AN IMPLEMENTATION TEST ON SUPPORT TO WEATHER SAFETY IN THE NORTH WEST APPROACHES – THROUGH THE USE OF SATELLITE DATA IN ASSESSING WAVE ENERGY DYNAMICS

Phase1 Report: Evaluation of Capability of EO Derived Wave Data Products to Satisfy HSE/BNSC Requirements

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The objective of the activities described in this report were to prepare an in depth evaluation of the potential use of satellite data to assess and monitor wave conditions in the NW approaches. That includes an identification of the sensors to be used, the algorithms required to derive the wave parameters and a definition and testing of the necessary processing chains.
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Disclaimer:
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0.1	23/11/04	D.Cotton SOS	1st draft
1.0	14/02/2005	D.Cotton SOS	2nd Draft taking in comments from HSE/BNSC regarding priorities for Phase 2

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A number of figures have been copied from other sources and have been individually referenced.

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CONTENTS

EXECUTIVE SUMMARY

This test project is being conducted under the British National Space Centre (BNSC) Government Information From The Space Sector (GIFTSS) Initiative in close collaboration with the Health and Safety Executive Offshore Division (HSE OSD).

The HSE OSD requirement is the safety of operations and equipment used for drilling and extraction of oil and gas in the North West Approaches to the UK, and covers the following:

- The need to assess the possible utilisation of all-weather information from ongoing spaceborne systems to measure offshore wave energy
- To add to the statistical and management base that is used to support offshore operations
- The potential for supporting safety in all weathers for operations in the UK North West Approaches

<u>A Summary of the Requirement to be Addressed</u>
A key consideration for safe operation of offshore installations is knowledge of the momentum transfer through wave energy onto fixed and mobile structures. Such wave momentum transfer varies with respect to changes in marine weather conditions. An important component within such dynamic marine weather is the changing energy power spectra of the marine wave trains.

Some key parameters that need to be monitored are: the wave length/wave height spectrum, wave direction, significant wave height, wave steepness, wave period and wave speed; all as a function of the generating conditions (the "forcing functions").

Consideration has therefore been given to assessing if sampling over the area to be investigated, within the UK North West Approaches, can provide both the detail, and the wider area information, on these key marine wave energy spectra characteristics from information derived from existing and ongoing EO satellites.

Such information could then be included routinely into HSE OSD operational processes to assist in meeting long term information needs for HSE OSD as they perform their statutory duties.

<u>This Report</u>
Within this document we report on activities under phase 1 of the test project. The aim of this phase is to prepare an in depth evaluation of the overall project. This includes an identification of the sensors to be used, the algorithms required to derive the wave parameters and a definition and testing of the necessary processing chains.

This report is a compilation of individual work package reports addressing sampling issues, capability of non-EO products, capability of EO products, demonstration and evaluation of the processing chain.

We finish with an assessment of the different satellite data sets available, an initial definition of a service concept designed to satisfy HSE requirements and a proposal towards implementation.

1 INTRODUCTION

This project addresses the HSE OSD responsibility for the safety of operations and equipment used for drilling and extraction of oil and gas in the North West Approaches to the UK, and covers the following:

- The need to assess the possible utilisation of all-weather information from ongoing spaceborne systems to measure offshore wave energy
- To add to the statistical and management base that is used to support offshore operations
- The potential for supporting safety in all weathers for operations in the UK North West Approaches

The Area of Interest defined by the sponsors covers the region 56°-64°N, and 10°W-2°E., which includes the NW approaches to the UK, (open water heavily influenced by Atlantic waves), and seas to the east and north of the Faroe and Shetland Islands, waters partly sheltered from the influence of the Atlantic, and also a variety of coastal waters (figure 1).

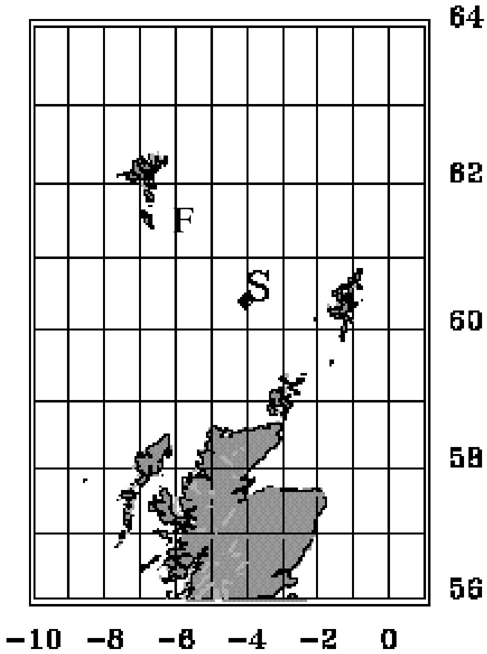

Figure 1 Area of interest, the location of Schiehallion FPSO is indicated (“S”),

The parameters to be considered in this project were listed in the ITT as:

wave length/wave height spectrum
wave direction - average direction and dominant or peak direction - Fm, Fp
significant wave height - Hs
wave steepness
wave period, zero up-crossing, or peak - Tz, Tp,
wave speed.

Some explanation of these terms is given in Annex A to this report.

Phase 1 of this project is aimed at the identification and evaluation of sensors and the determination of the techniques and algorithms available for transforming the satellite data into wave parameters. Based on this evaluation a proposal is made for a demonstration data set to be produced under phase 2

Activities were carried out as five separate tasks, or work packages, briefly outlined below:

Section 2 Task 1.1. Define sampling grid/interval
This task addressed the issue of identifying the appropriate sampling intervals in time and space, and length of time series of data, that were necessary to build a data base t support a reliable and authoritative statistical analysis of wave climate.

Section 3 Task 1.2 Capabilities of non-EO sources
This task provided an assessment of the techniques currently in use by various authorities and commercial organisations, for monitoring wave conditions over the area of interest.

Section 4 Task 1.3 Requirements and availability of EO data.
This task carried out a comprehensive assessment of the potential EO data sources for the required wave parameters.

Section 5 Task 1.4 EO data processing chain and evaluation of example data.
This task presented the processing chains for producing the identified wave parameters (and statistics) and evaluated some examples of data thus produced.

Section 6 Additional Summary on SAR wave products
On request from the project sponsors, SOS and QinetiQ have provided a further note addressing some specific questions with regard to SAR production of wave products. A summary of this note is included in Section 6

Section 7 Task 1.5 Wave Monitoring Service Initial Concept definition and Phase 2 Proposal
Section 7 includes a description of an initial concept for a wave monitoring service and a draft route map for implementation of that service. We also provide a summary of the demonstration product proposed for Phase 2.

This report contains material from the original work package reports, and is intended as a “Stand Alone” document. If further information is required, readers are referred to the full original reports.

2 WP 1.1 - DEFINE SAMPLING /GRID INTERVAL

2.1 INTRODUCTION

In this section we describe the consequences of the prevailing environmental conditions in the Area of Interest and the recommended grid scale and interval considering both the scales of interest and the limitations of sampling by the instruments.

2.2 SAMPLING GRID / INTERVAL OF EXISTING PRODUCTS

2.2.1 Observational

Over the last 60 years, there have been a number of networks of ships or buoys measuring wave parameters around the UK and in the Northwest approaches. Data from dedicated monitoring stations have never been sufficiently closely spaced to produce spatial fields of wave heights by direct interpolation or gridding. However, in the absence of other methods, wave climatologies were constructed from measurements at a variety of sites and times (Draper, 1991). It is difficult to place realistic uncertainties on these climatologies since they depended greatly on the experience and holistic knowledge of the wave specialist rather than standard interpolation methods with quantifiable uncertainties. A far more comprehensive (and global) set of data is available from the Voluntary Observing Ship (VOS) programme, but the reliability of individual data is doubtful. By careful screening and corrections a useful climatology can be produced (Gulev et al., 2003; http://www.sail.msk.ru/projects/waves/waves.htm). Data on wave height and wave period have been gridded monthly in 2° x 2° cells, and in well sampled regions (including most of the Area of Interest) the accuracy of this product is sufficient (< 1 metre for height, <1 second for periods) to be useful for open ocean use. The VOS-based products provide a discrimination between swell and wind sea; thus a height and peak period is given separately for both swell and wind sea. In addition to statistics on mean wave height and period, VOS-based estimates of extremes and exceedance values in wave climate are under development.

2.2.2 Model

A number of wave models are run operationally either globally or for specific oceans or seas. Typically these large-scale models use 1°- 2° grids (1° latitude ≈ 111km) and provide nowcasts and forecasts for 6 hour intervals up to 5 days in the future. Most use variants on the WAM model (The WAMDI Group, 1988) driven by forcing from Numerical Weather Prediction. The choice of 6 hour intervals reflects integration with NWP activities and to some extent the grid spacing reflects the scale of weather patterns, though computational efficiency is also a major factor. UK Met Office runs an earlier generation model, which is run globally at a relatively high resolution (~60km grid spacing). Within the global model UK Met Office nests higher resolutions for Europe (~35 km), and the UK (~12 km); UK Met Office plans to nest an ~ 2km resolution coastal model within the UK region. It might also be noted that while all models deal with directional wave spectrum, the resolution is fairly weak because of computational restraints. For example the UK Met Office wave model separates the wave spectrum into 16 directions and 13 frequencies.

There have also been a number of large projects to hindcast the wave climate of the last 40 or 50 years. These depend on driving the wave model with reanalysed weather data. NCEP reanalysis has been used to create global hindcasts ("GROW" 40 years, 1.25° x 2.5°, using the ODGP2 model) and at higher resolution in the North Atlantic ("AES40" 40 years, 0.625° x 0.833°, using the OWI 3-G model). The latest ECMWF reanalysis, ERA-40, has been used to produce a 40 year hindcast at 1.5 x 1.5 degrees resolution. This product has been carefully compared to buoy and altimeter data to produce a revised climatology. More details of this research project (and more background information on wave climatologies) can be found at http://www.knmi.nl/waveatlas. Figure 2 presents mean january Hs from this climatology.

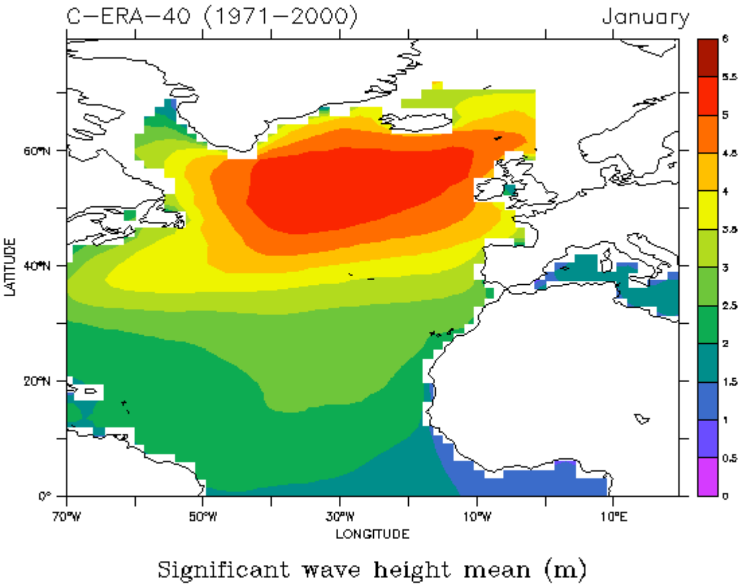

Figure 2 Mean SWH in the North Atlantic in January (http://www.knmi.nl/waveatlas)

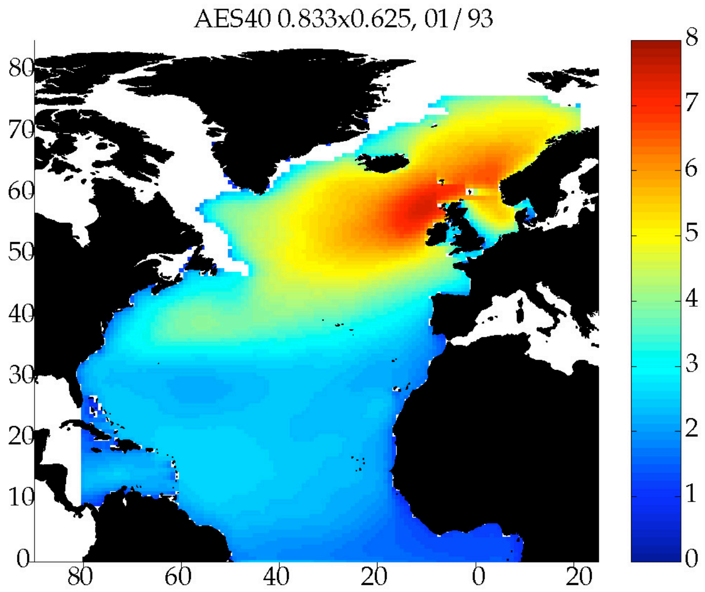

Figure 3 Mean SWH in the North Atlantic in January 1993 according to AES-40 climatology

Probably the best direct model climatology that includes the Area of Interest is AES-40; the means of SWH in one month according to AES-40 are shown in Figure 3. Two problems pertinent to the Area of Interest may be noted. Firstly, the wave climate in this region depends often on small and intense depressions (Polar Lows); the accuracy of a model climatology depends on both the ability of NWP to properly resolve these depressions and the wave model to describe the response. By careful analysis of weather systems AES-40 succeeds in accurately describing wave climate in the Northwest Approaches. Secondly, even a relatively high resolution model such as AES-40 only crudely describes the topography and bathymetry of coastlines and islands. The wave climate in the northern North Sea is sensitive to the propagation of Atlantic waves past the Shetlands and Orkneys and this is poorly represented in AES-40 and other models.

2.3 NATURAL SCALES OF VARIABILITY

2.3.1 Temporal Scales

Four primary temporal scales of variability can be identified: synoptic, seasonal, inter-annual, and multi-decadal or secular.

Synoptic

Synoptic variability is the primary time scale of weather systems. For the North Atlantic one atmospheric depression may succeed another spaced by a few days. The six-hour-interval typical of NWP products is equally appropriate for near-real time wave applications. A slightly shorter interval, e.g., 1 - 3 hours, may be helpful for operational purposes.

Seasonal

The wave climate of the Area of Interest shares the exceptionally strong seasonality of the North Atlantic region (Woolf et al., 2003). Annual means are of limited use and for most practical purposes the climate should be described at a minimum seasonally and better monthly. The seas are generally largest in the western part of the Area of Interest, where the influence of Atlantic waves is greatest. The winter is by far the roughest season with a typical mean significant wave height of 5 metres in the open sea to the west of Scotland. A similar seasonality is also seen in wave period.

Inter-annual

Strong inter-annual variability is another feature of the wave climate of the Area of Interest and the remainder of the north-eastern North Atlantic and northern North Sea (Woolf et al., 2003) particularly in the winter months. This variability is strongly linked to the North Atlantic Oscillation (Woolf et al., 2002 & 2003). This variability has major consequences for the design of climatologies. If a climatology is only based on one or a few years, there is a significant risk that it will be severely biased compared to the “true” climate of a longer baseline. A climatology based on ten or more years of data is clearly preferable, but it should be noted that wave climate in an individual month or season might deviate drastically from “climatology”.

Multi-decadal / secular

There is substantial evidence of significant longer-term variability in wave climate, either as a feature of natural climate variability or in response to Climate Change. This can undermine the utility of wave climatologies, even those built on data from several decades. However, there is no evidence of a true secular trend through the twentieth century and there is no obvious alternative to continuing to use twentieth century climatologies in the early twenty first century.

Temporal Variability within the Area of Interest

An analysis of altimeter significant wave height data over the area on interest, presented in detail in the full WP 1.1 report (Woolf 2004a) demonstrated the extent of variability on the seasonal and inter-annual scale. The annual cycle (fitted as a sine curve with a period of 365.25 days) accounted for 34% of the observed variance – peaking in January- February. Significant variations were also found at shorter and longer time scales, from day to day and year to year No long trends were found over the period covered by the available data (1993-2004) although other studies on data sets with longer coverage have found significant decadal variations.

2.3.2 Spatial Scales

The degree of spatial variability depends on location – offshore or coastal (within ~100km of the coast).

Offshore

It is important to be aware of the spatial scales of wave climate statistics when trying to estimate and map such parameters as monthly mean Hs or exceedence percentiles, especially when using data from a few altimeters with greatly varying distances between tracks. The problem is to balance the need to take data from as large an area as possible, to maximise the number of observation, with the need to restrict the area so that the statistics are stationary.

For estimating climate statistics in the open ocean, binning data from 2° latitude by 2° longitude areas is often used, e.g. Carter *et al*. (1991), Laing & Reid (1999). This bin size is consistent with the findings of Cooper & Forristall (1997) that sampling over distances of 200 - 300 km is satisfactory. The coherence in the resulting maps also indicates that this choice of bin size is reasonable - as does the coherence found in analyses of monthly means from 2° by 2° bins.

However, closer to land, wave climate statistics vary on smaller spatial scales, and analysing 2° bins, for example in the southern North Sea, is not satisfactory. During "Jericho" (a study for BNSC on the contribution that altimeter data could make to estimating wave climate in UK coastal waters) it was found that altimeter coverage was by then sufficient to enable monthly statistics to be computed in 1° latitude by 2° longitude bins. See Cotton et al. (1999) for details. There were then insufficient data to use 1° x 1° bins; but there are 5 years more data since "Jericho", so this increased resolution may now be possible. The 1° x 2° bin size was also used by Woolf *et al*. (2003).

Coastal

Spatial gradients are progressively greater as the coast is approached. This partly explains the UK Met Office approach of nesting progressively finer resolution models at more coastal locations. A number of coastal effects can be identified:

Coastal currents / tides - Can effect wave steepness and height when a strong current runs against the prevailing wave direction – usually only very localised effects.

Bottom topography - Only when waves can feel the bottom (depth < half wavelength). Affects wave height and period.

Local wind effects – Can be an issue where strong offshore winds occur (e.g. fohn winds, the Mistral in the Med, or the Meltemi in the Aegean) – but not likely to be an issue in Area of Interest.

Sheltering / refraction - Sheltering reduces the wave height in the lee of islands, and will alter direction through the refraction of waves.
Also reduces fetch for the generation of waves, and hinders the propagation of swell.

Analysis of altimeter data suggests that there is relatively little variation of wave climate further than 100km from the coast, if the waves are primarily directed from the open ocean (as in the case of the Northwest Approaches). In the case of locally generated waves and frequent offshore winds (e.g., east coast of Scotland) the wave climate may vary over several hundreds of kilometres from the coast. In the latter case there is a possible gain in reducing the resolution from 2 degrees to 1 degree or half a degree, but this will have to weighed against the increase in sampling errors. In some cases, it is possible to use satellite data to describe more coastal variation by analysing along specific repeated ground tracks but this method is generally more laborious than the "gridding method".

Sheltering and refraction appears to be the main coastal influence on wave properties. Coastal effects are generally limited to within 100 km of land to weather side (west) of main topography , but are more important to the east of islands and in enclosed waters. To the west, coastal effects are likely to be more significant in easterly winds (though these are less usual in the region). Each coastal site is likely to have a quite specific set of problems. Therefore while coastal studies are practical (especially utilising SAR), no generic solution is likely and one or a few sites of particular interest should be carefully chosen.

Spatial Variability within the Area of Interest

An analysis of along track altimeter significant wave height and wind speed data over the area of interest, was presented in detail in the full WP 1.1 report (Woolf 2004a).
High spatial correlations over 200 km and more were found for wave height data to the west of the Shetland Islands which could justify the adoption of a 2 degree resolution for this and more exposed regions (also see Carter 2004c). However, there was some evidence for strong gradients to the north and east of Scotland where the penetration of Atlantic waves diminishes eastwards. There are also strong gradients nearer the coast.

2.4 ENVIRONMENTAL CONDITIONS AND SUSCEPTIBILITY OF SATELLITE DATA

2.4.1 Climate of NW approaches

The climate of the NW approaches is notably wet and windy, especially in the winter months. Data on monthly rainfall is readily available at a number of web sites but data on the fraction of time it is raining heavily - which would be more useful - is not so easy to find. The KNMI global wave climatology (http://www.knmi.nl/waveatlas) provides information on wind climate. In Figure 4 we show the annual rate of exceedence of 11m/s and 17m/s winds. The Area of Interest has a very high incidence of high winds, with winds exceeding 11m/s on 60-90 days/year.

2.4.2 Susceptibility of Satellite Data to Wind and Rain

The technical aspects of the effect of wind and rain on satellite data are considered in section 4 (WP 1.3). While all the instruments considered here are radar instruments, that can penetrate cloud, and are normally classed as "all weather", both rain and wind can affect their performance. Measurements by altimeter are generally robust, but very heavy rain (such as the centre of hurricanes or intense tropical storms) can attenuate and corrupt the signal, but this is unusual. Very high winds alone weaken the returned signal but are unlikely to cause data loss, though the calibration of wave height and wind speed may be poorer. SAR is most sensitive to wind speed. Winds less than 3m/s are generally insufficient for imaging of waves.

Wave features are generally evident in images at higher wind speeds, but there is considerable uncertainty in the "Modulation Transfer Functions" and thus the accuracy of wave parameter retrieval at high wind speeds. SAR imaging of waves may also be lost through saturation of the signal at wind speeds in excess of 10m/s. Noting the high occurrence of wind speeds in excess of 11m/s (when SAR calibration is uncertain; Figure 4) and fairly numerous occasions when the wind speed is very high (and all calibrations may be suspect; Figure 4) in the Northwest Approaches, the susceptibility of the satellite data to high winds must be of concern. These limitations are likely to bias wave climatologies based on these sources. More significantly, uncertainties in SAR wave retrieval at high wind speeds are a major concern in the context of GIFTSS and near-real-time nowcasting.

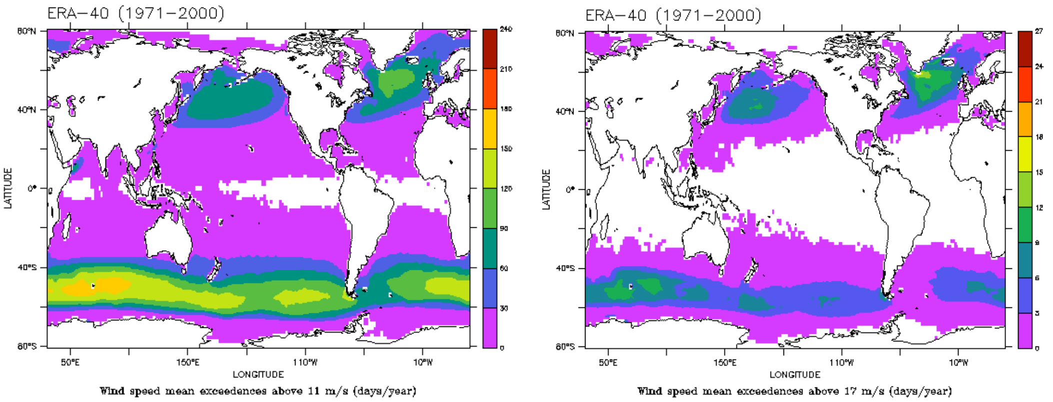

Figure 4 Number of days when wind speed exceeds (left) 11m/s (and therefore SAR imaging of waves will be unreliable), and right 17m/s (and therefore very limited validation data is available for all satellite data)

2.5 GRID SCALE AND INTERVAL OF SATELLITE CLIMATOLOGIES

Table 1 summarises estimates of sampling by ENVISAT (altimeter and both SAR modes) of grid cells of three possible sizes. The figures for ENVISAT are for sampling in the area of interest for this study are were acquired from the ESA ENVISAT data archive. Thus these figures represent actual data availability. The figures estimated for present satellites availability were simply generated by multiplying by the number of available satellites with suitable operational instrumentation.

Table 1 Number of independent samples per month in the GIFTSS Area Of Interest, from ENVISAT only and, *in italics*, estimated for present satellite availability.

	5° x 5°		**2° x 2°**		**1° x 1°**	
	Passes "Strips" / month	**Revisit interval days (mean/max)**	**Passes "Strips" / month**	**Revisit interval days (mean/max)**	**Passes "Strips" / month**	**Revisit interval days (mean/max)**
Altimeter	21	1.5 / 3	5	6 / 7	2	15 /22
	48	*0.4 / 0.8*	*20*	*1.5 / 1.75*	*8*	*4 / 5.5*
SAR image	8	4 / 10	5	6 / 11	3	10/11
	16	*2 / 5*	*10*	*3 / 5.5*	*6*	*5 / 5.5*
SAR wave	14	2 / 7	6	5 / 15	3	10 / 15
mode	*14*	*2 /7*	*6*	*5 /15*	*3*	*10 / 15*

It is important to note that:

- Presently there are 5 satellite altimeters operating – ERS-2, ENVISAT, Geosat Follow-On (GFO), TOPEX/Poseidon and JASON - for practical purposes we acquire separate sampling from 4 because ENVISAT and ERS-2 sample very close together in time (20 minutes apart) and space (same ground track).
- There are effectively 2 SAR image mode satellites available at present. ENVISAT and RADARSAT.
- ENVISAT ASAR wave mode seems to provide reliable data for most passes – ERS-2 SAR wave mode did/does not give good coverage in this region (due to different available modes on ERS and ENVISAT)
- Boxes that spread across more degrees of longitude capture more satellite passes, than "equal" lat and long boxes of same area.
- Results from early evaluation of ENVISAT ASAR wave mode by Met Agencies (for assimilation into wave models) indicates that a high proportion of Wave Mode spectra are not used because of difficulties with quality control[1].

In fact the situation may be slightly improved on this. QinetiQ has analysed the situation and found each SAR satellite may provide images on 4 passes per cycle. Given that we can expect SAR imagery from 2 satellites for the foreseeable future, this gives a possible 8 passes per month, or data, on average, once every 4 days. With 4 operational satellite altimeters, and allowing for the fact that sampling is enhanced at higher latitudes[2], we can expect 8-12 passes per month in any 1° x 1° bin – or an average interval of 3-4 days. Note however that altimeter coverage is expected to reduce to 2 altimeters only in the next few years.

Below we will consider the implications for gridding based on one or more type of instrument.

2.5.1 Scatterometry alone

Scatterometer swaths cover almost the entire globe in a twelve hour period. Therefore, a one degree grid is very well sampled in any month and a climatology at this resolution should be very accurate. However, scatterometers only measure wind speed and direction and cannot directly give information on larger waves.

2.5.2 Altimetry alone

As a point-measuring rather than a swath instrument, data sampling by altimeter is much sparser than that of swath radars, although Table 1 shows that they generate at least as high a number of ***independent*** samples per month (e.g. for climatologies) as the SAR. Certainly very high resolution and short interval climatologies cannot be achieved using one or a few altimeters. An individual altimeter in a 10-40 day repeat orbit will pass through each 2° x 2° degree on 5 to 10 occasions each month (depending on latitude), supplying this number of "independent samples" of the wave climate. Since 2° x 2° and 1 month is suitable for offshore wave climatologies, this is a reasonable compromise between resolution and sampling error for offshore applications. Achieving a satisfactory level of sampling <u>and</u> sufficient resolution for coastal applications is much more difficult.

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[1] A recommendation to address this issue was taken by ESA at the recent ENVISAT symposium in Salzburg (Sept '04). A recent note issued by NORUT (Johnsen, 2005) provides updated advice on quality control and advises that the land masking has been improved.

[2] Table 8 in WP 1.4 was based on altimeter sampling at the equator. At 60°latitude sampling in longitude is effectively doubled.

2.5.3 SAR alone

In principle, one might imagine that SAR as a swath instrument should be able to sample wave climatology far more intensively than altimetry, but Table 1 indicates that this is not the case. Effective sampling rates (in terms of independent samples per month) are at best only equal to altimetry, and depend on the operation of the instrument, whether an image is acquired and archived, and whether the image is fit for purpose. All these factors serve to create a particularly complicated and probably biased sampling regime from SAR. Waves can only be imaged under a specific range of wind conditions, and the lower wavelength cut-off can be significantly different in the along track and across track directions.
We include a preliminary discussion of these issues in Section 4 (WP 1.3), but the situation is complicated and a detailed, regional, study would be required to give a proper understanding of the true sampling density.

However, SAR has the advantage of providing coastal information (e.g., refraction is often clearly imaged) and fine gridding can take advantage of this capability, but this must be weighed against the limited sampling.

2.5.4 Combined Satellite Product

Initially 1° x 1° and monthly climatologies from both altimetry and SAR appear practical, though sampling errors may be large. If distributions are required in different direction sectors are required, then a larger grid size would be required to provide adequate sampling in each direction bin. Bringing together different EO sensors can extend the range of wave parameters and for some parameters can enhance sampling. The evaluation table (Section 4) identifies parameters (e.g., wave height) that can be measured by more than one sensor; and there is some theoretical benefit in using all the data. However, sensor combination can only be rigorously applied if the error characteristics (which are generally obscure and complicated for SAR) are known for both sensors.
Cliosat and ARGOSS offer commercial databases derived from satellite data. Cliosat provide seasonal time resolution, and fairly coarse spatial resolution with 169 grid squares (the resolution varies with location). ARGOSS offers a monthly SAR climatology on a (minimum) 200 km x 200 km grid, or altimeter / scatterometer derived statistics on a minimum 50 km x 50 km grid.

2.5.5 Composites of EO and non-EO

The promise of combining EO and non-EO wave products has been demonstrated by the KNMI global wave climatology. On the other hand, it seems practical to construct a climatology based on EO alone, and there is considerable benefit in having two genuinely independent products to compare.

2.6 CHARACTERISTICS OF EO NEAR REAL TIME DATA

Whilst scatterometers give useful twice-daily global coverage of wind speed and direction, satellite sampling of wave fields for real time use is significantly less frequent in time and space. Calculations and experience from analysis of specific incidents show that one may typically expect 2 passes per satellite altimeter per day over the Area of Interest. If recent data from a single altimeter is presented on its own the data is interesting but rarely is sufficient for operational purposes. Where there are a number of altimeters (currently there are up to 5, but 1 or 2 is more likely in the near future) the data density is more satisfactory, but can still be lacking. SAR images would help to provide greater coverage but this instrument is not necessarily a reliable source in a windy climate.

Thus, satellite data on their own, with present sampling availability, cannot provide a useful complete NRT wave information product. It is therefore necessary to use the data in combination with other sources. Presently, the widest NRT application of satellite wave data is through assimilation into wave models.

An alternative approach is use the satellite data to assess to accuracy or validity of other data sources. One such approach is to overlay the EO data on model data. This immediately alerts the user to possible faults in the model forecasts. A possible development of this approach would be to derive error or reliability flags which could be transmitted along with the conventional model derived forecast.

2.7 RECOMMENDATIONS FOR CLIMATOLOGIES

An offshore wave climatology based on EO retrievals of wave parameters should be constructed on a minimum 1° x 1° monthly grid.

This is a finer grid than is currently typical for altimetry (2° x 2°) and some analysis of the sampling errors should be considered. It may be sensible to recompose the data into 1° x 2° or 2° x 2° grid cells where spatial gradients are small but sampling errors are large. Also a larger grid size may be necessary if analyses of distributions of wave period (and other parameters) are required in different direction sectors. There is little available information on variability on smaller spatial scales. The nature of this variability is likely to be highly geographically dependent (due to effects of local topography) and so ***specific regional studies would be required to fully quantify variability on smaller spatial scales.***

Since strong inter-annual variability in wave climate is a feature of the Area of Interest, on a time scale of decades, ***the time base of the climatology should be as long a possible (ideally itself of the order of decades).***

3 WP 1.2 CAPABILITIES OF NON-EO DATA SOURCES

3.1 INTRODUCTION

The objective of Work Package 1.2 was to describe and assess non-EO sources of wave data and information (including forecasts) presently available for the NW Approaches to the UK. Some weather prediction models which provide the wind input to wave models and some wave models assimilate EO data; but the EO data are not specifically provided in the model output. This 'secondary' use of EO data will also be described here.

3.2 WAVE MEASUREMENTS

3.2.1 Non-directional Buoys

Non-directional buoys - or 'omni-directional' buoys - measure the vertical acceleration of a buoy. This is integrated twice to give the vertical displacement of the buoy (and hopefully of the water surface) with time; and from about a 17 minute record, the elevation spectrum is calculated, and the significant wave height (Hs), the average zero-upcrossing wave period (Tz) and other spectral parameters are extracted for transmission. The significant wave steepness is given by $2\pi Hs/gTz^2$ where g is gravitational acceleration.

During the past decade, the UK Met Office has established a number of weather buoys in open waters around the UK. These record and transmit hourly data including significant wave height and zero-upcrossing wave period. The locations of its buoys (and Light Vessels along the English Channel) are shown in Figure 5.

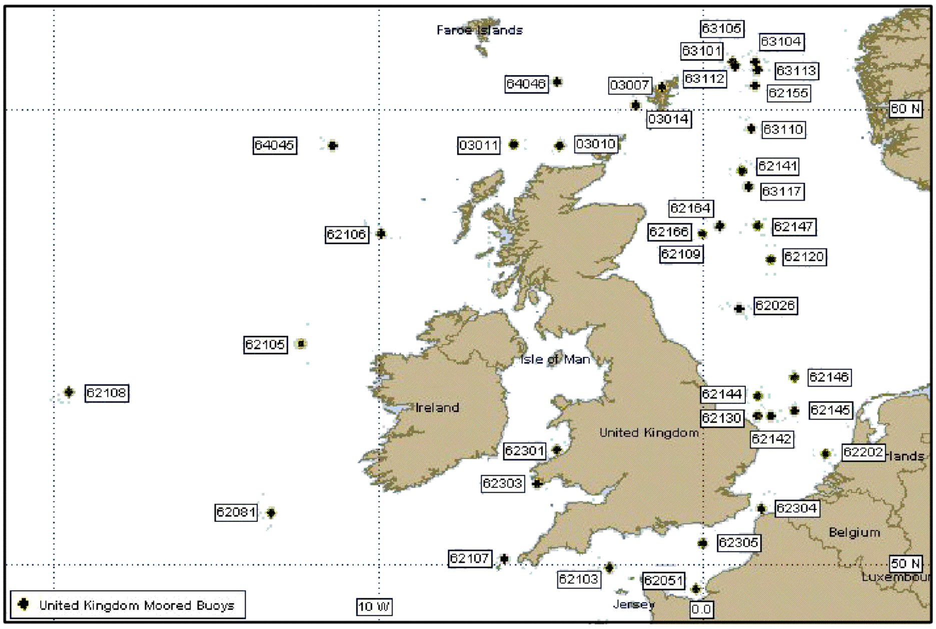

Figure 5 Location of UK Met Office buoys and Light Vessels, and North Sea rigs reporting weather observations

The observations from these sites are put on the Global Telecommunications System (GTS), and are also available on the web.

However, some of these sites (including the 03000 series) do not measure waves, and data from the other sites are not guaranteed; while those which do report wave conditions only give significant wave height and zero-upcross wave period. Even if in place, these buoys do not always report data in high sea states.

Buoys are also maintained by the Irish Met Office - but in Irish waters, south of our area.

3.2.2 Directional Buoys

Directional information can be obtained by measuring pitch and roll angles as well as the heave acceleration, or - more usually nowadays - by measuring the acceleration in 3 directions. Recently, buoys equipped with GPS have been developed which measure Doppler shifts of the carrier signals to obtain the buoy's speed in 3 directions[3]. From these data five Fourier coefficients in the expansion of the wave frequency spectrum, $F(f,\theta)$, can be estimated. Interpreting these coefficients is not straight forward, but they provide estimates of θ_1, the dominant wave direction at each frequency, and of s_1, the wave spread - assuming that the directional distribution, $G(f,\theta)$, is unimodal for given frequency f and proportional to $\cos^{2s_1}\left[\frac{1}{2}\left(\theta-\theta_1\right)\right]$. However, the estimate of s_1 is very sensitive to noise, and "its use in engineering design requires considerable discussion" (Tucker & Pitt, 2001).

If $G(f,\theta)$ is not unimodal for given f, for example if there are two wave systems from different directions but with similar peak frequencies, then the estimate of θ_1 can be seriously in error. But in high sea states, with much of the energy in the locally generated sea waves, the directional wave buoy seems to give good, robust estimates of the dominant wave direction at the wind sea peak frequency, as well as the direction of any swell with smaller frequency[4].

A Directional Waverider buoy is maintained south of the Faroe Islands, near 61.3°N 6.3°W, by the Faroes Oil Industry Group (Figure 6). This buoy provides wave height, period (peak and zero-upcross) and direction, as well as omni-direction spectra and tabulated directional information, for example in Figure 7. The buoy usually reports at half hourly intervals. The Faroes buoy is financed by an industrial consortium - the Faroes Oil Industry Group - which is hoping to continue to fund and operate the buoy during 2005, but this is not guaranteed.

The Waverider's frequency range extends to 0.035 Hz, i.e. to 40 seconds, but the spectral estimates are binned, with all energy from 0.025 to 0.0621 Hz (40 to 16.1 sec.) in a single bin, so it can measure the energy of swell waves with periods greater than 16 seconds but does not report the period distribution within this broad band.

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[3] *See Jeans* et al *(2003) for the very successful results of sea trials of a GPS system (up to wave heights of about 2 m).*

[4] *Frequency, f, and wave length, λ, are related through the dispersion relationship, which for deep water is $\lambda = g/(2\pi f^2)$ where g is gravitational acceleration. Wave period is 1/f.*

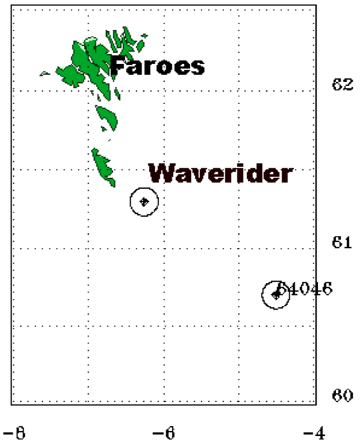


Figure 6 Location of the Faroes Oil Industry Group Directional Waverider - and Met. Office Buoy 64046

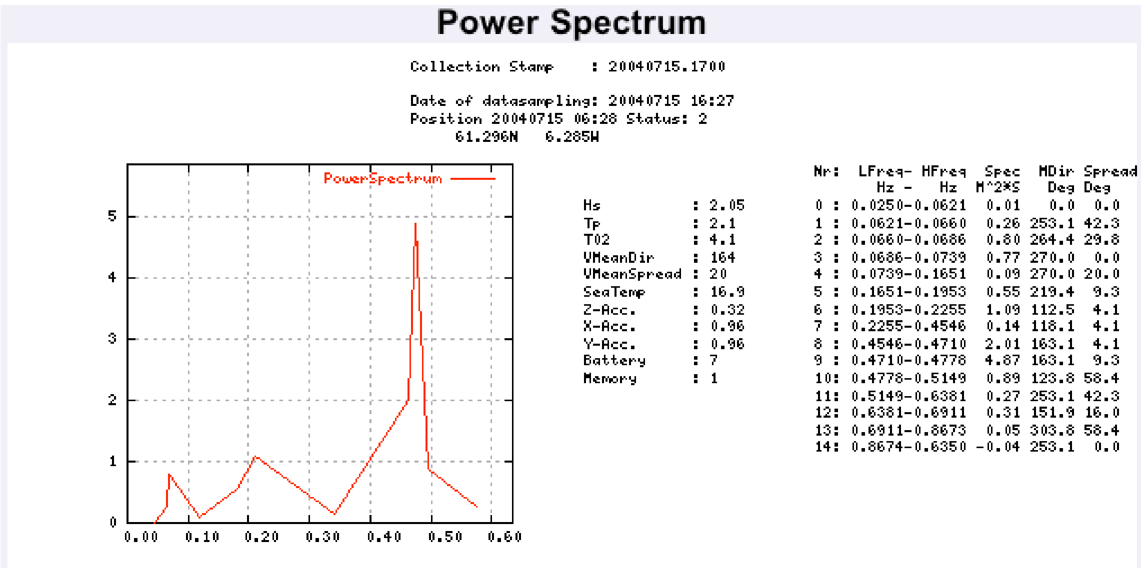


Figure 7 Wave spectral data from the FOIB Waverider web site.

3.2.3 Visual Observations

Visual estimates of sea and swell height, period and direction are included in meteorological reports from Voluntary Observing Ships, mostly at the main synoptic hours.

Plots of ship observations are available from Oceanweather Inc, from http://www.oceanweather.com/data/NorthSea/index.html, and clicking on marine observations. See Figure 8 for an example.

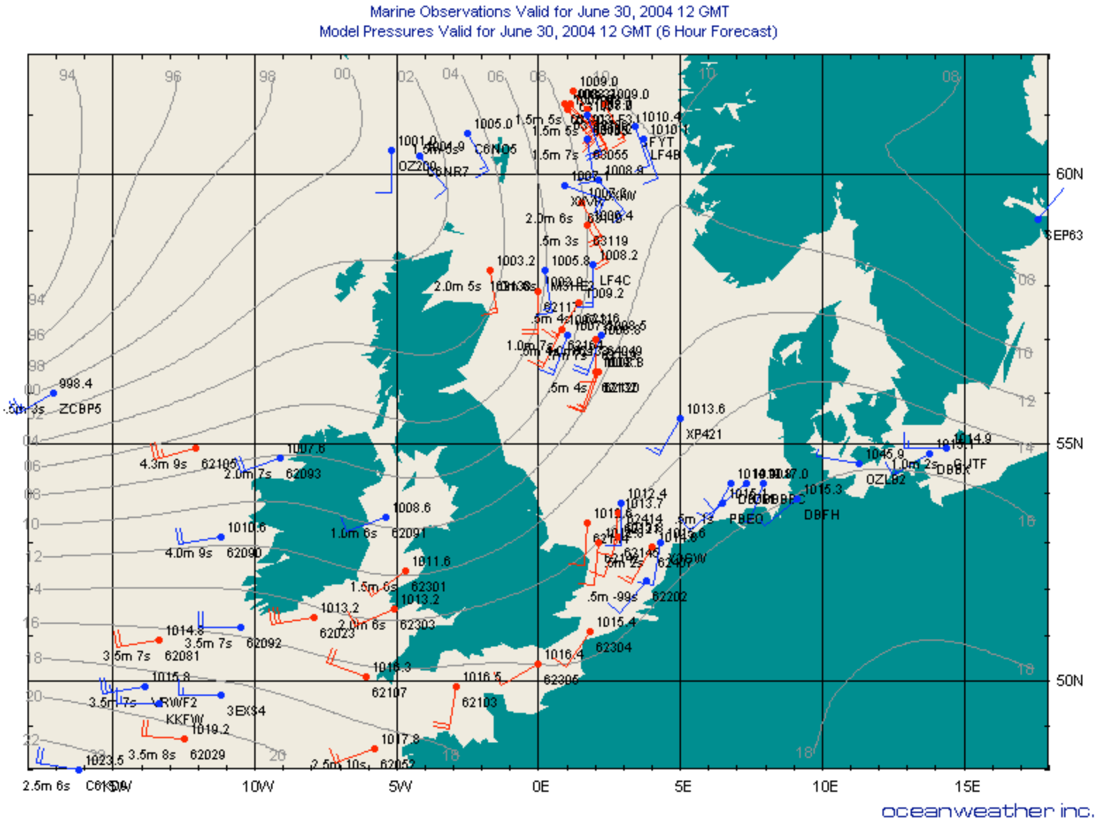


Figure 8. Example of marine observations including wave height and period.

3.2.4 Other Possible Sources of Data

Other instruments for measuring waves are currently being developed, and might be used in the GIFTSS area in the near future. One such method is to use HF radar. For example, an instrument now providing real-time measurements in the North Sea and off Norway, is "WAMOS", an X-band radar system from OceanWaves GmbH. The data from Ekofisk, in the central North Sea, and from Norne FPSO near 66°N 8°E are available from: http://www.oceanwaves.de/start.html

BP is planning to install a WAMOS radar on Schiehallion FPSO, probably in late 2004, together with an Axys directional wave buoy to assist in the calibration of the WAMOS output.

All instruments discussed so far in this report measure significant wave height and not the height of individual waves[5]. But some research has indicated that it might be possible to extract individual wave heights from WAMOS radar images (see Dankert & Rosenthal, 2003).

The MIROS wave radar, manufactured by the Norwegian company Miros A/S, also uses HF radar to estimate directional wave spectra. One such instrument is in operation, for Petroleum Geo-Services, on the Foinaven FPSO 11 km north of Schiehallion; but the data are not distributed.

[5] *Wave buoys can provide records of sea surface elevation, but these data are not usually transmitted, and a correction is necessary to compensate for the horizontal motion of the buoy which would underestimate the heights of the highest crests. See Magnusson* et al., *(2003).*

A development of the OSCR system (originally used for measuring surface currents) by Professor Wyatt of the University of Sheffield is at present undergoing trials in the Celtic Sea. This 'Pisces HF Radar Trial' is managed by the UK Met Office, and funded by DEFRA as part of its feasibility studies for a UK Wave Monitoring Network. A single, shore-based radar provides estimates of significant wave height (assuming the energy is not propagating perpendicular to the radar), while two radars give estimates of the directional wave spectrum.

Some other instruments, such as wave staffs and downward looking lasers might be used, but they are only practical close to fixed structures, and there is always the question of the effect of the structure on the waves.

3.3 ANALYSES AND FORECASTS

Numerous analyses and forecasts of wave height and other parameters are available from national Met Offices, ECMWF, US FNMOC, and commercial companies such as Oceanroutes (UK) Ltd and Oceanweather Inc. For example, The UK Met Office UK Waters Wave Model, covering the GIFTSS area up to 63°N with a resolution of about 12 km, is run 6 hourly, using hourly wind inputs and forecasting out to 5 days ahead (e.g. Figure 9).

Most of these organisations use 3rd Generation spectral wave models, including ECMWF, the Danish Met Institute (DMI), Oceanroutes and Oceanweather.

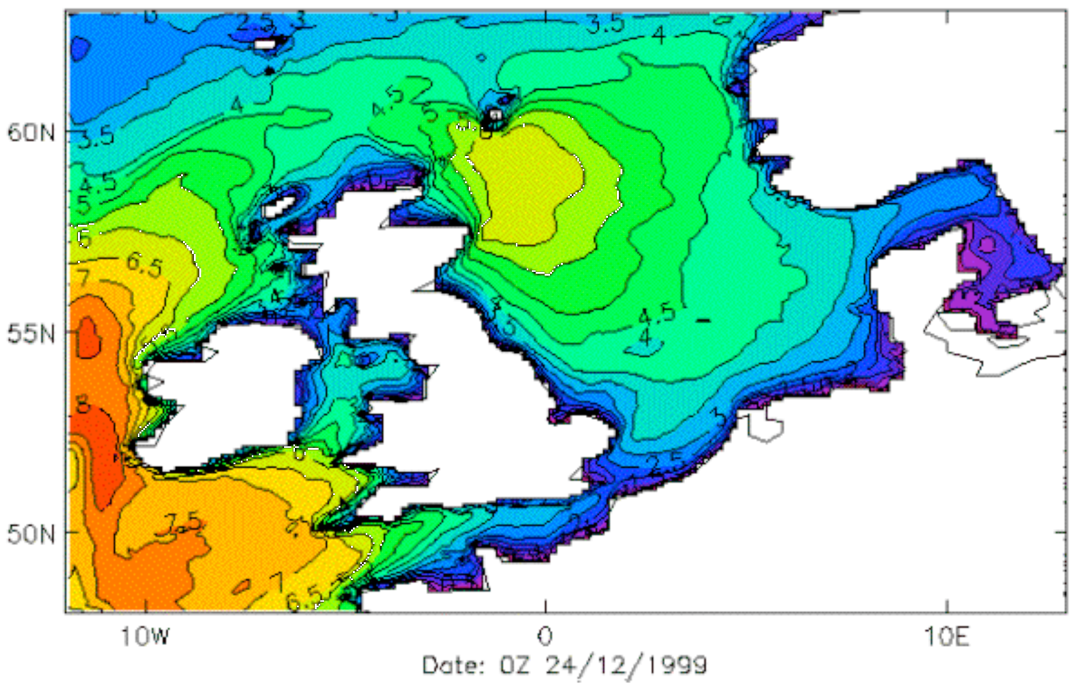


Figure 9 Example of the output from the Met Office's UK waters wave model

Figure 10 shows an analysis from the UK Met Office, distributed by GTS fax. Figure 11 is a DMI analysis for the same time. The fax output in Figure 10 is generated by sub-sampling the Met Office global wave model data on to a coarse grid. The underlying gridded fields are also available via GTS in “grib” format. The full model resolution gridded fields are available commercially - see:
http://www.metoffice.com/research/ocean/operational/dpds/dpds_wave.html

Wavewatch III is a 3rd generation wave model developed and run by NOAA and NCEP. Maps of wave height, peak period and direction, and wind speed in the N Atlantic and globally are available from: http://polar.ncep.noaa.gov/waves/latest_run/
(But the model excludes the Mediterranean.)

Clearer - but sometimes not so up-to-date - maps from Wavewatch III output are available from: http://facs/scripps.edu/surf/images/

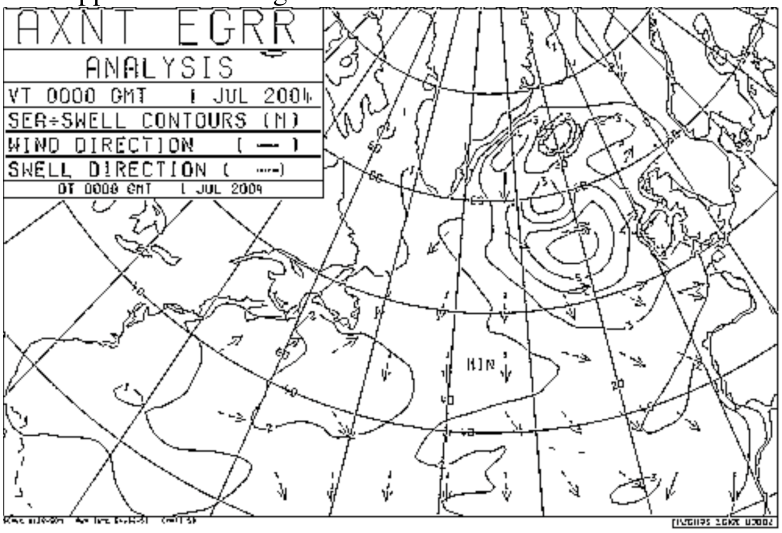


Figure 10 Wave height analysis from the UK Met Office, distributed by 'fax', for 0001Z 1 July 2004

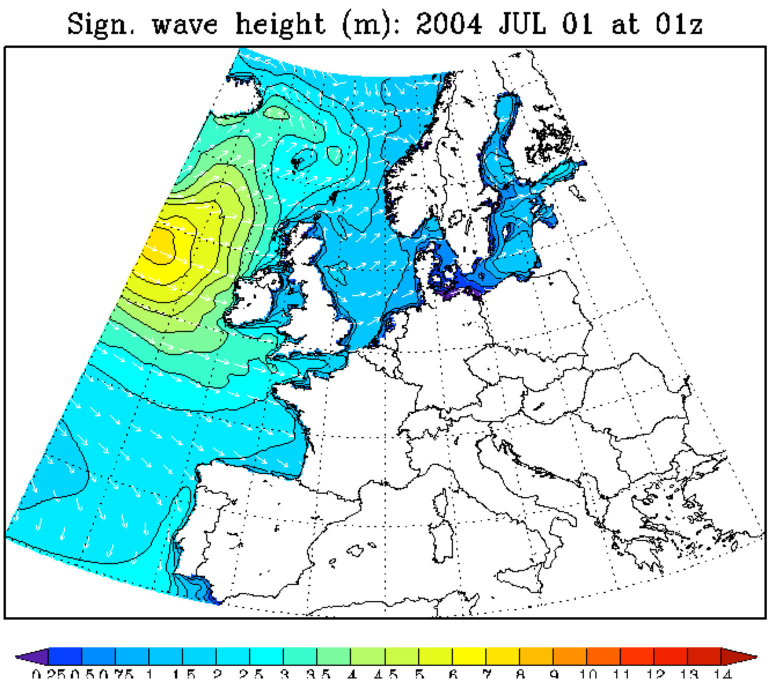


Figure 11 Wave height analysis from the Danish Met Inst. for 0001Z 1 July 2004

EO data, including wind scatterometer data, are widely assimilated into meteorological models to obtain weather analyses and hence predictions, including the wind data which are inputs to wave models (and, for example, Météo-France found that this use of scatterometer wind data did improve the results from its wave model). But, although altimeter data are used to validate the model results, the assimilation of EO wave data into the wave models is not universally carried out.

ECMWF and Météo France have developed assimilation techniques and used them to assimilate altimeter wave heights for some years, and we understand ECMWF has recently begun to assimilate SAR data. The UK Met Office assimilated data from the ERS-1 and ERS-2 altimeters for some years, but found the results unsatisfactory, and stopped in 2001 - although it now uses altimeter data to validate its model and is working towards the use of ENVISAT wave mode data for validation. Oceanroutes does not assimilate EO data into its wave model. Nor, according to Carretero (2002), does the Danish Meteorological Institute - nor (in 2002) did the Irish, Portuguese, and Spanish Met Offices.

3.4 WAVE CLIMATOLOGIES

Wave Model Hindcast Climatologies

The two most relevant wave model Hindcast based climatologies were mentioned in the previous section.

- The KNMI global wave climatology is based on a 45 year Hindcast, forced by ERA-40 winds and is available at http://www.knmi.nl/waveatlas.
- The AES-40 Oceanweather Hindcast is based on a 40 year analysis, but has been "kinemtatically enhanced" to provide an improved parameterisation of storms. This is available at http://www.oceanweather.com/metocean/aes40/index.html.

Visual Observations Climatologies

Two climatologies based on visual observations are available. They have there limitations, but are still quite widely used.

- BMT Global Wave Statistics http://www.globalwavestatisticsonline.com
- Compiled by Sergei Guleev from P.P. Shirshov Institute of Oceanology, Moscow http://www.sail.msk.ru/atlas/index.htm

3.5 ADEQUACY OF PRESENT WAVE INFORMATION

There is continuing activity among wave modellers to assess the accuracy of their wave models. Data are usually checked against observations from buoys - sometimes against EO data, as mentioned above. Often the bias (average difference between model and buoy) and the root mean square difference are calculated. The latter can be misleading because errors tend to increase with increasing wave height[6], so sometimes the 'scatter index' (standard deviation of model-buoy divided by buoy mean) is used.

For example, since 1995, a number of Met Offices, the US Fleet Numerical Meteorology and Oceanography Center (FNMOC), and ECMWF have been comparing their wave model outputs - analyses and forecasts out to 2□days ahead - against buoy data. Bidlot *et al.* (2002) report on the results from 1996 - 1999 model outputs. They conclude that ECMWF

[6] *For example, the sampling error in estimating significant wave height (Hs) from a 20 minute buoy record is proportional to Hs - roughly 4% of Hs, depending on the spectral shape (Carter & Tucker, 1986).*

performed the best "as a whole", but it had problems on the western sides of ocean basins. Bidlot *et al.*, showed a significant under-estimation of ECMWF and FNMOC wave heights in high sea states (globally); the UK Met Office had smaller bias - although its overall scatter index was 0.21 compared to 0.17 and 0.20 for ECMWF and FNMOC.

Assessing adequacy is more difficult. This will depend on the particular operational requirement. For example, significant wave height, Hs, of about 5 m is a critical level for loading at the Schiehallion FPSO. How often do forecasts of 5 m prove correct as opposed to false alarms; how often does Hs exceed 5 m without warning? Adequacy will also depend on the relative cost of false alarms and missed alarms.

The large amounts of wave data and information available are, according to Dr Grant (pers comm) generally adequate for his purposes as BP's metocean advisor. However, the selection and assimilation of so much information is a problem. Gathering the data and presenting them in a readily comprehendable format is a serious problem. BP currently uses Nowcasting International which obtains meteorological and wave analyses and forecasts from a range of national meteorological services and from private weather companies, and prepares a clear presentation to meet its customers' individual needs.

Recent incidents have shown that, while for most of the time there are sufficient wave data, there are occasions when the data are inadequate. These occasions are usually in times of storms, but this is not always the case. There were concerns that long-period swell (of 15 - 20 seconds, and hence wave lengths of 330 - 590 metres) could seriously affect operations at Schiehallion; and the UK Met Office extracted the energy on this frequency band from its wave model for BP.

3.6 CONCLUSIONS

Information and data on sea state in the GIFTSS area are available from a wide range of non-EO sources. Measurements are available, normally hourly, but only at a few locations, and data are not provided reliably - and are especially likely to fail in stormy situations.

The Met Office buoys transmit two wave parameter values: estimates of significant wave height (Hs) and zero-upcrossing period (Tz) - but wind measurements can give estimates of the direction of wind-sea waves. However, there is only one such buoy in the GIFTSS area. There is also one directional buoy in the area which provides tabulated directional information: the dominant direction and energy in a range of frequency bands and estimates of the directional spread of the waves. (There is also a location in the extreme southeast of the area at 57.2°N 0.5°E which reports Hs and Tz.)

Wave length can be readily obtained from frequency using the dispersion relationship. The significant steepness can be calculated from Hs and Tz.

A summary of wave parameters measurements in the GIFTSS area is given in Table 2.

None of these sources provides any measure of individual wave heights, although it is possible that the WAMOS radar might be able to do so, and buoy data can be processed to do so if the individual accelerations or elevations are recorded.

There are numerous wave models which provide estimates of directional spectra at grid points throughout the area, at spacing down to 12 km from the UK Met Office. Maps of Hs, wave period (either Tz or Tp) and dominant direction are usually available in near-real time, but output can be obtained of other parameters such as wave energy in long-period swell or the JONSWAP peakedness factor. Models also give forecasts of all these parameters out to a few days ahead. But the accuracy of model outputs on some occasions - particularly in high sea states - is still questionable.

Table 2 Wave parameter measurements available within the GIFTSS area.

Wave Parameter	*No. of Locations*	*Location*	*Comment*
wave spectrum	1	FOIB	
wave direction	1	FOIB	
sign. wave height	2	FOIB & 64046	& at 57.2˚ 0.5°E
wave steepness	2	FOIB & 64046	significant steepness
wave period	2 (Tz)	FOIB & 64046	& at 57.2˚ 0.5°E
	and 1 (Tp)	FOIB	
wave speed	1	FOIB	at peak frequency

FOIB: Faroes Waverider at 61.3°N 6.3°W (Prob. till end of 2005);
64046: Met.O Buoy at 60.7°N 4.5°W. Numbers may all increase by 1 with deployment of instruments at Schiehallion by the end of 2004.

4 WP 1.3 REQUIREMENTS AND AVAILABILITY OF EO DATA

4.1 INTRODUCTION

The objective of Work Package 1.3 was to describe and provide an initial assessment of the sources of wave data and information available for the NW Approaches to the UK from Earth Observation sources, i.e. satellite mounted instruments.
In this section of the report we briefly outline the satellites, instruments and data sets that are available, then, instrument by instrument describe important characteristics that have a bearing on the accuracy and reliability of the wave information that can be extracted. We close with an assessment of the "readiness" of the available data sets for operational implementation.
Readers are referred to the full WP 1.3 report (Woolf 2004b) if more detail is required.

4.2 PARAMETERS / INSTRUMENTS

4.2.1 Radar Altimeter

Nadir looking radar altimeter
One measurement every 1 second (or 6-7 km) along satellite ground track.
Spatial average over 5-10km diameter region

Parameters
Significant wave height: accuracy 0.3m (0.5 - 15m), resolution 0.01m
10m wind speed: accuracy 1.5 ms^{-1} (0.5 - 15 ms^{-1}), resolution 0.01 ms^{-1}
Estimate of zero upcrossing period (experimental), accuracy 1 s (4-15 s)
(Potentially) significant steepness – A function of significant wave height and wave period
(Potentially) peak period – derived emprically in a similay to zero upcrossing wave period, but further development required.
(Potentially) wave speed (proportional to wave period). But validation would be difficult

Reliability
Measurements generally robust. No measurements available when non-ocean feature lies within altimeter footprint. Very heavy rain (centre of hurricanes of intense tropical storms) can attenuate and corrupt signal.

4.2.2 Wind Scatterometer

Wide swath active microwave instrument (500 km to 1800 km swath).
Vector measurements in 25-50km (25 km for QuikSCAT) grid cells across swath.

Parameters
Wind speed (accuracy 2 ms^{-1}) and direction (accuracy 20°) providing spatial average in 25 x 25km, or 50 x 50 km grid cells.
Used in some experimental applications to generate wind sea part of wave spectrum, as a complement to the long-wave spectrum retrieved from SAR

Reliability
Occasional problems with retrieving correct "alias" wind vector, can lead to some directional ambiguities. Problems in close proximity to land (~50 km). Rain affected (especially Ku band QuikSCAT)

4.2.3 Synthetic Aperture Radar (wave mode)

"Snapshot" imagette of wave field over 10km x 6 km region every 100 km along track.

Parameters

Processed to produce (with 180° ambiguity, now resolved by ENVISAT ASAR) energy in 12 directional sectors at 12 wave lengths.

Reliability

Due to limited aperture and speed over ground of satellite, radar cannot resolve wavelengths < 100m. Combination with wave models is often used to retrieve shorter wavelength signal, and to resolve directional ambiguity problem.

4.2.4 Synthetic Aperture Radar (Image mode)

Active microwave sensor operated through a steerable antenna that directs the transmitted energy in a narrow beam normal to the satellite track. SAR is able to collect data over a 1,175 km wide area for a wide range of imaging options - up to 7 beam modes (8m to 100m nominal resolution) and up to 35 beam positions.

Parameters

Wind speed, long wavelength wave spectrum (lower cut-off determined in part by image resolution and hence image mode – wide scan, narrow scan, etc) small scale surface roughness, and for the detection of dynamic ocean features (e.g. eddies, fronts, internal waves).

Reliability

Problems determining surface roughness for wind speeds <3m/s and >11m/s.

4.3 SATELLITE DATA SETS

ERS-2 radar altimeter (1995-)

- Significant wave height, wind speed, wave period estimate.
- Global along track (at satellite nadir) coverage between 82°S and 82°N, measurements at 1 second intervals, providing spatial average over 5-10km diameter region.
- 35 day repeat orbit
- Near Real Time: < 4 hours delay (N Atlantic and some N Pacific orbits only – where satellite is in direct line of site of ESA ground stations).

ERS-2 Synthetic Aperture Radar wave mode (1995-)

- Swell wave height and direction (with 180° ambiguity)
- Global coverage between 82°S and 82°N, measurements at 200 km intervals, providing spatial average over 10 x 6 km grid region.
- 35 day repeat orbit
- Near Real Time: < 4 hours delay

ERS-2 Synthetic Aperture Radar image mode (1995-)

- Swell wave height and direction (with 180° ambiguity)
- Potential for high resolution of coastal spatial variability
- Global coverage between 82°S and 82°N, BUT dependent on operational mode
- Near Real Time – In theory possible but full NRT processing chain (reception at W

Freugh, transmission to e.g. QinetiQ , and image processing to generate wave fields) not tested.

ERS-2 wind scatterometer (1995-)

- Wind speed and direction
- North Atlantic 500km swath coverage, spatial average on 25x25 km grid.
- Near Real Time (in NE Atlantic only): <3 hours delay

TOPEX/Poseidon radar altimeter (1992-)

- Significant wave height, wind speed, wave period estimate.
- Global along track (at satellite nadir) coverage between 65°S and 65°N.
- 10 day repeat orbit
- Near Real Time: > 8 hours delay

QUIKSCAT "Seawinds" wind scatterometer (1999-)

- Wind speed and direction
- Global daily wide swath coverage (1800 km), spatial average on 25x25 km grid.
- Near Real Time: <3 hours delay

Geosat Follow-On radar altimeter (launched 1999, operational 12/2000)

- Significant wave height, wind speed, wave period estimate.
- Global along track (at satellite nadir) coverage between 72°S and 72°N.
- 17 day repeat orbit
- Near Real Time: not available

Jason radar altimeter (December 2001-)

- Significant wave height, wind speed, wave period estimate.
- Global along track (at satellite nadir) coverage between 65°S and 65°N.
- Near Real Time: < 6 hours

ENVISAT radar altimeter (March 2002-)

- Significant wave height, wind speed, wave period estimate.
- Global along track (at satellite nadir) coverage between 82°S and 82N.
- Near Real Time: < 4 hours delay
-

ENVISAT synthetic aperture radar wave mode (March 2002-)

- Swell wave height and direction
- Global coverage between 82°S and 82°N, measurements at 100 km intervals, providing spatial average over 5 x5 km grid region.
- Near Real Time: < 4 hours delay

ENVISAT synthetic aperture radar image mode (March 2002-)

- Swell wave height and direction
- Potential for high resolution of coastal spatial variability
- Global coverage between 82°S and 82°N, BUT dependent on operational mode
- Near Real Time – Not tested – see comments for ERS-2 image mode.

Radarsat-1 synthetic aperture radar image mode (1995-)

- Swell wave height and direction
- Potential for high resolution of coastal spatial variability
- Coverage dependent on operational mode
- Near Real Time –if in view of ground station - then see above.

ERS-2 is not expected to continue for much longer, it has already experience failure in 6 (out of 6) gyroscopes, and the tape recorder has failed – so that data can now only be taken whilst the satellite is in view of ground stations. TOPEX has significantly exceeded its planned lifetime (originally 4 years), it too has experienced tape recorder failure, and was switched to the back up electronics in 1996.
JASON has a nominal lifetime of 5 years and its planned replacement should be launched in 2008. Geosat Follow-On was launched in 1999 on a 5 year mission. ENVISAT has a nominal 5 year mission. RadarSat-1 should be replaced/supplemented by Radarsat-2 in 2005.

4.4 SYNTHETIC APERTURE RADAR

4.4.1 Overview

The synthetic aperture radar is a side-looking wide swath instrument which achieves high spatial resolution by integrating returns from the surface along a typically 10 km aperture, over a time of typically 1 second.

A SAR image can be thought of as a (nonlinear) mapping of surface roughness at the scale of the radar wavelength (for C-band, ENVISAT, ERS-2 and Radarsat ~10cm). The physics of the backscattering process, and the techniques by which information about the wave spectrum are extracted from the SAR image spectrum are complex and described in detail in the full WP 1.3 report (Woolf 2004b).

Location within the image is determined by the signal timing in the range direction, and by the Doppler history of the signal in the azimuth direction (Figure 12). SAR data is thus affected by surface motion – this contributes to the imaging mechanism for azimuth travelling waves, but can also degrade the imaging of the same waves. Ground resolution of the order of 30 m is obtained over a swath that varies from 100 km to a few hundred kilometres (but often with reduced resolution at wider swaths). Surface spectra obtained from the SAR image spectra can provide dominant wavelength and direction. However the SAR-derived surface spectrum only covers a restricted part of the surface wave spectrum. Typically for ERS the SAR spectrum covers range-travelling waves longer than 100m, and azimuth travelling waves longer than 200 m. In situations where the waves of interest are longer than these limits, SAR data compares well with wave models and buoy data. SAR data is affected by other ocean and atmospheric phenomena that modify surface roughness, (e.g. surface slicks) and requires low to moderate surface winds (typically 3 – 11 m/s, but this is radar wavelength dependent).

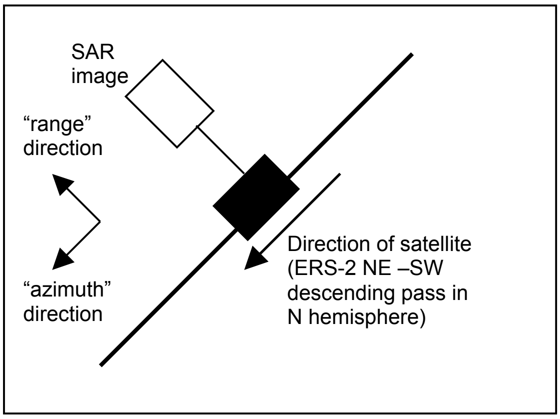


Figure 12 The Geometry of the SAR Instrument

4.4.2 SAR Direction Information

"Conventional" multi-look/intensity imagery – 180° ambiguity in direction

The symmetry of the image spectrum means that using the spectrum alone, there is a 180° ambiguity in the direction of the waves. In some cases there is other information in the image which can be used to resolve the ambiguity. The analysis system used by QinetiQ, "MaST" , uses the presence of land and assumes waves are travelling towards the nearest land. Alternatively a wave model is often used to determine the correct direction. All Fast Fourier Transform (FFT) (or equivalent) based image spectra methods using multi-look/ intensity only data as the starting point suffer from the problem of wave direction ambiguity, and require ancillary data to resolve it.

Cross-Spectra Methods

Cross spectra methods use single look complex data, and exploit the movement of swell waves in the time between single look acquisition. For ERS the time between looks is 0.37 sec, and swell waves move sufficiently in this time that the direction of movement can be determined and the 180° ambiguity resolved. This cross spectrum method is also applied to Envisat ASAR data.

4.4.3 Wave parameters measurable by SAR

As we have discussed, a SAR image has the potential to provide a surface spectrum over a (limited) range of wavelengths and directions. A Modulation Transfer Function (MTF) relates the SAR image spectrum to the surface spectrum. If more than one wave train is present on the surface and is imaged, then it will be included in the spectrum. Peak wavelength and direction (to within 180 degrees just using the intensity spectrum) can then be read off the spectrum. Wave height (of the peak wavelength) or significant wave height (averaged over the spectrum) can then be obtained, if the instrument has been suitable calibrated

As noted above short wind-waves are not imaged, and the azimuth and range components of the surface wave field have generally different limits.

Other wave parameters can then be derived using the wave dispersion relation and the peak wavelength (or spectrum).

Wave parameters that can be measured (directly)

- Wavelength (spectrum)
- Wave direction
- Wave height (spectrum)

Wave parameters that can be derived from these primary measurements

- Significant wave height
- Wave period
- Wave speed
- Wave steepness

4.4.4 SAR Products

SAR ocean data are available either as images, or (for the ESA ERS and ENVISAT satellites, in wave mode format.

Wave Mode

Perhaps the most widely known use of SAR is through the application of single large images of a region of the earth's surface (either on land or over the ocean). The ERS-1, ERS-2 and ENVISAT SARs have(d) an additional operating mode, known as the wave mode. In this

mode the satellite regularly (once every ~100km along track) takes a small (usually 10 km x 6 km) “imagette” specifically for the purposes of providing wave measurements. These “imagettes” also offer a smaller pixel spacing (20 m in range, 16 m in azimuth) than many of the conventional image modes. These imagettes are processed for ESA as part of the Near Real Time and offline operational data processing chains to provide wave spectra and derived wave parameters.
A specific problem for application of historical SAR wave mode data in our area of interest is that the operation of the active microwave instrument (AMI) on ERS-1 and ERS-2 meant that the SAR wave mode and SAR image mode could not operate at the same time. This had a significant impact on SAR wave mode coverage over the northern North Sea, though recent discussions with ECMWF have indicated that the impact over the North-Western Approaches may not be as severe as was originally thought. The ESA help desk has been contacted with a request for clarification of ERS-1 and ERS-2 wave mode coverage of this region, but we have not yet received a response.

One possibility is that SAR image mode data could be used to “fill in the gaps” during the periods, and over locations, when wave mode data are unavailable, or sparsely available. By definition, ERS SAR image data should be available when the wave mode data are not.

ENVISAT ASAR WM Data
Two types of products are available from the ENVISAT ASAR wave mode: The Level 1B products which include the “imagettes” and the radar cross-spectra, and the Level 2 wave mode product which provides the ocean spectra plus derived parameters (Hs, period,..).
Most operational users, such as Met Offices running operational wave models, choose to use the level 2 product (see Figure 13). More advanced users use the imagettes or radar cross spectra to develop and apply their own retrieval techniques. For instance the MAXWAVE team used ERS-2 wave mode imagettes to search for features they associate with unusually high and steep waves.
The ASAR wave mode on ENVISAT can operate at the same time as the image mode, and so better coverage should be available than was the case for ERS-1 and ERS-2.

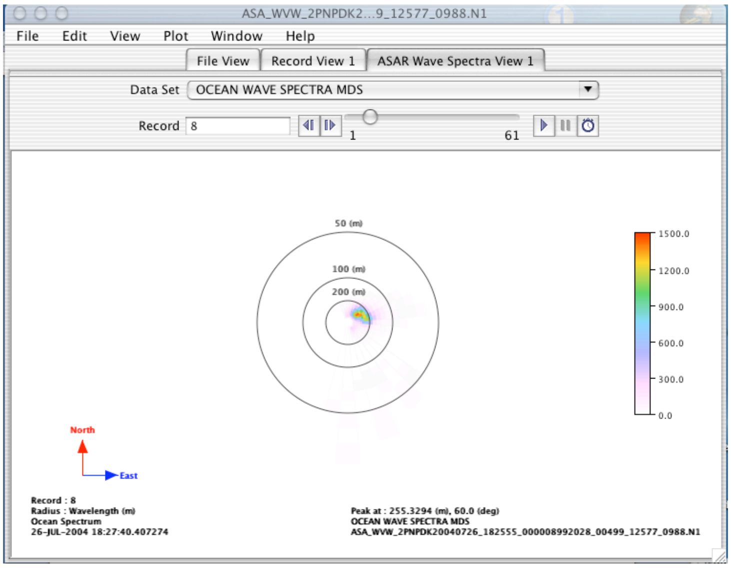


Figure 13 Wave Spectra (right) and data product content (right) from ENVISAT ASAR Wave Mode Data. Produced with the ESA ENVIVIEW software

Since its first introduction over a year ago, the ENVISAT ASAR wave mode processing software has undergone a number of modifications - responding to results from a validation campaign, and experience from some early users of the data set (as discussed below). Thus the archived ASAR wave mode data set is not homogeneous. It is understood that ESA will start to reprocess archived ENVISAT ASAR WM data early in 2005, and so produce a consistent data set.
The UK Met Office, Météo France, ECMWF and others have been evaluating the ENVISAT ASAR wave mode data for the past year, and presented their findings at the recent ENVISAT symposium in Salzburg (September, 2004). There is a high interest in the wave mode product from wave forecasters, because tests have shown that the assimilation of wave spectra has a longer term impact on the wave forecast than if wave height data alone are assimilated. This is believed to be because the wave spectra provides separate information about swell -and the models still have some difficulty in accurately representing the growth and propagation of swell.

The consensus of these "beta" testers was that the data could be very useful, and were shown to be accurate under a range of conditions, but that one must be aware of the limitations and apply careful quality control. For instance, although the estimated wave height was accurate to 0.4m for 50% of the data, overall the rms was 0.8m. Also users were finding that up to 75% of the wave mode data were discarded by their assimilation schemes. However, from recent communications with the ENVIWAVE team (Johnsen pers. comm.) we understand the situation has recently improved, ESA have modified the land masking procedure, and updated advice on quality control is now available (In Johnsen, 2005)

Thus issues to bear in mind when using ENVISAT ASAR wave mode data are:

- Parameters relate to long wavelengths only. The wave period window 8-15s has been identified as providing the most reliable data.
- Apply careful quality control. Checks should include the normalised variance, the azimith cut-off, and co-located model wind speed.
- Under certain conditions, specifically strong winds in the azimuth direction, severe distortion of the extracted spectra can occur.

Image Mode

A number of different SAR image modes are available, with a trade off between wider coverage and small scale resolution. Radarsat provides options from a fine mode with a resolution of 10m, and an image scan width of only 50km, to a "Scan Wide" mode with a swath width of 300km, but a surface resolution of 100m. With the ERS SAR the usual image mode of operation offers a 100 km x 100 km image, at a resolution of 50 m.

These image mode data are not routinely processed by the satellite agency to provide wave measurements, this must be achieved through a subsequent, separate, processing scheme. In this study we considered two applications for carrying out this processing – the QinetiQ MaST application, and the BOOST Sartool both process the SAR image to provide wave information in a number of sub-cells across the image.

In general images over a specific area for a specified time can be requested in advance. Usually these orders will have to be programmed in advance into the satellite retrieval timetable on a cycle-by-cycle basis (one cycle for ERS / ENVISAT is 35 days), and the satellite agency will prioritise requests. Otherwise, one must make do with the ad-hoc sampling available according to existing programmed requests.

MaST application

QinetiQ has developed an automated maritime surveillance tool (MaST), which uses a suite of software modules, written in C++, to detect maritime features from satellite SAR imagery. MaST is capable of supporting the formats from ERS-2, Envisat and Radarsat-1.

To characterise the swell wave field, the SAR image is segmented into a grid of square subscenes. The user is given the option to reduce the number of pixels by averaging over their values by a chosen factor. The model uses a two-dimensional Fast Fourier Transform (FFT) to obtain the SAR Image spectrum. From this the two-dimensional surface height spectrum is obtained from a Modulation Transfer Function (which takes into account tilt modulation and velocity bunching). The spectrum is filtered to the range of wavelengths of interest. To identify true wave signals against the noise in the spectrum, only peaks above a threshold are considered. The model is able to identify multiple peaks within a segment in this fashion, corresponding to different swell wave trains.

This technique identifies the orientation of swell wave crest patterns in an image but cannot determine in which, out of the two opposite directions, they are travelling (the 180 degree ambiguity).

MaST can apply a land mask so that any subscene encompassing pixels of land are ignored. For the ocean areas the centres of subscenes for which swell waves are identified are displayed by blue circles with red lines showing the direction of travel (within the 180° ambiguity), see Figure 14. The length of red lines is proportional to the phase speed of the swell waves calculated from the wavelength using the linear, deepwater dispersion relation.

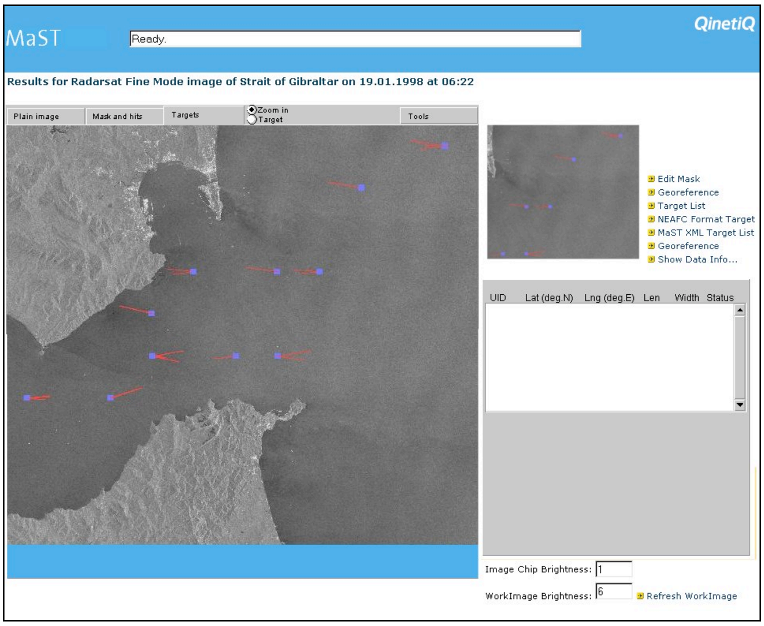


Figure 14 MaST swell wave detection

BOOST SARtool application

The French company, BOOST, have developed a SAR processing tool called "SARtool". SARtool can be used to process Single Look Complex SAR images (.SLC) from ERS-1, ERS-2, RadarSat and ENVISAT. SARtool uses the cross-spectrum to generate wave spectra without any 180° ambiguity (it uses the same algorithms developed for, and applied to, the ENVISAT ASAR wave mode data). Output from use of this tool on an ENVISAT ASAR image is demonstrated in Figure 15.

Demonstration / operational capabilities of SAR Tool include:

- Oil spill monitoring
- Ship detection
- High resolution winds fields
- Two dimensional wave spectrum retrieval

New capabilities under development at BOOST include the analysis of coastal wave fields, and estimates of "radial" sea surface velocity (i.e. perpendicular to the satellite ground track). This latter is achieved through an analysis of the doppler shift on the returned signal. This leads to a possible capability to identify and locate frontal features (so long as they have an expression in the appropriate direction with respect to the satellite track).

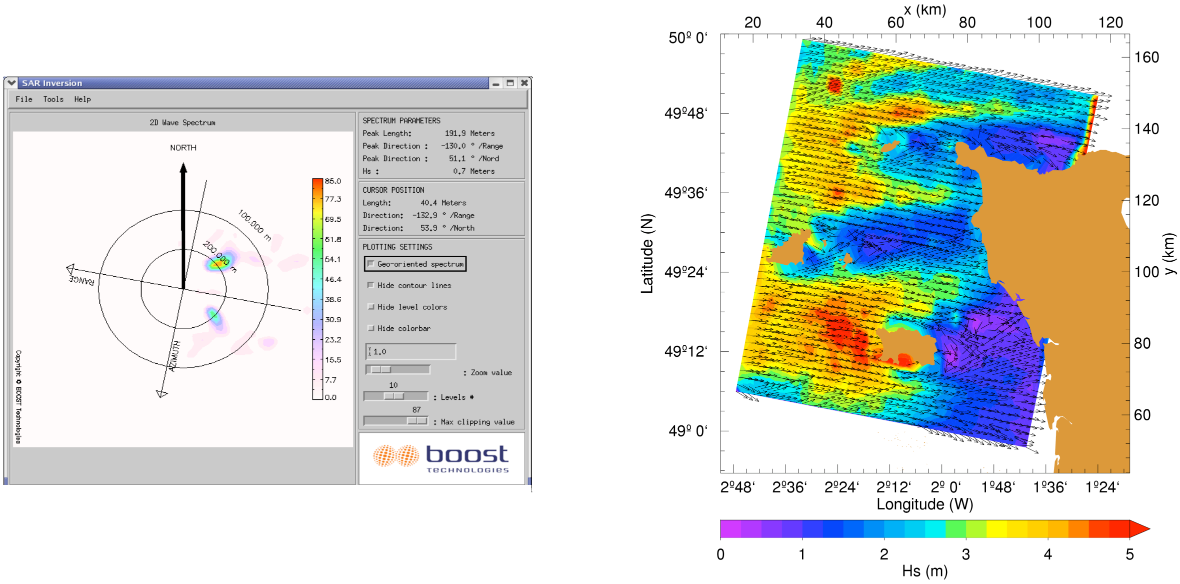


Figure 15 Wave Spectra and high-resolution coastal wave fields from ENVISAT ASAR Image Mode Data. Produced using the BOOST SARtool.

4.4.5 SAR Data Availability

Archive images at West Freugh

The QinetiQ image data base at West Freugh holds a large volume of SAR data within the Area of Interest (AOI) (56°-64°N, 1°E-10°W), including over 3000 ERS-1 images (for 1991-2000) and more than 5000 ERS-2 images (1995-present).

Potential Future Image Acquisitions

QinetiQ through the West Freugh ground station is now capable of downloading (within the Ground Station footprint) Radarsat, ERS-2 SAR and Envisat ASAR NRT. With the new ASAR processor it is now possible to download and process an ASAR image within 45 minutes and to analyse it subsequently within a further 15 minutes, giving around a 1 hour turnaround from time of acquisition to dispatch of results.

In terms of the number of images this is difficult to address without reference to a specific AOI. The repeat cycle determines how often one can reacquire the same frame, i.e. once every 35 days for ERS-2 and Envisat and once every 26 days for Radarsat. Operationally, repeat acquisition of a specific frame is an unlikely scenario and the AOI will be detailed in terms of an area. It therefore follows that a number of different frames will either fully or partly cover the AOI and thus the number of potential acquisitions in a single repeat cycle will be greater than the repeat acquisition of the same frame. Clearly as the size of the AOI increases the greater the number of images that fall within the region. We present some examples below:

EXAMPLE 1: 4 ERS-2 images that could be acquired over a 1°x1° in the NW Approaches (where at least 50% of the image falls within the AOI), in a single repeat cycle.

EXAMPLE 2: 4 Envisat ASAR Narrow Swath Mode images that could be acquired over a 1°x1° in the NW Approaches (where at least 50% of the image falls within the AOI), in a single repeat cycle.

EXAMPLE 3: 12 Envisat ASAR Narrow Swath Mode images that could be acquired over a 2°x2° in the NW Approaches (where at least 50% of the image falls within the AOI), in a single repeat cycle.

4.5 RADAR ALTIMETER

4.5.1 Overview

The radar altimeter is a nadir-pointing instrument operating by timing the delay between emission of a short microwave pulse and the subsequent detection of the returned echo, recording both the time and distortion of the returned signal. This distortion gives a spatial average of the significant wave height over a 5 to 10km diameter footprint every 6-7km along the satellite ground track. The accuracy is 0.3m over the range 0.5 to 15m, with a measurement resolution of 0.01m. Under some conditions of wind and waves it is also possible to estimate the wave period with an accuracy of 1 m/s over the range 4 to 15 s. Measurements are generally robust, but no measurements are available when land lies within the altimeter footprint. Also very heavy rain (such as the centre of hurricanes or intense tropical storms) can attenuate and corrupt the signal.

4.5.2 Capabilities

Wave length/wave height spectrum,

Wave direction - average direction and dominant or peak direction,

Altimeter data is limited to integral measures of surface roughness over the 5-10km footprint. Thus, it is unlikely that any "spectral resolution" can be achieved from a standard altimeter, and certainly such a capability has not been demonstrated. Similarly, a standard altimeter views at nadir and is insensitive to wave direction.

Significant wave height

Significant wave height (Hs) is closely related to the leading slope of the returned signal. The accuracy is approximately 0.3m over the range 0.5 to 10m, with a measurement resolution of 0.01m, which is comparable to the best wave buoys. For wave heights in excess of 10 metres the quality of all measurement methods is uncertain, but the limited number of collocations in these conditions suggest that buoy and altimeter estimates remain consistent.

Wind speed

Wind speed is not one of the selected wave parameters, but it is important to note that an accurate estimate of surface wind speed (co-located with other wave parameters) is available from the satellite altimeter. Wind speed is derived from the surface backscatter (σ^0). Single parameters algorithms (e.g. Witter and Chelton 1991) give an accuracy to 1.5 ms^{-1}, two parameter (Hs and σ^0) algorithms improve this to 1.3 ms^{-1}.

Wave period i.e. Tz and Tp,

A novel empirical approach for retrieving wave period from altimeter σ^0 and Hs data has recently been published (Gommenginger et al., 2003). Through heuristic arguments they relate wave period to Hs and σ^0 through the proportional dependency $T \sim (\sigma^0 . Hs^2)^{1/4}$

This model function was fitted using a dataset of Topex altimeter data collocated with NDBC buoy spectra and validation using an independent dataset of Topex data collocated with buoys demonstrated global retrieval errors of ~ 0.8 s (rms error) for Tz, and ~ 1 s for Tm. A preliminary analysis by geographical area (Hawaii, Gulf of Mexico) suggested that altimeter wave period may be more reliable in wind dominated conditions. On the other hand, comparison with numerical wave models suggests that the altimeter wave period approach is valid for both wind-dominated and swell conditions.

An attempt was made to derive a peak wave period, but this was not so successful and further development work is necessary

Wave steepness,

It is plausible to seek an empirical relationship between wave steepness and the basic "measurements", σ^0 and Hs. This has not been attempted directly. However, for deep water gravity waves, a significant wave steepness can be defined in terms of significant wave height and mean wave period (see annex A). Currently there are no estimates of the likely bias or scatter in such estimates. An estimate of accuracy might be made by comparing altimeter-retrieved steepness statistics to similar statistics from wave buoys.

Wave speed.

For deep water gravity waves, wave speed (group or phase) is simply proportional to wave period and thus wave speed can be estimated indirectly from the estimates of period described above. It would be most appropriate to use the peak wave period in this case – but we are then confronted with the difficulty in acquiring an accurate estimate of peak period.

In addition, it is difficult to see how any direct validation of wave speed estimates might be made.

4.5.3 Coverage and Sampling

Altimeters are set in near-polar orbits viewing at nadir. Thus, coverage is "near Global" with no data in polar regions. The Area of Interest is covered by all satellite altimeters. However, altimeters are essentially "point measuring" at each pulse measuring single integral values for a 5-10 km patch immediately beneath the instrument. Thus the volume of information is very much smaller than "imaging" or "swath" instruments that collect data separately from very many points on the surface simultaneously. Note also that altimeters are generally set in a repetition mode, such that the altimeter repeats an exact ground track after a fixed number of orbits. Thus data is eventually collected on numerous occasions at the same point, but there are also fairly large areas between ground tracks that are not measured. Standard ground tracks around the UK are shown in Figure 16. The "sparse sampling" characteristics of altimetry have considerable consequences for appropriate "gridding" of data (see section 2 - WP 1.1), though they still offer better spatial sampling than existing buoy observations.

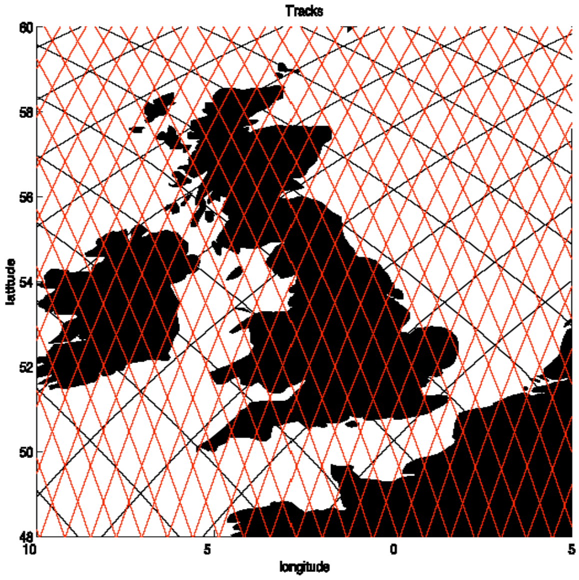


Figure 16 Ground tracks of altimeters near the UK. Tracks in black are the standard tracks for Topex / Jason, repeated every 9 days 22 hours. Tracks in red are the standard 35 day repetition for ERS / Envisat

4.6 OTHER SOURCES OF DATA

Currently, the only other source of ocean sea state data is scatterometry, and this does not provide any of the wave parameters required, though it is a rich source of ancillary data Scatterometer data have been used to estimate the directional wind sea. Use of reflections from future Global Navigation Satellite Systems missions may produce a "Sea State Parameter" of sorts but this is unlikely to coincide with any of the required wave parameters.

4.7 SUMMARY AND CONCLUSIONS

Wave heights are measured directly by the radar altimeter, and (long wavelength) dominant wavelength (and thus wave period) and direction can be derived from SAR measurements. Wave period is also an experimental parameter derived from the altimeter. Wave steepness and wave speed can also be estimated in principle from altimeter data, but the accuracy of these parameters is unknown. SAR can in principle be used to derive quite detailed characteristics of the wave field including all the parameters requested by HSE, but the level of confidence is generally uncertain. SAR is also ineffective in very low winds and very high winds.

For both altimetry and SAR, the availability of information is constrained by the satellite passes. With a single satellite there is insufficient information for routine monitoring of wave conditions in coastal areas on a daily basis, and even with the 5 altimeters fine-scale geographical detail of the wave field is not revealed. Because of the long record of measurements (dating back to Geosat in 1985), however, altimeter measurements are especially useful for deriving statistics such as monthly mean values and the 100 year return values (largest waves expected over 100 year period), shown for the UK area in Figure 17.

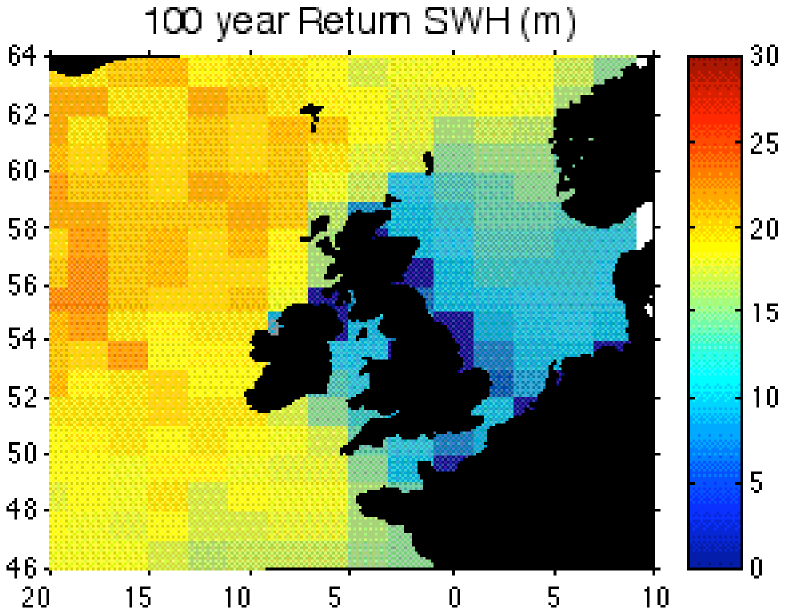


Figure 17 100 year return value of significant wave height around the UK, calculated from a 15-year archive of altimeter wave measurements.

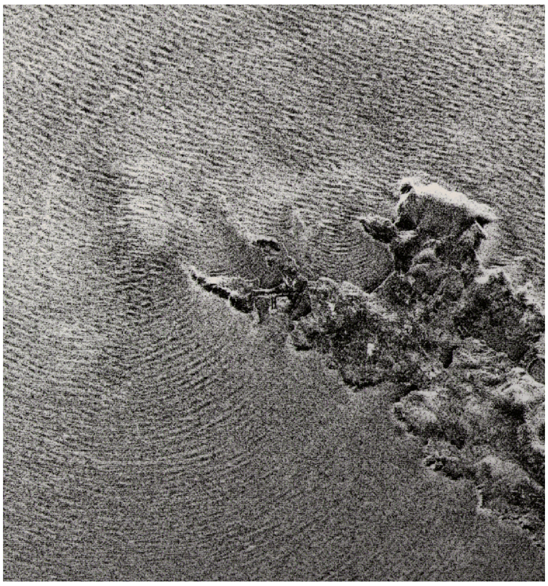


Figure 18 Diffraction of surface waves around Sumburgh Head, Shetlands, captured by a SAR image

Coastal wave conditions will relate to prevailing offshore conditions to some extent, but local effects will be significant and highly variable, so near-shore wave conditions can only be obtained from space by analysing individual SAR (or in some cases optical) images. Figure 18 gives a good example of how long-period waves are well captured by SAR imagery.

Information and data on sea state in the GIFTSS area are available from a number of EO sources, but SAR and altimetry are the most important sources. Both instruments have important limitations in terms of the parameter capabilities and data availability. These limitations must be considered carefully in the definition of suitable sampling grid/interval, and product definition.

4.7.1 Evaluation of EO Capabilities to Measure HSE Required Wave Parameters

Significant Wave Height: H_s

The altimeter can provide an accurate and reliable estimate of Hs, suitable for many statistical analysis applications without need for further data. The main issue for NRT applications is poor temporal sampling.

Recent developments have shown it is possible to extract an estimate for (long wavelength) Hs from (A)SAR images and wave mode data (following calibration of energy levels and backscatter amplitude). A separate estimate of swell Hs may have some useful applications. However, presently available sampling (in both time and space) from SAR is a limitation.

Zero Upcrossing, mean, wave period: $T_{z,m}$

Recent developments have shown that a useful estimate of zero upcrossing wave period can be extracted from altimeter data, though it has not yet been applied widely. Temporal sampling is again poor from altimeters for NRT applications.

A mean wave period can be extracted by integrating the 2D SAR spectrum, though again only the longer part of the spectrum is sensed.

Peak wave period: T_p

Although a peak period can be derived from altimetry, further development and testing is required. The peak wavelength (for long waves) can in theory be identified unambiguously in SAR data. However validation programmes against modelled spectra gave rms ~ 3s. There is an inherent difficulty in validating this parameter, against model or in-situ data (in the latter case the problem is very limited resolution, 5s, at large periods). Nonetheless, this could prove one of the most useful measurements available from the SAR because of its importance in deep-water operations. Sampling in time and space (from SAR) is again poor.

Peak Direction: θ_p

A peak direction can be identified from analysis of SAR imagery, and extracted from the wave mode imagettes. The same sampling and wavelength sensitivity issues as above apply. Direction information cannot be extracted from altimetry.

Significant Steepness: Stp_{sig}

A significant steepness parameter can be estimated from the ratio of H_s and T_z^2 (Annex A). To our knowledge, such a parameter has not been tested before and so careful validation would be required before any operational application. However, this parameter can be easily generated, so we recommend an initial evaluation is carried out within this project.

As this parameter is derived directly from H_s and T_z, the limitations identified in the discussions above apply. Thus we might hope for an accurate estimate from altimeter data (because Hs and Tz are thought to be reliable), but a SAR derived estimate would only refer to long wavelength waves.

Wave (Group) Speed: C_g

A wave speed parameter can be estimated directly from the relation $c_g = gt / 4\pi$. As above, such a parameter has not been tested before and so careful validation would be required before any operational application. Again, we recommend an initial evaluation is carried out within this project.

We would anticipate that this parameter is derived from T_p , so we might anticipate difficulty in gaining an accurate estimate from altimeter data, but perhaps more success (in the case of long wavelengths) from SAR data.

2-D Spectrum: E(□,□)

A 2D spectrum is available from the ERS and ENVISAT wave mode, and from the BOOST SARtool analysis of SAR imagery. In the case of the ERS wave mode, there is a 180° ambiguity on the retrieved spectrum. As identified above, only the long wavelength part of the spectrum is sensed.

Grading for HSE Application

In Table 3 we assign "grades" to each parameter, from each EO data source, based on the team's experience , a review of the most up to date literature and reports, and the evaluation carried out in WP 1.4 The "grading" scale (see below) was adapted from a suggestion by HSE, to aid identification of data sets which could be adopted immediately in a wave conditions monitoring application (grades 1 and 2), or which showed a potential capability for such applications if certain issues were addressed (grades 2 and 3).

We have graded separately measurements for Near Real Time (NRT) and statistical analysis applications as different sampling regimes are preferred, and different levels of accuracy may be acceptable. We have not, at this stage, discussed how measurements from different instruments may be combined. It should be remembered that for NRT applications, a NRT data stream throughout the whole processing chain from satellite to end-product must be provided – we have not included a consideration of the availability (or otherwise) of such NRT processing chains in the allocations of grades.

We have considered two applications packages that are available for the processing and analysis of SAR images: the QinetiQ MaST package which can provide estimates of peak wave length (period) and direction (with 180° ambiguity); and the "BOOST" SARtool which can provide a full 2-D spectra (given a single look complex image). As we have established in the previous discussions within this report both of these techniques provide information on long wavelength waves only. Validation programmes for the ENVISAT ASAR indicate that the part of the wave spectrum with wavelengths between 8 and 15 s is most accurately sensed. It should also be recalled that there will usually be different wavelength "cut-offs" in the along track (azimuth) and across track (range) directions.

HSE "Grade"

1 – Satellite can satisfy requirements with no supplementary data
2 – Satellite major source but other data required to derive estimates
3 – Other source more important, EO data can play important validation – quality control function
4 – With present state of the art satellite data cannot make useful estimate

2,3 are further sub-divided to identify issues that could be addressed to achieve a wider application

- a – no major issue – other sources better suited
- b – limited accuracy (including application according to environmental conditions)
- c – limited spatial sampling (i.e. better resolution in space required)
- d – limited temporal sampling (i.e. more frequent revisits a priority)
- e – algorithm development required

References for Table 3: [1]Challenor and Cotton, (2001), [2]Johnsen et al., (2003), [3]Gommenginger et al (2003).

Table 3 Evaluation of the capability of EO instrumentation to provide measurements of the identified wave parameters.

Parameter	Satellite Source	Validated accuracy	Limitations	Sampling in “Area of Interest”	Need for external data	Grade Stats / NRT
Significant wave height	Altimeter Hs (Ku)	rrms[1]< 0.3m Validated for 0 - 12m	No known environmental dependencies Values 7-20km from coast	At present 4 satellites 8 passes in total per day in AOI Along track resolution 7km	In situ for validation Models for better NRT coverage	1 / 3d
	(A)SAR: 2-D spectrum & wave mode	For ASAR wave mode rms^2 = 0.8m (0.6m if T > 12s)	Only for □ > 100m. Overestimates wave height at low wind speeds, “deviation” at higher wind speeds	Wave Mode (WM): ENVISAT ~ 1-2 passes per day Image Mode (IM): ENVISAT, ERS-2 and RadarSat 3-6 passes / day	In situ for validation Models for better NRT coverage	3bc / 3bd
	MaST	Not available				-
Wave period (zero upcrossing - Tz, or “mean” period, Tm	Altimeter (Hs and □0)	rrms[3] ~0. 8s	Performs better for wind sea than swell	4 sats: 8 passes per day Along track resolution 7km	In situ for validation Models for better NRT coverage	2e / 3d
	(A)SAR: 2-D spectrum & WM	For ASAR wave mode rms^2 = 1.7s, bias ~ 1s. (rms = 1.1 s T > 12s)	Only for □ > 100m. Bias (~ 1s)	WM: 1-2 passes per day IM: 3-6 passes / day	In situ for validation Models for better coverage	2bc / 3d
	MaST	Not available				-
Wave period (peak - Tp)	Altimeter (Hs and □0)	Limited validation indicates rrms[3] = 3.1s (1.7s for wind sea)	Difficulties in validation against buoy data. Tp algorithm requires further development	4 sats: 8 passes per day Along track resolution 7km	In situ and models for validation Models for better coverage	3be / 3bde
	(A)SAR: 2-D spectrum & WM	For ASAR wave mode rms^2 = 3.1s	Only for □ > 100m. SAR should provide better estimates of Tp?	WM: 1-2 passes per day IM: 3-6 passes / day	Models and in situ for validation Models for better coverage	2bc / 3d
	MaST		Only for □ > 100m.	3-6 passes / day	Models and in situ for validation Models for better coverage	2bc / 3d
Wave steepness = f(Hs/Tz^2)	Altimeter	Not tested	“Significant steepness” calculated from ratio of Hs and Tz^2, *but not validated*.	4 sats: 8 passes per day Along track resolution 7km	In situ and models for validation.	3ce / 3de
	(A)SAR: 2-D spectrum & WM	Not tested	Only for Wavelengths > 100m.	WM: 1-2 passes per day IM: 3-6 passes / day	In situ and models for validation	3ce/ 3de
	MaST	Not available				-
Wave speed, group speed, cg = g□/4□	Altimeter: f(T)	Not tested	Group speed, cg = g□/4□, *not validated*.	4 sats: 8 passes per day Along track resolution 7km	Models, in situ for validation.	3e / 3de
	(A)SAR: 2-D spectrum & WM	Not tested	Only for □ > 100m,	WM: 1-2 passes per day IM: 3-6 passes / day	Models, in situ for validation.	3ce/ 3de
	MaST		Only for □ > 100m.	3-6 passes / day	Models, in situ for validation Models for better coverage	3ce / 3de
Wave dirn spectrum	Altimeter	Not available				-
	(A)SAR: 2-D spectrum & WM	ASAR wave mode rms^2 = 1.0 rads for $□_{mean}$ and $□_{peak}$	Only for □ > 100m.	WM: 1-2 passes per day IM: 3-6 passes / day	Models, in situ for validation, & to resolve 180° ambiguity for ERS-2 Models for better coverage	2bc / 3bd
	MaST		Only for □ > 100m. Peak direction and wavelength only (not full spectrum)	3-6 passes / day	Models, in situ for validation Models for better coverage	2bc / 3bd

5 WP 1.4 PROCESSING CHAIN FOR EO WAVE PARAMETERS EXAMPLES OF DATA PRODUCTS AND EVALUATION

5.1 INTRODUCTION

The objectives of this Work Package were to specify and demonstrate the EO data processing chains, required to derive the requested wave parameters from EO data.

For the these initial demonstration products we have focussed on the area 60°-62°N, 2°-8°W (the Shetland – Faroes channel), to take advantage of the availability of directional *in situ* wave data from the Faroes directional wave-rider buoy (Figure 18).

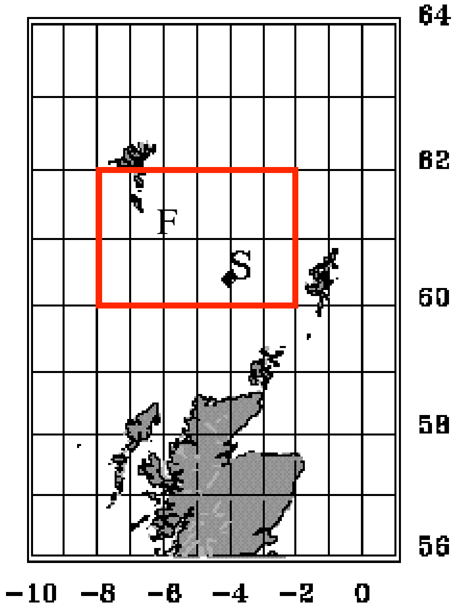


Figure 19 Area of interest, with proposed area for demonstration data set highlighted, and location of Schiehallion FPSO (“S”), and Faroes Wave-Rider (“F”)

Specific aims were to:
Generate a representative set of EO derived estimates of requested wave parameters.
Validate and evaluate EO derived estimates of wave parameters through comparison against available in-situ and model data.
Inter-compare altimeter, SAR image mode, and SAR wave mode data.
Provide demonstrations of statistical analyses (based on archived altimeter data) and an example of possible Near Real Time presentation of data.

In addition we provided an assessment of the spatial and temporal scales of variability of wave fields in the Faroes-Shetland Channel region, to help establish how representative the wave measurements from the Faroes buoy are of general conditions in the Faroes-Shetland Channel region.

5.2 SUMMARY OF EO DATA

Four short example data sets were produced, two from satellite altimeter data and one each from SAR Image Mode and SAR Wave Mode data.

5.2.1 Altimeter Data

For Demonstration Statistical Analysis

Altimeter data used for the demonstration of climate statistics consisted of off-line 1 Hz records from the Ku-altimeters in the area outlined in Figure 9 from 4 satellites, for the periods shown in Table 4.

Table 4 Sources of altimeter data for statistical analysis

Satellite	*Start date*	*End date*	*No. of 1 Hz records*
ERS-2 (OPR[7])	29 April 1995	17 May 2004	43662
Envisat	13 January 2003	12 April 2004	5123
Jason	15 January 2002	27 April 2004	13212
TOPEX	20 January 1993	27 April 2004	79818

Parameters generated and analysed were significant wave height, 10m ocean wind speed, zero upcrossing wave period, peak wave period, significant steepness and wave phase speed.

Along Track Data.

Altimeter ERS-2 (Fast Delivery), ENVISAT, TOPEX, JASON-1 and Geosat Follow-On data were retrieved for times within +/- 12 hours of the SAR image data that were processed as part of this study (see below), in an area 20°W to 10°E and 56°-64°N (see Table 5). Parameters generated at 1Hz resolution (~7km long track separation) were significant wave height, 10m ocean wind speed, Zero Up-crossing wave period, Peak wave period, significant steepness and wave phase speed.

Table 5 ERS-2 SAR Scenes extracted by QinetiQ

Date	*Time*	*Area of Interest*	*Orbit*	*Frame*	*A/D*
09/04/02	22:13	Waverider	36442	1233	Ascending
07/07/02	22:16	Waverider	37716	1233	Ascending
31/05/03	22:07	K7	42411	1197	Ascending
03/06/03	22:14	Waverider	42454	1233	Ascending
19/06/03	22:10	K7	42683	1197	Ascending
31/08/03	22:17	Waverider	43728	1233	Ascending
18/05/04	22:13	Waverider	47464	1233	Ascending
27/07/04	22:14	Waverider	48466	1233	Ascending

5.2.2 SAR Image Data

8 Scenes were extracted from the West Freugh satellite SAR archive (Table 5), and .PRI images generated. These 8 scenes were processed using the QinetiQ MaST application to extract wave speed (and hence period, wavelength, and group velocity), and direction, at a user defined resolution across the scene.

One of these scenes (for 07/07/20002) was processed to .SLC format and sent to BOOST for processing with SARtool. As discussed, this tool can extract gridded 2-D swell spectra, significant wave height, peak and mean direction, peak wavelength (and hence derived

[7] *"OPR" – Ocean PRoduct – The "offline" ERS-2 altimeter product.*

significant steepness and wave velocity). These were again provided at a user-defined resolution across the scene.

5.2.3 ENVISAT ASAR Wave Mode Data

All available ENVISAT ASAR Wave Mode pass files which contained data within the region 52°-68N, 20°W-10°E for September and October 2004 were extracted from the ESA fast delivery data stream and processed.

In addition archived ENVISAT ASAR Wave mode data that were available within the region of interest for 3 of the dates on which ERS-2 SAR images were requested and provided though ESA. The ASAR wave mode level 2 data provide estimates of the 2-D swell spectrum, significant wave height, peak period, and peak direction

5.3 DATA FOR VALIDATION AND EVALUATION

5.3.1 Faroes Directional Wave Rider data

The Faroes Oil Industry Group, FOIB, has installed and operate a buoy to the South of the Faroes (See Section 3.1). Through FOIB SOS acquired CDs containing historical data from 10 February 1999 to 13 February 2004.
The buoy data were processed to generate monthly statistics and directional spectra and derived parameters for comparison against the ERS-2 SAR images. Carter (2004) provides a technical report.

5.3.2 Wave Model Output

Danish Meteorological Institute (DMI) Archived Nowcast Data

The Danish Meteorological Institute (DMI) provided archived wave model nowcast data for the dates and times of the processed SAR images. The DMI wave model domain covers the North Sea, North Atlantic, Baltic Sea and Mediterranean Sea.
Parameters were: significant wave height, mean wave period, peak wave period, mean wave direction, swell height, swell direction, swell period and Charnock Number.

KNMI (Royal Netherlands Meteorological Institute) WAM ERA40 Global Wave Climatology)

KNMI have generated a 45 year global wave climatology, forcing their global WAM wave model with the ECMWF[8] "40 year" reanalysis wind fields ("ERA-40). Data were extracted to allow comparison of monthly statistics from the buoy and altimeter data with the long-term model based climatology.

5.4 SATELLITE ALTIMETER DATA PROCESSING CHAIN

Altimeter Data for Climate Analysis

Altimeter data for climate analysis were retrieved from the Satellite Observing Systems' WAVSAT database. The data extraction program applies validation checks on the 1Hz records, developed over the years to remove the bulk of dubious values.
The median wave height and wind speed from each transect of a 1° x 1° area was then extracted (where there are at least 5 'good' 1Hz records), and used as the basis for analysis.

[8] *ECMWF- European Centre for Medium Range Weather Forecasting*

Calibration

From comparisons with buoy measurements, it has been found that in most cases relatively small linear corrections are needed to get agreement in significant wave height (Hs) and wind speed estimates between altimeter and buoy values. The corrections depend upon the altimeter, and are described in the WP 1.4 report (Cotton et al., 2004).

Along Track Data

"Along track" ENVISAT, TOPEX , Jason-1, Geosat Follow-On and ERS-2 (Fast Delivery) data were extracted for the days on which QinetiQ SAR imagery was available .

Calculation of Derived Products

Wind speed

In most cases altimeter wind speed is calculated from the σ^0 value, using an algorithm derived by Witter & Chelton (1991). The exception is Jason, winds from this altimeter are estimated from an algorithm involving σ^0 and Hs developed by Gourrion *et al* (2002). In all cases the σ^0 values are adjusted to match the climate values measured by Geosat.

Wave periods

Zero-upcrossing period and spectral frequency peak period were calculated using the algorithm given by Gommenginger *et a*l (2003)

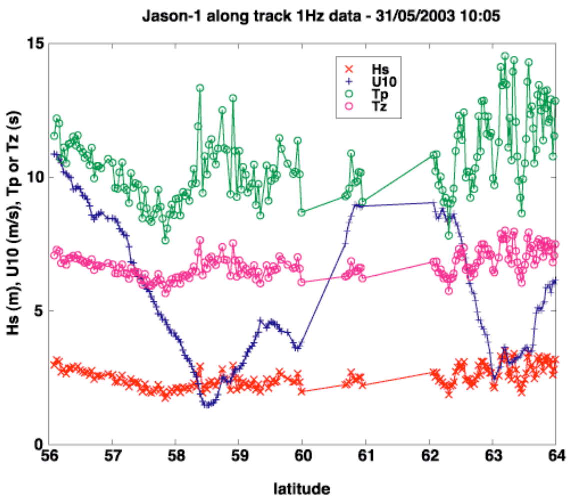


Figure 20 Example of Jason-1 Data –Hs, U10, Tp and Tz plotted against latitude. The Jason track crosses land between 60°-61°, and 61°-62° (see Figure 21)

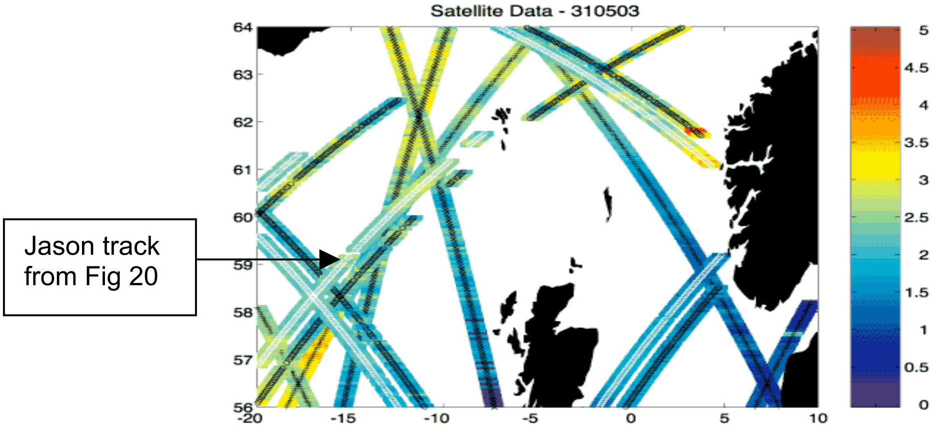


Figure 21 Map plot of altimeter Hs data for all available data within +/- 12 hours of 22:00 on 31/05/2004 – colour scale to right of plot. Different satellites are represented by different symbols at the centre of the coloured bars: GFO – black '+', JASON – black 'o', TOPEX – white 'o' and ENVISAT – black 'x').

Examples of Along Track Altimeter Data

The along track altimeter data (significant wave height, wind speed, wave period) and further derived parameters (wave steepness, wave speed) can be presented in a number of ways. Here we demonstrate 2 forms of presentation, a simple line plot against latitude (Figure 20), and on a map, with the value of significant wave height colour coded (Figure 21). Figure 21 also demonstrates the coverage presently available from altimeters in a 24 hour period.

5.5 SATELLITE SYNTHETIC APERTURE RADAR PROCESSING CHAIN

5.5.1 Satellite Synthetic Aperture Radar Image Mode Processing Chain

Retrieval of Images

The West Freugh data archive was searched for ERS-2 images acquired since 2002. Attention was focused to two areas that fell within the main AOI:

- Waverider Buoy at 61.3°N, 6.3°W
- UKMO K7 Buoy at 60.7°N, 4.5°W

8 ERS-2 images were identified from the archive, and retrieved from W Freugh. One of these was processed to .SLC format and sent to BOOST for processing with their SARtool.

Data Processing in MaST

Processing of the ERS-2 SAR image data with MaST was carried out iteratively to determine the most effective and universal set of parameters that could be achieved.

The time taken to process an image is largely dependent upon the factor at which the image is processed. All bar one of the SAR images were processed at Factor 2 (the other at Factor 4) and this took approximately 45 seconds. Post-processing, a Jpeg was saved for both the plain (original) image and the target image. The target list was copied and pasted into a .txt file in a tab delimited format, allowing the data to be later opened in MS excel.

Automation of the SAR Processing Chain

Automation of the SAR processing chain would significantly reduce the requirement for user intervention. An automated approach has been tested and successfully used for ship detection using MaST and a similar approach for wave detection could be implemented.

Examples of Wave Parameter Output from MaST

Figures 22 gives a demonstration of the output from the MaST application. The tool can identify a number of wave trains in each cell. It calculates a wave speed, which can easily be converted into a wave period, through equation (1):

$$T_p = 4\pi . c_g / g \quad (1)$$

and thence to wave length through the dispersion relation

$$\lambda = g.T_p^2 / 2\pi . \quad (2)$$

Note that the MaST application is not able to provide an estimate of significant wave height, or of the energy in different frequency bands and directions. In its present configuration the application is not able to resolve a 180° ambiguity in the wave direction, and the tool defaults to select the wave direction pointing towards the closest land.

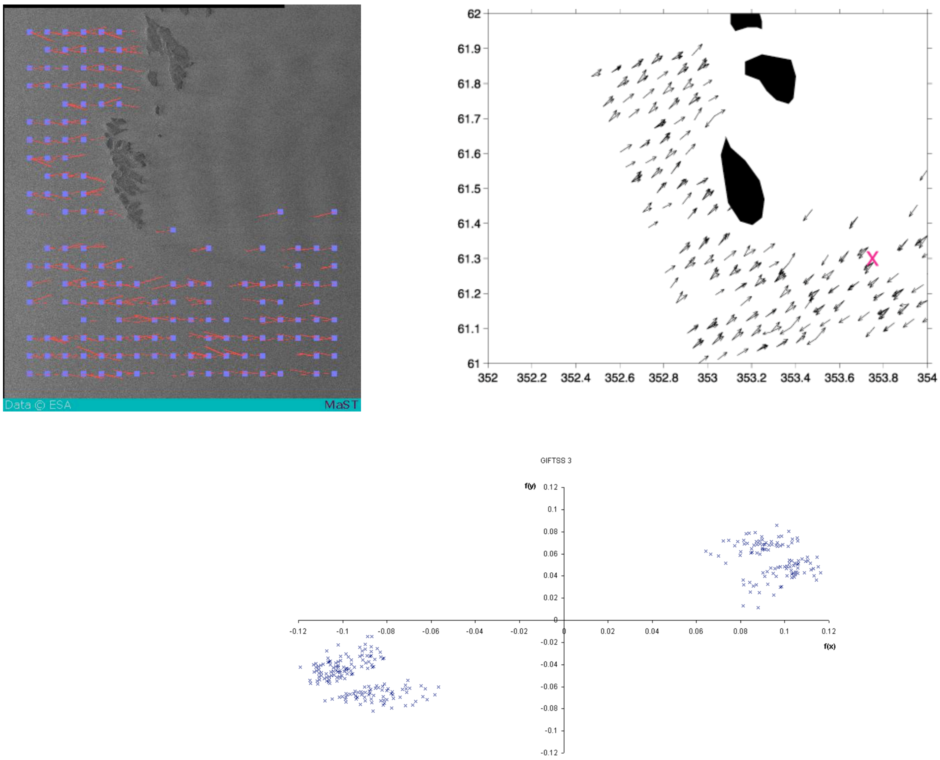


Figure 22 Processed SAR Image for 09/04/2002 22:13:20: Top left – Raw output from MaST, Top right – Extracted wave vectors replotted as Time, and on a true lat-long grid to give true direction, bottom – polar plot of Frequency and direction of resolved wave vectors

The first panel of Figure 22 shows the overlay image as output direct from the MaST processor (the red bars indicated direction and wave speed, the blue dots the centre of each cell), the second panel shows the analysed data re-plotted on a true lat/long, with the wave speed converted to wave period, and the third panel gives a polar plot representation of the extracted wave vectors, plotted as direction against frequency. Note that the image in the first panel is distorted to form the shape displayed, and so the directions indicated are not the true directions (they are accurately depicted in the second panel). The magenta cross on panel 2 marks the location of the FOIB buoy.

On Figure 22 one can see that the default selection of direction towards the nearest land leads to a (probably) unrealistic representation of the true wave direction for the cells lying to the east of the Faroe Islands. This leads to a split distribution in the polar plot (again probably not realistic).

Note that some cells display multiple solutions. This may represent the true situation on the ocean surface, with waves coming from different directions and with different wavelengths.

BOOST Application

A single (.SLC format) scene was sent to BOOST for processing on their SARtool application. Their technique resolves the 180° directional ambiguity and is also able to extract energy levels associated with the resolved wave fields, and so can provide an estimate of significant wave height, as well as wave direction and wave length.

After initial setup it takes roughly half a day to process each image. The application is configured primarily to provide high-resolution coastal wind and wave fields, and it is understood that an external estimate of wind direction is necessary to allow wind speeds to be determined. The wave field is determined independently of any external information – apart from bottom topography, which is used in the image set up procedure.

This application thus allows the potential extraction of addition information (significant wave height) not presently available through MaST, and resolves the 180° directional ambiguity. The costs are higher than MaST, reflecting the time required in the initial setup procedure, because the scheme is configured to provide high resolution coastal information.

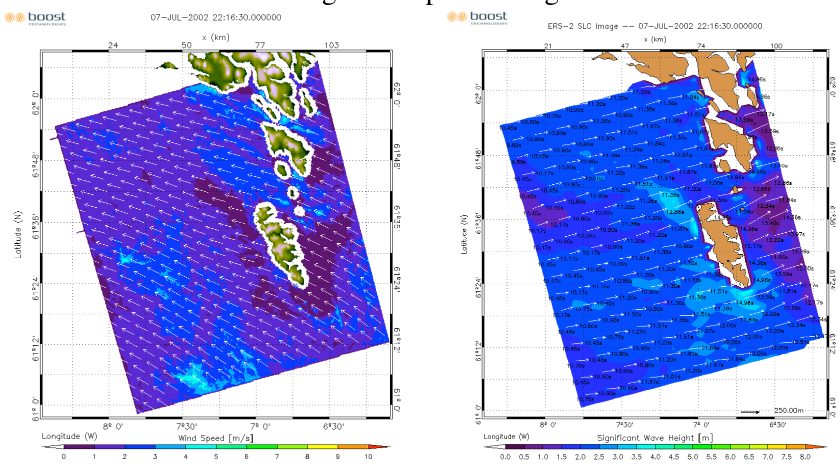


Figure 23 Output from BOOST SarTool for the 07/07/2002 ERS-2 SAR image. Left Panel surface wind speed and direction (wind speed key below the figure), right panel wave period and direction (colour key below each panel).

Generating a Climatology from SAR image data

It would be possible in principle to build a directional (long wavelength) climatology based on SAR image data. This climatology could give frequency of occurrence in selected directional sectors, and also directional occurrence statistics against wavelength. Analysis should take into account the large annual cycle, and ideally a separate analysis provided for each calendar month. The exact methodology would depend on the required application –

offshore or coastal. For offshore climatologies it would probably be most efficient to extract a subset of representative information from each processed scene, and then to compile information over a period of time , sufficiently long to support a reliable statistical analysis.

A number of factors come into consideration:

- How to deal with any 180° ambiguity (from MaST)?
- How to identify the most significant wave vectors?
- How to select representative values?
- How to deal in the statistical analysis of the restricted wind speed window within which SAR data can be used to acquire wave information?
- How to deal with the asymmetric lower cut-off wavelengths in the along track (azimuth) and across track (range) directions.

Of course, all climatologies have their limitations, and a SAR based climatology should not be dismissed purely on account of the above issues. Indeed a SAR climatology could provide valuable information on swell wavelength and direction –especially important for large floating oil and gas production platforms.

To our knowledge nobody to date has attempted to build an offshore wave climatology from SAR image data. It is suggested that the best way forward may be through a pragmatic empirical approach. Analysis of a number of SAR images could be used be to build a short but representative data set, and statistics derived from this data set then compared with those available from other sources (directional wave buoys, wave models).

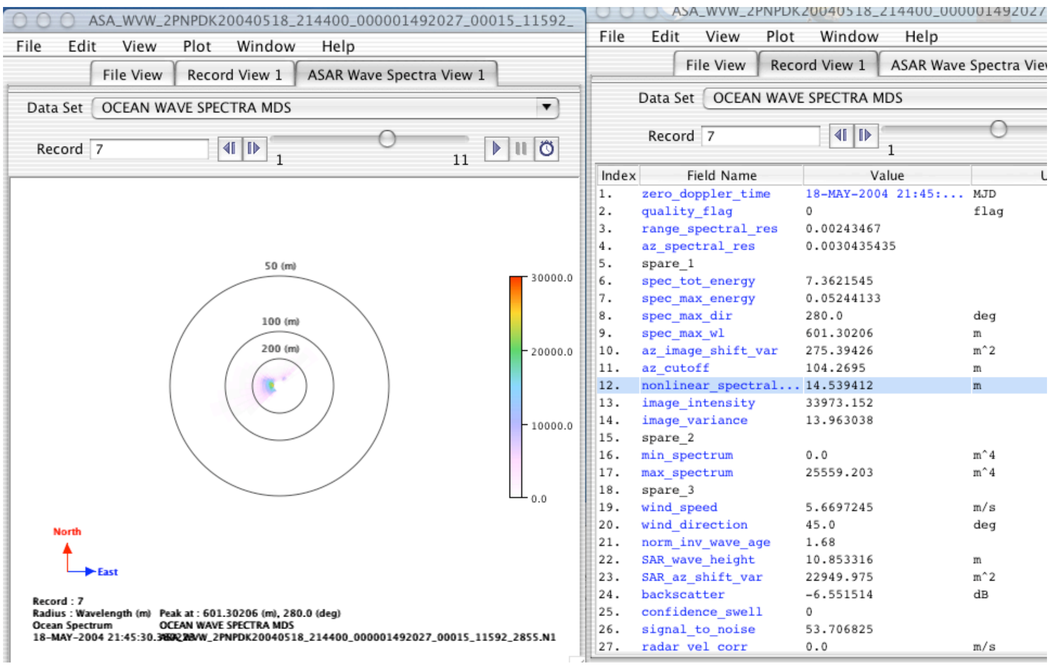


Figure 24 ENVISAT ASAR wave mode "level 2" data for 18/05/2004

5.5.2 Satellite Synthetic Aperture Radar Wave Mode Processing Chain

The ESA ENVISAT ASAR wave mode "level 2" wave spectrum product provides a directional wave spectrum as energy levels in 24 wavelength and 36 direction bins. It also provides an estimate of significant wave height, peak wavelength and wind speed. This product is the standard ESA wave mode ocean product as available in the Near Real Time and “offline” data sets. Figure 24 demonstrates the presentation of SAR wave mode data that is provided through the ESA ENVIVIEW tool.

A Near Real Time operational processing chain would include daily extraction of ASAR wave mode level 2 data from the ESA Near Real Time “Meteo” data stream – through an automated ftp pull shell script. The same shell script would call (e.g. perl) routines to identify the locations of the retrieved data and then process any data within the Area of Interest to produce ASCII or XML files. Earlier versions of such a process implemented at Satellite Observing Systems were run twice daily, with a maximum of 10 minutes entire processing time.

5.5.3 Generating a Climatology from SAR wave mode data

ASAR wave mode data could be used to build a directional (long wavelength) climatology. A particular problem affecting our region of interest is that it has received less sampling from ERS-1 and ERS-2 SAR wave mode than other areas due to instrument mode conflicts. Our Area of Interest is now sampled by ENVISAT ASAR wave mode – but only 2 years data are available, to date processed by a number of different versions of processing software.

An ASAR wave mode based climatology could take a similar form to that proposed for SAR image data. However, it would be possible to add in an extra important variables through the availability of (swell) significant wave height. As for the SAR image mode data, the ASAR wave mode information relates to long wavelengths only, and analysis must bear in mind the impact of the limited range of wind conditions within which wave information can be reliably extracted (and the asymmetric wavelength cut-off).

The main issues impeding the development of such a climatology are the limited period of availability of data (since 2002 only), the inhomogeneity of the data set so far available (though reprocessing is planned by ESA starting early in 2005), and problems in establishing suitable quality control criteria for the user to apply[9].

5.6 ALTIMETER WAVE CLIMATOLOGY

A limited climate data set, derived from altimeter data only, was generated to illustrate the scope and style of products that could be set up in Phase 2.

A pronounced feature of the wave climate off Scotland is the within-year variability, with a large annual cycle. So for most purposes, such as planning operations or investigating whether conditions are particularly severe for the time of year, this cycle has to be taken into account. This is generally achieved approximately by presenting statistics for each of the 12 calendar months - and this is what has been done for the demonstrator. (Sometimes all the data are analysed together, for example when estimating the 100-year return value.)

However, this division into 12 months can result in too few data numbers for useful estimates. Figure 25 shows the number of medians (i.e. to the number of transects with at least five 1 Hz records) in the demonstrator for each 1° bin for January. Note the significant reduction in the number for the bin containing the Faroes.) This gives a useful estimate of the January mean Hs (with a standard error of 0.1 ~ 0.2 m - calculated assuming the data are independent) but only poor estimates of the parameter distributions, for example, of wave period - see Figure 26.

[9] *Now addressed, see Johnsen (2005)*

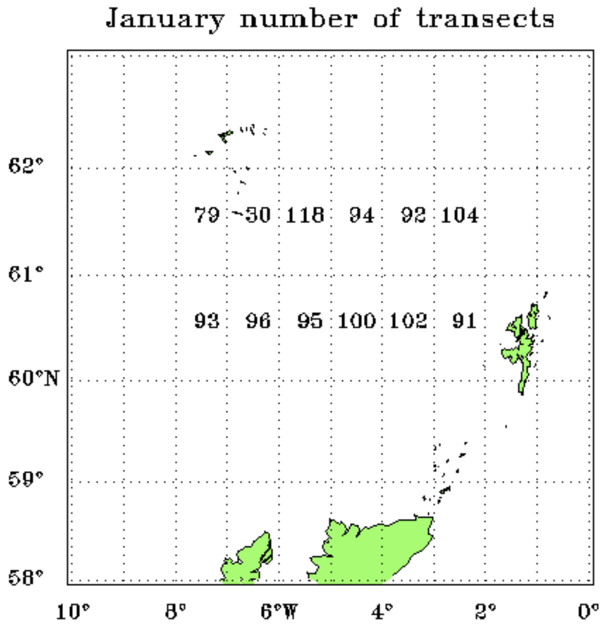


Figure 25 Number of medians in each 1° bin during January.

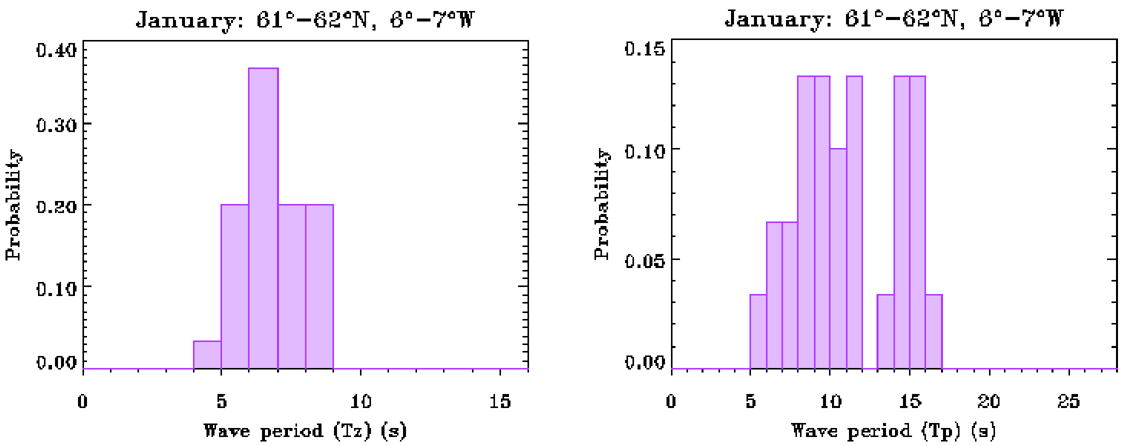


Figure 26 Distributions of Tz and Tp during January near the Faroes.

This shortage of data is clearly seen in scatterplots, for example of Hs:Tz. These are normally presented as parts per thousand in 0.5 m by 0.5 second boxes, but with so few values (N=373), the data are better described by the individual counts in each box - Figure 27. The method seems fairly robust, providing we remain within the range of the bulk of data; i.e. providing that we are interpolating and not extrapolating. Estimates of 0.1%ile or of the 50-year return value should not be extracted without at least a visual inspection of the goodness of fit of the log-normal distribution.

The lack of data would be easier to cope with if we knew the statistical distribution from which the data were drawn. Unfortunately we do not. However, Hs values for any calendar month do appear to have roughly a 2-parameter log-normal distribution. The values of the two parameters can be estimated from the mean and standard deviation of the data. Then, say the upper 10%ile of Hs for the month can readily be calculated. This was the technique used to produce the results shown in Figure 28.

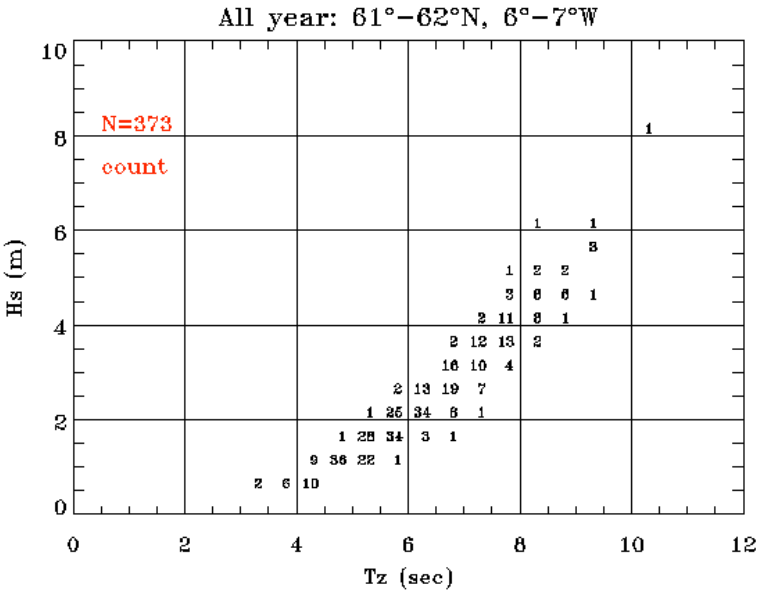


Figure 27 Wave height: Wave period scatterplot (count of observations).

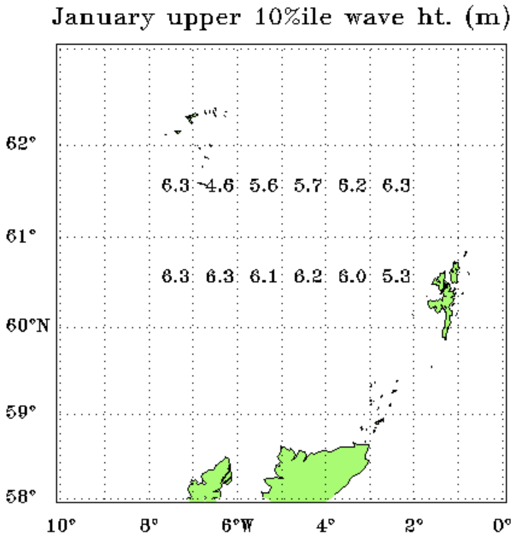


Figure 28 Significant wave height exceeded for 10% of the time during January.

The nadir-looking satellite altimeter does not measure any directional information, but as an example we provide an example of how directional wave data can be presented within a climate analysis (figure 29). These data are from the FOIB waverider. In principle, if the SAR data were thought to be sufficiently reliable and accurate, and a suitably long time series of data were available, it should be possible to generate similar analyses for long period, swell waves.

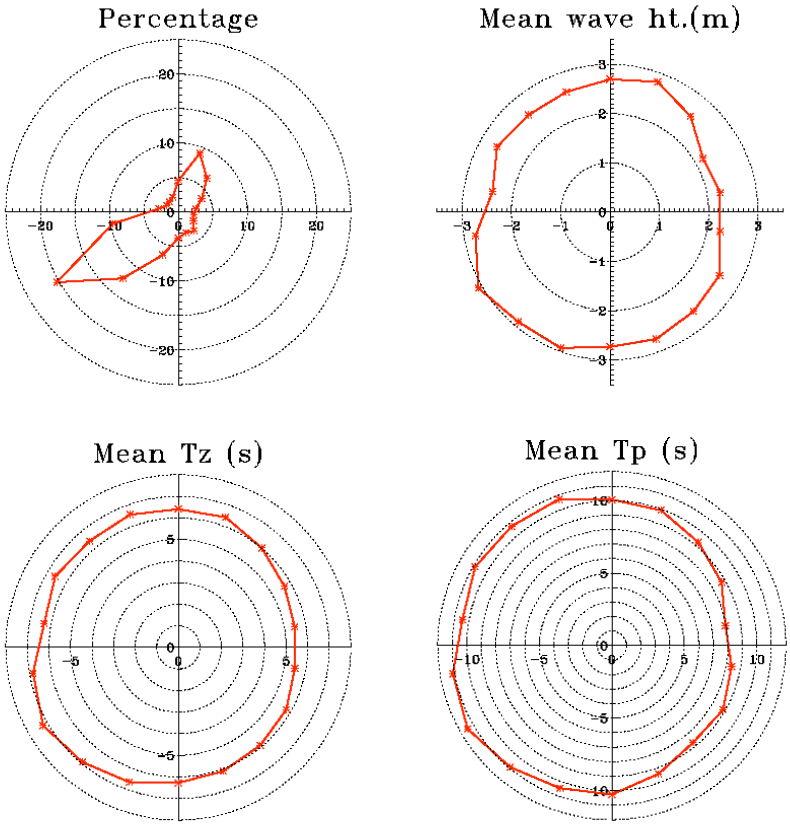


Figure 29 Presentations of directional wave measurements from the FOIB buoy measurements, Top left- Percentage of observations with waves from the indicated direction. (Data in 20° bins, with true North vertically up.), Top Right – Mean all year Hs from various directions. Bottom Left – Mean Tz from various directions. Bottom Right – Mean Tp from various directions.

Web Site Demonstrator (http://www/satobsys.co.uk/Private/giftss_demo)
Example statistics were made available through a web-site demonstrator. For this demonstration each display (or .gif) had to be prepared in advance and linked to the web site. A more sophisticated approach would be to connect the demonstrator to the SOS database, so that the data could be extracted and analysed to provide the user with his required statistics upon request. Such an approach would allow statistics to be more easily updated and, once established, it could be easier to add additional procedures and presentations. The GIFTSS Project might determine whether there is sufficient demand for such an on-line facility to justify its development.

Figures 25-28 have been taken from the demonstrator.

5.7 NEAR REAL TIME PRESENTATIONS OF DATA

In this section we show some possible presentations of satellite data for near real time application. In the first example (figure 30), altimeter and ASAR wave mode data are colour scaled and overlaid on the DMI nowcast model fields. Altimeter data are all the available data within +/- 6 hours of the model nowcast time 22:00 UTC on the 19th June 2003, the ENVISAT ASAR wave mode data were taken at 22:10

In Figure 30 the altimeter data can be seen as the “strips” of colour passing up the left and (lower) right hand sides of the images. The ASAR wave mode data are presented in four “boxes” moving from the north of Scotland to the East of the Faroe Islands. The larger box indicates the position of SAR image mode data that have been extracted for the same time.

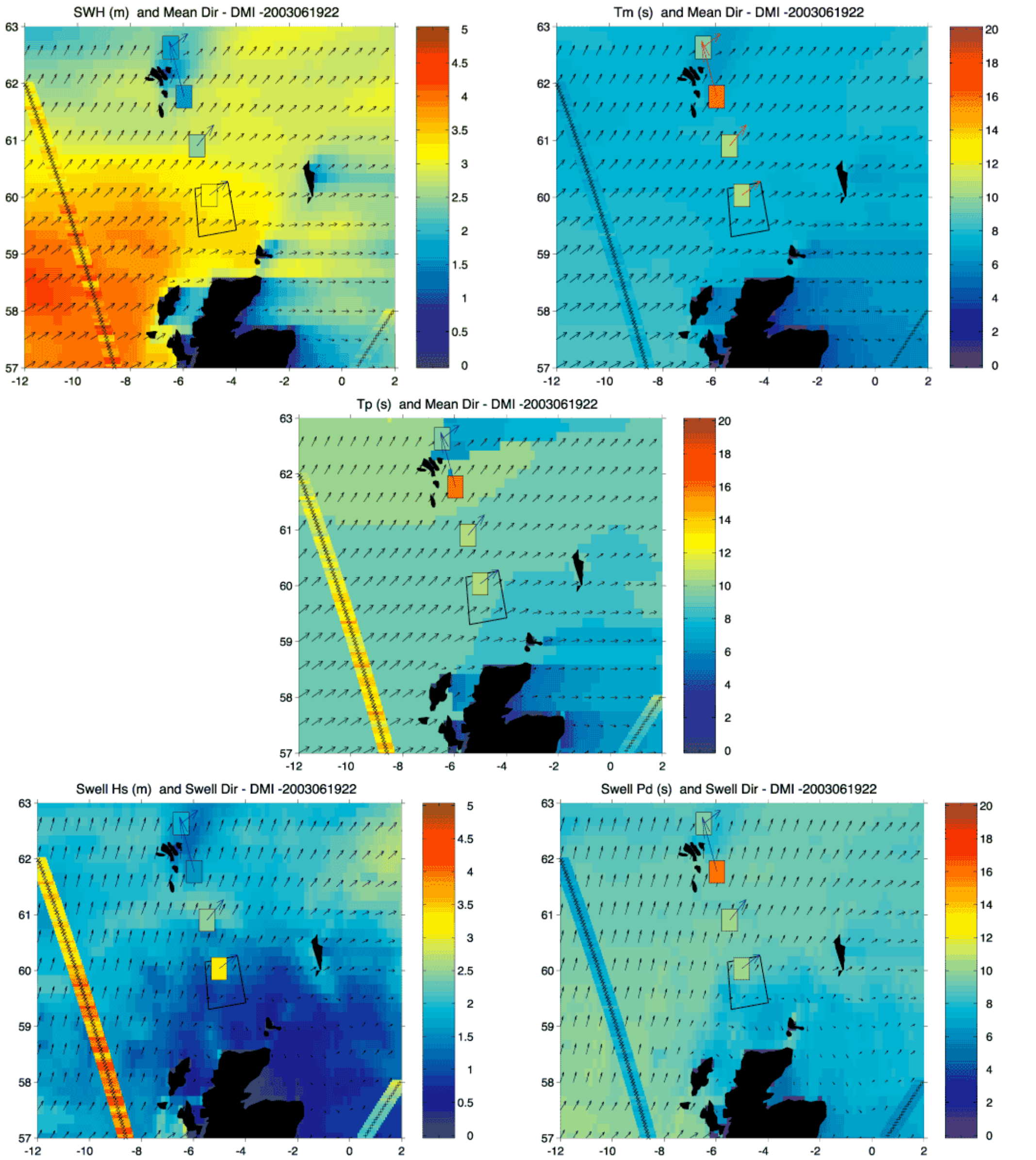


Figure 30 Example of possible Near Real Time Presentation of altimeter, ASAR wave mode and model wave data, for 22:00 on 19/06/2003. Top left- Model Hs and altimeter Hs, and ASAR wave mode Hs and peak direction. Top Right – model mean period, altimeter Tz and ASAR peak period. Middle – model, altimeter and ASAR peak period. Bottom left – model swell Hs, altimeter Hs and ASAR Hs. Bottom right model swell period, altimeter Tz, and ASAR peak period.

A number of important points should be noted:

- The ASAR data closest to the Faroes seems to be invalid. It gives a direction close to N, and an anomalously large period. It is possible the footprint of the SAR 'imagette" contains some land which would effect the analysis scheme.
- Significant Wave Height - Altimeter and model Hs are seen to be in good agreement (top left), but the ASAR wave mode Hs does not agree so well (bottom left). ASAR Hs agrees better with the swell significant wave height (as may be expected).
- Mean Direction and Swell Direction– There is little difference in this case between model mean direction and swell direction. The ASAR directions agree well with both.
- Mean, Peak and swell period – The model mean period and altimeter zero up-crossing period are seen to be in good agreement (top right). The ASAR "peak" period agrees best with the model swell period (central panel and bottom right).
- The ASAR swell Hs (bottom left panel) is too high. This can occur if the local wind speed is low.

Key points are:

- It is important to compare like with like, i.e altimeter Hs and model Hs, ASAR Hs and model swell Hs, altimeter Tz and model Tmean, ASAR Tpeak and model Tswell.
- Altimeter Tpeak does not at present compare well to the model fields (centre and bottom right panels.
- Better a priori quality control is required for ASAR wave mode data.

Figure 31 shows example output from the CAMMEO project, in which "layers" of satellite altimeter and scatterometer data are presented on an interactive web map server interface. This service is being developed under the European Space Agency's Earth Observation Market Development Programme, in a co-operation between the Norwegian Meteorological Office and Satellite Observing Systems.

The user can click to advance or move back through time, to select different data sets for display, to query individual data points, and to zoom in or out.

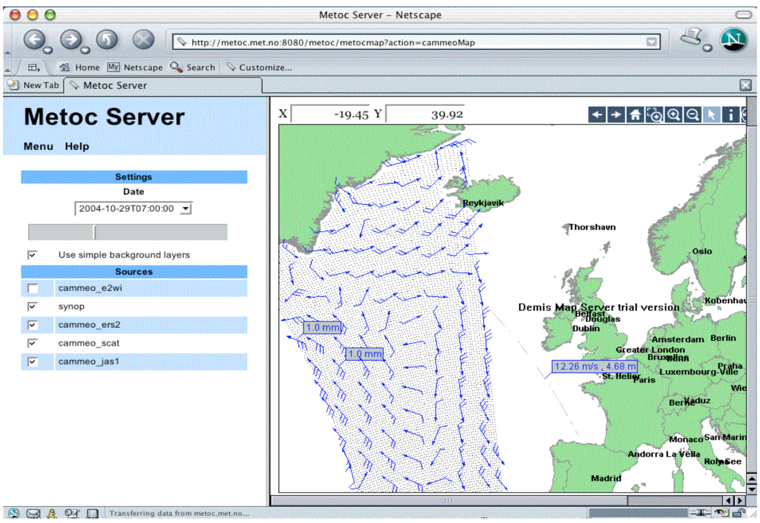


Figure 31 Example from CAMMEO web map server, with scatterometer data.

5.8 PRELIMINARY EVALUATION OF EO DATA

In this section we present a limited initial evaluation of the data sets that have been produced – this is beyond the strict scope of the Work Package 1.4 definition, but important to support the specification of a demonstration product for Phase 2 of the project.

5.8.1 Altimeter Data

The altimeter derived estimates of significant wave height and 10m ocean wind speed have been extensively validated (Woolf 2004b and references therein). The altimeter derived zero upcrossing wave period, Tz, has been shown to be accurate to better than 1s (Gommenginger et al, (2003). As has been discussed, peak wave period, Tp, is less easy to validate, at least partly because of the unstable nature of this parameter. With regard to altimeter derived estimates of wave steepness and wave speed, the issues are the lack of availability of reference data to validate these estimates against, and the reliability of the initial parameters from which these secondary values are derived – Hs and Tz in the case of wave steepness, and Tp in the case of wave speed.

Within this project we have been able to carry out an evaluation some of the altimeter products – through a comparison of individual data records against the Faroes buoy data, and a comparison of monthly mean values against buoy and KNMI model data.

TOPEX altimeter data are available near 61.24°N 6.1°W, within 12 km of the Faroes Waverider buoy at 61.3°N 6.28°W. Estimates of significant wave height (Hs), zero-upcross wave period (Tz) and spectral peak frequency period (Tp) from the Faroes buoy and the TOPEX altimeter were compared. The Hs and Tz values from the altimeter were not found to be significantly different from the measurements by the FOIB waverider buoy, but Tp did not show good agreement.

The monthly means of Hs from the different sources (altimeter, buoy and model) appear to agree well, especially when bearing in mind the different periods of time covered by the different data sets, and the fact that the altimeter and model data are averaged over larger regions, and the buoy data are for a single location only. The monthly mean wave periods (Tz, Tm) also show encouraging correlation – but such good correlation was not seen in the comparison of buoy and altimeter monthly mean peak period (See Woolf, 2004b, for more detail).

A technical note by David Carter provides a detailed comparison between Faroes buoy and altimeter derived monthly means (Carter 2004d). He found that the means from the buoy - in an exposed location to the South of the Faroes - are higher than those estimated from the altimeter data using the 1° 'square' immediately around the Faroes (61°-62°N, 6°-7°W), which includes some sheltered sea areas. Comparisons of altimeter data averaged over a more exposed area, 61°-62°N 4°-5°W, and from a larger area 60°-62°N 2°-8°W areas with the buoy means showed better agreement.

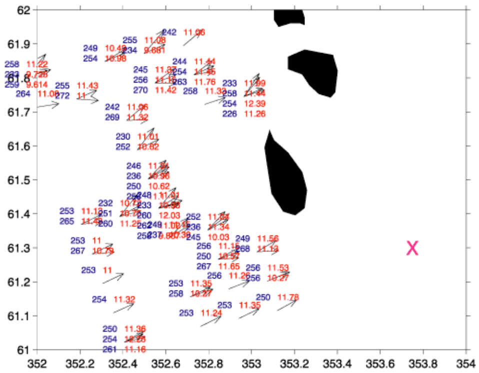
This result illustrates that a 1° 'square' can be too large an area for estimating wave climate at a specific, near-coastal location, whilst in open waters the climate can be statistically stationary over larger areas than 1° 'squares'.

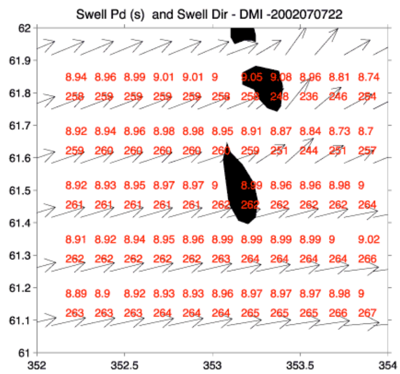
5.8.2 Preliminary Comparison of SAR, Model and Buoy Data

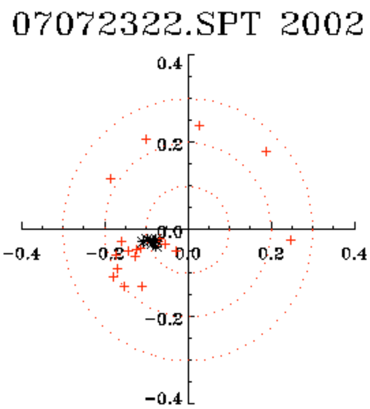
To date only a preliminary qualitative evaluation of the wave parameters derived from the ERS-2 SAR images has been possible. Below, we present one of a series of comparative plots of wave spectra from the Faroes Buoy, swell period and direction from the DMI wave model, and wave period and direction arrows derived from the SAR imagery.

Figure 32 compares the different data sources available for 07/07/2002. Table 6 gives approximate average estimates of wave parameters retrieved from the SAR image, the DMI nowcast model, the Faroes waverider buoy, and, where available, ENVISAT ASAR wave mode data.

In the case of the example in figure 32 we seem to get good quantitative agreement between all sources of data. All sources show swell direction from 250°-260°, the SAR estimated wave periods of 11.0-11.8s agree well with the buoy peak period of 11.8s (the model nowcast predicted slightly lower swell periods of ~9s). The analysis from the SARtool processing scheme (Figure 23) gave peak periods of 11.5-12.0 s, directions of 260° and significant wave height of 2.0-2.5 m. SARtool has been found to overestimate wave heights under low wind speed conditions, and BOOST plan to incorporate a calibration to take this factor into account.







H_s= 1.51m T_p=11.8s,
T_{02} = 7.41s Mean dir =260°

Figure 32 7th July 2002 22:00 UTC- ERS-2 SAR data (top left), DMI Wave model nowcast (top right) and Faroes Waverider Buoy spectra (bottom left) and buoy wave parameters (bottom left. ERS-2 SAR Wave period and direction are given in red and blue respectively. Model swell period and direction are given next to the respective arrows.

One should be careful of taking too much from these initial comparisons– noting in particular the limited range of conditions covered - with wave direction predominantly from the south-west and periods ranging between 8 and 15 s. A much more extensive study, covering a wider range of parameters would be required before it would be possible to generate estimates of errors in the wave parameters extracted from the SAR image data, and ENVISAT ASAR wave mode data.

Nonetheless we are able to note on a qualitative basis that there is an encouraging degree of consistency between the wave parameters extracted from the ERS-2 SAR images, the ENVISAT ASAR mode, the Faroes buoy spectra and the wave model nowcasts. This gives us confidence that the SAR data can be used to generate useful estimates of wavelength and direction of long wavelength waves in our area of interest.

Table 6 Summary of directional wave parameters retrieved from different data sets

Date	**SAR Image mode**		**SAR Wave Mode / *SARTool***			**Buoy Spectra**			**DMI wave model**		
	Tp (s)	**Dir (°)**	**Tp (s)**	**Dir pk (°)**	**Hs (m)**	**Tp / T02 (s)**	**Dir mean (°)**	**Hs (m)**	**Tp /Tsw (s)**	**Dir/ Dir sw (°)**	**Hs /Hs sw (m)**
09/04/02	8.5	240				10.5 / 5.98	241	2.1	9.23 / 9.28	253 / 264	2.9 / 2.5
07/07/02	10.5	250	*11.5*	*260*	*2.2*	11.8/7.41	260	1.5	10.2 / 9.0	262 /264	1.7 / 1.7
31/05/03	9-10	245				(8.3 / 6.67)	(253)	(2.8)	10.2 / 8.1	90 / 50	2.3 / 2.2
03/06/03	10-11	225				8.3 / -	90 / 230	1.8	11.0 / 9.0	90 /50	2.4 / 2.2
19/06/03	10-11	230	10.3	250	3.2	(10.5 / 6.45)	(236)	(3.2)	8.4 / 8.6	250 /240	2.9 / 2.4
31/08/03	14	250									
18/05/04	11	235	11.0	230	2.4	10.5 / 7.14	263	3.4	10.2 / 9.58	250 / 241	2.9 / 2.4
27/07/04	11-12	260							10.2 / -	280 / 280	1.9 / 1.9

Table 6 notes: SARTool wave parameters given in the ASAR wave mode column in italics for 07/07/2002. ASAR WM directions +180°.
On 03/06/2003 2 separate wave peaks are seen in the buoy spectrum at 8.3s and 5s, directions 230° and 90' respectively model is 17 hr forecast.

5.9 COMBINING ALTIMETER AND SAR WAVE INFORMATION

Section 7 of the WP 1.4 report (Cotton et al, 2004) discussed the issues related to the combination of wave information from different satellite data sets.

Four general approaches can be taken, two of which integrate the satellite data into model based services, and two in which the satellite data remain independent:

1. Assimilation of the satellite data into operational nowcast, forecast or hindcast wave models.
2. Use of satellite data to validate or calibrate wave models.
3. Direct combination of information from different satellite sources.
4. Combined presentation of separately sourced satellite data sets.

Approach 1) - is already implemented, in operational nowcast and forecast models (e.g. by ECMWF, Météo France), and this approach is also under test in the EDOWA project using the Météomer Hindcast model.

Approach 2) - has been taken to build the Eurowaves and WorldWaves services (Oceanor), and the Oceanweather hindcast model data base.

Approach 3) - is of interest, as it would provide a single source of (satellite-derived) data, independent of models and so capable of acting as independent verification. ARGOSS have taken this approach in using scatterometer data to force a single cell wave model and so produce the short wavelength wind-sea spectrum, which they have then combined with the long wavelength spectrum from SAR. However, to our knowledge nobody has tried to directly combine two independent sources of wave data gathered at times and places separated by intervals greater than the known time and length scales of wave field variability- except through the medium of a wave model (approach 1). In their climatologies, ARGOSS and Météomer offer wave statistics based on analyses of altimeter and SAR data – but the two sets of statistics are presented separately. Techniques do exist which could be used to combine the two data sets to enable the production of joint statistics, such as the use of simple propagation models, or the use of optimal interpolation techniques. Such approaches would however require some specific research (in particular to ascertain whether the bias introduced in the SAR data by the wind speed limitation on its data could be resolved). The application of these would lie beyond the range of this project. The project could make a recommendation to carry out such research, however, if the sponsors felt there was a strong argument to do so.

Approach 4) - the presentation of SAR and altimeter data separately, is certainly possible. An example of this type of presentation was demonstrated in Figure 30. This type of presentation allows the user to interpolate by eye between measurements made at different locations, evaluate the consistency between different data sources and so estimate a level of confidence in the information provided. Experience in use of data presented in this way could lead to an understanding of the conditions in which different data sets may be regarded as more reliable.

5.10 SAMPLING AND REQUIREMENTS FOR FURTHER DATA

5.10.1 Sampling and Grid Scales

Table 1 in section 2 summarised sampling available from ENVISAT for the altimeter and both SAR modes.

Altimeter Data

Figure 21 gives an indication of the availability of altimeter data from all presently operational satellites for a 24 hour period. Data from only 2 of these satellites (Jason and ENVISAT) are available in real time. Data from other satellites is available at a few days delay. Figure 25 shows an example of how many independent samples from satellite altimeter data are available for generating climate means on a 1° x 1° grid – between 80-100 for an open ocean region in a given calendar month over ~10 years. Note that the square directly over the Faroes buoy receives much less sampling.

SAR wave mode data

SAR wave mode data could be used to build a direction and wave length climatology of longer period waves – though possibly on a relatively coarse grid (larger than 2° x 2°). A specific problem for application of historical SAR wave mode data in our area of interest is that the operation of the active microwave instrument (AMI) on ERS-1 and ERS-2 meant that the SAR wave mode and SAR image mode could not operate at the same time. This had a significant impact on SAR wave mode coverage over the northern North Sea, though recent discussions with ECMWF have indicated that the impact over the North-Western Approaches may not be as severe as was originally thought. The ESA help desk has been contacted with a request for clarification of ERS-1 and ERS-2 wave mode coverage of this region, but we have not yet received a response.

One possibility is that SAR image mode data could be used to “fill in the gaps” during the periods, and over locations, when wave mode data are unavailable. By definition, ERS SAR image data should normally be available when the wave mode data are not.

The ASAR wave mode on ENVISAT can, however, operate at the same time as the image mode, and so better coverage is being provided in our area of interest. The main issue with ENVISAT ASAR wave mode is that the archive from 2002 onwards is not homogeneous, as the data processing software has been modified during the ENVISAT mission. Use of ENVISAT ASAR wave mode data for climatology would require the historical data set to be reprocessed. As noted above, we understand that this is planned at ESA, starting in January 2005.

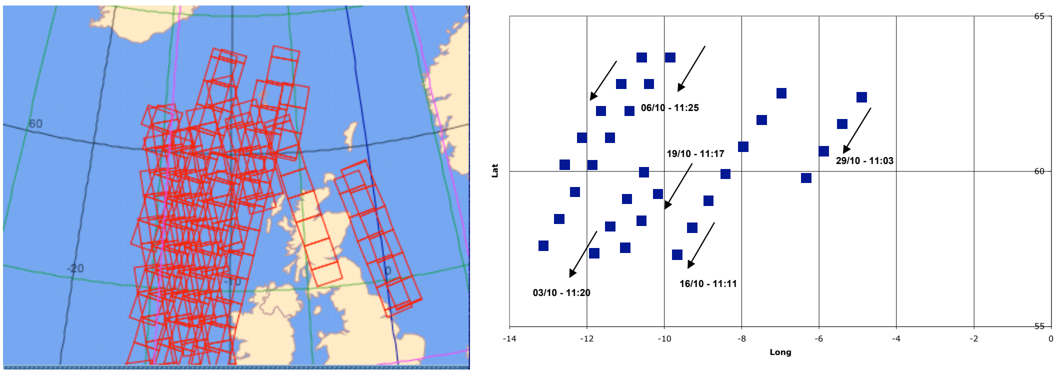


Figure 33 Coverage of ENVISAT ASAR Wave mode data for October 2004 – all archived data (left), and data products available in Near Real Time (right)

Figure 33 shows the coverage of ENVISAT ASAR wave mode data for October 2004. The maps seem to suggest a preferential sampling to the NW of Scotland – with the Shetland Faroes channel perhaps receiving less dense coverage.
When wave mode data were retrieved from the Near Real Time data stream, only a subset of these data seemed to be available as Fast Delivery (right panel) – such that in October 2004 31 wave spectra in total are available in the area 52°-68°N, 20°W-10°E

SAR image data
Coverage from SAR Image mode is probably sufficient to build a direction and wavelength climatology of longer period waves, at least for the open ocean.
The ERS-2, ENVISAT and RADARsat SARs take images on a pre-programmed schedule according to orders from the user community. In the case of ERS-2 and ENVISAT orders are taken and programmed in once per repeat cycle (35 days). Thus if it were necessary to provide guaranteed repeat coverage over a particular area of interest then a regular order would have to be placed with ESA (or RADARSAT). If one wanted more than one image per cycle (i.e. once every 35 days) then a multiple order, requesting acquisitions from different orbits would be required.

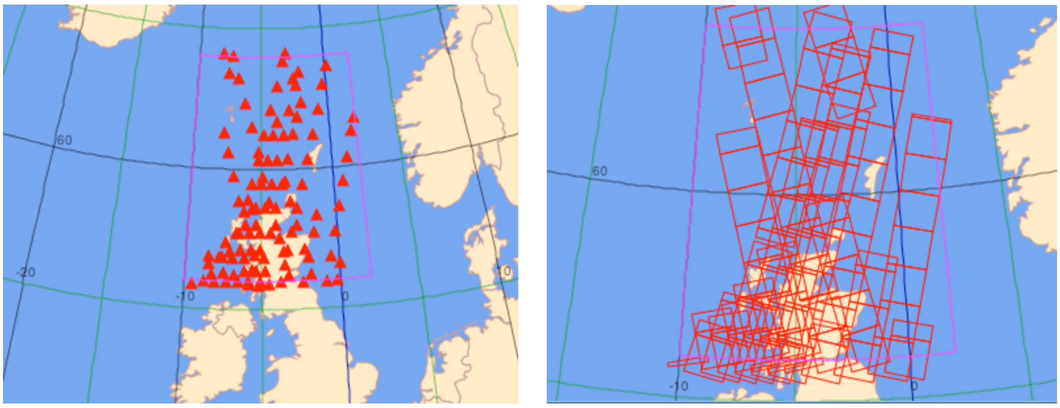


Figure 34 ENVISAT ASAR image mode scenes available for October 2004. Left – centre of scenes, right, actual coverage

Provided an image order is placed at least 14 days in advance it is unlikely the acquisition cannot be made (provided no higher priority customer requests a download in the time up to the acquisition date). The Ground Station will manage the schedule in order to download as many as possible of the requested images. Should, for example, an ERS-2 pass not be acquired it is still possible to acquire data from either Envisat or Radarsat.

Figure 34 shows ENVISAT ASAR Image Mode coverage achieved in October 2004. 113 image mode scenes are potentially available from 20 separate passes. This figure suggests that such ad-hoc coverage (if available and processed in real time), even from ENVISAT alone, may be sufficient to support a useful Near Real Time monitoring scheme, and also to build a climatology, though perhaps a coarser grid than 2° x 2° would be required.

5.10.2 Requirement for Additional Data

For Climate Analyses

A rule of thumb is that, to cover sufficient inter-annual variability, a climatology should cover at least 5 years (ideally tens of years – see Woolf 2004a). For analyses of significant wave height based on altimetry data we require that a grid square receive at least 5 samples per month for us to regard the grid to be adequately sampled (from a comparison of altimeter derived monthly means against buoy data - see Cotton and Carter, 1994). Analyses carried out for this project have indicated that higher sampling rates may be required for analysis of other parameters (wave period) and for the generation of 2D scatter plots. Thus for certain analyses a larger grid than 1° x 1°may be necessary.

So, for a directional climatology (assuming that the SAR derived data can be validated satisfactorily for safety applications) we would require wave mode data for at least 5 years, possibly averaged over larger grid squares. On this same basis, if a climatology were to be based purely on SAR image data, it would be necessary to acquire and process, 5 yrs x 12 months x 5 samples per month – *300 images for each grid square* to be covered.

For Near Real Time Monitoring

The requirement depends on the way that EO data are used. A number of studies have demonstrated that the assimilation of significant wave height data (provided they are sufficiently reliable and accurate) into a wave model improves the accuracy of the model forecast. If the number of satellites is increased the impact is also increased (Lefevre, pers. comm.). The assimilation of data with information on the wave spectra has a longer lasting impact than just significant wave height, as it allows the swell generation and propagation terms to be corrected.

EO data can be used in other ways in real time monitoring systems– for instance as an overlay on a model derived wave forecast or as a layer in a real time display system with information layers from a number of sources (see figures 30 and 31). In such applications the EO data must be available as quickly as possible, ideally in under 3 hours. To be effective in such systems one would require satellite measurements at least daily (preferably more frequently) within the domain of the display system. To achieve this over our area of interest, sampling from at least 2 satellites is required.

5.11 SUMMARY

Within this section we have described the processing chains established to process altimeter, SAR image mode, and ASAR wave mode data. We have presented examples of the data products thus produced, including a statistical climatological analysis based on altimeter data. We have further assessed these data through comparison against wave model nowcasts and climatologies, and directional buoy data from the FOIB buoy to the south of the Faroes. Additional analyses have used the data to assess scales of variability, and how well the sampling presently available from satellites meets the requirements for Near Real Time services and the compilation of climate statistics.

It is clear from these analyses that different parameters from the various processing chains meet the requirements for operational use to varying degrees, in terms of accuracy, sampling capability and maturity of development. We summarise below the status of the various data sets produced (refer also to Table 3 in Section 4).

Altimeter Data

Altimeter significant wave height, wind speed and zero upcrossing wave period are validated, accurate, and found to be reliable over a range of conditions (through extensive comparisons against buoy data). Data are presently available in near real time from two satellites (ENVISAT and Jason), and there is an archive of global data going back to 1985. Coverage is sufficient to compile a global monthly climatology on a 2° x 2° grid from 1985, or on a regional NE Atlantic / Northern N Sea 1° x 1° grid from 1992 onwards.
Coverage with altimeter data alone is not sufficient to support a useful real time wave monitoring service. Reference to data with higher spatial and temporal coverage is required.

The altimeter estimate of peak wave period is not sufficiently mature for implementation. Comparison against other sources of peak wave period show large variability, suggesting that further algorithm development is required.

Significant steepness is derived from significant wave height and zero up-crossing wave period (Annex A). We have confidence in both these source measurements and so might hope a parameter derived from these parameters would be reliable. However, there is little available information for validation of this parameter. Thus an altimeter significant steepness could be implemented for trial operational use, but its use should be subject to further validation against reliable reference data sets.

Group wave speed is derived from peak wave period (Annex A). Given our lack of confidence in altimeter derived peak wave period, we would not recommend use of an altimeter derived wave speed.

Hence for climatological applications, altimeter measured Hs (graded 1) and wave period (graded 2e) were identified as potential stand alone, or major, data sources. Altimeter measurements of peak period, significant steepness and wave (group) velocity were all graded

3e, indicating that future application may be possible the subscript e indicating that further algorithm development would be required. Of these latter three parameters, significant steepness perhaps shows the most promise.
For Near Real Time applications, limited sampling results in all altimeter derived wave parameters being graded 3d (other data sources more important, limited sampling in time being the problem). Even so, it should be recognised that altimeter data can play an important role in NRT systems, as they provide an actual measurement of conditions against which modelled predictions can be evaluated.

SAR Data

General SAR issues

Satellite SAR is able to image longer wavelength waves only (with a minimum lower wavelength cut-off of 100m in the range direction and 200m in the azimuth direction). Recent analyses of ENVISAT data (Johnsen et al, 2003) have suggested best results are gained for seas with wave periods of over 8 s.

The imaging mechanism is highly dependant on wind speed, with the extraction of wave parameters being most successful in the wind speed range 3-11 ms^{-1}.

The movement of the satellite creates an additional complicating factor in the imaging process – such that the lower wavelength cut-off is asymmetric in the azimuth (along track) and range (across track) directions. This creates the possibility that wave statistics gathered from tracks passing the area of interest in one direction (e.g. ascending passes moving from SW to NE) will show different directional distributions than statistics gathered from passes in the other direction (SE-NW).

SAR image mode (MaST)

SAR image mode data processed through the QinetiQ MaST application can provide potentially valuable direction and wavelength (and wave speed) information on longer ocean waves. SAR image data processed with similar techniques have been used for case studies of wave fields along particular stretches of coastline but not, to our knowledge, for the generation of offshore wave climatologies or to support near real time wave monitoring systems (except through assimilation into operational wave models).
The limited evaluation that has been possible within this project has identified that a number of different wave trains can be identified for each sub-cell within an image, but that it is not possible to identify the dominant wave system, as no estimate of wave energy is available. In addition, the scheme retains a 180° ambiguity on the direction of identified wave systems, presently resolved by assuming the waves are traveling towards the nearest land.

It is suggested that these data are sufficiently mature for a trial application, but would require a more thorough validation before implementation in a safety critical use. Hence SAR wave period and direction derived from MaST were graded 2bc for climatological application (further algorithm development required – spatial sampling may be an issue), and 3d for NRT applications (sampling in time an issue). Wave speed is graded at 3 for both NRT and climatological applications – the sampling limitations still apply, and in addition further validation is required.

SAR image mode (SARtool)

The new SAR image processing technique implemented by BOOST makes use of complex SAR image data and is able to estimate wave energy as well as resolve the 180° ambiguity. It is thus able to provide estimates of significant wave height and wind speed, and to identify the peak frequency and direction. It is also possible therefore (in principle) to generate estimates of significant steepness (of longer waves) and wave speed. The operation of the system is presently operator intensive, as it is set up to provide high-resolution coastal wave fields.

The processing algorithms, developed by the ENVIWAVE consortium, are the same as those used by ESA to process the ENVISAT ASAR wave mode data. Validation has been undertaken, continues, and has been reported in a number of ENVISAT studies (e.g. Johnsen et al., 2003). Wave parameters (Hs, direction, wavelength) estimated through this scheme have been found to be reliable in the wave period range 8 – 15 s.

This processing scheme therefore shows some potential advantages against MaST, but the operating costs are currently much higher, as the system is set up for coastal applications.

SAR wave period and direction derived from SARtool were given the same gradings as the MaST derived estimates. The additional parameters possible from SARtool (Hs, mean period and significant steepness) were graded at 3 for climatological and NRT applications, as further testing (and possibly algorithm development) are required.

(A)SAR wave mode

Since 1991, ERS-1 and ERS-2 SAR wave mode data have been used to generate global and regional directional wave climatologies, and have been assimilated into operational wave models. However, success has been variable. Early processing schemes required a first guess spectra from a wave model, or estimates from scatterometer winds, and the processing schemes were not able to resolve the 180° wave direction ambiguity problem.

The new instrument and processing chain for the ASAR wave mode on ENVISAT employs a more sophisticated wave retrieval algorithm which does not require a first guess wave field from a model, can provide an estimate of significant wave height (and wind speed) and resolves the 180° wave direction ambiguity. This is the same algorithm that is implemented in the BOOST SARtool. Thus this instrument and data set show much promise for practical operational implementation in that it offers measurements of (long wavelength) significant wave height, peak direction and period, and wind speed.

The data could be used for:

i) near real time applications (the ASAR wave mode level 2 data are included in the ESA ENVISAT near real time data stream and are received at Satellite Observing Systems), and
ii) for the generation of directional wave climatologies in the area of interest.

Unfortunately there have been some early teething problems in the generation of the ENVISAT ASAR wave mode data set. Following initial (and subsequent) validation of the product by ESA, periodic modifications were made to the processing chain such that the archived data set is not homogeneous. Thus, for implementation in a climatological data base a reprocessing of the (2 years) of archived data will be necessary. We now understand that ESA plan to reprocess the backlog of data (from December 2002 onwards) starting in January 2005. In addition, there have been some issues in identifying and applying suitable quality control criteria. We understand that ESA have now implemented an improved land masking procedure (Johnsen, pers. comm.) Also Johnsen (2005) provides some updated guidance for quality control.

Thus, the ENVISAT ASAR wave mode data show a potential value for application to support weather safety in the NW approaches – in that they could provide important directional wave

information together with estimates of wave height, that the data are already available on an operational near real time data stream, and that the potential costs for acquiring and processing these data are significantly lower than for SAR image mode. NRT data are available now, and a system using ASAR WM data could be implemented immediately, for climatological/ statistical applications it may be necessary to wait for 6 months to a year for the generation of a homogeneous archive, and for the quality control issues to be settled.
SAR WM derived parameters were given the same gradings as those derived from Image Mode data using SARtool – as essentially the same algorithms are used.

6 SPECIFIC SUMMARY ON SAR CAPABILITIES

6.1 TO WHAT EXTENT CAN SAR ASSIST HSE TO EXECUTE ITS DUTIES?

Accurate information on wave height, direction and period is essential to support the safety of offshore operations. This includes the use of data to build climatology and long-term statistics for the safe planning of offshore operations and design of structures and vessels, plus the use of near real time data, and forecasts, for decision support during operations,

The requirement for directional wave information has become even more important since oil and gas exploration moved into deeper water, off the NW approaches to the UK and elsewhere. New or changed requirements for wave measurements include:

- The need to design safe operational procedures in new operating conditions.
- The need for reliable monitoring of potentially more extreme operating conditions.
- The need to operate within strict, safety critical, wave conditions limits.

For most of the area of interest, satellite SAR offers the only available measured source of direction and period of long wavelength waves, the very waves to which offshore structures can be particularly vulnerable. Such information is otherwise only available through very sparse in situ data, or wave-model predictions. Wave models are known to have difficulty in accurately predicting the propagation of long wavelength swell. Therefore, potentially SAR data can play a very important role.

However, SAR cannot be relied upon as the ONLY source of information, because of the infrequent sampling available, the limited range of wind speeds over which reliable measurements can be made, and other limitations detailed elsewhere. It is essential that SAR data be viewed as one element of an integrated service which combines SAR data with information from other sources (altimeters, scatterometers, in-situ instrumentation and models). This sampling limitation is the principle reason why SAR derived wave products were given a “2” grading for climatological applications (- a major source of data) and a “3” grading for NRT applications (one of a number of sources, and not THE major source).

The previous section outlined what SAR data were capable of providing in the short term. These are:

- A Near Real Time monitoring system which combines information from SAR, with measurements from satellite altimeters and scatterometers as layers on top of model predictions, to allow the user to evaluate the information from each source and come to a view as to the reliability of the predictions /measurements and so take appropriate action.
- A demonstration of SAR based climatology, and evaluation, which would provide a more thorough basis for costed recommendations for the development of a full (SAR based) wave statistics database.

6.2 WHAT WOULD BE REQUIRED TO IMPROVE THE SITUATION AND WHAT ARE THE LIKELY TIME SCALES ASSOCIATED WITH THIS?

Validation

Because of the known limitations of SAR wave data it is especially important to validate fully all new applications of SAR wave data. A limited validation would be possible on the demonstration SAR based wave statistics set proposed for phase 2 and could be achieved within 3 months. A full validation would require the wave detection algorithm of MaST to be run on imagery over AOI where timely in situ data available on swell wave direction and speed are available, under the full range of meteorological and sea state conditions under consideration. The assessment in WP1.4 was provided after a limited qualitative comparison between SAR, model and buoy measurements, from only 10 occasions and over a limited range of conditions. This analysis is not sufficient as validation to support a full and final operational implementation, and a much larger data set is clearly required to provide reliable error statistics. A more complete validation would require a larger data set, and would therefore be a longer term prospect (~ 1 year)

Processing Chain Developments

To include SAR image mode data into the NRT monitoring system QinetiQ would need to implement an automatic processing chain from the reception of data, pre-processing, transfer to QinetiQ, processing on MaST and then transfer to the web–based monitoring system. There are no technical difficulties in establishing such a chain, which could be achieved within an estimated time scale of 1 month.

The SAR wave product would be enhanced if the “ENVIVIEW” processing algorithms could be incorporated, then estimates of wave energy and swell significant wave height would be possible (and the 180° directional ambiguity removed). Again there are no major technical obstacles. The estimated time scale here is 2 months, assuming that the algorithms require no further development and are available in a form easy to implement.

Another possible enhancement would include the use of scatterometer data to generate the short wavelength spectrum - which could then be combined with the long wavelength spectrum available from SAR. With support, this capability could be developed within a 3-month period.

Archive Data Base for Wave Statistics

At least 5 years data are required for a valid statistical wave data base, to include the effects of inter-annual variability. For SAR wave mode data, archived ERS-1 and ERS-2 data are available and we understand that reprocessed ENVISAT ASAR wave mode data should be available in 2005. Thus an archive SAR wave mode data base should be possible within a period 6 months to 1 year. Careful validation would be required, (see above) possibly adding 3-6 months to this time scale.

If SAR image mode data are to be used to generate a statistical data base (either to supplement or as an replacement for the wave mode data base), again 5 years data would be required. We have identified that this would require the processing of 300 images per grid cell. It has been estimated this could be achieved within a 3 month period, including the automation of the SAR analysis process discussed above.

Research

HSE /BNSC have expressed a strong interest in achieving a more direct combination of different EO sources of wave data. We have indicated that in our opinion this would require some specific targeted research, to allow the exploration and testing of different possible techniques. Hence for this aspect we can expect time scales of order 1 year.

Capacity Building

To date, in the UK, relatively little use has been made of SAR data for offshore wave monitoring and wave climate analysis. Presently, the "State of the Art" in the UK, in terms of operational application of wave products from SAR, lies somewhat behind that of other countries in Europe. In addition, the NW Approaches region presents a particular set of wave conditions and operational circumstances which require a carefully validated product.

This leads to the situation whereby, in the short term, the capability does not exist in the UK to implement an operational service which can exploit SAR data to its fullest extent. However, the project team are able to provide a demonstration service, an assessment of the present and potential capability of such a service, and a costed "route map" towards a full implementation of a service which includes NRT monitoring, and the provision of wave climate statistics.

Some of this development will require research, and the development of expertise within the UK. Acknowledging that there is a need to build UK capability to at least match that of our European competitors, SOS and SOC are investigating a possible bid into the NERC Knowledge Transfer fund.

7 INITIAL CONCEPT FOR A NW APPROACHES WAVE MONITORING SERVICE

7.1 INTRODUCTION

This section describes an initial concept for a "NW Approaches Wave Conditions Monitoring and Analysis Service", and proposes a data product for Phase 2 of the project which will demonstrate key aspects of the final service and lead to fully evaluated and costed recommendations for future service implementation and development

The objective is to provide an initial specification for a service which will:

a) Satisfy the joint sponsor priorities of providing statistical analyses of archived wave data (including directional information) and a near real time wave monitoring service.

b) Offer a useful capability in the short term (i.e. was based upon existing capability, and available operational data sets), but which will allow for future planned incorporation of additional data sets and analysis capabilities. Costed recommendations for implementation and service development will be provided as part of Phase 2

In addition, because the application was related to safety of offshore operations, it was taken as a requirement that the data sets and analysis applications must be robust, validated and reliable, or alternatively that the limitations of the component and combined data sets are clearly established.

The proposed initial service will use satellite radar altimeter and satellite synthetic aperture radar data. The former will provide along track information on wave height, wave period and wind speed, the latter directional information on long wavelength waves along track and across a ~100 km wide swath. Other data sources could be included to provide supplementary information, for instance scatterometer data to provide wind speed and direction, and wave model nowcasts to provide a larger spatial context to the satellite data.

Other capabilities can be developed and integrated in the medium and longer term (see the draft "Route Map" below)

Figure 35 demonstrates the key points of the proposed service architecture, and indicative examples of the types of data product presentations that could be offered.

The overall concept is a web-based service providing a single entry point with links to two effectively separate services:

- NW Approaches Wave Climate Statistics:
  - A web based user interface generating queries into a MySQL wave climate database.
- NW Approaches Wave Conditions Monitoring Service
  - A web map server accessing data from near real time data feeds based on XML format data products.

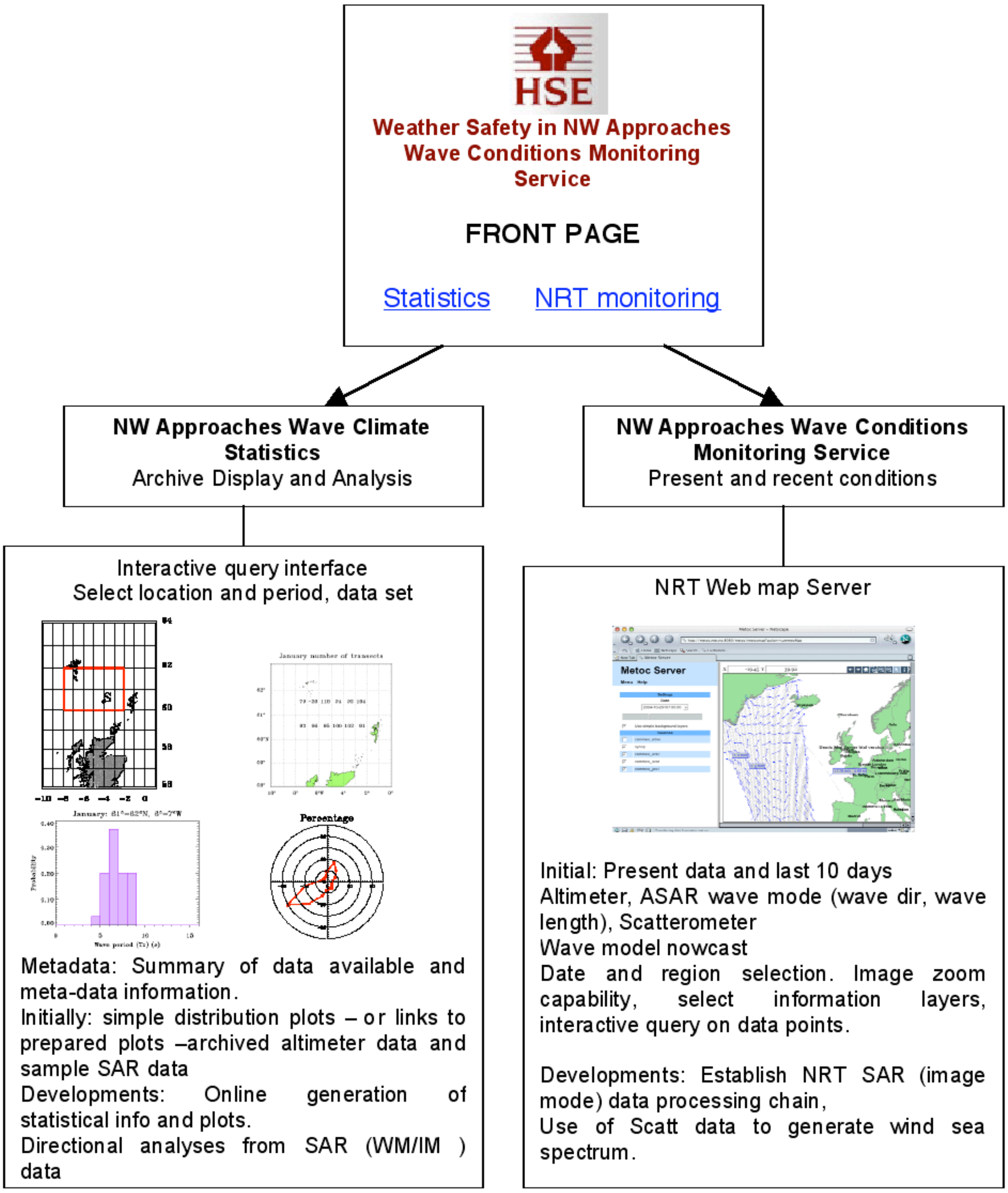


Figure 35 Concept for Initial NW Approaches Wave Monitoring Service.

7.2 CONCEPT FOR WAVE CLIMATE STATISTICS - ARCHIVE DISPLAY AND ANALYSIS

7.2.1 Overview

A user interface, in the initial case probably a table–based text query interface, to be replaced in the medium term by a web map server, will generate queries into a (MySQL) wave climate database.

This query page will allow the user to specify area of interest (and time, if requested) and will first return summary of available information. The minimum area resolution will be 1° x 1°, or possibly 1° x 2°.
The summary data display will be in the form of text tables (e.g. data sources, available parameters, no of records,…..)
In the first service there will then be capability to link to summary plots (e.g. histograms, distributions, ……)., later versions would provide a capability to generate requested plots on-line.

7.2.2 Description of Data Sets Available

Two data streams will be available: non-directional and directional data. Table 7 provides an overview.

Table 7 Data table for the wave statistics service. Data sets in bold would form the basis of the initial service. Data sets in italic could be added subsequently.

Instrument	Source	Parameters	Spatial overage	Time coverage
Altimeter	**Geosat**			1985-89
	ERS-1			1991-96
	ERS-2	**Hs, Tz, U10**	Whole region,	1995-2004
	TOPEX / Poseidon	Sig steepness	transect medians on	1992-2004
	Jason		1° x 1° or 1° x 2°	2002-2004
	Envisat		grid	2002-2004
	GFO			2000-2004
(A)SAR Image		(long period)	Pre selected sub	**27 images**
Mode	**ERS-2**	**Wave**	area (~1° x 2°)	
		direction, wave		
	ENVISAT	**period, wave**	*Whole region*	
	Radarsat	**speed**		*1992-2004*
		Hs, steepness		
(A)SAR Wave	*ENVISAT*	*(long period)*		*2002*
Mode		***Wave direction,***		*onwards*
		wave period,	*Whole region –*	
		wave speed	*possibly at reduced*	
		Hs, steepness	*resolution*	
	ERS1,2	*dirn, period*		*1991-2002*

Non-directional information

Altimeter derived wave parameters: Hs, Tz, wind speed and significant steepness
A complete archive of these data, from 1985-2004, exists. It is proposed that the database would include median values of transects on a 1°x 1° or 1° x 2 grid.
These median values would form the basic data set for the generation of statistics (distribution functions, percentile plots, occurrence histograms/scatter plots, etc.). Figures 25-28 gave examples of possible analyses of non-directional data.

Directional Swell Information

This could be derived from (A)SAR Image Mode data or (A)SAR Wave Mode data, or a combination of the two.

(A)SAR Wave Mode
Historical ERS-1, ERS-2 SAR Wave Mode data are potentially available for the period 1991-2002. Unless supplemented by external information (from wave models or scatterometer winds) these data could provide swell wave direction (with 180° ambiguity) and wave period statistics only. ERS-1 and ERS-2 SAR Wave Mode could not operate when the SAR was in Image Mode.
ENVISAT ASAR Wave Mode (2002 onwards) can provide swell direction (without 180° ambiguity), period and significant wave height, but reprocessing is required to generate a homogeneous archive (planned to be started by ESA early in 2005). There is no operational conflict between the ENVISAT ASAR Wave Mode and Image Modes.
(A)SAR Image Mode
There is a considerable historical archive of (A)SAR Image Mode data, which could be used to fill in sampling gaps when the SAR Wave Mode data were unavailable, or to provide improved spatial resolution (e.g. close to coasts). The QinetiQ MaST tool, as it stands, will provide swell wave direction (with 180° ambiguity) and period only. If modified to implement the ENVIWAVE algorithms an unambiguous swell wave direction could be retrieved as well as an estimate of (swell) significant wave height.

For a climatology at least 5 independent samples (i.e. from images, or Wave Mode imagettes, on separate passes) per month will be required for a minimum period of 5 years, *per grid cell*. It follows that each grid cell would require a minimum of 300 images (or Wave Mode imagettes) to be processed.

Directional wave statistics presentation
In the first instance percentage occurrence in 20° direction bins, and Tp occurrence against direction can be plotted (see figure 29). When a greater volume of data becomes available, these analyses could be sub-divided according to season, and possibly local wind conditions.

7.3 CONCEPT FOR NW APPROACHES NEAR REAL TIME WAVE CONDITIONS MONITORING SERVICE

7.3.1 Overview
The NRT wave conditions monitoring service would be provided through a web based map server displaying present and recent sea state conditions in the NE Atlantic region. The user will be able to select data sets, zoom in and out on selected areas, move backwards and forwards in time, and query individual data points.

7.3.2 Description of Data Sets Available
In the initial implementation, altimeter (wave height and wind speed), ASAR Wave Mode data (swell wavelength, direction, and swell significant wave height) and scatterometer (wind speed and direction) data could be available, together with a layer containing a wave model nowcast (see Table 8, figure 36 and figure 30 in section 5). EO data will be available at geophysical data record maximum resolution (~7 km along track for altimeter data, along track ASAR Wave Mode data at 100 km separation, and a 25 km x 25 km grid for scatterometer data).

7.4 POSSIBLE DEVELOPMENTS
Possible developments include:
- Incorporation of ENVIWAVE algorithms into MaST processing scheme, to remove direction ambiguity, and allow extraction of swell significant wave height from SAR Image Mode.
- Generation of wind sea spectrum from scatterometer data and combination with SAR derived swell spectra to generate full wave spectra.

- Combination of wave information from sources separated in time and/or space, through simple propagation models, optimal interpolation or other techniques to allow e.g. generation of joint statistics of alt and SAR derived wave parameters.
- Warning advisory notices on unusually long period waves, or severe conditions.

Table 8 EO Data table for the near real time wave monitoring service. Data sets in bold will form the basis of the initial service. Data sets in italic could be added in the longer term.

Instrument	Source	Parameters	Spatial overage	No. of passes /day over area of interest	Delay
Altimeter	**Jason** **Envisat**	**Hs, U10** **Tz**, *Sig steepness*	**Whole region, along track data at 7 km res.**	**~4 / day**	**< 3 hrs**
Scatterometer	**ERS-2** **Quikscat**	**Vx, Vy**	**Whole region, 25 km x 2km cells**	**2 / day 500 km swath** **2 / day 1800 km swath**	**< 3 hrs**
(ASAR Wave Mode	Envisat	(long period) **Wave direction, wave period, wave speed** **Hs,** Sig. *steepness*	**Whole region –along track products at 100 km separation**	**~ 2 / day**	**< 3 hrs**
(A)SAR Image Mode	*ENVISAT* *ERS-2* *Radarsat*	*(long period) Wave direction, wave period, wave speed Hs, steepness*	*Whole region – either pre-ordered or on ad-hoc basis*	*Up to 6 /day depending on NRT availability through W Freugh* *100 km swath (or less) for useful wave detection*	*To be determined in feasibility study*

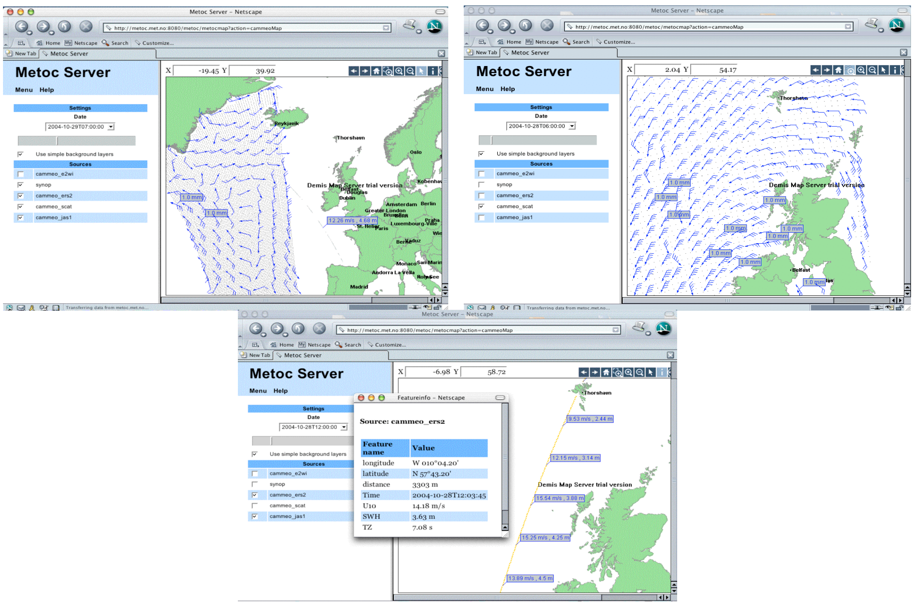


Figure 36 Example web map server display, with scatterometer (top panels), and altimeter (bottom panel) data.

7.3 DRAFT ROUTE TO IMPLEMENTATION

Here we provide a draft definition of the service capability that could be implemented immediately (i.e. in under 3 months), in the medium term (from 3 months to 1 year), or capability which requires a more prolonged development before implementation (over 1 year).

7.3.1 Wave Statistics

Immediately Available Capability (< 3 months)

- Altimeter based wave statistics at 1° x 1°, or 1° x 2° resolution, covering the entire Area of Interest based on a > 10 year archived database.
- A demonstration of SAR derived wave statistics based on a limited region and season of specific interest (from the analysis of 27 SAR images using the MaST tool as it currently operates). This could allow for a more thorough validation of the MaST wave product, in particular with regard to its capability to accurately represent the most important characteristics of the long period wave climate in the NW approaches

Medium Term Added Capability (3 months –1 year)

- Implementation of the ENVIWAVE processing scheme into the QinetiQ MaST tool – to allow extraction of wave energy/ wave height from the SAR image and remove 180° direction ambiguity.
- An initial SAR Image Mode based climatology (with or without implementation of ENVIWAVE algorithms).
- An initial (A)SAR Wave Mode climatology, based on ERS-1, ERS-2 and (reprocessed) ENVISAT ASAR Wave Mode data.
- Statistical analysis of distributions based on full wave spectra achieved by a combination of SAR (Image Mode or Wave Mode) and scatterometer derived directional spectra
- Initial validation.

Longer Term Possibilities (> 1 year)

- Full SAR climatology for the NW approaches (Image Mode and / or Wave Mode).
- Following research into the use of simple propagation models, and /or optimal interpolation techniques, it may be possible to generate combined distribution functions from SAR and altimeter (e.g. wave energy/ wave height vs wave direction).

7.3.2 Near Real Time Wave Monitoring

Immediately Available Capability (< 3 months)

- The pilot NRT CAMMEO system, as demonstrated in the WP 1.4 report (already including scatterometer and altimeter data), can be provided to HSE immediately. Near Real Time ASAR Wave Mode data will be added within the time scale of the GIFTSS project.
- A demonstration "delayed mode" version of the above, to allow a demonstration of example Image Mode SAR data is planned within GIFTSS phase 2.

Medium Term Added Capability (3 months –1 year)

- An operational, automatic SAR image processing chain is feasible within the medium term. SAR images would be received at West Freugh, pre-processed then transferred to Farnborough and automatically processed using an updated version of the MaST tool. These SAR data could then be directly fed into a web map server based application (such as CAMMEO, or the QinetiQ MIDAS system).

- On the same time scale it would also be possible to generate a directional wave spectrum including wind sea and swell, by using the scatterometer wind data to generate a wind sea spectrum and combining with the long wave length SAR spectrum.
- The system could also be developed to provide extra "added-value" capability, for example, specific information (including warnings) on long period waves, and unusually severe conditions.

Longer Term Possibilities (> 1 year)

- Following research into the use of simple propagation models, and /or optimal interpolation techniques, a NRT monitoring system could include a more integrated presentation of satellite derived wave information.

7.4 PROPOSAL FOR PHASE 2 DATA PRODUCT

The aims of the demonstration data product will be to:

- Generate and evaluate a swell direction and period climatology derived from SAR Image Mode data.
- Demonstrate a prototype Near Real Time wave conditions monitoring service, covering the North-Western Approaches, which includes EO data (altimeter, SAR Wave Mode, scatterometer), model predictions, and some in-situ data.

We describe these two aspects separately below, first considering the use of SAR Image Mode data to generate swell wave statistics.

7.4.1 SWELL Wave Statistics

Overview

Commercial organisations have used SAR *Wave Mode* data to provide a service which offers swell wavelength and direction statistics, and some of these provide details of the validation procedures they have carried out. However, we believe that there are particular circumstances surrounding this specific application of SAR data that demand specific further evaluation.

Key issues are:

- SAR *Image Mode* data have not been previously used to generate a climatology. A first implementation should be carefully tested.
- The NW Approaches is an area of high wind speeds. SAR wave imaging is only effective for winds between 3-11 ms^{-1}. It will be important to see how this dependency effects sampling and so the generation of accurate, representative wave statistics.
- The direction of the ascending and descending passes from the ERS and ENVISAT satellites is such that the SAR azimuth direction for descending passes, and the SAR range direction for ascending passes, lie in the NE-SW direction – the dominant direction for swell waves. The lower wavelength cut-off in the azimuth direction can be expected to be at least twice that in the range direction. Thus ascending passes will have a lower wavelength cut-off of 100m in the predominant wave direction, whereas descending passes will have a cut-off of at least 200m. It will be necessary to test for any consequent asymmetry in sampling.

SAR Data to be processed

The aims of the SAR Image Mode data products to be produced for Phase 2 (for statistical analyses) are therefore:

- To generate a representative swell direction and wavelength database, for a selected region and season.
- To provide a demonstration display of direction and wavelength statistics.

- To assess the impact of high wind speed conditions on the sampling of the region by SAR.
- To establish if there is any difference in wave statistics derived from ascending and descending passes and, if there is, develop a strategy to overcome it.

We propose to concentrate on an area to the South of the Faroe Islands, an area in which the offshore oil and gas exploration industry are active, and for which representative in-situ buoy data are available.

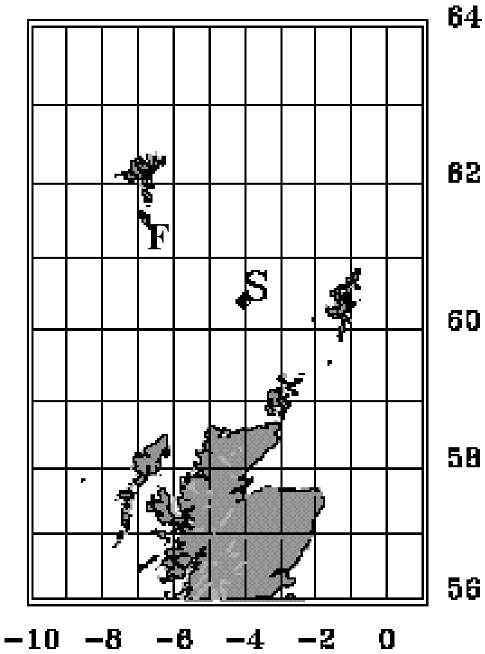


Figure 37 The GIFTSS Area of Interest. The red square indicates the region for which SAR Image Mode data will be extracted (plus the possible expansion, as a dashed line). The location of the Schiehallion production platform ("S") and the Faroes waverider buoy ("F") are also indicated.

Carter (2004a) compared wave data from the Faroes buoy (at 61.3°N, 6.28° W) with altimeter data averaged over 3 areas (61°-62°N, 6°-7°W; 61°-62°N, 4°-5°W; 60°-62°N, 2°-8°W), and although the first area lay directly over the Faroes buoy, found the altimeter data from the last two regions agreed better with the buoy data, suggesting that the altimeter data in the first region was affected by measurements in sheltered areas to the east of the Faroes.

Thus we propose to select SAR image data from 60°-61°, 4°-6°W, to provide sampling of conditions representative of the Shetland-Faroes channel, and in wave climate found to be similar to that experienced by the Faroes wave rider buoy. We will look for images in the winter season (Dec-Feb). If this initial region does not yield a sufficient number of SAR images, the search area will be widened longitudinally to 4°-8° W.

QinetiQ will identify, acquire and process 27 ERS-2 / ENVISAT SAR images in this area.

SAR processing

After pre-processing each SAR image will be processed with the QinetiQ MaST package to produce a file of wave field solutions with location, wave period and wave direction. For each of these files an occurrence distribution on a direction / period grid (e.g. 10° x 0.5s resolution) will be generated and the primary and secondary peaks (according to occurrence), will be identified. Figure 38 provides an overview of this SAR Image processing chain.

The direction and period of these primary and secondary occurrence peaks will be stored and used to generate the statistical analyses, for instance as percentage occurrence in direction sectors, and occurrence of peak swell period (see Figure 3). Note that we will only have a maximum 35 samples (even if we are able to include data from all the SAR images analysed in Phase 1), so the statistical analysis possible on the data set will be limited.

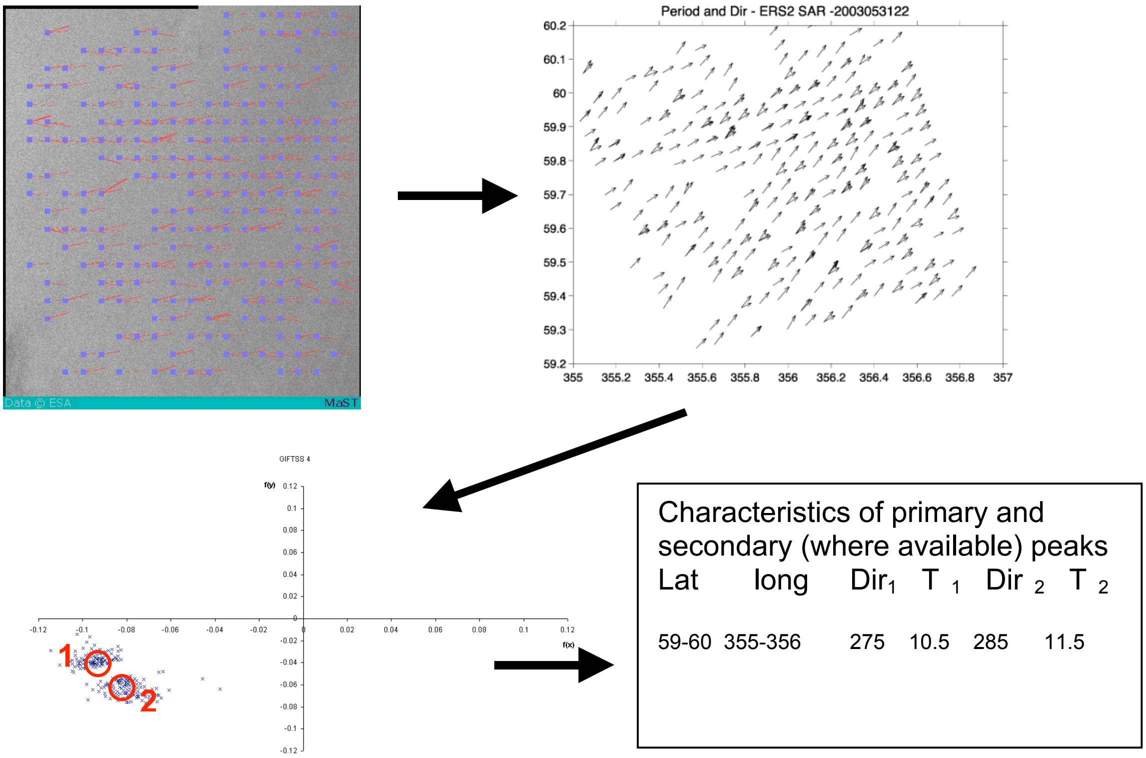


Figure 38 Processed SAR Image for 31/05/2003 22:07:23 over a location to the south of the Faroe Islands and north of the Scottish mainland (close to the "K7" buoy). Top left – the processed SAR image, top right the geo-corrected wave vectors, bottom left, a polar occurrence plot (here direction v frequency), bottom right extracted wave characteristics of primary and secondary occurrence peaks

Evaluation

Evaluation will take the following form:

- Direct comparison of SAR derived wave products against co-temperaneous Faroes waverider buoy data.
- Comparison of SAR derived statistics against equivalent statistics from
    - Faroes waverider
    - KNMI wave model climatology
- Search for significant differences between SAR wave statistics from ascending and descending passes
- Evaluation of the effect on the statistics of the limited wind speed window within which the SAR can provide measurements of the wave field.

This evaluation is possible through the availability to the team of Faroes waverider buoy data (1999-2004), and the KNMI wave climatology (1957-2002), and Quikscat scatterometer wind vector data.

7.4.2 NRT Monitoring

Overview

A prototype NRT wave conditions monitoring service will be provided through a web based map server displaying present and recent sea state conditions in the NE Atlantic region. The user will be able to select data sets, zoom into and out from selected areas, move backwards and forwards in time, and query individual data points.

This service will be based on an update of the SOS/Met Norway "CAMMEO" service, built on a web map server accessing data from near real time data feeds based on XML format data products.

Description of Data Sets Available

In the demonstration, NRT (< 3 hrs) altimeter data (wave height and wind speed), ASAR Wave Mode data (swell peak wavelength , direction and significant wave height), and scatterometer data (wind speed and direction) will be provided, together with a layer containing a wave model nowcast (probably from Met Norway). Table 9 details the EO data sources and figure 36 a demonstration of output from the unmodified CAMMEO service.

EO data will be available at geophysical data record maximum resolution (~7 km along track for altimeter data, at 100km intervals for the ASAR Wave Mode data, and on a 25 km x 25 km grid for scatterometer data).

It is also proposed to demonstrate (possibly offline) and assess the inclusion of wave products derived from SAR Image Mode data.

Table 9 EO Data table for the near real time wave monitoring service.

Instrument	Source	Parameters	Spatial overage	No. of passes /day over area of interest	Delay
Altimeter	Jason Envisat	Hs, U10 Tz, Sig steepness	Whole region, along track data at 7 km res.	~4 / day	< 3 hrs
ASAR Wave Mode	Envisat	Swell direction, period & Hs	Whole region –along track products at 100 km separation	~ 2 / day	< 3 hrs
Scatterometer	ERS-2 Quikscat	Vx, Vy	Whole region, 25 km x 2km cells	2 / day 500 km swath 2 / day 1800 km swath	< 3 hrs

Evaluation

Evaluation will take the following form:

- Direct comparison of SAR and altimeter wave products against Faroes waverider, and other available (UKMO) buoy data
- Direct comparison of SAR and altimeter wave products against the wave model.
- Generation of data processing statistics, assessment of reliability of all parts of the (EO) processing chain (e.g. % data retrieved in < 3 hours, 6 hours).
- Evaluation from the potential user (HSE).

This evaluation possible through the availability to the team of Faroes waverider buoy data (1999-2004), the Met Norway wave nowcast, and UKMO open ocean buoy data through the Met Office web site.

8 CONCLUSIONS

This report has summarised the work undertaken for each task in phase 1, and provided an overview of the results from each work package.

8.1 SENSORS AND PROCEDURES

The sensors and processes used to derive the various wave products,for NRT monitoring and for statistics, have been described in Section 4 (sensors) and Section 5 (processing chains).

8.2 ACCURACY AND TIMELINESS

The capabilities of EO data to provide the wave products identified by the sponsors are discussed in Section 4, and sumarised in Table 3. Section 5 provides a further evaluation of early products generated specifically for this GIFTSS project.

8.3 SAR DATA

The project sponsors requested a specific summary on the capability of SAR data, this is provided in Section 6 – although all sections have been updated to reflect the latest infomation available, and where necessary to add extra detail to answer specific queries from the sponsors. As the project progressed it became apparent that the state of the art (at least with regard to capability that exists in the UK) was not as far advanced as the sponsors had initially understood. Thus to fully satisfy sponsor requirements some longer term capacity building would be required.

8.4 FINAL COMMENTS

The approach taken by the project team has been to give an honest, "warts and all" appraisal of the wave products that can be derived from satellite measurements. However, whilst the limitations of the various data products have been discussed in detail, this should not detract from the fact that EO data can play a very important, central, role in a service which provides monitoring and assessment of the sea state conditions in the NW Approaches to the UK. One should always bear in mind the limitations of non-EO sources of infomation (Section 3), and the fact that often satellites provide the only source of directly measured information on wave conditions.

Section 7 outlines a vision for a service which would provide climate analyses based on EO data, and a NRT monitoring system which integrates input from satellites, models and in situ instrumentation. This section also provides an initial suggestion as to how this system could be implemented. The data product proposed for Phase 2 would allow this implementation plan to be fully assessed in terms of costs and benefits, and so lead to a more detailed, costed recommendation for the implementation and development of a NW Approaches Sea State Monitoring System.

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GLOSSARY

ADEOS	Short lived (1996-97) Japanese EO satellite
AES-40	40 yr North Atlantic Wave Climatology, developed by Oceanweather
AGU	American Geophysical Union
ALOS	Japanese Earth Observing satellite, with L-band SAR (built for land observation). Was due for launch in 2004
AMI	Active Microwave Instrument (ERS-1 and ERS-2)
AOI	Area of Interest (56°-64°N, 10°W – 1°E)
ASAR:	Advanced Synthetic Aperture Radar (carried on ENVISAT).
Azimuth	Orthogonal to direction of SAR look, for side looking SAR - along track direction
BNSC	British National Space Centre
BOOST	Young French SME, based in Brest, with SAR expertise
Bragg /scattering:	Scattering of incident radar signal of similar wavelength to facets on the reflecting surface (in this case, ocean waves – cm scale)
C-Band	Radar frequency / wave length range (for both altimeters and SAR) ~ 4-6 GHz
CERSAT	IFREMER laboratory dedicated to processing and archiving of satellite data - Centre ERS d'Archivage et de Traitement (http://www.ifremer.fr/cersat/en/index.htm)
DEFRA	Government Department for Environment, Food and Rural Affairs.
DLR	Deutsches Zentrum für Luft und Raumfart (German Space Agency).
DMC	Disaster Monitoring Constellation. SSTL constellation of optical satellites.
DMI	Danish Meteorological Institute
EC	European Community
ECMWF	European Centre for Medium-Range Weather Forecasts
EM	Electro-Magnetic
ENVISAT:	European Environment Monitoring Satellite, launched 2002.
ENVIVIEW	Software distributed by ESA to view ENVISAT data products, (including ASAR wave mode)
ENVIWAVE	EC "Framework" project to develop ocean wave products from ENVISAT.
EO	Earth Observation
EOF	Empirical Orthogonal Function. Technique to identify modes of variability in a data set.
EOLI	Online catalogue for ERS and ENVISAT data
ERA-40	ECMWF Re-Analysis. 40 year atmospheric hind-cast
ERS-1:	1st European Remote Sensing Satellite (launched 1991)
ERS-2:	2nd European Remote Sensing Satellite (launched 1995)
ESA	European Space Agency
FFT	Fast Fourier Transform
FNMOC	US Fleet Numerical Meteorology and Oceanography Center
FOAM:	Forecasting Ocean Atmosphere Model. Ocean circulation model at the UK Met. Office
FOIB	Faroes Oil Industry Group
FPSO	Floating Production, Storage and Offloading Installations
(EC) Framework Programmes	A series of EC science and technology support programmes
GAMBLE	An EC "Thematic Network", led by SOS to review future requirements for satellite altimetry.
Geosat	US Navy Altimeter Satellite (1985-90).
GIFTSS	Government Information from the Space Sector – BNSC programme to help UK government agencies implement information that has been derived from satellites

GFO	Geosat Follow-On - Follow on to Geosat (1998-)
GKSS	Large Publicly funded German Research Organisation, The Institute for Coastal Research is based at Geesthacht
GNSS:	Global Navigation Satellite System
GPS:	Global Positioning System.
GRIB	Data format e.g for meteorological data as distributed on GTS
GROW	Oceanweather's global wave model
GTS	Global Telecommunications System – used by national met agencies to transfer/ exchange data.
HSE	Health and Safety Executive
HF	High Frequency
HH	Horizontal polarisation of incident and reflected radar waves
IFREMER	French Government Oceanographic Research Institute (Institut Francais de Recherche pour l'Exploitation de la Mer
IM	Image Mode
ITT	Invitation To Tender
Jason:	Ku / C-band altimeter launched in December 2001.
Jericho	BNSC "LINK" project led by SOS to investigate possible consequences of a changing coastal wave climate.
JONSWAP	JOint North Sea WAve Project – a wave spectrum developed for fetch limited waves.
Ka-Band	Radar frequency band (18-40 Ghz), proposed for new technology satellite radar altimeters
KNMI	Royal Netherlands Meteorological Institute
Ku-Band	Radar frequency band (12-18 Ghz), commonly used by satellite radar altimeters
L-Band	Radar frequency band (0.39-1.55 Ghz or 20 cm), proposed for some new SAR satellites.
Level-0, 1, 2	Categories of data according to level of processing - Level-0 represent raw instrument output, level 2 data processed to provide geophysical parameters, with location and time.
MARSAIS	Marine SAR analysis and Interpretation System. EC framework programme to develop a generic SAR processing tool for Coastal Applications
MaST	Maritime Surveillance Tool. QinetiQ tool for analysing SAR data.
MAWS	Marine Automatic Weather Station (acronym for UK Met Office Buoys)
MAXWAVE	An EC framework research programme investigating the physics and occurrence of rogue waves.
Météo France	French National Meteorological agency.
MIROS	Wave radar (supplied by MIROS AS – A Norwegian company)
MTF	Model Transfer Function
NAO	North Atlantic Oscillation (Index)
NASA	(USA) National Aeronautics and Space Administration. USA's space agency.
NCEP:	(USA) National Center for Environmental Prediction
NDBC	(USA) National Data Buoy Center
NOAA:	(USA) National Oceanographic and Atmospheric Administration
NRT	Near Real Time
NWP	Numerical Weather Prediction
NORUT	Norwegian Research Group, of not for profit companies, based in Tromsø
Nyquist Freq.	The cutoff frequency above which a signal must be sampled in order to be able to fully reconstruct it.
ODGP2	A 2nd generation ocean spectral wave model used by Oceanweather.
Oceanweather	USA marine met-ocean company
OWI-3G	Oceanweather wave model (3rd generation)
PRI	ERS SAR product (Precision Image product)

Quikscat	Ocean wind measuring radar scatterometer. Launched in 199 by NASA to replace instrument lost when ADEOS failed
RadarSat	Canadian commercial SAR satellite – to be replaced by Radarsat-2 in near future.
RAR	Real Aperture Radar
Range (direction)	Along direction of SAR look, for side looking SAR - across track direction
SAR:	Synthetic Aperture Radar
SARtool	A tool for processing SAR data (ERS, Radarsat and ENVISAT), developed by BOOST
Scatterometer	Satellite radar instrument to measure ocean surface wind
Seasat	The first marine EO satellite, launched in 1978. Had a scatterometer, altimeter, SAR and radiometer.
Seawinds	The scatterometer instrument on board the Quikscat satellite.
SOC	Southampton Oceanography Centre
SOS	Satellite Observing Systems (UK)
SSTL	Surrey Satellite Technology Limited (UK).
SWIMSAT:	A (French) proposal for a satellite -borne wave measuring radar.
TerraSAR	German X-band SAR satellite to be launched in 2006.
TOPEX/Poseidon:	Ku/C band altimeter launched in 1992 by CNES/NASA
UKMO	United Kingdom Meteorological Office.
VOS	Voluntary Observing Ship (Programme) – agreement through which (mostly visual) ship observations are recorded and archived.
VV	Vertically polarised incident and reflected radar signal.
WW3	Wavewatch 3 – A 3rd Generation wave model used by NOAA.
WAM:	A widely used computer model for wave generation, propagation and dissipation
WAMDI	Wave Model Development and Implementation Group
WAMOS	An X-band directional wave radar
WM	(for SAR) Wave Mode.
WMO	World Meteorological Office
X-Band	Radar and communications frequency band (5.2-10.9 Ghz)

Mathematical Symbols and Terms:

$C_{g,p}$	wave group speed, wave phase speed
f	frequency
F(f,□)	frequency spectrum
g	gravity
g_{ii}	term for polarisation dependant modification of Fresnel coefficient
G(f,□)	directional distribution
H_s, SWH	significant wave height
i	polarisation
k	wave number
I(k)	intensity spectrum
l(k)	image spectrum
m	tilt component of modulation of radar cross section
m_0, m_1, m_2	zeroth, first and second order moments of the wave spectrum
mss	mean square slope
R	range (from antenna to target)
s	wave speed
sd	standard deviation
se	*standard error*
Sig_{stp},*SS*	*significant steepness*
S_m	polarisation dependant term in tilt modulation function

$S_h(k)$	surface height spectrum
$S_s(k)$	ocean wave slope spectrum
$T_{m,p,z}$	mean, peak and zero up-crossing wave period
$T^{hydro}{}_m$	hydrodynamic term for modulation of radar cross section
$T^{tilt}{}_m$	tilt term for modulation of radar cross section
$T_x(k)$	range shift in MTF
$T_y(k)$	azimuth shift in MTF
RMS:	root mean square (a measure of data scatter)
rrms	residual root mean square (after applying calibration)
SWH:	significant wave height.
U_{10}:	wind speed referenced to 10m above the ocean surface
V	platform velocity
v^2	variance of sea surface
x	range
y	azimuth
□	wind growth rate (of Bragg waves)
□	JONSWAP peakedness parameter
□	incidence angle
□$_1$,□(f)	dominant wave direction (at specified frequency)
□	wavelength
□	correlation coefficient
□^{0}	Surface Radar Backscatter, at nadir incidence.
□	angle from azimuth direction (horizontal projection)
□$_{mean,peak}$	mean, peak, wave direction
□	wave frequency (radians)

ANNEX A WAVE PARAMETERS

WAVE LENGTH/WAVE HEIGHT SPECTRUM.

We assume the wave number or wave frequency spectrum is meant; i.e. the distribution of wave energy as a function of wave number or of wave frequency. (In practice the distribution of surface elevation squared, which is proportional to energy.) If directional information is available then the 2-dimensional spectrum is usually given in terms of wave number, if it is a non-directional spectrum then it is usually given in terms of frequency.

Wave number, k, and wave frequency, ω (radians), are related by the dispersion relationship, which in deep water is $\omega^2=gk$.

Wave length and wave period are given by $\lambda=2\pi/k$ and $T=2\pi/\omega$.

WAVE DIRECTION

Given a directional spectrum, the peak (or dominant) direction is that in which the wave with the maximum spectral energy is travelling. Often there are two local maxima, one at a relatively high wave number ('wind sea') and the other at a lower wave number ('swell'); then both sea and swell directions can be given. The term 'average direction' is not normally used.

SIGNIFICANT WAVE HEIGHT

This is given by 4v where v^2 is the variance of the sea surface elevation (which can be estimated either from a time record, such as a 17-minute buoy record, or from a spatial record, such as a radar altimeter return from a footprint of about 7 km diameter). It is assumed that the sea state is stationary over the time or space sampled.

The force of a wave on a ship or fixed structure depends on the height (crest to trough) of the individual wave hitting it. The statistical distribution of individual wave height can generally be estimated from the spectrum, but there remain questions concerning the upper tail - i.e. concerning the very highest, extreme waves.

WAVE STEEPNESS

The steepness of an individual wave is defined by its height:length ratio - and is a factor affecting the force of the wave on a structure. By analogy, the term 'significant steepness', which is widely used to describe the general appearance of the sea, is defined by the ratio of significant wave height to a length obtained from the dispersion relationship and zero-upcross wave period (see below).

The significant wave steepness, *ss*, is given by

$$ss = \frac{2\pi Hs}{gTz^2} \approx 0.6406\frac{Hs}{Tz^2} \quad \text{with } Hs \text{ in metres and } Tz \text{ in seconds.}$$

In practice, the significant steepness is often expressed as 1/*ss*.

WAVE PERIOD (TZ AND TP)

For ocean waves, the period of an individual wave is either the period between the passing of one crest and the next or that between one upcrossing of the mean sea level and the next.

Tz is the average period between upcrossings; this value can be estimated from the moments of the non-directional frequency spectrum.

Tp is the period corresponding to the spectral frequency with the maximum energy. Plots of Tp often appear to be more erratic than Tz - since it involves estimating a maximum rather than spectral moments.

Other periods can be obtained from the spectrum, such as the average period between successive crests and the 'energy period' which, with significant wave height, gives the power being transmitted by the waves. But the force on a structure depends on the individual upcross wave period.

WAVE SPEED

The phase speed of an individual sine wave is the time for a crest to pass i.e. wave length/wave period. In deep water, using the dispersion relationship, gives that cp=g□/2□.

So, for example, a wave with the spectral peak frequency has a phase speed of gtp/2□. However, the energy in a wave train, which determines the travel time of swell across the ocean, travels at half this speed; so it is this speed, the 'group speed cg = g□/4□, that is of interest to forecaster.

The group velocity of the wave corresponding to that with the spectral peak frequency is given by

$$c_g = \frac{gT_p}{4\square} \square 0.781 T_p \text{ m/s} \quad \text{with } Tp \text{ in seconds}$$