 2-5%. The effects decrease rapidly away from the windfarm to reach background values a distance of 2-3 turbine spacings away. These changes in wave climate will marginally reduce the tendency for sediment transport by waves. The results signify that wave diffraction effects from a monopile based offshore windfarm only affect sediment transport to a marginal extent, so that the potential concerns relating to this process can be eliminated.

Large lengths of the East Anglian coastline are protected from waves propagating onshore by either by single banks or a series of banks and thus the results from this study at Scroby Bank are applicable to many regions around the UK. Examples of Offshore Windfarm FEPA applications are Gunfleet Sands under Round 1, and the Burbo Bank OWFs). In these locations, compared to Scroby Bank, the windfarm is either further offshore (Gunfleet), in deeper water (Burbo) or in relatively smooth bathymetry (North Hoyle), so these cases are probably less likely to produce coastal impacts by wave diffraction or refraction.

8. Future Research

This project has shown that wave diffraction caused by monopiles in an OWF is not significant compared with variations of wave height due to other mechanisms. Wave diffraction is not a significant issue for FEPA regulators. However, there are some issues that have arisen during the course of this project, most notably, the impact of gravity and hybrid structures on the seabed. Such foundation structures could have a larger direct impact than monopiles on the seabed due to their larger cross-sectional area. There are potential effects on scour, which means that monitoring of scour associated with these structures will be useful, especially during large storms. Significant benefits can also be gained from learning lessons from monitoring of Round 1 wind farm sites in order to better assess potential impacts of Round 2 offshore wind farms. Hence, DTI and Defra have already commissioned work to review lessons learnt into this subject from the existing Round 1 monitoring data.

9. Resulting Actions

Defra's Marine Consents and Environment Unit (MCEU) are advised **not** to require developers of OWFs to monitor waves for diffraction/interference effects under a FEPA licence.

10. References

Bell, P.S., 1995, Routine X-band monitoring of the nearshore wave climate, Oceans'95, "Challenge of Our Changing Global Environment", Vol1 Page 520-525.

Bell, P. S., 2005. Deployment of X-Band Radar at Great Yarmouth 16th April 2003 – 4th June 2003, Defra-funded A1227 sub-contract report. Proudman Oceanographic Laboratory, 17 pp.

Bell, P. S., 2005. Deployment of X-Band Radar at Great Yarmouth 20th January 2004– 9th March 2005, Defra-funded A1227 sub-contract report. Proudman Oceanographic Laboratory. 18pp.

Chandrasekera, C.N. and **Cheung**, K.F., 2001, Linear Refraction-diffraction model for steep bathymetry, Journal of Waterway, Port, Coastal and ocean engineering, vol 127, p161-170.

Cooper, W.S.J. and **Beiboer**, F., 2002. Potential effects of offshore wind developments on coastal processes. ETSU W/35/00596/00/REP. URN 02/1336.

Halcrow, 1996. Wave Climate/Scour Study, Sarah Jane Offshore Wind Monitoring Station. Study Report. Powergen plc. September 1996.

Li, Bin, 2003. Offshore Windfarm Array Assessment: Wave Modelling. Halcrow Group Limited, 13pp.

Oakes, T., 2006, Assessment of the Significance of changes to the inshore wave regime as a consequence of an Offshore wind array, Terry Oakes Associates, 4pp.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

Project Outputs:

Project Proposal on Cefas Renewables Web-site:
http://www.Cefas.co.uk/renewables/AE1227.htm

PowerPoint presentations to Steering Group - 13th May 2005; 8th March 2004; 4th June 2003

PowerPoint presentation to AE12 Commission Review - 25th September 2002

Sub-contractor Reports:

Bell, P. S., 2003. Deployment of X-Band Radar at Great Yarmouth 16th April 2003 – 4th June 2003, Defra-funded A1227 sub-contract report. Proudman Oceanographic Laboratory, 17 pp.

Bell, P. S., 2005. Deployment of X-Band Radar at Great Yarmouth 20th Jan 2004 – 9th March 2004, Defra-funded A1227 sub-contract report. Proudman Oceanographic Laboratory, 18 pp.

Li, Bin, 2003. Offshore Windfarm Array Assessment: Wave Modelling. Halcrow Group Limited, 13 pp.