GAMBLE

WP3 –Scientific/Technical theme 2 – sea-state error budgets, future detectibility

Intermediate Report

July 2002

1 - Introduction

This is the intermediate report for the 3rd work package of the GAMBLE project. It provides a first review of the present state of the art and of recent progresses in the use of altimeter data in oceanography, more specifically on the measurement of the sea state and related quantities.

The report is built as the assemblage of the contributions by different partners of the project. With a partial overlapping, each contribution focuses on a different aspect of the problem, highlighting the present achievements and what we can expect in the future. Given the target, i.e. what the users would like to have available, the practical possibilities are discussed, showing what can be obtained and the trade-offs imposed by opposing requirements.

Section 2 summarises the various contributions, briefly discussing the problems presently faced by scientists and users, the possible proposed solutions, what can be expected and how to get the best out of the data. Section 3 provides a summary of the present state of the art of altimetry, both for the basic principles and implied accuracy, and for applications. Section 4 is devoted to an analysis of the practical use of the altimeter data, and how this could be best achieved with different scenarios. Section 5 focuses on the great potential offered by the innovative use of altimeter for the measurement of the two dimensional wave spectrum. Section 6 briefly describes the Jason mission and the plan for the use of the data. On a separate section we provide a description of the state of the art of radar altimetry and some new concepts for the future developments of this instrument.

2 – Key issues

Altimeter data, for both wind speed and wave height, have been collected for more than a decade, making available an unprecedented volume of data. Key advantages have been the capacity of providing data in areas where virtually no measurement was previously available, and independently of the local wind and wave conditions. This wealth of data drastically improved the knowledge of the conditions to be expected in the sea, and boosted the publication of wind and wave atlases (e.g., the one by Oceanor, Norway). The assimilation of these data into the numerical models operational at the major meteo-oceanographic centres caused a substantial improvement of their skill, both for analysis and forecast products.

While all this sounds very good, problems still exist. However abundant with respect to the previous situation, the altimeter data are still relatively scarce on a global scale, with large gaps in space and time. An orbit with a return period of, e.g., ten days implies at each visited location less than forty data per year, with a gap of 2.5° between adjacent tracks. The number can double if we consider both the up- and down-going parts of the orbit, but this is not always the case. Of course the data are more dense along the track (one every 7 km), but in practice the sampling variability suggests to average these data on much longer distances, providing the so-called, more reliable but less frequent, super-observations.

Also the accuracy of these measurements is still an issue, more for wind speed than for wave height. Both the parameters have strong uncertainties in extreme conditions. This is exactly one of the areas where the users are posing their most pressing demands, particularly for offshore operations.

In the application to forecast models, while for wind the altimeter is complementary to the scatterometer (but it provides high frequency data along the track), it has been the basic instrument for the supply of wave height information. However, the impact of the altimeter is appreciable in a relatively narrow band on the sides of the ground track. The main drawback has been the lack of capability of singularly correcting, with data assimilation, the single wave systems that compose the two-dimensional spectrum at a given location. SAR data have been used and useful in this respect, boosting the development of techniques for the assimilation of the measured spectra. Apart from the computer resources required, and the consequent simplifications introduced for practical applications, an underlying objection has been that the extraction of the spectral information from the original signal requires an a priori knowledge of the spectrum, which is obtained from the model where the data are to be assimilated.

The knowledge of the conditions in coastal areas present a particular challenge. On one hand the altimeter cannot provide information very close to the coasts, the minimum distance being in principle half the diameter of the area sampled by the radar. Besides, when flying offshore, a few seconds are required for the instrument to lock again on the sea surface. In this case data are available only from 20-30 km offwards. On the other hand the spatial variability that characterises the coastal environment cannot be adequately sampled by a single altimeter.

One of the key issues for the improvement of the numerical wave model is a better knowledge, hence formulation, of the physics of waves, and of their interaction with the atmosphere. Waves are the interface that controls the fluxes between the two large systems, ocean and atmosphere, that in turn control the earth climate. A better knowledge of the involved processes is clearly highly desirable. However, the basic difficulty in studying the physics of waves , p.e. their generation by wind, is the characteristic of the processes of taking place as a sequence of single, highly concentrated, events, but sparse in space and time. Therefore a satellite can only detect the integrated effect, and be used as the verification tool of a numerical model trying to represent the physical truth. While this approach can be very effective, it is potentially hampered by the much larger distances over which the altimeter data are presently available. It is also clear that the single knowledge of H_s is a rather crude information, and the availability of the two-dimensional spectrum is highly desirable.

From the above it is clear that there is still plenty to do. We need to improve the altimeter information both as quantity (number of satellites) and quality (wave spectra). As discussed later, ad hoc solutions, with synergy with other systems, are required in coastal areas.

GANDER, discussed in more details in section 4, is the obvious solution for quantity. The twelve proposed satellites imply a corresponding increase of the available information, solving some of the points just discussed. The question becomes the optimisation of the orbits. The choice depends on the use of the data. For analysis and forecast purposes it is relevant to have the data covering all the oceans. However, no particular constraint exists about the return period and an exact determination of the orbit, provided no area is left unvisited for too long. If the focus is on climatology, we can choose sampling more frequently certain areas (short return period), providing highly reliable results at only part of the sea surface. Alternatively, a longer return period would provide less data per point or area, but with a very dense distribution. The number of satellite proposed for GANDER allows a trade-off between the two approaches. Three satellites on each of four equally separated orbital planes, or six ones on each of two planes, would satisfy both the requirements.

The value of the information available from GANDER would be highly enhanced if coupled with information on the spectral distribution of energy, as it could be provided by SWIMSAT, without any a priori knowledge of the spectrum. Extensive tests, described in section 5, have clearly shown the advantage of assimilating into the operational wave models directional information rather the single wave heights. On one hand, in principle this allows a correction of the model first guess for every wave system that is part of the spectrum. Generated by different, and often distant, storms, each system is represented in the model with a different level of accuracy. As the tests have shown, a specific correction has a much longer lasting effect on the quality of the forecast. Perhaps the greatest impact will be on swell, frequently the most difficult part of the forecast because of its generation at previous times and often far distances. On the other hand the system, and the model, have a long lasting memory for swell. Therefore any correction in the frequency part of the spectrum will have a positive impact not only locally, but also in the areas where the swell is propagating.

Providing all the required information in coastal areas is quite a different matter. The spatial variability of the wind and wave conditions close to the coasts is such that no presently conceivable satellite system can supply the required data. On the other hand the narrow band of sea that borders the continents, with their full and complicated geometry, is where most of the economical and safety issues are concentrated. The solution can only be a synergy among complementary systems. The combined use of global or large scale meteorological and oceanographic models will supply the conditions offshore, where, although affected by the continents, the conditions do not show yet the variability that will characterise them once closer to coasts. This offshore information can be the input to local high resolution models, possibly complemented with local measurements, e.g. radar or buoys. Clearly, in general this (especially the measurement part) is not possible on the whole coastline, but it is certainly feasible for specific locations of interest. The vision we anticipate for the future is a continuous sequence of local scale high resolution models all along the coasts, complemented here and there, where necessary or required, with local measurements. It is not excessive to stress the role of the altimeter data in such a system. A local model can provide correct results only as far as the input data are correct. Particularly in continental areas, the present global model results (U_{10} and H_s) are often underestimated. Altimeter data are essential to provide a necessary reference for their correction and assimilation.

The climatological use of altimetry requires continuity in the measurements. Given the limited time span of each mission (although ERS and especially T/P were successful beyond expectations), and to avoid multiple and complicated calibration campaigns, an overlap of the different missions is highly recommendable. The almost twelve consecutive years provided by ERS1-2 and T/P have been taken over by ENVISAT and by Jason-1, a follow up of T/P. Jason-1 has a similar set of instruments as T/P, but with a much reduced weight and volume. It is planned to be followed by Jason-2 in 2005.

While the conventional nadir looking altimeters have provided a wealth of data previously unknown, new concepts are being proposed that will greatly increase the possibilities offered by the instrument. The new concepts act both on quantity, the obvious example being the mentioned GANDER, and on innovative techniques. SWIMSAT has already been mentioned, and the availability of wave spectra will substantially improve the quality of the wave forecast. The delay doppler altimetry (the WITTEX proposal) will have the capability of sampling small cells within the altimeter footprint combining the signal from three mini satellites flying with a short separation along closely parallel ground tracks. Altika proposes a low cost Ka-band integrated altimeter/radiometer, with the capability of a noise reduction that would allow the detection on the ocean surface of shorter wavelengths than it is presently possible, and a better performance when approaching or leaving coastal boundaries. This would be extremely important for all the coastal studies, as we have discussed above. WSOA (Wide Swath Ocean Altimeter) aims at solving one of the main limitations of the present altimeter data concerning the ocean circulation. In order to map ocean mesoscale phenomena adequately, it is necessary to be able to resolves phenomena that are on the order of the Rossby radius of deformation (30 km or more). The corresponding lifetime is on the order of a month. A simple nadir looking signal would not be able to visit adequately a region to follow the evolution of such systems. WSOA proposes to supplement a conventional, although improved, altimeter with an interferometer. This would allow sampling the surface with between 100 and 670 m cross-track resolution, and 13.5 km in the along-track direction. Still reduced to the average every 15 km for noise reduction, the resolution would be sufficient for the detection of the small surface features, while the 200 wide swath would ensure visiting the same area frequently enough to follow the evolution of the circulation systems.

More futuristic concepts are the inclined swath altimeter and the GPS altimetry. The latter one would provide the same data of a conventional altimeter, but making use of the signals emitted by the GPS satellites and reflected by the sea surface. The echoes would be recorded by “parasitic” cheap satellites. The concepts are very promising, but still at the level of study, not feasible for a mission before 5-10 years from now.

3 - Wind and Waves

While the primary mission of altimeters over the oceans is the measurement of sea surface height, the measurement of ocean winds and waves by satellite altimeters is a major additional benefit. In addition, the effect of sea state on retrieval of sea surface height, so-called "sea state bias", requires consideration of the wave field for the primary mission. In this section, we summarise the many potential uses of wind and wave data, the characteristics and quality of altimeter data, and the main factors determining satisfaction of end-user requirements for both current missions and possible future missions.

3.1 - Background and Key Issues

The oceans are essential to mankind both for everyday commerce and for their role in moderating climate. Wind and waves directly affect both commerce (e.g., disruption of trade, oil production and fishing by storms) and climate forcing (through their relationship to atmosphere-ocean fluxes [Jones and Toba 2001]). Where accidents do occur due to storms, there is often a severe risk of pollution. The oceans are also increasingly seen as a source of renewable energy, with wave and offshore wind prominent in development plans.

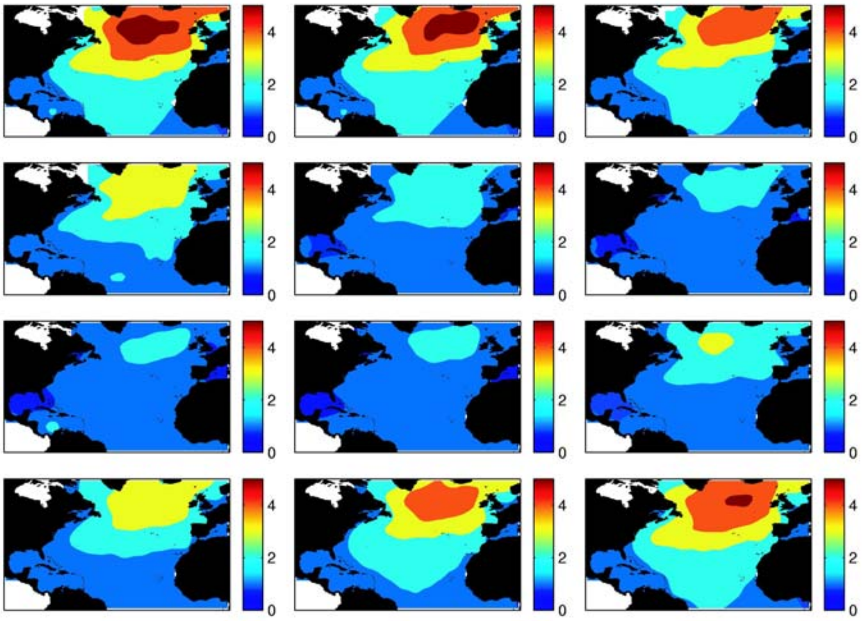


Figure 1. Mean significant wave height in the North Atlantic in each month (units: metres). Top row, left to right: January, February, March; continuing to December in bottom right. [Woolf et al. 2002a].

One of the main practical applications of wind and wave data derived from altimeter measurements is the production of reliable atlases of wind and wave climate [Young and Holland 1996]. An example is given in Figure 1. Scientific applications include validation of meteorological hindcasts [Sterl et al. 1998; Woolf and Challenor 2002] and as the basis for flux climatologies. Commercial applications include evaluation of wind and wave energy resource, and evaluation of risks to shipping, marine structures and coastal defences.

Applications of individual orbit data, especially real-time data, include assimilation into the forecasts produced by operational meteorological and wave models operational at various centres (e.g., the European Centre for Medium-Range Weather Forecast, Reading, UK) and as part of a weather warning system to shipping [e.g., http://www.satobsys.co.uk/WWWaves]

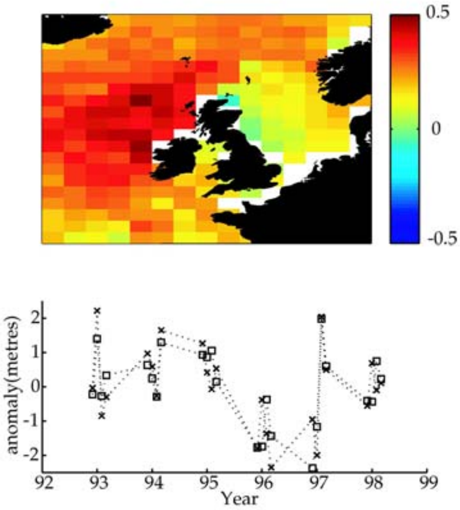


Figure 2: The relationship of inter-annual variability in mean monthly wave heights during the winter months (December - March) to the North Atlantic Oscillation. The upper panel maps the apparent sensitivity of mean monthly wave height to the NAO index (units are metres/unit NAO index). The lower panel shows the measured anomaly in wave height (crosses) and that implied by the NAO index (squares) at the edge of the Hebridean shelf (57^o-58^oN, 8^o-10^oW). [Woolf et al. 2002b]

Where long-term altimeter records exist, e.g., the continuous 10 years dataset from Topex/Poseidon, altimeter wind and wave information can also serve to monitor inter-annual and decadal variability of the atmospheric forcing and the response of the ocean. As well as monitoring its temporal variability, the global capabilities of spaceborne altimeters allow changes in spatial distribution to be detected. Thus, it is possible (see Figure 2) to establish an association between variability in the North Atlantic wave climate and the North Atlantic Oscillation [Woolf et al. 2002a, 2002b]:

3.2 - Measurement Principles

Estimates of wind and waves from altimeter data originate in analysis of the return from the sea surface. A purely theoretical analysis of altimeter return signals can lead to significant uncertainties, and calibration against *in situ* wind and wave data is recommended [Challenor and Cotton 2002]. The back scatter, σ_o, from the sea surface is mainly sensitive to small scale surface roughness (short ocean waves), and since these respond rapidly to the local wind, σ_o is the primary variable used in estimating wind speed [e.g., Witter and Chelton 1991] or wind stress. However, σ_o is also sensitive to much larger waves that are only related weakly to the local wind; therefore some recent algorithms for wind speed [Gourrion et al 2000; Gommenginger et al 2002a] also include the altimeter estimate of significant wave height.

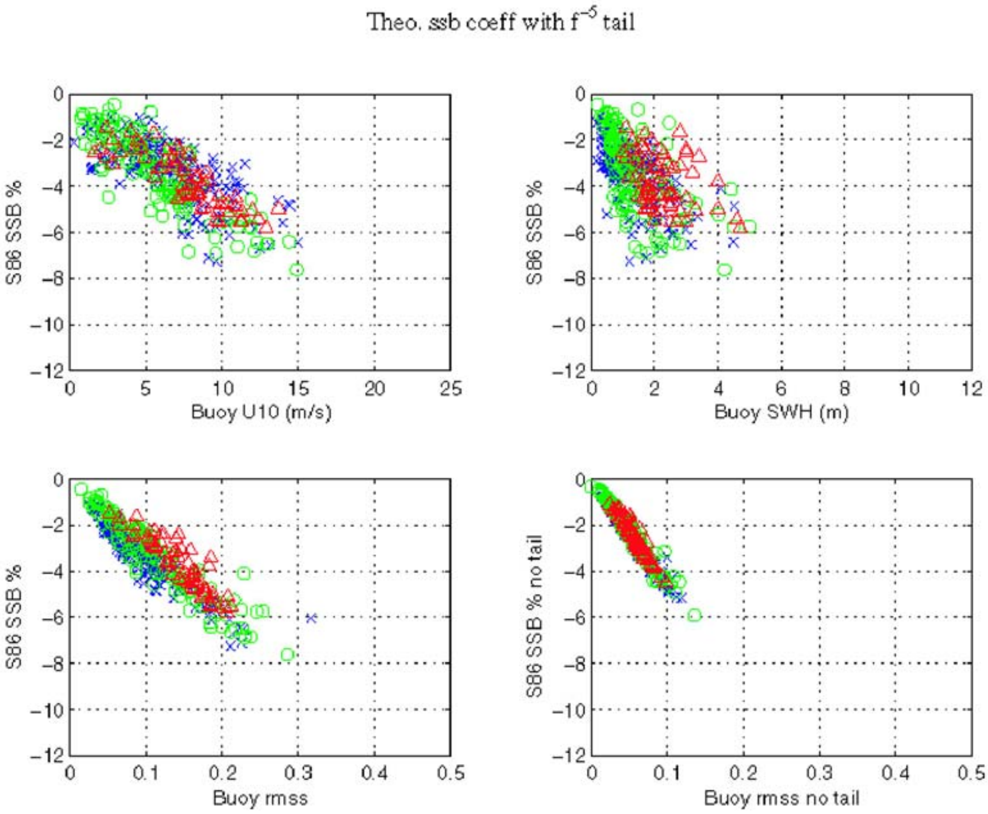


Figure 3: Theoretical SSB coefficient after Srokosz [1986] for NDBC directional spectra against (a) buoy wind speed, (b) buoy SWH (c) buoy rms slope in the case of an f^5 tail extension, and (d) in the “no-tail” case against rms slope. Key to symbols: ‘x’: G.Mexico (42002), ‘o’: Virginia Beach (44014), ‘Δ’: Hawaii (51026).

Significant wave height (SWH) can be estimated due to the blurring of the leading edge of the return pulse by large waves, since the radar signal can be reflected from both the troughs and peaks of waves. The sea surface height is usually estimated from the centre point of the leading edge. Estimates of sea surface height can be affected by the statistics of wave elevation and slope, resulting in an error known as "sea state bias" (SSB). Due to the presence of non-linear ocean waves, the mean sea level is underestimated [Srokosz 1986]. This error (see Figure 3) is currently corrected for in operational altimeters using an empirical dependence on the altimeter wind speed and significant wave height data [Gaspar 1994; Gaspar and Florens 1998], although more recent findings relate SSB more closely to the surface rms slope [Gommenginger et al. 2002b; Millet et al. 2002].

Additional wave properties that can be estimated directly by altimeter include wave period [Davies and Challenor 1997].

Calculation of wind and wave properties can also be affected by onboard processing of altimeter waveform data [Quartly 2000]. For wind speed and wave height, imperfections of the waveform and processing errors are generally not a major issue compared to other retrieval errors. However, some developments, e.g., study of the skewness of ocean waves, may require more precise waveforms and exact processing.

Each datum is a statistical value for an area of sea surface of approximately 10 km diameter. Overlapping of the footprint with land restricts use of data in coastal regions. There also tends to be a delay of tens of kilometres after the footprint leaves land before it satisfactorily "locks on" to the sea surface. Since each altimeter can only measure a single value at any one time (compared to many for an "imaging" sensor), a major issue is the sparse sampling by one or a few satellite altimeters. This is particularly significant for wind and waves (especially wind) which have short auto-correlation lengths (both spatially and temporally) making adequate sampling difficult. For climatology, the globe is divided into grid squares and for each orbit a single value of each variable is retained (the median of valid retrievals) for each grid square crossed. Grid square dimensions should not be larger than the auto-correlation length of the geophysical variable (otherwise the set of median values will not truly represent the climate), and particularly for wind speed this tends to lead to a very sparsely sampled climate for a single month or less.

3.3 - Expectations and Current Performance

Altimeter significant wave height (SWH) measurements have been shown to compare satisfactorily with collocated *in situ* buoy wave height estimates [Cotton 1998; Challenor and Cotton 2002]. Systematic bias is less than 0.1 metres and random bias on individual passes is ≈ 0.3 metres. There is a theoretical risk that a mismatch between the distribution of surface elevations assumed by the retrieval algorithm (gaussian) and the true statistics (non-gaussian in a steep sea) can produce an error in the estimated significant wave height. This error would be expected to require different calibrations between regions dominated by swell and regions dominated by steep wind-driven sea; but in fact, there is no convincing evidence that altimeter-buoy relations vary regionally. For SWH, the precision of current satellite radar altimeters is similar or better than that of wave buoys; both are sufficient for most purposes. Only the performance of both altimeters and buoys in extreme conditions is an outstanding concern. Calibrations against *in situ* data thus far have been limited to linear relations. There is some evidence of weak non-linearities. This may be an issue for extreme wave heights, and both the sparsity and reliability of calibration data for very large wave heights remains problematic. Systematic and random bias may be significantly greater than the general values for wave heights in excess of 10 metres.

Estimated errors in wind speed or wind stress retrieval from the altimeter remain stubbornly high. There are two main reasons why the accuracy of altimeters is generally poorer than for scatterometers. Firstly, there is less calibration data for altimeters. Secondly, altimeter back scatter is far more sensitive to long surface waves than is scatterometer back scatter. The algorithm of Witter and Chelton [1991] is still widely used, but one extensive study [Gommenginger et al 2002a] estimates a systematic bias in wind speed ≈ 0.3 metres/second and RMS errors for individual passes ≈ 1.5 m/s for this algorithm of TOPEX compared to collocated buoy data. The systematic bias can be eliminated with newly fitted algorithms, but an algorithm fitted to data in one region may lead to substantial biases in another region. Incorporating the estimate of SWH in algorithms can slightly reduce RMS error, to ≈ 1.3 m/s. The relation between the altimeter back scatter measurements and the ocean surface properties are not entirely resolved. Altimeter wind speeds include residual sea state effects [Glazman and Greyshuk 1993; Gommenginger et al. 2002a] that may lead to seasonal and regional biases (Figure 4). Even recently proposed altimeter wind speed models that include SWH [Gourrion et al. 2000] nevertheless display a residual dependence on wave age (Figure 5). At the same time, the widely used relation between wind stress and the ocean wave age has been challenged [Taylor and Yelland 2001] in favour of a dependence on wave height and wave length, both of which may be extracted from altimeter data [Davies and Challenor 1997]. Meanwhile, the availability of dual frequency backscatter measurements from the TOPEX altimeter has resulted in a number of studies into the retrieval of for example wind stress [Elfouhaily et al 1998] or rain rate [Quartly 1998], using nadir altimeter measurements. However, there is no convincing statistical evidence that using dual-frequency data improves the accuracy of wind speed or wind stress retrieval from TOPEX [Gommenginger et al. 2002].

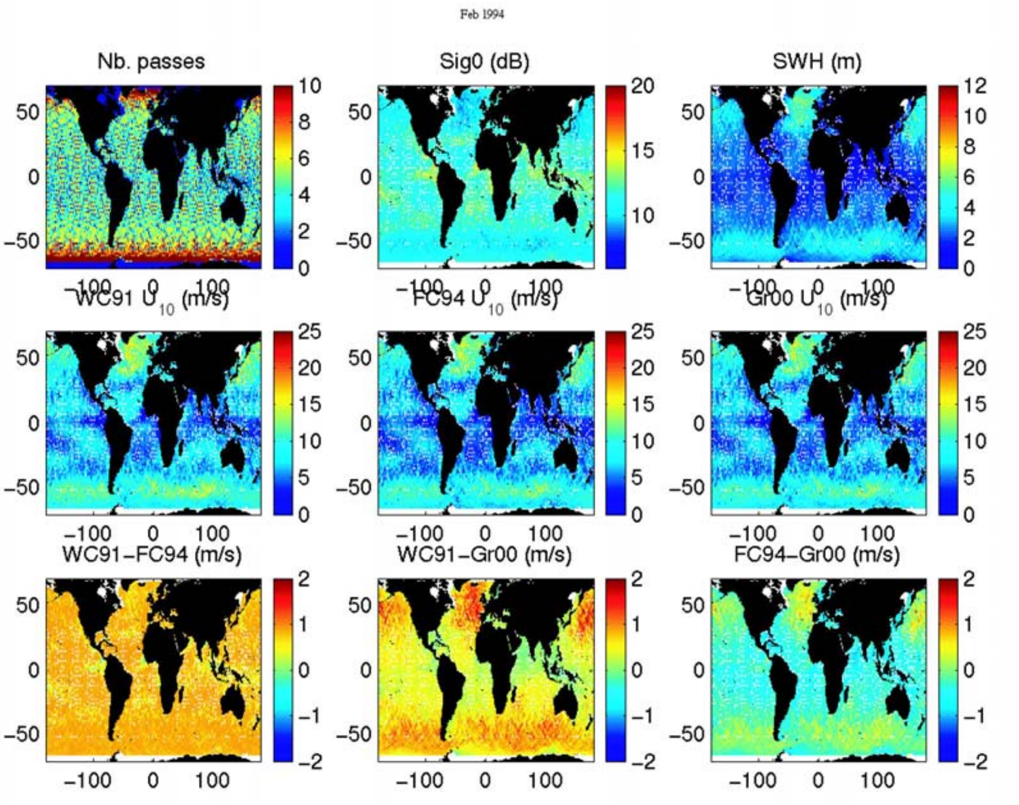


Figure 4. Global monthly (February 1994) averaged altimeter wind speed gridded over 1.5x1.5 degree boxes. Subplots from top left to bottom right show respectively (a) number of Topex passes, (b) altimeter backscatter at Ku-band, σ^0_{Ku}, (c) altimeter significant wave height at Ku band, (d) altimeter wind speed after Witter and Chelton [1991], (e) altimeter wind speed after Freilich and Challenor [1994], (f) altimeter wind speed after Gourrion et al. [2000], (g) = (d) - (e), (h) = (d) – (f), (i) = (e) – (f). In (i), see how the wind speed difference between the σ^0_{Ku}-only model by Freilich and Challenor and the (σ^0_{Ku},SWH) model by Gourrion et al. [2000] reaches up to 1 m/s in the monthly mean. This SWH effect is in addition to the wave age effect see in Figure 5. [Gommenginger et al. 2002c].

Another, possibly more critical, application of altimeter wind and wave data, lies in the need to correct the altimeter mean sea level measurements for sea state bias (SSB) error. The SSB error is the largest remaining error in the altimeter sea surface height measurements, and can easily obscure genuine ocean circulation feature as the height error can reach several percent of the significant wave height (e.g. 4% of 3 m SWH = 12 cm). The error in SSB estimates using current algorithms is difficult to assess but should be < 1% of SWH.

It is possible to retrieve zero-upcrossing period to an RMS accuracy of 0.5 seconds [Davies et al. 1997].

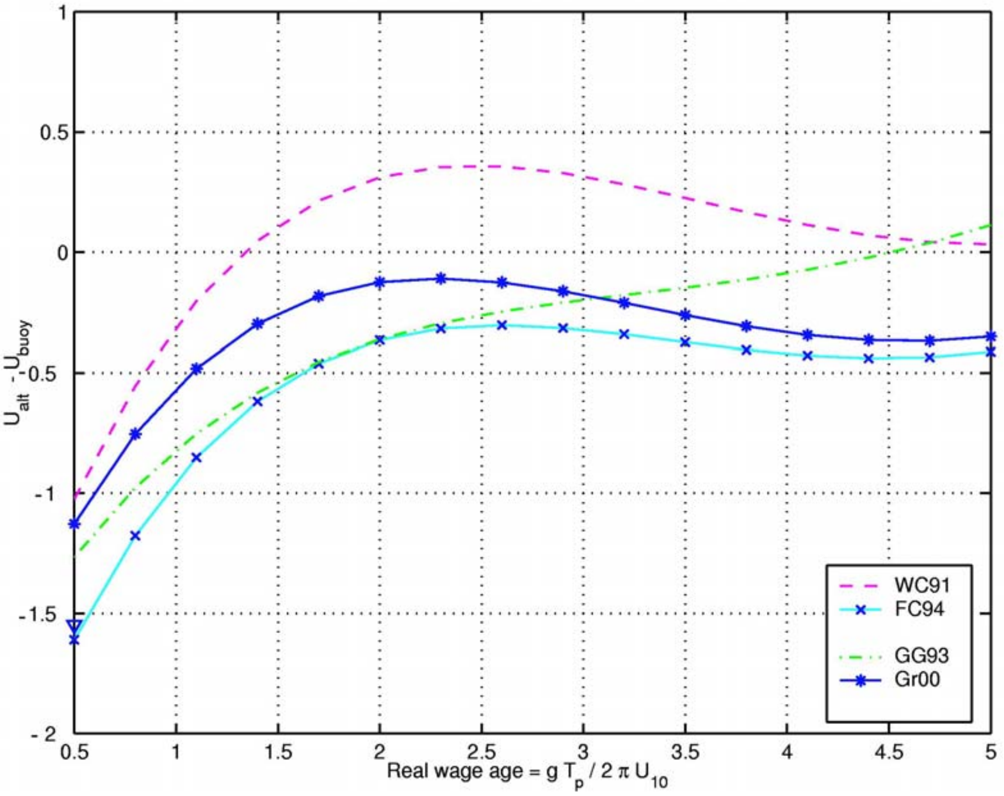


Figure 5: Residual altimeter wind speed error against wave age for a number of altimeter wind speed retrieval models. The trend was observed using a dataset of collocated Topex/buoy measurements [Gommenginger et al. 2002a] with available in situ information on wave period.

In climatology, the accuracy of individual estimates is secondary to the accuracy of statistics for a given region and season. Tokmakian and Challenor [1999] described a simple method for estimating errors in climatologies and Woolf and Challenor [2002] have applied this to gridded climatologies of monthly SWH statistics. The estimated error in monthly mean SWH for individual 4.5x4.5 degree grid squares from a single satellite is typically ≈ 0.2 metres (Figure 6), but is higher for smaller grid squares and in relatively stormy regions. This error is generally slightly lower than a simple estimate of the uncertainty in the mean based on an estimate of population variance and gaussian statistics (Figure 7). Higher moments of SWH statistics (e.g. inter-month variance) are yet more adversely affected by sparse sampling. Most of the limitations in satellite climatologies of SWH appear to arise from sparse sampling rather than inaccuracy in individual measurements.

While individual estimates of wind speed are poor compared to those of SWH, sparse sampling is again the greater problem for wind speed. Related estimates, e.g., gas transfer velocity [Glover et al. 2001], will also be adversely affected by sparse sampling. Wind speed estimates from altimeter on their own are not particularly important, where scatterometer data is also available. However, the unique combination of measurements of short and long wave roughness has a number of applications.

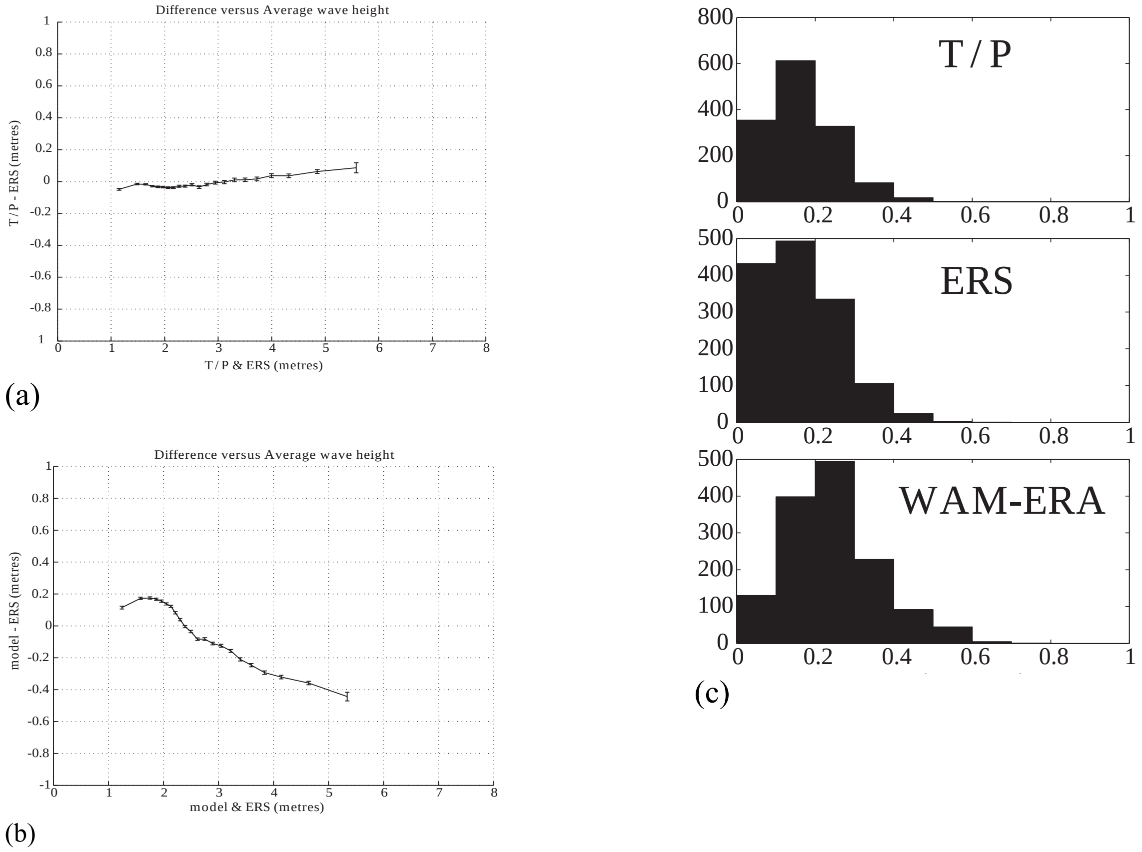


Figure 6. Errors in satellite and model climatologies: global study. (a) Systematic bias in monthly mean significant wave height between Topex/Poseidon and ERS-1 plotted against wave height (the average of the two estimates). (b) Systematic bias between WAM-ERA and ERS-1 plotted against wave height. (c) Histograms of estimated root-mean-square errors of each climatology from all grid squares common to all three climatologies. [Woolf and Challenor 2002].

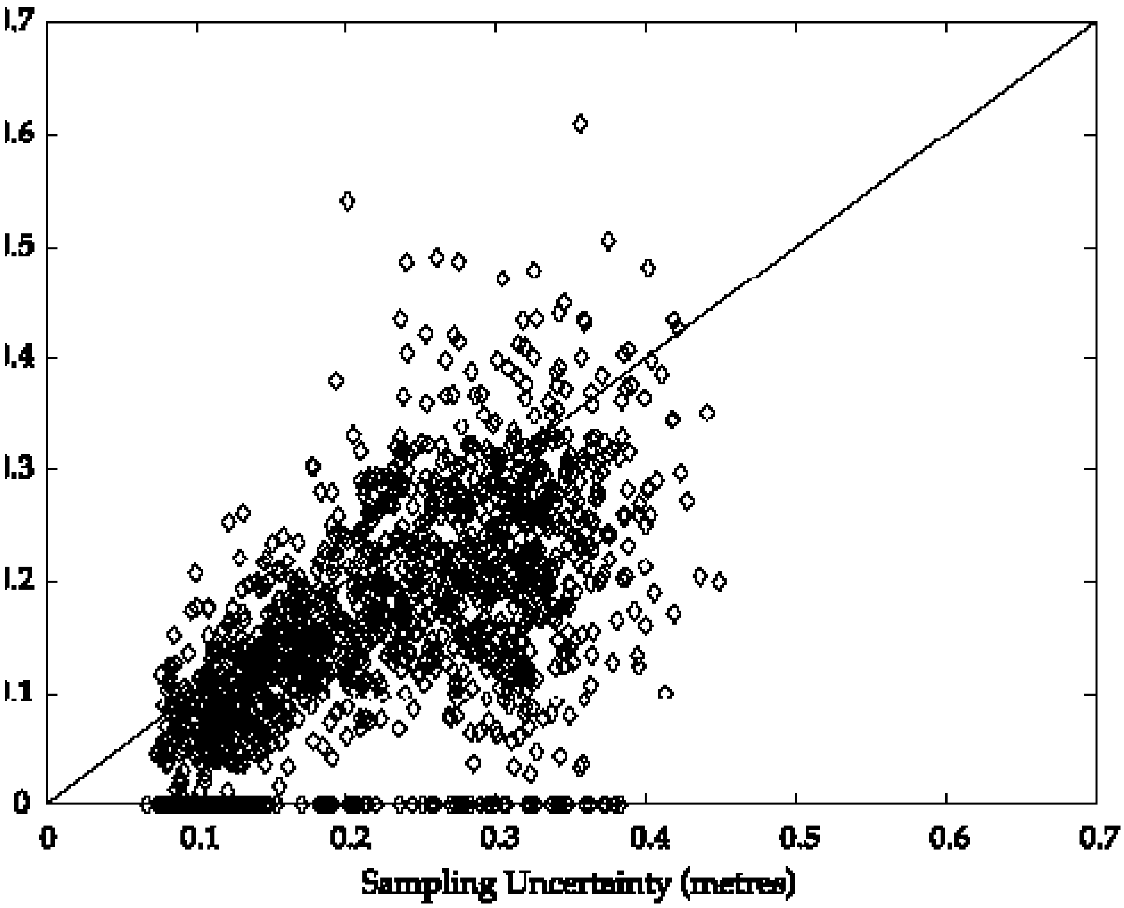


Figure 7. Estimates of root-mean-square error in ERS-1 values of mean monthly significant wave height in each grid square plotted against an estimate of "sampling uncertainty" calculated from the measured variability within each month and the number of samples of the particular grid square in each month. The diagonal line shows the 1:1 ratio of the quantities. [Woolf and Challenor 2002].

3.4 - Mission Characteristics

The outstanding characteristic for wind and wave climatology is the density of sampling. Sampling density can only be addressed substantially by increasing the number of satellite altimeters. There is a trade off between spatial and temporal sampling according to return period and therefore the period is not especially crucial for open ocean climatology. However, if the return period is reduced much below that of TOPEX/Poseidon (9 days 22 hours), there will be a large number of gaps in a gridded climatology. Nearer the coast, the sampling demand is much higher since wave climate will vary on much shorter scales. Gridded data is not suitable in this case and climatology must be calculated from repeated individual tracks. For coastal applications using a single satellite, a relatively short repeat cycle is more useful since at least a few locations are sampled adequately, but this leaves large unsampled swathes. A constellation ~12 altimeters uniformly spaced on a common orbit of repetition ~35 days would give reasonable spatial and temporal sampling. In the open ocean, an accurate orbit is not crucial, but nearer shore exact repetition (<5km) of orbits is fairly important.

Application	Parameter	Critical Steps, Auxilary Data	Relevant Future Developments	Main F	Second F	Altimeter Type	Mission characteristics			
							Constellation type	No sats	Repeat cycle	Accurate orbit
Wind and Wave Climatology	Wind speed, wind stress, significant wave height, wave period, wave power	In situ validation data	Improvements in waveform Validation networks Bistatic Directional capability	Ku	C or S		Relatively unimportant	Most Important	Compromise of spatial and temporal resolution	Only important near coasts

3.5 - Future Developments

Improvements or elaborations of the basic altimeter concept are of only secondary importance to increasing the number of satellite altimeters. It should be noted that wide swath altimeters such as WSOA do not measure wave height across the swath. However, some useful developments can be identified.

The quality of the waveform on current altimeters is generally adequate, but improvement may benefit relatively demanding wave applications such as estimating the skewness of sea surface elevation.

The measurement of RMS slope from altimeter would be useful, for example for SSB and gas transfer velocity applications. Elfouhaily et al (2001) have suggested a method relying on the Doppler-delay spectrum in GNSS bistatic configurations.

Validation data from meteorological buoys is a continuing need, and future deployments in more remote regions (e.g., Southern Ocean) would be helpful.

Development of a directional capability (suggestions include a rotating near-nadir beam, and a "knife-edge" beam) would open up new applications.

4 - Observations on the use of satellite altimeter wave measurements for offshore operations

4.1 - Introduction

We can separate the applications of altimeter wave data for offshore operations into two types – listed below with some suggested key issues:

- *Near Real Time Applications*
  Combination with other data sources – models, HF Radar, in situ (buoys, ships).
  Accurate representation of severe conditions.
  Difficulties in monitoring high frequency small scale variability close to coasts.
  Higher accuracy requirements from operational users.

- *Climatological Applications*
  How to include year to year variability in statistics.
  Including tropical cyclones etc in statistical data bases.
  Need to estimate very low probability occurrences.
  Accurate measurements and estimates of extreme values.

Near real time applications will typically involve data from a number of sources – possibly including assimilation into wave models. Users will use this information to aid short term planning and on site decision making. Climatological data are used for vessel, platform and operations design, and for longer term planning (e.g. to identify the likely occurrence of suitable "weather windows"). Again data from a variety of sources may be used, satellite data, ship/buoy data, and long term (> 10 year) wave model hindcasts.

The EC COMKISS study (Cotton et al, 2000c) considered how satellite data could be better used in both types of applications. Some of the recommendations will be discussed here, but the reader is referred to the project web site for more detailed information (http://www.satobsys.co.uk/Projects/Comkiss/index.html)

4.2 - Near Real Time Applications

The COMKISS study concluded that many offshore users require higher accuracy sea state forecasts than are provided by the present sources. Problems are encountered when unexpectedly severe conditions occur. Many forecast sources now have an impressive reliability, but the few occasions when they fail are often during severe events when the consequences are the most serious. It is perhaps surprising that it is difficult to find statistics on the level of reliability with which particularly severe conditions are predicted.

The main requirements for improved provision, for offshore users, are:

- Improved resolution in coastal regions (ideally 3 hourly, < 10km – obviously cannot be satisfied by satellite measurements alone, but requires combination of techniques).
- Improved provision in semi-enclosed areas where wave models can be deficient.
- Increase temporal and spatial coverage offshore, by at least one order of magnitude.
- Separate information on wind sea and swell.
- Wave Direction and period information.

Grant et al. (1995) summarised the particular requirements of sea state and current information for floating platforms (perhaps one of the most important new developments in offshore exploration). Priorities are:

- wave period relationships (Tz (Zero upcrossing period) and Tp (peak period)
- wave steepness
- wave spreading and directionality
- wave spectral formulations
- extended scatter diagrams (i.e. 2D histograms - significant wave height against wave period).
- assessments of the joint occurrence of winds, waves and currents.

They also noted that the lack of long term simultaneous wind, wave and current data was a problem, because there was a requirement for joint probability statistics. In particular there was a noted lack of surface current data.

Satellite data in Operational Wave models

Many operational wave models now incorporate altimeter wave data through assimilation schemes – e.g. UKMO, ECMWF, Méteo-France and NCEP (USA). See various papers by Bauer et al. (1992), Guillaume and Hansen(1993), Hauser(2001), Komen et al. (1994), Lefevre and Cotton (2001), Lionello et al (1992), and many others. All agree that assimilation of wave data has a beneficial impact on wave models, improving the analysis and forecast close to the time and location of the assimilated data. However, the significance of the impact is limited in time and space, by the nature of the sea state – it appears that swell is more affected by assimilation than locally generated wind sea, and also by the type of assimilation scheme that is used.

Lefevre (1992) found that the impact of assimilation was significant for short range forecasts (up to 2 days) in windy areas and for medium range forecasts (3-10 days) in areas dominated by swell. Komen et al. (1994) assessed that impact of assimilation was reduced in one day by a factor of three in the tropics and a factor of four on the whole globe. Impact is reduced by a factor of 10 after 5 days in the tropics and after two days globally.

Guillaume and Hanssen (1993) analysed the spatial extent of the impact of assimilating ERS-1 data during a single 6 hour period. They found an impact ~5° either side of the altimeter track.

Thus it seems that a single satellite can only impact a very limited area of the world's oceans in a wave model assimilation scheme, and that this impact will be lost significantly (if not completely) by the time the altimeter revisits (> 3 days).

GANDER

Satellite Observing Systems (SOS) proposed the GANDER multi-satellite mission as a way to provide a global operational near real time monitoring system for ocean sea state. As part of the feasibility study for the GANDER satellite proposal SOS initiated studies with Environmental Systems Science Centre (ESSC) to determine the best orbital arrangement for a constellation of satellites to capture variability in sea state fields (Cotton et al, 2000a).

Orbits Study

Specifications for the study were.

- 12 operational satellites.
- 4 orbital planes maximum.
- Sampling must at least reach 70°N.
- 800 km orbit assumed for this study - acceptable range 600-1000 km.

The study was based upon an analysis of orbital patterns and sampling of the ECMWF model hindcast wave fields, 6 hourly intervals, 1° x 1° grid 1993-94, and 1997-98.

The study analysed the sampling of the wave fields within 5 scenarios:

1) 2 planes, 6 per plane 180° plane separation 72° inclination.
2) 12 planes, 1 per plane evenly separated 72° inclination.
3) 2 planes, 6 per plane 90° plane separation sun synchronous.
4) 4 planes, 3 per plane 90° plane separation 72° inclination.
5) 4 planes, 3 per plane 90° plane separation sun synchronous

Characteristics of wave fields associated with Northern Hemisphere storms

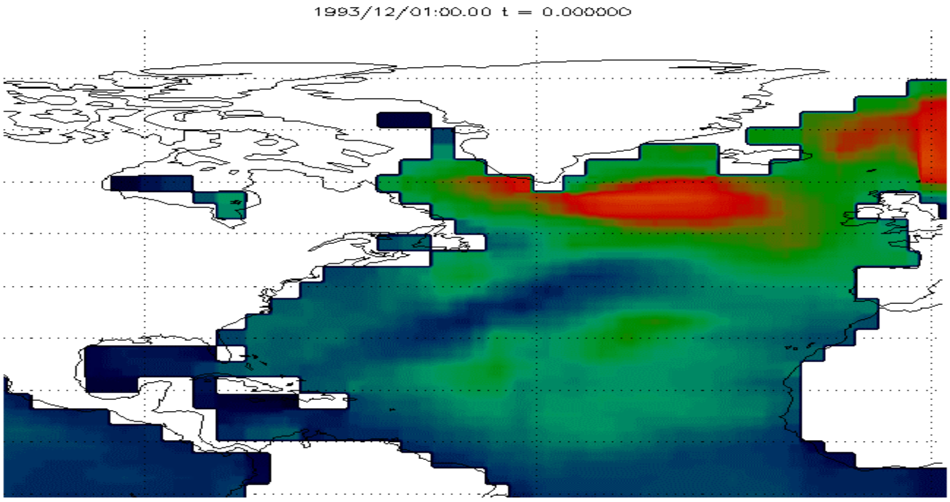


Figure 1 ECMWF 1 degree 6 hourly modelled wave height data.
The regions of high significant wave heights (>5m) are shown in red.

Figure 1 gives an example of the significant wave height field at one model forecast time step. General characteristics are:

- High significant wave heights (> 5m) cover large areas.
- Significant variability exists on short time scales (6-24 hours). (Note with a 6 hr time step it is not possible to assess variability on time scales less than 6 hours)
- Highest variability occurs in the 40°-60° latitude band.
- Winter storms are more intense and quicker moving (but not more numerous).

Sampling Patterns

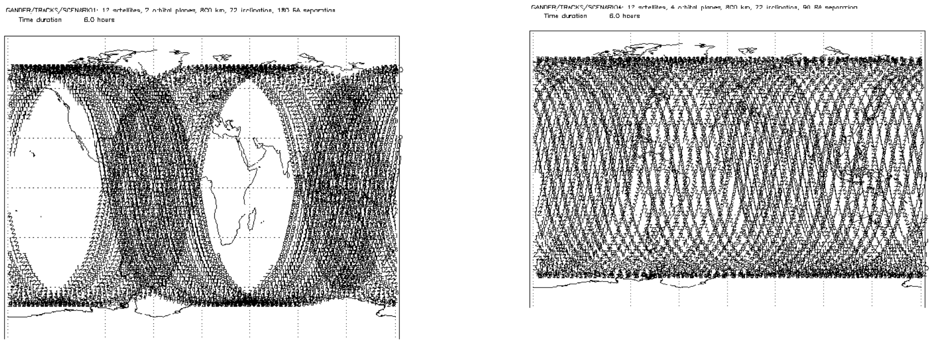


Figure 2 (a) 6 hour propagation of scenario 1, 2 planes, 6 satellites in each, (b) 6 hour propagation of scenario 4, 4 planes 3 satellites in each.

Figure 2 shows the ground track coverage of two of the orbit scenarios proposed for GANDER (1 and 4). Scenario 4 gives the better coverage, scenario 1 leaves large regions un-sampled in the 6 hour interval.

Indicative Sampling Characteristics for Multi-Satellite constellations

Table 1 gives an overview of the time and space sampling characteristics of various 12 satellite constellations:

No. Planes	Sats per plane	Plane spacing	Sat spacing	Track spacing at equator	Track spacing at 45°	Mean time between planes
1	12	360°	2.1°	233 km	163 km	12 hrs
2	6	90°	4.2°	466 km	326 km	6 hrs
4	3	45°	8.3°	921 km	645 km	3 hrs
6	2	30°	12.5°	1387 km	971 km	2 hrs
12	1	15°	25°	2775 km	1943 km	1 hr

Table 1. Indicative ground track spacing characteristics for a 12 satellite constellation
N.B. If 2nd plane is interleaved, then ground track spacing is halved for 12 hour sampling. Satellite spacing assumes ~ 100 min orbital period.

We note from Figure 2 and Table 1:

- More satellites per plane gives smaller spatial separation between satellite tracks - but a longer gap between revisit times.
- 12 satellites per plane gives best one-off representation per pass, but 12 hours before revisit.
- 3 satellites on each of 4 planes gives more even coverage in time and space and are able to capture more of the variability than other options.

For the purposes of the GANDER proposal (Jolly et al, 2000), which aimed to provide an operational near real time global sea state monitoring service, it was concluded that the best solution was given by:

6 satellites in each of two planes, ~90° apart, with an inclination of ~80°

One plane would give inadequate revisit interval to ocean regions (12 hours). Four planes would significantly add to launch costs, or delay to reach operational configuration, not justified by improvement in sampling.

GANDER and Wave Models

A constellation of 12 operational satellites, 6 each in two orbit planes would, in a period of 6 hours provide measurements at track separations of 4° over the globe (see Table 1). If we interpret this in terms of Guillaume and Hansen's (1993) findings for assimilation into wave models, this means that assimilation of these data into an ocean model will have an effect on every part of the world's oceans – and that this impact will be refreshed every 6 hours, before the impact of the previous observations (6 hours ago) has been lost.

This simplistic approach would indicate that, if used in conjunction with wave models, a 12 satellite constellation would provide an improvement to the analysis and forecast wave field (effective for more than 3 days in the case of swell dominated regions) at all ocean locations.

Coastal Studies

Monitoring sea state in near real time over coastal regions provides a significant challenge, because so much important variability occurs at high frequency (of the order of hours or less) and on small spatial scales (kms).

We have suggested that 12 or more satellites carrying (nadir) radar altimeters would be required to supply an effective monitoring service over the offshore ocean. The coastal requirements are even more demanding (~10 km every three hours), implying a requirement of 60 satellites in each of four planes – 240, all told. Even if a wide swath wave measuring radar were available with dual sided 100 km swath, it would take 10 or more such instruments to provide the required coverage. Thus it is not realistic to expect that satellite altimeter data alone can meet the coastal data requirements. The present state of the art scatterometers (e.g. Quikscat) provide wind fields with a daily coverage at 25 km resolution, and so even these instruments would not provide wind fields at the necessary resolution (<10km). Another option may be SAR image data. These data have been seen to provide highly detailed information of wind wave variability near the coast (see e.g. Alpers et al, 1998). However, there are associated processing and cost problems and coverage is again limited. The ERS-2 SAR has a swath width of 100 km (giving a latitudinal coverage of 2800 km per day, so one such satellite would take approximately 15 days to provide complete global coverage.

Therefore in the short term the best practical solutions are tailor made solutions for any given area, making use of the infra structure and capabilities that are locally available.

The ability of HF wave radar to measure ocean waves has been demonstrated by a number of researchers (see. e.g Wyatt 1999). Other developments have demonstrated how a modified ship's X-band radar can measure local wave fields (Reichert et al., 1999). A series of EC projects have carried out trials of combined operational wave models and surface radar (EUROROSE, SCAWVEX).

A combination of such measurements with local wave models (validated by in situ and altimeter data) should be able to provide an adequate monitoring service in coastal waters. In this case altimeter would provide a validation / verification role, rather than through direct input to forecast/nowcast systems.

4.3 - Climatological Applications

Various data sources have been used to generate ocean wave climatologies, which are put to use in a wide range of applications.

Wave Climate Databases

Visual observations of winds and waves by commercial ships have been archived for a century and a half. The most well-known compilations of these observations are the OWS (Ocean Wave Statistics, Hogben & Lumb, 1967) and the more recent Global Wave Statistics (GWS, Dacunha and Hogben, 1989). The main advantages are the length of the collection period and their suitability to shipping applications, because they incorporate the effect of bad weather avoidance and are well-documented for the major shipping routes. The main drawbacks are the lack of information outside the main routes, the poor accuracy for wave periods (poorly estimated even by experienced observers), the lack of wind information, and some deficiencies in seasonal representation and in reporting extremes.

Hindcasts compute wave heights from historical wind databases. The computer codes which simulate the physical wave processes have reached a good level of maturity, but errors and uncertainties in the input wind fields are amplified by this process, as wave heights are roughly proportional to the square of the wind speed. The quality of the results is thus often impaired by the lack of accuracy or of validation of the wind data, especially for regions where few observations are available, such as in most of the southern hemisphere. The main advantages of hindcasts are that they provide world-wide, long-duration histories of waves. The main drawbacks are that they are proprietary and costly, that they depend on the personal skills of the analysts who verified and corrected the wind fields, and that they have limited accuracy in extreme conditions. However, it should be noted that the availability of satellite scatterometer measurements of winds during the last decade has significantly improved the accuracy of the wind field. Cotton et al., (2000b) compare three types of wave climatology: one derived from visually observed ship data, one from a 15 year hindcast and one from satellite altimeter data. They show that the visually observed data tend to overestimate low waves and underestimate high waves, as do the hindcast model output (though to a lesser extent). Interestingly, they also found that the hindcast and visually observed climatologies show different patterns of long term trends in the North Atlantic. The altimeter data do not provide a long enough time series to consider decadal patterns of variability.

In comparison to “conventional” databases, satellite information brings in the advantages of better quality and accuracy, especially in areas where there are few reliable field measurements to calibrate hindcast models. If SAR wave mode data and radiometer data are also included, they could in principle provide a more detailed characterisation of sea conditions (directional spectra, sea surface temperature). Of course satellite data provide complete global coverage (for instance GWS provides no coverage in the seas off West Africa). One of the main drawbacks of satellite data is that the length of record, though now over 10 years, is still too short to take into account long-term variability or decadal trends. In addition, satellites (in their present mode of operation) may under-sample small and fast moving storms such as tropical cyclones. Finally, it is not possible to reconstruct histories for use in Monte Carlo simulations because of the sparseness of the time-space sampling.

IMDSS (Integrated Marine Decision Support System) – OceanWeather.

Perhaps the state of the art hindcast derived data base is IMDSS, generated from a 40 years re-analysis wind field (ERA40 see Swail and Cox, 2000). The grid is 2.5° x 2.5°, and directional wave spectra are available, represented by 12 parameters. Each gridpoint has 45 normalised scatter diagrams, under 5 time categories (long time average, four three-month seasons) and 9 directions. For other purposes all the forecast data are also separately archived and available (useful for Monte Carlo simulations).

Comparison of Wave Climate Databases

A comparison of wave climate data bases was carried out within the COMKISS project (Brugghe et al, 2000). Key findings were:

- The visual observations database consistently gave higher waves (by about 30%), than the hindcast and satellite databases, which were in good agreement.
- Areas affected by cyclones give different results for the hindcast and satellite data bases. This is probably because the databases cover relatively short time periods and may contain different numbers of such events. This anomaly should diminish as databases cover longer periods of time. Differences were noted between databases because of different representation of the monsoon season (i.e. the seasonal separation was not consistent between databases).
- The input data used in the visual observations database covers a longer period than the hindcast and satellite data, and so should have a better representation of cyclones.

Year to Year Variability

Anderson et al (2001) carried out a study into the important effect of year to year variability on the accuracy of estimates of extreme values (e.g. 100 yr return values for significant wave height). Estimates of extremes for use in the design of offshore structures are often obtained by analysing only one or two years of data from a nearby location, so long-term variability is not present in the data set. Even when longer periods of data or hindcast estimates are available, the analysis rarely considers temporal variability and takes no account of spatial variability. Thus estimates in extremes can be sometimes significantly in error. There are further difficulties in detecting any increase in extreme waves, associated with man-induced changes in storm activity, because of the shortage of data and the lack of knowledge of the natural variability.

This analysis therefore emphasises the need for a long time series of consistent data.

Climatology Requirements

Requirements of data bases for design, and operational planning were:

- Wave climate data bases with joint distributions of wave height and period.
- Availability of directional and wavelength information.
- Distribution functions with data into tails of distributions – for accurate estimates of extremes (implying higher sampling rate).
- Accurate representation of seasonal variability.
- An understanding of the characteristics of inter annual variability, and the consequences on the extrapolation of extreme values from a limited time series of data.
- Time ordered (or time registered) data bases.

A question to ask for this study is – How would we design future altimeter missions to make the best contribution to climate databases.

Other questions :

- How well do the data bases capture/represent inter-annual variability?
- How well do they capture extreme events (e.g. tropical cyclones)?
- Do they contain all the important parameters (significant wave height, direction, period, separate wind sea and swell)?
- Are the data easy to use and affordable (important factors!)?

Coastal Climate

A similar problem confront those trying to develop near coast climatologies as do those developing coastal applications of near real time wave data – that of small scale spatial variability. The wave climate can vary on very small spatial scales (~ km) following variability in coastline, bottom topography and exposure to dominant wave fields.

Generally, a hybrid approach is required (as for near real time), whereby various data sources are combined with input from hindcast models, and then used as input to shallow water, gridded or ray tracing, models. Examples are the EUROWAVES project (Cavaleri et al, 1999) which provides a solution for the whole European coastline, or the JERICHO study (Cotton et al, 1999) which investigated wave climate variability at a number of locations on the UK coastline

It is important to note here the value of high resolution along track measurements of significant wave height that are available from altimeters – particularly where the satellite track lies orthogonal to the coast. Often these measurements provide the only accurate measurements of decay in wave heights as land sheltering, and bottom shelving come into play.

4.4 - Conclusions

Satellite radar altimeter data are now widely accepted and used by offshore operators. It is recognised that they provide reliable, global, significant wave height data information that would otherwise not be available. In addition they have helped to identify problems to enhance the reliability of other data sources (through assimilation / validation).

Some final summary points:

- More intense sampling is required, for both near real time (to give up to date local information on conditions) and climatological applications (to provide information in the tails of distributions, and to get a better chance of sampling small fast moving features such as tropical cyclones.
- Ideally, directional, and wave period information are required. Separate information on wind sea and swell is especially requested.
- Long consistent time series of data are required to capture inter-annual reliability.
- High spatial resolution (~5 km) data are required close to the coast.
- A constellation of 12 satellites, distributed evenly across two orbital planes, would provide measurements within ± 233 km of any ocean location every 6 hours.

Appendices

Appendix A. Offshore Operator’s Requirements
EUROGOOS questionnaire

Fischer and Flemming, (1999) report on a detailed EUROGOOS Requirements Survey (ERS). There were a wide range of respondents (155 data using agencies) from 6 countries. Although only a subset of countries were represented, the replies were found to be stable and are so representative of the general European community of users.

	Most chosen		Ranked by no of sectors, then by no of respondents		Research	Transport	Environment	Building	Defence	Food	Energy
Variable	rank	No	rank	No sectors / respondents	rank	rank	Rank	Rank	rank	Rank	Rank
current vel.	1	*94*	2	*7/34*	4	2	8	2	8	2	2
current dir.	2	*93*	1	*7/35*	3	1	7	1	7	1	1
wave Hs	3	*85*	6	*7/23*	12	10	-	4	11	5	4
wave period	4	*81*	7	*7/22*	19	7	-	5	12	7	5
wave dir. spectrum	6	*75*	5	*7/25*	11	6	-	3	1	4	3
wind stress	7	*71*	4	*7/26*	5	5	10	8	10	6	-
wave spectrum	8	*68*	8	*7/21*	13	8	-	7	2	11	-
wave swell	9	*67*	9	*7/20*	-	9	-	6	13	12	6
surface currents	14	*55*	14	*5/17*	-	-	-	-	4	15	7
hourly mean sea level	15	*48*	12	*6/16*	-	-	13	11	15	-	-
oceanic tides	19 =	*38*	16 =	*5/13*	-	11	-	-	-	-	-

geostrophic currents	20= *35*	33= *4/11*	-	-	-	-	-	-	-
precipitation	20= *35*	30= *4/12*	18	-	-	-	-	-	-
meteorological forcing	24= *34*	39= *4/10*	-	-	17	-	-	-	-
monthly mean sea level	24= *34*	39= *4/10*	-	3	-	-	-	-	-
sea level anomaly	29 *33*	33= *4/11*	-	-	-	20	-	-	-
Eddies, fronts and jets	34 *30*	30= *4/12*	-	-	-	-	-	-	10

Table A1. Oceanographic parameters requested in the Eurogoos Requirements Survey.

Fischer and Flemming (1999) list priorities of data types according to sector, ranked according to the number of respondents who showed an interest in each data type. There is no ranking according to economic value or scientific importance. Table A1 provides a summary of the interest in sea state fields and sea surface topography variables.

The survey does not tell us whether the users are already satisfied with the provision of the "most popular" parameters, or which data sources they would prefer to use. The list does not tell us where the provision of marine variables is insufficient to meet user needs, nor does it give an indication of the scientific or economic importance of any of the variables. However, with all this in mind we find that, out of 134 possible variables, current velocity and direction consistently appear as the two most requested parameters. Wave measurements (including direction, period, and spectrum) are the next most popular group.

Applica-tion	Parameter	Optimum requirements				Threshold requirements			
		Spatial res (km)	Time res	latency	accuracy	Spatial res (km)	Time res	latency	accuracy
near real time	surface current^{A,B}	2.0	15 min	15 min	0.05 ms^{-1} / 1°	10	1 hr	1 hr	0.1 ms^{-1} / 5°
climate	surface current^{B}	1	1 mon	3 mon	0.05 ms^{-1} / 1°	4	1 mon	6 mon	0.1 ms^{-1} / 5°
near real time	current profile^{B}	2.0	30 min	30 min	0.05 ms^{-1} / 1°	10	1 hr	1 hr	0.1 ms^{-1} / 5°
climate	current profile^{B}	1	1 mon	3 mon	0.05 ms^{-1} / 1°	4	1 mon	6 mon	0.1 ms^{-1} / 5°
near real time	sig. wave ht.^{A,B}	10	20 min	1 hr	0.1 m	30	1 hr	3 hr	0.5 m
climate	sig. wave ht.^{A,B}	10	6 hr	years	0.1 m	1° x 1°	1 mon	Years	0.1 m
near real time	wave period^{1A,B}	10	20 min	1 hr	0.1 s	30	1 hr	3 hr	0.5 s
climate	wave period^{1A,B}	10	6 hr	years	0.1 s	1° x 1°	1 mon	Years	0.2 s
near real time	wave dir.^{A,B,C}	10	20 min	1 hr	±5°	30	1 hr	3 hr	±10°
climate	wave dir.^{A,B}	10	6 hr	years	±5°	1° x 1°	1 mon	Years	±10°
near real time	swell swh^{A,B}	10	30 min	1 hr	0.1 m	30	1 hr	3 hr	0.5 m
climate	swell swh^{A,B}	10	6 hr	years	0.1 m	1° x 1°	1 mon	Years	0.1 m
near real time	swell period^{A,B}	10	30 min	1 hr	0.1 s	30	1 hr	3 hr	0.5 s
Climate	swell period^{A,B}	10	6 hr	years	0.1 s	1° x 1°	1 mon	Years	0.5 s
Near real time	swell dir.^{A,B}	10	30 min	1 hr	±5°	30	1 hr	3 hr	±10°
Climate	swell dir.^{A,B}	10	6 hr	years	±5°	1° x 1°	1 mon	Years	±10°
Near	dir.	10	30	1 hr	1% max	30	1 hr	3 hrs	1% max

real time	wave spectrum [2] [A,B,C]		min		energy				energy
Climate	dir. wave spectrum [3,D]					100 km	7d	3hr	15° dirn, 10% wavelength
Joint swh/period prob. dist fns. [4,E]						1° x 1°	1 mon	Years	0.1 m / 0.2 s
Joint wind/wave prob. dist fns. [4,E]						1° x 1°	1 mon	Years	0.1 m /2 ms^{-1}

Table A2. Offshore industry data requirements for ocean waves and currents.

Footnotes: Requirements are derived from Fischer and Flemming[A], questionnaires sent to representative users[B], ,IORDII [C], Hauser et al (2002)[D] and Grant and Shaw (2001)[E]

[1] Average wave period, T_a– or equivalent (e.g. zero up-crossing period T_z)

[2] Accuracy requirement for maximum energy in spectrum.

[3] Assimilation test for the Swimsat proposal[E], demonstrated that SWIMSAT data products would make a measurable impact on accuracy. The SWIMSAT specifications are given as the threshold requirements.

[4] Joint probability distributions functions (pdfs) require the different parameters to be gathered simultaneously at the same location.

Table A2 provides a summary of requirements for ocean waves and surface currents (data which could in principle be supplied by, or derived from, altimeter data). It has been generated from discussions with representative members of the operational offshore community and analysis of the Eurogoos Requirements Survey Data Base.

Glossary/Links

COMKISS: http://www.satobsys.co.uk/Projects/Comkiss/index.html
ECMWF: European Centre for Medium range Weather Forecasting.
ESSC: Environmental Systems Science Centre, Reading, UK .
EUROGOOS: European Contribution to the Global Ocean Observing System.
EUROROSE: http://ifmaxp1.ifm.uni-hamburg.de/EuroROSE/index.html,
GANDER: Proposal for a constellation of wave measuring altimeters on Microsatellites (http://www.satobsys.co.uk/GANDER/)
GWS: Global Wave Statistics (Wave Climate data base)
HF Radar: Surface High Frequency Radar, for remote sensing of waves and surface currents
IMDSS: Integrated Marine Decision Support System (Wave Climate data base).
JERICHO http://www.satobsys.co.uk/Projects/Jericho
NCEP: (US) National Center for Environmental Prediction
OWS: Ocean Wave Statistics (Wave Climate data base)
SCAWVEX: http://www.shef.ac.uk/~sceos/environmental/scawvex/home.html.
SOS: Satellite Observing Systems
UKMO: United Kingdom Meteorological Office

5 – SWIMSAT – the use of altimeter for the measurement of the 2-D wave spectrum

5.1 - Objectives

SWIMSAT (Surface Wave Investigation and Monitoring by Satellite) is a mission concept proposed with the general objective of improving **knowledge and modelling of sea-surface processes related to the presence of surface ocean waves**: sea-state evolution, role of waves in atmosphere and ocean, sea-ice properties and evolution in marginal ice zones, coastal processes, determination of ocean surface parameters by remote sensing.

The first main objective of SWIMSAT is to contribute to the improvement **of wave prediction and sea-state monitoring** by providing spectral observations of ocean surface waves and wind estimates. The second objective of SWIMSAT is to provide information on sea-state to **better account for surface ocean wave effects in atmospheric and oceanic circulation models**. Although theoretical and numerical studies have shown that waves have a significant impact on both the atmospheric boundary layer and the ocean mixed layer, and hence on the atmospheric and oceanic general circulation, there is presently a lack of observations to take those effects into account.

In addition, secondary objectives related to surface ocean waves also exist. The first one is to complement the observations of ocean ice-covered regions by **estimating ice-thickness** in marginal ice-zones of the ocean. The second one is to provide spectral information on waves necessary to **improve the estimate of other parameters from microwave remote sensing**, in particular topography and wind estimates in certain conditions from radar altimeter missions. The third objective is to improve our knowledge of the statistics of waves, in particular the **wave slope probability distribution function**. This is needed on the one hand to better describe the physics of the waves (in particular non-linear interactions and breaking) and the atmospheric/surface interaction (relation between wind-stress and wave statistics), and on the other hand to better understand the effect of roughness on various remote sensing signals.

5.2 - Basic principles and characteristics

Mission requirements

The SWIMSAT mission consists of a **polar** orbiting system at **about 500 km** altitude. The payload is a **real-aperture radar** (RAR) system at **Ku-band** (13.6 GHz), with the radar beam **scanning both in incidence** (0-10°) **and in azimuth** (0-360°).

The choice of the orbit altitude (450 to 500 km) is guided by the main objective of SWIMSAT (estimate of directional spectra of ocean waves) and is the result of a trade-off between constraints related to the power link budget of the instrument and to the swath. Hence, in the context of examining the synergy with the other missions discussed in GAMBLE, this parameter cannot be changed too much.

The choice of the orbit inclination is presently about 97°, in order to cover the oceans up to latitudes of 83 S to 83 N. This is required in the context of wave prediction applications, and also for the objective of estimating ice-thickness in marginal ice-zones (by analysing the wave spectra modifications at the boundary of ice-covered regions).

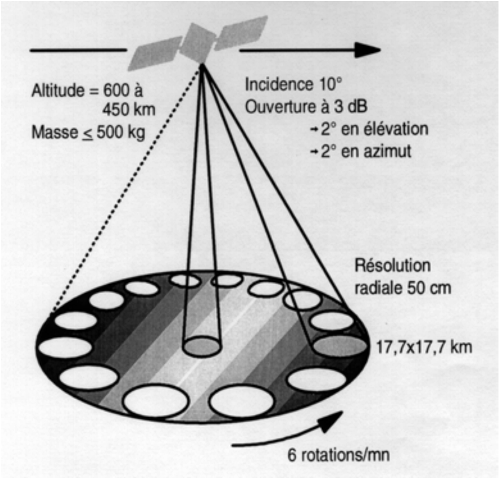
The repeat cycle is still an open choice. Presently, the proposal is to get a global coverage of the ocean for latitudes higher than 35° (N or S). A cycle of 8 days is thus proposed, but this choice remains open. Indeed, for operational objectives (wave forecast) the impact of assimilation will be basically insensitive to the choice of cycle length (from 8 to 35 days). However for climate purposes, this choice has an impact on the time requested to cover the oceans on a global scale. The final choice may depend on the weight put on the climate aspects, and also on the complementarity with other missions.

Instrument characteristics

The nadir looking mode of the instrument has characteristics and requirements similar to radar altimeters used in the standard altimeter missions in terms of range resolution, and accuracy on significant wave height and wind speed. The observations at nadir will be used in a way similar to other radar-altimeters (ERS-2, Topex-Poseidon, JASON) for estimating wind speed and significant wave height.

The off-nadir looking observations are defined to fulfil the objective of measuring the directional ocean wave spectra, and statistics of wave slopes. In particular range resolution is 0.47 to 0.75 m (depending on the incidence angle). The off-nadir observations will be used to i) estimate the spectral properties of the wave field ii) estimate the profile of the radar cross-section with incidence (0-10°) and as a function of azimuth.

A scheme of the geometry of observation is shown in Figure 1 for two incidences (nadir and 10°). For an orbit altitude of 500 km, the footprint will be about 18 km x 18 km. This footprint will sweep a pseudo-circle with a diameter ranging from 18 to 90 km for incidence angles ranging from 2 to 10°. The surface pattern described by the instrument for the [2-10°] incidence angles is shown in Figure 2 for two successive scans over 360° in azimuth, for a satellite motion of 7 km/s, and for a scan rate of 6 rotations per minute.



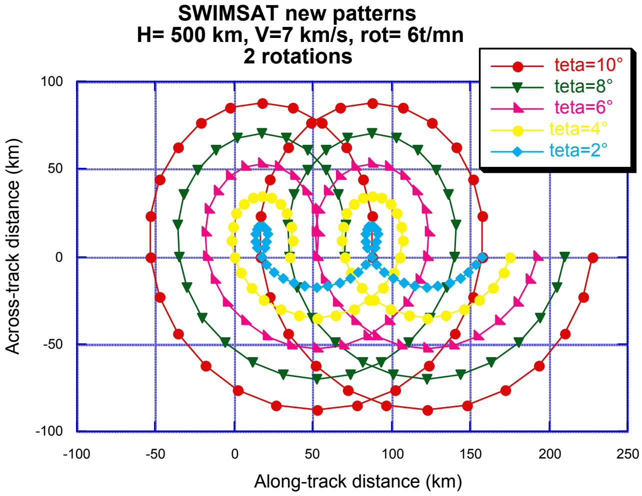


Figure .1: Geometry of observations of SWIMSAT for 2 incidence beams (0 and 10°)

Figure .2: Surface pattern described by the beams at incidences from 2 to 10°. Each symbol on the lines represent the centre of the footprint, plotted here every 15° in azimuth.

Wave spectra retrieval

The validity of the principle to derive the spectra of ocean waves from a real-aperture radar has been demonstrated several times using airborne systems developed at NASA (ROWS system, Jackson et al, 1985 a-b) and in France (RESSAC radar at CETP/CNRS, Hauser et al, 1992, Hauser et al, 1995, Hauser and Caudal, 1996, Pettersson et al, 2001). Recent studies supported by the French Space Agency CNES and performed at ALCATEL SPACE INDUSTRIES and CETP/CNRS have proved the feasibility of the proposed space-borne system (Hauser et al, 2001a).

At low incidence, the backscattering mechanism is dominated by quasi-specular reflection from facets oriented perpendicular to the radar look direction. Facets with wavelengths larger than three to five times the electromagnetic wavelength contribute to this process. The normalised radar-cross section σ_0 is related to the probability density function of the slopes of short waves forced by the wind stress. Within the footprint (of the order of 18 x 18 km for SWIMSAT), this normalised radar-cross section is modulated by the local slope of the surface due to the long waves. This is the so-called "tilt modulation". This modulation is maximum for look directions aligned with the wave propagation direction and minimum in perpendicular directions.

It is recognised (Jackson et al, 1985 a,b, Hauser et al, 1992) that in the configuration of low incidence angle, and large footprint with respect to the wavelength of the waves to be measured, the density spectrum of the modulation of the backscattered signal $P_m(k,\phi)$ is linearly related to the slope spectrum $k^2F(k,\phi)$ of the waves, for wavelengths larger than about 40 m:

$$P_m(k,\phi) = \frac{\sqrt{2\pi}}{L_y}\alpha^2 k^2 F(k,\phi) \qquad (1)$$

where L_y is the width of the footprint in the azimuth direction, k is the wavenumber of the waves, ϕ their travelling direction, and α is related to the fall-off of the normalised radar cross-section σ_0 with incidence angle θ:

$$\alpha = \cot g\theta - \frac{1}{\sigma_0}\frac{\partial\sigma_0}{\partial\theta} \qquad (2)$$

In α, the derivative of σ_0 is dependent on the mean square slope of the surface; i.e. mainly wind-conditions. With the multi-incidence configuration of SWIMSAT it can be estimated directly from the observations (see also Hauser et al, 1992).

If there are no perturbing noise sources, the wave-height spectrum $F(k,\phi)$ in the look direction ϕ can be inverted from the modulation spectrum $P_m(k,\phi)$ using Equation (1). To retrieve the full spectral information, scanning of the radar beam over 360° in azimuth provides the wave spectrum F in all directions ϕ (with however an 180° ambiguity in the propagation direction).

Perturbation noise sources are the thermal noise and speckle noise (see Hauser et al, 2001a for details). Thermal noise corrections can be applied by estimating the noise level from appropriate radar sequences and correcting the received power. In addition, simulation studies have shown that with a transmitted power of at least 100 watt, this effect remains very small. In opposite, the effect of speckle noise must be taken into account. For that, speckle is assumed to have a Gaussian statistics and the following equation can be used:

$$P_m(k) \approx P_c(k) + P_s(k) \qquad (3)$$

where $P_m(k)$ is the measured spectral energy of the backscatter modulation, P_c is the modulation spectrum which would be observed in absence of speckle and $P_s(k)$ is the spectral energy density of speckle. This latter is given by:

$$P_s(k) = \frac{1}{N_{\text{int}}\sqrt{2\pi}} \cdot \frac{\Delta x}{2\sqrt{2\ln 2}} \tag{4}$$

where N_{int} in the number of independent samples (of the order of 100 for SWIMSAT) and Δx is the intrinsic horizontal resolution (3 to 14 m depending on the incidence angle). After subtracting the speckle contribution, Eq.(1) can be used to retrieve the energy density of the waves, for wavenumbers k smaller than a certain threshold. This threshold corresponds to the wavenumber where the density spectrum of speckle is of the order of that of the modulation spectrum.

Figure 3 illustrates the expected performance at incidence 10°, for a fully-developed wind sea case following a Pierson-Moskowitz shape (with a 13 m/s wind speed) and for a swell case (H_s= 4 m peak wavelength λ_{peak}=200 m, 13 m/s wind-speed). These results show the inverted radial spectrum $P_c(k)$ when the radar look direction is aligned with the wave propagation direction. The full solid line shows the reference. The line with symbol correspond to the inverted product, after averaging over 16 individual estimates and where correction of thermal noise and speckle noise have been taken into account. The heavy horizontal line shows the speckle noise level. This shows that both the shape and the level of the spectrum can be correctly retrieved.

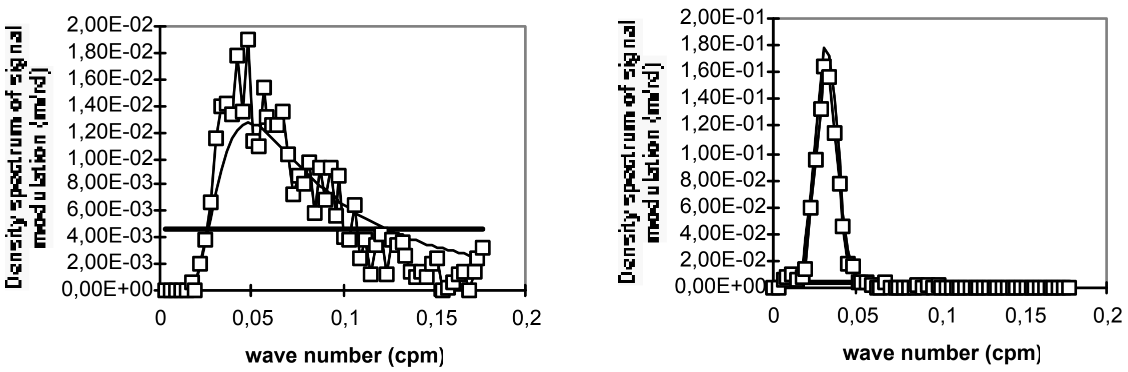


Figure .3: Modulation spectra for a look direction aligned with the wave propagation direction (lines with square symbols). Left plot: Pierson-Moskowitz spectrum at a wind speed U=13 m/s. Right plot: swell spectrum with H_s=4m, λ_{peak}=200 m, U=13 m/s. Thin line without symbols: reference spectrum. Solid line with symbols: simulated SWIMSAT product, after correction of thermal and speckled noises and averaging over16 individual samples . Heavy horizontal line: Speckle noise level.

As concerns the 180° ambiguity, several methods are envisaged: the first one could be a scheme similar to what has been developed to process the ASAR wave mode data (Engen an Johnson, 1995), which is based on the analysis of the inter-correlation of successive samples. Alternative processing schemes based on singular values decomposition methods or to analysis of the skewness of reflectivity can also be envisaged.

The combination of several incidence angles is proposed first to optimise the spatial scale for the retrieval of the wave spectral properties. As seen in Figure.2 a complete spectrum may be obtained at a scale of 50 x 50 km to 90 x 90 km. The multi-incidence observations will be used to obtain information at the smaller scale, to increase the number of estimates in a given area, and to balance the advantages and drawbacks of the very small (2-6°) and larger (8-10°) incidence angles (a better spatial resolution can be obtained at very small incidence, but with less accuracy in terms of wave spectral density).

In addition, to the estimate of the directional wave spectrum at a scale of about 50 x 50 km up to 90 x 90 km, the significant wave height will be estimated from the nadir-looking beam, as for conventional altimeter missions.

5.3 - Expected geophysical parameters

SWIMSAT is designed to provide at the global scale, observations of directional energy spectra of ocean waves, significant wave height, steepness of long waves, wind, and parameters characterising the statistics of wave slopes. The mission is designed to get a global full coverage (on a complete cycle) of these parameters for latitudes from 35° to 83° (N or S), where the main ocean storms develop, propagate and decay.

5.4 - How SWIMSAT will contribute to answer to the key issues

Better knowledge of global climate

By providing continuous observations over several years, SWIMSAT will provide wave climatology (significant wave height, dominant wavelengths and directions). There are three important areas which would benefit from applications of directional wave climatologies derived from SWIMSAT: climate research, wave model development, and operational applications. Analysis of global wave climatologies derived from satellite altimeters (significant wave height only) has demonstrated the existence of significant and important year to year variability in wave climate and demonstrated links with major climate indices, such as the North Atlantic Oscillation (Woolf et al., 2002). However, the exact nature of this variability (directional and spectral character) remains uncertain until reliable measured directional and spectral climatologies are available (from SWIMSAT). The availability of such climatologies, derived directly from measurements, is particularly important because the analyses of altimeter derived wave climatologies also highlighted shortcomings in wave model fields, in particular an underestimation of variability and range (Sterl et al , 1998, Cotton et al, 2001). Measurements of wave climate are also important for coastal management and for estimation of air-sea fluxes. In shallow water, long waves feel the bottom earlier and provide energy to sediment transport processes in the near-shore zone. A better representation of the energy at low frequencies in wave climatology will therefore improve the wave input to sediment transport models.

Modern ocean wave atlases all nowadays integrate satellite data as a primary data source (Barstow et al, 2000). In these atlases, the satellite data also complement in situ measurements and global wave and atmospheric model data, thus resulting in increasingly more reliable deep water long term offshore wave statistics. Further more, efforts are undertaken to develop easy-to-use software package on a European scale, containing both an offshore wave atlas and all the tools necessary to calculate wave conditions anywhere in coastal Europe (bathymetry, coastline, shallow water wave models and statistical tools) (Barstow et al, 2000). The SWIMSAT mission will provide wave spectra measurements of significance importance for such applications.

Altimeter measurements can already be exploited in these fields, but both the direction and period of waves are critical to both air-sea fluxes and coastal impacts. Directional and spectral wave climatologies derived directly from satellite measurements are therefore required to develop a more complete understanding of wave climate, and to continue improvements in global wave models. To illustrate the importance of this, we can mention that within the EU Fourth Framework Programme the project COMKISS asked offshore operators what improvements they wish to see in satellite provision of wave data (Cotton et al, 2000). One of the highest priorities was better provision of spectral and directional wave information, which are of particular importance for design and operational planning.

Real-Time data for forecasting systems

Wave prediction at the global scale

Knowledge and prediction of the sea-state is a necessity for many applications over the ocean (navigation, offshore activity, coastal applications, ship routine, wave energy installation, etc). For this reason, most meteorological centres run wave prediction models (Bidlot and Holt, 1999). The performance of wave models has significantly improved in the last decade (Janssen et al. 1997, Janssen, 2001), due to improved accuracy in the wind forcing fields, and to the assimilation of altimeter data (observations of significant wave height). However improvements are still needed, in particular for high sea-state conditions, and for providing accurate prediction not only in terms of wave height but also in terms of peak wavelength and direction (important for swell). The accurate prediction of low frequency swell, propagating great distances from the generation regions, has become a priority for wave prediction models. We are now at a stage where the most effective means of decreasing errors in wave prediction will need assimilation of spectral and directional observations of wave energy with global coverage. SWIMSAT will be a demonstrator that will provide observations, which will be used on one hand to improve the physics of the models and validate them, and on the other hand to constrain the models through assimilation techniques. It will also be a tool for short-term forecast of high sea-state.

Presently, operational assimilation in wave prediction models is based upon observations of the total energy (or significant wave height) of the wave spectrum, ignoring their spectral properties (Janssen et al, 1989, Lionello et al, 1992, Breivik and Reistad, 1994). The main drawback of these methods is that they need certain assumptions about the characteristics of the wave field, and in particular the separation between swell and wind-sea. This generates errors and reduces the positive impact of assimilation. Only in recent studies attempts have been made to include spectral observations in the assimilation process (De La Heras et al, 1994, Voorrips et al, 1997, Breivik et al, 1998, Hasselmann et al,1997, Herbash et al 1998, Dunlap et al, 1998), but these studies remain limited to methodological developments, to case studies or to the application to small geographical zones. The relatively small impact in assimilating Synthetic Aperture Radar (SAR) data (Breivik et al, 1998, Dunlap et al, 1998) can be attributed to the limits of wave information provided by SAR (large cutoff in wavelength, sampling every 200 km,…). A poor angular resolution in the wave directional spectrum as well as a poor signal-to-noise ratio in the ERS fast delivery products may have also hampered these studies.

Recent work based on wave data assimilation simulating the SWIMSAT configuration at the global scale (Hauser et al, 2001b, Aouf et al 2002) show that the impact of assimilating wave data is quite significant, and that it is larger when spectral information is used than when only using the significant wave height. The main characteristics and results of the assimilation study performed in this context is presented here below.

The scheme is based on a sequential assimilation method. It uses the wave model forecast at a certain time at which observations are available and it combines the model state at that time (first guess) with the observations to compute an analysed model state. This latter is used as an initial condition for a new model run until a new observation is processed. The observations are assimilated simultaneously over a certain period called "assimilation window" typically 3 or 6 hours. The assimilation scheme is an adaptation of the scheme developed by Vooripps et al (1997) and is based on Optimum Interpolation method and on the partitioning concept. This scheme originally developed by Hasselmann et al (1997) has been adapted for buoy data by Vooripps (1997). The idea is to assimilate details of the spectrum and in particular mean parameters (energy, frequency, direction) of all separate wave systems which can be identified in observed and modelled wave spectra. To reduce the number of free parameters in a wave spectrum, the concept of "spectral partitioning" is applied. This consists in decomposing the wave spectrum in a few distinct partitions, which correspond to the various peaks in the spectrum. They represent independent wave systems corresponding to a certain meteorological event (for example swell generated by storms or wind waves generated by local strong wind). Each partition is characterised by its mean parameters (energy, direction, frequency). The first step of the scheme is to cross-assign each partition of the observed spectrum to the equivalent partition of the first guess spectrum. To this aim, a criterion based on the distance in the spectral space between the mean parameters of the observed and model partitions is used. If the estimated distance is less than the assumed "threshold" value then the partitions are cross-assigned and they are ready for the optimal interpolation (OI) procedure. On the other hand, if the distance is more than the threshold, the model partition remains unchanged. The error correlation function used in the statistical interpolation is of a Gaussian form and is dependent on the error correlation length and the radius of influence of the observations. By choosing appropriate values of these parameters, the optimal interpolation procedure combines mean parameters of the cross-assigned model and observed partitions to obtain an analysed field of partition parameters. For wind-sea partitions the driving wind velocity is corrected by using some empirical relations obtained from a growth curve relation (Lionello et al, 1992, Vooripps et al, 1999).

To illustrate these recent developments, results of assimilation based on the global wave prediction model WAM and on synthetic SWIMSAT data are presented here. The spatial resolution of the model is of 1x1 degrees in longitude and latitude, while the wave spectrum is discretised in 24 directions and 25 frequencies starting from 0.041 to 0.41 Hz. The simulation consisted at first to running the wave model without assimilation and with analysed wind fields from the ECMWF atmospheric model as input. The obtained directional wave spectra at the observation locations were considered as synthetic SWIMSAT data. Secondly the wind fields were disturbed to make a small change in the wave field. Several wind perturbation were tested. The results presented here below were obtained by using wind fields corresponding to the forecast of several days before (4 days) instead of the last analysis. Assimilation of the synthetic SWIMSAT data was applied to the wave field generated by the wave model forced by the perturbed wind fields. The wave model with assimilation was run for a period of 4 days starting from October 22, 2000 until October 25, 2000 at 21:00. After this date a forecast period was analysed to estimate the effect of the assimilation with time. The assimilation time step was chosen as 3 hours. The observation locations follow an orbit track for SWIMSAT chosen here with a repeat cycle of approximately 17 days. Other cases were tested with an ERS-2 orbit track. Assimilation was also performed with data corresponding to an altimeter (significant wave height), i.e. without spectral information.

The main results are summarised as follows :

1. During the period of assimilation (4 days) the impact of assimilation on the wave height is significant (not shown). In some cases it exceeds 2 metres. During this analysis period, the correlation coefficient for the significant wave height between model and synthetic observations is much larger for the results with assimilation compared with the first guess (not shown). This shows the efficiency of the assimilation method.

2. During the period of forecast, the impact of assimilation on significant wave height is quite significant: 3 days after stopping the assimilation it reaches more than 1 m (Fig 4a) and decreases progressively until it reaches about 0.3 m, 6 days after the end of assimilation (Fig 5).

3. The comparison with assimilation of the significant wave height only (as given by an altimeter) shows that the spectral information increases the impact on wave height and consequently much better corrects the sea state (compare Figures Fig4a and 4b).

4. The statistical analysis of the wave parameters over all grid points confirms the significant correction of sea state in the analysis period and the progressive damping of the assimilation effect in the forecast period (Fig 7). This analysis also confirms the larger impact of the assimilation of spectral data with respect to the assimilation of significant wave height only. Results obtained on the mean period (not shown) indicate that the impact of assimilation in the forecast period decreases less rapidly for the mean wave direction than for the wave height.

5. The use of a 35 days repeat cycle (not shown) instead of a 17 days repeat cycle (as illustrated here) qualitatively induces the same results.

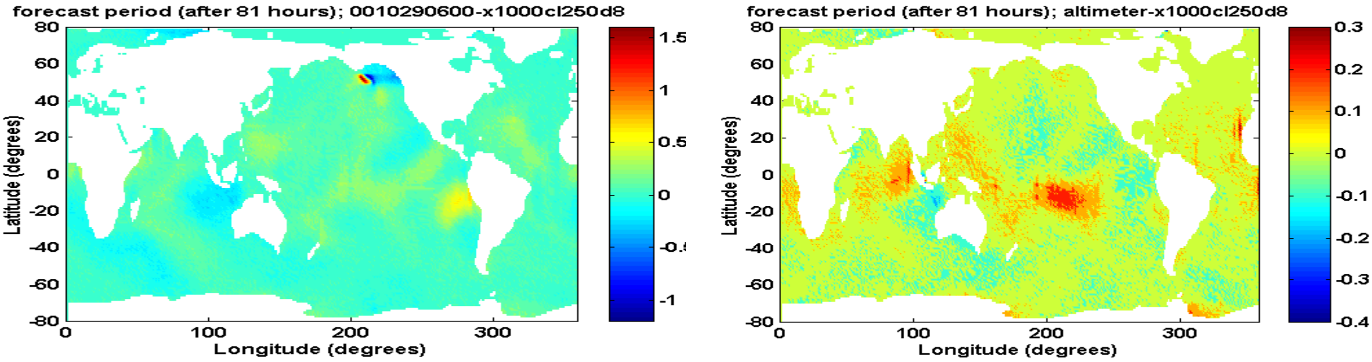


Figure 4: Difference in the forecasted significant wave heights (in meters) between the cases with and without assimilation, 81 hours (3.375 days) after the end of assimilation. (a) with assimilation of spectral data (b) with assimilation of significant wave height only.

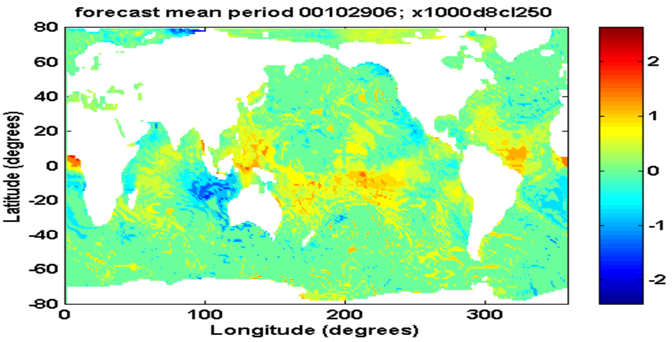


Figure 5: Difference in the forecasted mean wave period (in seconds) between the cases with and without assimilation, 81 hours (3.375 days) after the end of the assimilation

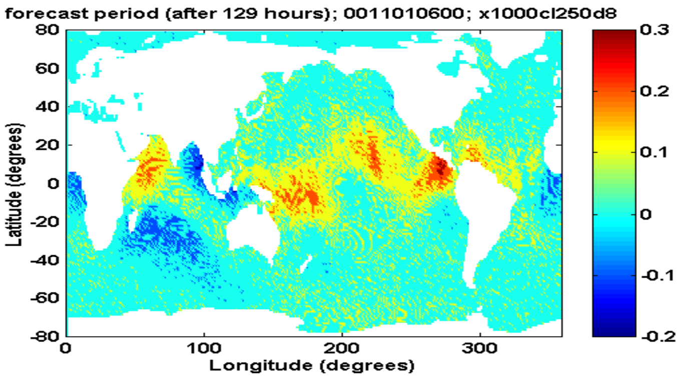


Figure 6: Difference in the forecasted significant wave heights (in meters) between the cases with and without assimilation, 129 hours (5.375 days) after the end of assimilation.

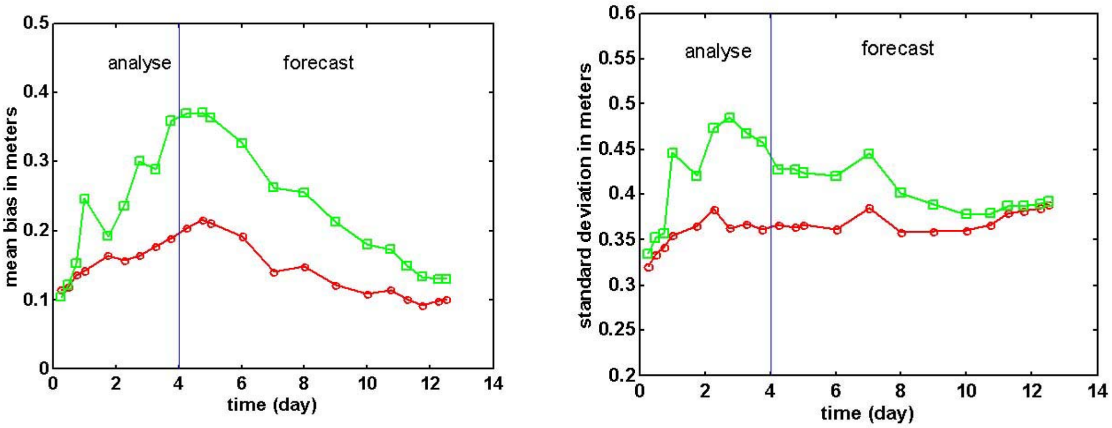


Figure 7: Mean bias (left plot) and standard deviation (right plot) for the significant wave height between forecast (or analysis) and synthetic observations. Squares: assimilation of significant wave height only; Circles: assimilation of the spectral information. The analysis period (with assimilation) lasts for 4 days. Then the model fields evolve without assimilation.

In summary, this assimilation study, (based on synthetic data) has shown that there is a significant impact of assimilation and that this impact is larger when parameters derived from the full spectral information (wave height, mean period, mean direction for several wave trains) are used, compared to the case where only significant wave height is assimilated. These results were obtained with "synthetic observations" generated with the WAM model. Hopefully, the recent availability of the ENVISAT SAR data will make it possible to assess these conclusions with real data.

Coastal studies

Voorrips et al (1997) have demonstrated the benefits of assimilating wave spectra in a wave prediction system for the North-Sea for applications near the Dutch coast. Although the assimilated information came from pitch-and-roll buoys, the underlying reason for the success was the availability of information when several wave systems were present at the same time. In particular the timely detection and assimilation of swell had a positive impact up to around 24 hours in the forecast. Not all coastal regions however can rely on the availability of directional buoy information at the right moment and at the right location. The information that SWIMSAT can provide, will be particularly useful in these regions. Assessing the impact of assimilation needs adequate wave information in the region of interest. Therefore this assessment can best be done in a region that is well covered with instruments.

In regions under the influence of strong surface currents (e.g. Gulf-Stream), sudden changes of the wave spectrum have been detected (Beal et al, 1986, Hauser and Caudal, 1992). These changes depend on the relative direction of wave propagation and surface current structure. SWIMSAT will be able to provide information on wave spectra in the region of such currents and hence improve the analysis and forecast of waves approaching coastal regions affected by these currents.

Define wave characteristics for the evaluation of electromagnetic bias

Ocean waves influence the microwave signal backscattered or transmitted from the surface to the various sensors developed for oceanic applications. In particular the major remaining source of error in the estimate of the electromagnetic bias, which affects the retrieval of ocean topography from radar altimeter observations from satellite is due to ocean waves (Gaspar et al, 1994, Chapron et al, 2001). Recent theoretical studies by Elfouhaily et al (2001) show that the bias due to hydrodynamic processes on the surface depend not only on the elevation variance (or significant wave height), but also on orbital velocity variance, which is affected by the long wave components of the wave spectrum. By providing spectral information on the long waves, it is expected that SWIMSAT will help to better estimate the contribution of sea-state in the electromagnetic biais.

Define wave characteristics to improve the estimate of wind speed from conventional altimeter missions

Recent results obtained from altimeter missions also show that wind-speed estimated from nadir radar observations at low sea-state condition is influenced by the sea-state development (Gourrion et al, 2000). By providing information on sea-state in conjunction with altimeter observations, SWIMSAT will help to improve wind estimates from radar altimeter missions**.**

5 - Relation with other missions concerned by the GAMBLE project

Synergy of objectives and complementarity of parameters to be measured

There is a synergy of objectives and of parameters to be obtained, with those of the other missions analysed in this GAMBLE project.

First, SWIMSAT will provide the directional spectra of ocean waves which provide a more complete information on sea-state that the sole significant wave height provided by the conventional radar altimeter missions. Indeed, this information is quite important i) for marine applications (wave forecast, wave monitoring), ii) for wave climatology, iii) for decreasing the errors in the estimate of ocean topography, by providing a detailed description of long waves which influence the electromagnetic bias in the topography estimate.

Secondly, information on statistics on short waves should be accessible to SWIMSAT. This is a new information which should complement the analysis of conventional radar altimeters data which is presently based on the hypothesis of a Gaussian statistics. Furthermore, SWIMSAT should be able to provide the wind direction which will also complement data from conventional radar missions which provide only the wind speed.

Finally, the data acquired with the nadir-looking beam of SWIMSAT will provide an information on the topography of the ocean surface as done by conventional altimeters, except that a precise determination of the orbit and estimate of atmospheric corrections are not planned at this stage. Further work is required to estimate how the topographic information provided by SWIMSAT can be used in this context.

Complementarity in terms of orbit and sampling

As mentioned here-above, the proposed orbit for SWIMSAT covers high latitude regions. Hence, SWIMSAT may complement other altimeter missions of the type of JASON 2 which do not cover high latitude regions.

For wave forecasting objectives, the repeat cycle of SWIMSAT is not a critical parameter and hence the final choice could take into account requirements from other missions to obtain optimal multi-mission coverage for marine and topography applications.

For climate studies of the wave state, the choice of this cycle has more impact. Presently, the proposed cycle of 8 days allows to get a global coverage of the ocean for latitudes higher than 35° (N or S). Inreasing the length of this cycle would allow to have a better coverage but on a longer time duration.

So, the final choice will depend on the weight put on the climate aspects, and also on the complementarity with the characteristics of other missions.

The requirement for the orbit altitude is more important for SWIMSAT. With respect to altimeter missions devoted to topographic measurement (sea surface height) the proposed altitude (450-500 km) is rather low and could make it difficult to obtain precise orbits and precise topographic measurements. However, the recent advances in the knowledge of the earth gravity field thanks to missions like GRACE or CHAMPS will make it possible in the future to obtain precise orbits and topographic measurements even with low orbit satellites. In addition, one could envisage the addition of accelerometer measurements on board the SWIMSAT mission, which would largely improve the orbit determination. In any case, as shown by the synergetic use of TOPEX-POSEIDON and ERS-2, data from high- and low- orbit altitudes can be used to obtain very useful information.

Common characteristics of instrument and data processing

In its principle, SWIMSAT has several common points with existing or planned radar altimeter missions. It will use a radar system derived from previous altimeter missions (POSEIDON2 on JASON 2). Specification of part of the instrument, of the data acquisition and of the data processing for the nadir looking beam is also derived from existing altimeter missions.

6 - JASON-1

6.1 - The Jason-1 mission

The Jason-1 satellite was launched on December 7, 2001 from the Vandenberg launch facilities in US (California). This satellite has been developped jointly by CNES and NASA to follow up the TOPEX/POSEIDON mission. The payload has been designed to meet the pre-launch specifications, identical to the post-launch T/P specifications (see table I). The instruments (figure 1) provided by CNES include a solid state bi-frequency (Ku and C bands) altimeter (developped by Alcatel Space Industries) and a DORIS Precise Orbit Determination system (developped by Thales) (Escudier et al.,2000). The payload provided by NASA includes the TRSR/GPS receiver (developped by JPL, built by Spectrum Astro Inc.) and the laser retroreflector (from ITE inc.) for POD support, and the JMR radiometer (developped by JPL). The new mini-satellite (500 kg) platform, named PROTEUS, has been jointly developped by Alcatel Space Industries and CNES as a multi-mission platform. It was launched by a Boeing-Delta II rocket. The satellite has been designed for a minimum life time of 3 years with the potential for an additional 2 years.

As for TOPEX/POSEIDON, the main objective of the Jason-1 mission is the precise monitoring of the sea surface ocean topography for large scale ocean circulation and climate-related studies (Y. Menard et al., 2000) However, even if Jason-1 was not specifically designed for sea-state applications, its contribution in this field is very useful. In addition to the sea surface height, the radar altimeter on-board Jason-1 measures the significant wave-height (derived from the waveform shape) and the wind speed (derived from the returned echo power) at the nadir of the satellite. The corresponding accuracy for a sampling of 1 Hz is indicated in table I. These data can then be used for many applications including sea-state climatology studies (satellite provides a unique global coverage), improvement of sea-state models forecast, release of warning bulletins for ship routing and offshore activities...

Jason-1 is exactly on the same orbit as TOPEX/POSEIDON, with an inclination of 66° and an altitude of 1336 km. This makes the orbit repeating on the same ground-tracks at exacly 9.985 days and an inter-tracks separation of about 350 km at the equator. Thus, the whole ocean surface is sampled by the satellite, but clearly with a sampling not dense enough fo sea-state related objectives. In this regard, combination of Jason-1 sea-state data with other satellite data sets (e.g. ERS2, ENVISAT) and existing sparse in-situ data is very useful for adjusting at the best the forecast sea-state models.

6.2 - Jason-1 products and ground segment

As mentioned in table I, three different types of products will be delivered to the users when the verification phase will be completed (i.e. end of 2002). Interim Geophysical Data Records (IGDR) and Geophysical Datat Records (GDR) products are identical to T/P products. They will be released respectively within 3 days (95% of the time) and within 30 days (95% of the time), the GDR being the final fully validated products. These products contain all needed measurements to analyse the data, including environmental and geophysical corrections, precise orbit coordinates. Ku band significant wave-height, Ku and C bands sigma-naught plus wind speed (derived from the adjusted algorithm recommended after the end of the verification phase) will be provided in IGDR and GDR. In terms of accuracy, IGDR and GDR wind speed and wave-height performances are the same.

In addition to IGDR and GDR, a new Operational Sensor Data Record (OSDR) product has been defined for Jason-1 in order to satisfy the near-real time requirements. Indeed this product is delivered within 3 hours (75% of the time) to 5 hours (95% of the time) to the users, after on-board acquisition, and is based entirely upon the on-board processing. It comprises the main usual parameters, i.e. time, altimeter range, real-time orbit position (a new Doris function) accurate within less than 30 cm for the radial component, the Ku band wave-height, the Ku and C bands sigma-naught and the wind speed (from Ku band). The wind speed accuracy is slightly degraded with respect to IGDR and GDR, but it is still very acceptable for near-real time marine meteorology applications.

As for TOPEX/POSEIDON, IGDR and GDR products will be made freely available to users. They just need to register at one of the two data production and distribution centers, i.e. the AVISO facilities in CNES and the PODACC at JPL. Also, the OSDR will be made available upon request to these two centers. The media support will be CD-Roms for GDR, when IGDR will be ftp site accessible. OSDR will be either ftp site or GTS accessible (OSDR will be directly put on GTS network by Météo-France during the routine phase).

The ground network designed for the down and up link data transmission between the satellite and the data control and processing centers (located in Toulouse, CNES and in Pasadena, JPL) comprises two telemetry stations, one in Poker Flat (Alaska) and another one in Aussaguel (France) (figure 2). The Wallops station (USA) is also used as a backup station.

Based on expected improvements in ground processing algorithms, a more ambitious error budget is indicated in table I for GDR products. The improvement for significant wave height, sigma-naught and wind speed should be significant (specially for wave-height).

6.3 - Jason-1 CALVAL phase

Soon after the launch of the Jason-1 satellite, end of March 2002, the first IGDR data have been released to the Principal and Co-investigators of the mission for calibration and validation purpose (cf. Jason-1 CalVal plan). On June 10-12, 2002 in Biarritz, at mid-term of the verification phase, the Science Working Group was convened to discuss the first results and establish a preliminary error budget and performance status of the mission (cf. minutes of this meeting).

Regarding the Jason sea-state data, it has been demonstrated that their accuracy is compliant with the prelaunch objectives. Three kind of analysis have been conducted by different teams. One is by directly comparing the T/P and Jason data (the fact that they are following the same tracks just separated by one minute, make it easy), another way is by comparing model outputs (VAG, WAM, ECMWF models) and Jason data and a third one is by comparing them with in-situ buoy data and other satellite data (ERS2 and GFO). All these preliminary comparisons have shown a very good consistency of Jason-1 data with the other data sets (J.M. Lefevre et al., D. Cotton et al., P. Queffeulou et al., presented at the June 2002 SWT meeting). As illustrated on figures 3 and 4, observed differences are not significant and stay within the pre-launch specifications.

Of course these results need to be consolidated with the extension of the time series and further final adjustments of sigma naught biases and algorithm coefficients. One action to proceed with is the evaluation of the various wind speed algorithms and their adjustment before the GDR production. These on-going analysis should still improve the results. All these investigations as well as a complete error budget will be presented at the final SWT verification workshop in New Orleans, october 21-23, 2002. This will mark the end of the verification phase and the beginning of the routine phase with the systematic production of GDR, in adddition to IGDR, and the near-real time release of the OSDR.

6.4 - The Jason 2/OSTM mission to follow up Jason-1

In order to maintain the continuity of the Jason mission beyond 2006, the CNES and NASA space agencies have already proposed the follow-on Jason-2 (part of the Ocean Surface Topography Mission on US side). This new mission, to be launched in 2006, is based on the same PROTEUS platform and the same payload as Jason-1, providing at least the same performances. Orbit characteristics will be the same. Only a new instrumental concept, the wide swath altimeter developped by JPL, is being studied as an option on-board the satellite to demonstrate its capabilities. If Jason-1 was considered as a pre-operational mission, operational applications will be enterely part of the Jason-2 mission. This is reinforced by the implication of two operational agencies in the project. Indeed, Eumetsat on European side and NOAA on US side will be the two other partners of this mission.

TABLE I. JASON-1 PERFORMANCES AS A FUNCTION OF LATENCY AND PRODUCTS.

Measurement	3 hour (OSDR)	3 day (IGDR)	30 day (GDR)	30 day (goal)
Range to surface (cm, corrected)	4.5	3.3	3.3	2.3
Radial orbit height (cm)	30	4.0	2.5	1.0
Sea-surface height (cm)	N/A	5.0	4.2	2.5
Significant wave height (cm) whichever is greater	**50 or 10%**	**50 or 10%**	**50 or 10%**	**25 or 5%**
Sima-naught (dB)	**0.7**	**0.7**	**0.7**	**0.5**
Wind speed (m/s)	**2**	**1.7**	**1.7**	**1.5**

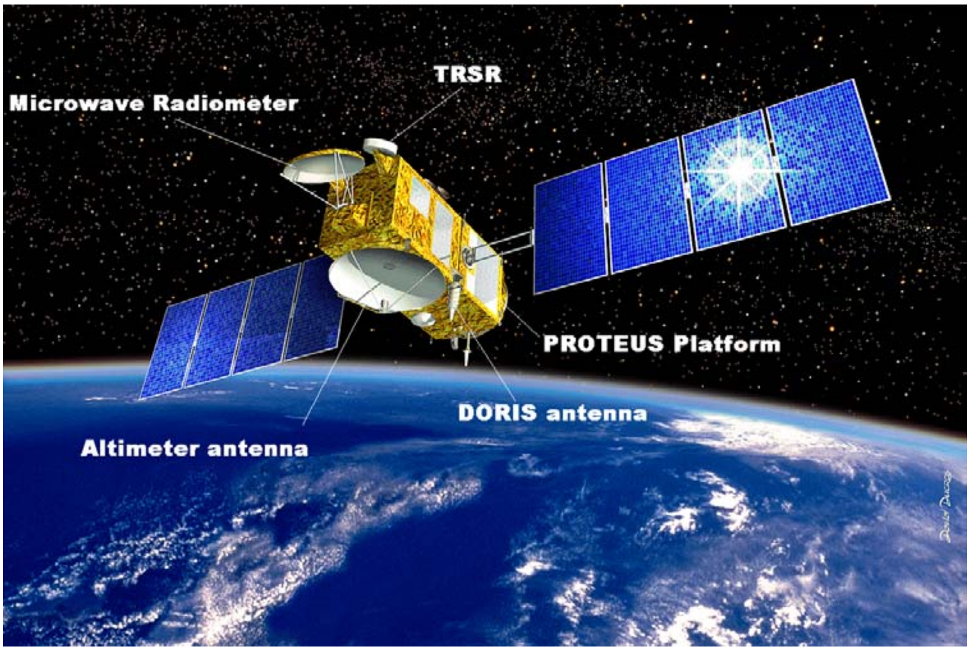


Figure 1: The Jason-1 satellite on its orbit

Figure 2 : The Jason-1 ground segment

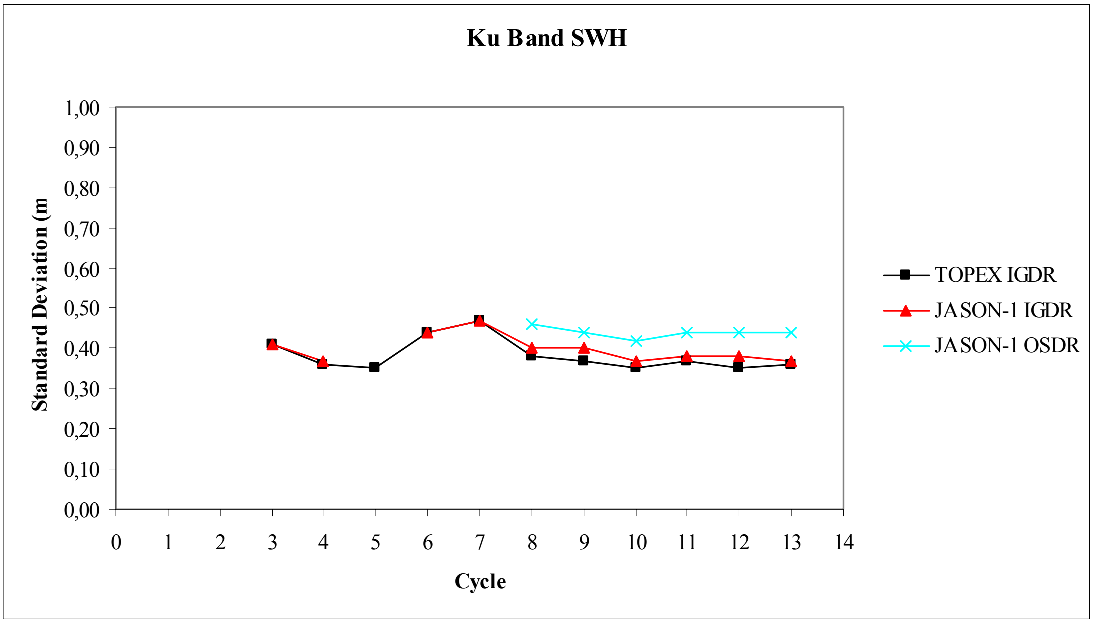


Figure 3 : Comparison of SWH measured by T/P (IGDR), Jason-1 (IGDR and OSDR) with WAM model for 11 simultaneous cycles (Lefevre et al., 2002) :

- T/P IGDR: bias = - 0.12, **rms = 0.38 m**, cc = 0.97
- Jason IGDR: bias = - 0.01, **rms = 0.37 m**, cc = 0.96
- Jason OSDR: bias = - 0.19, **rms = 0.48 m**, cc = 0.96

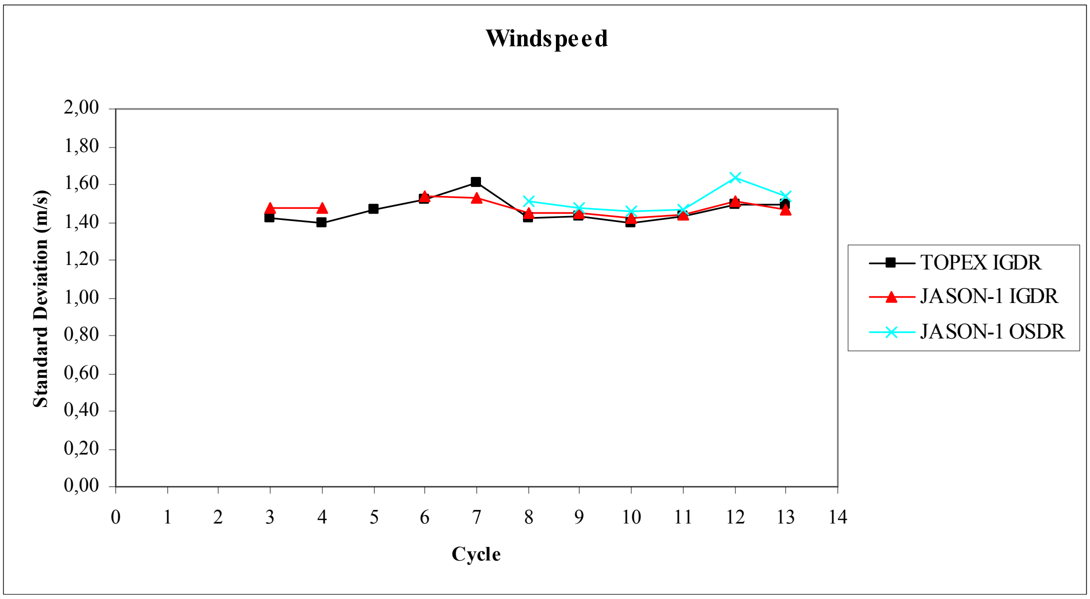


Figure 4 : Comparison of wind speed measured by T/P (IGDR) and Jason-1 (IGDR and OSDR) with ECMWF model, for 11 simultaneous cycles (Lefevre et al., 2002) :
T/P IGDR: bias = -0.38, **rms = 1.54 m/s**, cc = 0.92
Jason IGDR: bias = 0.20, **rms = 1.49 m/s**, cc = 0.91
Jason OSDR: bias = -0.14, **rms = 1.55 m/s**, cc = 0.91

Bibliography

Alcock, G. and L. Rickards, 2001. *Climate of UK waters at the Millennium; status and trends*. IACMST Information Document No. 9, 48 pages. Southampton, UK: The Inter-Agency Committee on Marine Science and Technology

Allan, J. and P. Komar. 2000. Are ocean wave heights increasing in the eastern North Pacific? *EOS Transactions*, **81**, 561-567.

Alpers, W., U. Pahl, and G. Gross, 1998, Katabatic wind fields in coastal areas studied by ERS-1 synthetic aperture radar imagery. *J. Geophys. Res*., 103, C4, 7875-7886.

Anderson, C.W. Carter, D.J.T, and Cotton P.D. 2001, Wave Climate Variability and the Impact on Offshore Design Extremes, A report for the MetOcean Committee of the Offshore Oil and Gas Producers.

Aouf L., J-M. Lefèvre, and D. Hauser, Assimilation of synthetic SWIMSAT directional wave spectre in the wave model WAM, ISOPE Conference, Tokyo, May 2002

Bacon, S. and D.J.T. Carter. 1991. Wave climate changes in the North Atlantic and North Sea. *Int. J. Climatol*., **11**, 545-558.

Bacon, S. and D.J.T. Carter. 1993. A connection between mean wave height and atmospheric pressure gradient in the North Atlantic. *Int. J. Climatol*., **13**, 423-436.

Barstow, S.F., Athanassoulis, M.A., and Cavaleri, L.. EUROWAVES: Integration of data from many sources in a user-friendly software package for calculation of wave statistics in European coastal waters. Proc. Oceanology International 2000 Conference, Brighton, UK, March 2000, pp. 269-277 (CD-ROM), 2000

Bauer E., Hasselmann, S, Hasselmann, K., and Graber, H.C, 1992, Validation and assimilation of Seasat Altimeter wave heights using the WAM wave model. *J. Geophys. Res.,* 12671-12682.

Beal, R. C., T. W. Gerling, D. E. Irvine, F. M. Monaldo, and D. G. Tiley , Spatial variations of ocean wave directional spectra from the Seasat synthetic aperture radar. J. Geophys. Res. 91(C2), 2433-2449, 1986.

Bidlot, J.-R. and Holt, M.W.,. Numerical wave modelling at operational weather centres. Coastal Engineering, 37, 409-429., 1999.

Breivik L-A., and M. Reistad, Assimilation of ERS-1 altimeter wave heights in an operational numerical wave model, Weather Forecasting, 9 (3), 440-451, 1994

Breivik L-A., M. Reistad, H. Schyberg, J. Sunde, H. Krogstad, and H. Johnsen, Assimilation of ERS SAR wave spectra in an operational wave model, J. Geophys. Res., 103, C4, 7887-7900, 1998

Brugghe, P., Leenaars, C., and Louazel, S. 2000. Comparison of wave data bases and design methods for major shipping routes. Technical report, Internal Report for COMKISS, July 2000.

Carter, D.J.T. and L. Draper. 1988. Has the north-east Atlantic become rougher? *Nature*, **332**, 494.

Carter, D.J.T., P.G. Challenor and M.A. Srokosz. 1992. An assessment of Geosat wave height and wind speed measurements. *J. Geophys. Res.*, **97**, 11383-11392.

Carter, D.J.T. 1999. Variability and trends in the wave climate of the North Atlantic: A review. *Proc. 9th ISOPE Conference*, Volume III, pp. 12-18, Brest, France, June 1999, ISOPE, Cupertino, CA.

Cavaleri, L., G.A. Athanassoulis and S. Barstow, 1999, EUROWAVES: A user friendly approach to the evaluation of the nearshore wave conditions, Proceedings of the ninth ISOPE, Brest, France, May 30 – June 4, 1999, Vol. III, pp158-163.

Challenor, P.G. and P.D. Cotton. 2002. The joint calibration of altimeter and in situ wave heights. *Advances in the Applications of Marine Climatology - The Dynamic Part of the WMO Guide* *to the Applications of Marine Climatology. WMO/TD-No.1081 JCOMM Technical Report No.13.* World Meteorological Organization, Geneva (in press).

Chapron B., D. Vandemark, and T. Elfouhaily, Altimeter electromagnetic bias : A new look at global range error estimates, Geophysical Research Letters, 2001, in press.

Chelton, D. B., K.J. Hussey and M.E. Parke. 1981. Global satellite measurements of water vapor, wind speed and wave height. *Nature,* **294**. 529-532.

Cotton, P.D. and D.J.T. Carter. 1994. Cross calibration of TOPEX, ERS-1, and Geosat wave heights. *J. Geophys. Res*., **99**, 25025-25033. (Correction, *J.Geophys. Res*., **100**, 7095, 1995.)

Cotton, P.D. 1998. A feasibility study for a global satellite buoy intercalibration experiment. *Southampton Oceanography Centre Research and Consultancy Report, No. 26*, Southampton, U.K., 73pp.

Cotton, P. D., D. J. T. Carter, P. G. Challenor, D. K. Woolf, J. Wolf, J. C. Hargeaves, R. A. Flather, Li Bin, N. Holden and D. Palmer, 1999, «JERICHO» – Joint Evaluation of Remote Sensing Information for Coastal and Harbour Organisations – Final Report for the British National Space Centre, 37 pp.

Cotton, P. D., Astin, I., and Hodges, K. 2000a. GANDER technical feasibility study, WP300, orbit definition. Technical report.

Cotton, P. D, Lindgren, G., Rychlik, I., Olagnon M., Prevosto P., Nerzic, R., Leenaars C., Brugghe P., Parmentier G., 2000, COMKISS (Conveying Metocean Knowledge Improvements onto Shipping Safety- Supported by CEO of the European Commission (ENV4-CT98-0751), Final report (http://www.satobsys.co.uk/projects/COMKISS), 63 pages, 2000

Cotton P. D., Challenor, P. G., Redbourn-Marsh, L, Gulev, S. K, Sterl, A., Bortkovskii, R.S., An inter-comparison of voluntary observing, satellite data and modelling wind wave climatologies. The Dynamic Part of the WMO Guide to Applications of Marine Climatology, WMO/TD-No. 1081, Geneva., 2001.

Cotton, P.D., and P. Challenor, communication at the Jason- SWT meeting, Biarritz, 2002

Cox, A.T., and V.R. Swail. 2001. A global wave hindcast over the period 1958-1997: validation and climate assessment. *J. Geophys. Res. (Oceans)*, **106 (C2)**, 2313-2329.

Cox, A.T., V.J. Cardone and V.R. Swail. 2002. On the use of in situ and satellite wave measurements for evaluation of wave hindcasts. *Advances in the Applications of Marine Climatology - The Dynamic Part of the WMO Guide to the Applications of Marine Climatology. WMO/TD-No.1081 JCOMM Technical Report No.13*. World Meteorological Organization. Geneva, Switzerland (in press).

Dacunha, N.M.C and N. Hogben, 1989, The development of a new global atlas of wave statistics. Journal of Navigation, 38(1), pp145-149.

Davies, C. and P.G. Challenor. 1997. Validation of wave period measurements from radar altimeter data. In proc, ASCE Waves 1997 conference.

De La Heras M. M., G. Burgers, and P.E.M. Janssen, Variational wave data assimilation in a third-generation wave model, J. Atmos. and Oceanic Tech., Vol 11, p130-1369, 1994

Draper, L. 1980. Wave climatology of the U.K. continental shelf. In *The north-west European shelf seas: the sea bed and sea in motion. II. Physical and chemical oceanography and physical resources* (ed. F.T. Banner, M.B. Collins & K.S. Massie), pp. 353-368. Amsterdam: Elsevier.

Draper, L. 1991. *Wave climate atlas of the British Isles*. Offshore Technology Report OTH 89 303, 11 pp. and plates. London: HMSO.

Dunlap E.M., E.B. Olsen, L. Wilso, S. De Margerie, and R. Lalbehrry, The effect of assimilating ERS-1 fats delivery wave data into the North Atlantic WAM model, J. Geophys. Res., 103(C4), 7901-7915, 1998

Elfouhaily, T., D. Vandemark, J. Gourrion and B. Chapron. 1998 Estimation of wind stress using dual-frequency TOPEX data. *J. Geophys Res.*, **103**, 25101-25108.

Elfouhaily, T. , D.R. Thompson and L.A. Linstrom. 2001. Delay-Doppler analysis of bistatically reflected signals from the ocean surface: theory and application. Submitted to *IEEE Trans. Geosc. Rem. Sens*.

Elfouhaily T., D.R. Thompson, B. Chapron, D. Vandemark, Improved electromagnetic bias theory: inclusion of hyrodynamic modulatons, J. Geophys. Res., 106 (C3), 4655-4664, 2001

Engen G., and H. Johnson, Sar-Ocean wave inversion using image cross spectra, IEEE Trans. on Geoscience and Remote Sensing, vol 33, No 4, 1047-1056, 1995

Escudier P. et al., Jason system overview and status, AVISO Newsletter, N°7, edited by CNES, January 2000

Freilich, M.H. and P. G. Challenor. 1994. A new approach for determining fully empirical altimeter wind speed model functions. *J. Geophys. Res*., **99**, 25051-25062.

Gaspar, P., F. Ogor, P.-Y. Le Traon and O.-Z. Zanif. 1994. Estimating the sea state bias of the TOPEX and POSEIDON altimeters from crossover differences. *J. Geophys. Res.*, **99**, 24981-24994.

Gaspar P. and J-P. Florens. 1998. Estimation of the sea state bias in radar altimeter measurements of sea level: Results from a new non-parametric method. *J. Geophys Res.*, **103**, 15803-15814.

Glazman, R.E. and A. Greyshuk. 1993. Satellite altimeter measurements of surface wind. *J. Geophys. Res*., **98**, 2475-2483.

Glover, D.M., N.M. Frew, S.J. McCue and E.J. Bock. 2001. A multi-year time series of global gas transfer velocity from the TOPEX dual frequency, normalized radar backscatter algorithm. In *Gas Transfer at Water Surfaces*, ed.s M.A. Donelan, W.M. Drennan, E.S. Saltzman and R. Wanninkhof, AGU, Washington, pp. 325-331.

Gommenginger, C.P., M.A. Srokosz, P.G. Challenor and P.D.Cotton. 2002a. Development and validation of altimeter wind speed algorithms using an extended collocated buoy/Topex dataset. *IEEE TGARS*, **40**, 251-260.

Gommenginger, C.P., M.A.Srokosz, J.Wolf, & P.A.E.M. Janssen. 2002b. A theoretical investigation of altimeter sea state bias. Submitted.

Gommenginger, C.P., M.A. Srokosz, P.G. Challenor, V.Y. Karaev and P.D.Cotton. 2002c. Ocean wave effects on global altimeter wind climate retrieval. In *Ocean Wave Measurement and Analysis*, Ed.s B.L. Edge and J.M. Hemsley, ASCE, Virginia, Virginia, 144-153.

Gourrion. J., D. Vandemark, S. Bailey and B. Chapron. 2000. Satellite altimeter models for surface wind speed developed using ocean satellite crossovers. *Report IFREMER-DROOS–2000-02*, 60 pp. Available from http://topex.wff.nasa.gov/docs/docs.html.

Graham, N. E. and H.F. Diaz. 2001. Evidence for intensification of North Pacific winter cyclones since 1948. *Bulletin A.M.S.*, **82**, 1869-1893.

Grant, Dyer, and Leggett (1995), Development of a new metocean design basis for the NW Shelf of Europe, OTC 7685, Offshore Technology Conference, Houston pp 415-424

Grant C., and C. Shaw, 2001, Operational Oceanographic Needs for the Offshore Oil and Gas Industry. GOOS Data products and Services Bulletin, Volume 1 (at http://www.ioc.unexco.org/gpsbulletin/Vol1article.htm.

Grevemeyer, I., R. Herber and H.-H. Essen. 2000. Microseismological evidence for a changing wave climate in the northeast Atlantic Ocean. *Nature*, **408**, 349-352.

Guillaume A., and Hansen B. 1993, Operational use of ERS-1 observations in ocean wave forecasting at ECMWF. In Proceedings 2nd ERS-1 Symposium: Space at the Service of our Environment, Hamburg, Germany, 11-14 October 1993. ESA SP - 361. ESA,

Gulev, S.K. and L. Hasse. 1999. Changes of wind waves in the North Atlantic over the last 30 years. *Int. J. Climatol.*, **19**, 1091-1117.

Gulev, S.K., D. Cotton and A. Sterl. 1998. Intercomparison of the North Atlantic wave climatology from Voluntary Observing Ships, satellite data and modelling. *Phys. Chem. Earth*, **23**, 587-592.

Günther, H., W. Rosenthal, M. Stawarz, J.C. Carretero, M. Gomez, I. Lozano, O. Serrano and M. Reistad. 1998. The wave climate of the Northeast Atlantic over the period 1955-1994: The WASA wave hindcast. *Global Atmos. Ocean Sys.*, **6**, 121-163.

Hasselmann S.,P. Lionello; K. Hasselmann, An interpolation scheme for the assimilation of spectral wave data, J. Geophys. Res., 102, C7, 15823-15836, 1997

Hauser, D., Caudal, G., Rijckenberg, G. J., Vidal-Madjar, D., Laurent, G., Lancelin, P., "RESSAC: A new airborne FM/CW radar ocean wave spectrometer", IEEE Trans. on Geoscience and Remote Sensing, Vol. 30 N° 5, pp 981-995, 1992

Hauser D., Caudal G., Participation of RESSAC to SWADE, Final Report, May 1992

Hauser, D., G. Caudal, and L.K. Shay, Behavior of the ocean radar cros-section at low incidence, observed in the vicinity of the Gulf-Stream,IEEE Trans.on Geoscience and Remote sensing, vol 33, No 1, 162-171, 1995

Hauser D., and G. Caudal, Combined analysis of the radar cross-section modulation due to the long ocean waves around 14 and 34° incidence: implication for the hydrodynamic modulation, J. Geophys. Res., vol. 101, No. C11, 25,833-25,846, 1996

Hauser D., 2001, SWIMSAT - Surface Waves Investigation and monitoring from Satellite, A proposal to the Earth Explorer Opportunity Missions of ESA.

Hauser D., E. Soussi, E.,Thouvenot, L. Rey: SWIMSAT: A real aperture radar to measure directional spectra of ocean waves from space, Main characteristics and performance simulation, Jour. Atmos. and Oceanic Tech, vol 18 No3, 421-437, 2001a

Hauser D., L. Aouf, J-M Lefèvre, Prospect of new ocean waves spectral observations from the SWIMSAT satellite: measurements and assimilation, Proceedings of the ECMWF Workshop on Ocean Wave Forecasting, Reading, 2 to 4 July 2001b

Hersbach, H. Application of the adjoint of the WAM model to inverse wave modeling, JGR vol 103 pp10,469-10,487, 1998

Hogben N., and F. E. Lumb, 1967, *Ocean Wave Statistics*, Her Majesty's Stationery Office, London, UK

IORD II, 2001, Integrated Operational Requirements Document For National Polar-Orbiting Operational Environmental Satellite System (NPOESS) ACAT 1d

Jackson, F. C., Walton, W. T. et Peng, C. Y., A comparison of in situ and airborne radar observatios of ocean wave directionality, J. Geophys. Res., Vol. 90, N° C1, pp. 1005-1018, 1985a

Jackson, F. C., Walton, W. T. et Baker, P.L., Aircraft and satellite measurement of ocean wave directional spectra using scanning-beam microwave radars, J. Geophys. Res., Vol 90 N° C1, pp 987-1004, 1985b

Janssen P., Lionello, P. Reistad, M., et Hollingsworth A., Hindcasts and data assimilation studies with the WAM model during the seasat period, J. Geophys. Res., Vol 94, No.C1, pp 973-993, 1989

Janssen, P.A.E.M., Hansen, B. and Bidlot, J.-R., Verification of the ECMWF Wave Forecasting System Against Buoy and Altimeter Data. Weather and Forecasting, 12, 763-784, 1997.

Janssen, P.A.E.M, Present status of wave forecasting at ECMWF, Proceedings of the EVMWF Workshop on Ocean Wave Forecasting, Reading, 2-4 July 2001, p 1-4

Jason-1 CALVAL Plan, edited by Y. Menard and B. Haines, Ref CNES: TP2-J0-PL-974-CN, April 2001Fischer, J., and N. C. Flemming, 1999, Operational Oceanography: Data Requirements Survey», J., EuroGOOS Publication No. 12, Southampton Oceanography Centre, Southampton, ISBN 0-904175-36-7.

Jolly, G. W., P. D. Cotton, C. Challinor, and A.De Silva Curiel, 2000, GANDER Technical Feasibility Study – Final Report, Unpublished contract report for BNSC.

Jones, I.S.F. and Y. Toba. 2001. *Wind Stress over the Ocean*. Cambridge University Press, 307pp.

Komen. G.J., Cavaleri L., Donelan M., Hasselmann K., Hasselmann S., Janssen P.A.E.M , 1994, editors *Dynamics and modelling of Ocean Waves*, Cambridge University Press, Cambridge 532 pp

Kushnir, Y., V.J. Cardone, J.G. Greenwood and M.A. Cane. 1997. The recent increase in North Atlantic wave heights. *J. Climate*, **10**, 2107-2113.

Lefevre, J-M., 1992, The impact of altimeter data assimilation for wave forecasting in the Mediterranean sea., in «Proceedings of the third international workshop on wav hindcasting and forecasting,» May19-22 Montreal.

Lefevre, J.-M. and Cotton, P. D. 2001. Ocean surface waves. In Fu, L.-L. and Cazenave, A., editors, Satellite Altimetry and Earth Sciences. Academic Press, International Geophysics Series Vol 69..

Lefevre, J.M., and H. Le Berre, communication at the Jason- SWT meeting, Biarritz, 2002

Lionello, P. et Günther H. , Assimilation of altimeter data in a global third-generation wave model, J. Geophys. Res., Vol 97, No.C9, pp 14,453-14,474, 1992

Menard Y. et al., Cruising the Ocean from Space with Jason-1, Eos, Transactions, AGU, Vol.81, N° 34, 2000

Millet, F.W., D.Arnold, P. Gaspar, K. Warnick and J. Smith. 2002. Electromagnetic bias estimation using in situ and satellite data: a nonparametric approach. Submitted .

Pettersson H., H.C. Graber, D. Hauser, C. Quentin, K. Kahma, W.M. Drennan, and M.A. Donelan Directional wave measurements from three wave sensors during the FETCH experiment, in press, J. Geophys. Res, 2002

Quartly, G.D. 1998. Determination of oceanic rain rate and rain cell structure from altimeter waveform data. Part I: Theory, *Journal of Atmospheric and Oceanic Technology*, **15**, 1362-1379.

Quartly, G.D. 2000. The gate dependence of geophysical retrievals from the TOPEX altimeter. *Journal of Atmospheric and Oceanic Technology*, **17**, 1247-1251.

Queffeulou, P., and P.D. Cotton, communication at the Jason- SWT meeting, Biarritz, 2002, Science Working Team meeting, Biarritz, June 10-12, 2002, Mid-term verification workshop, Minutes edited by Y. Menard and

Reichert, K., K. Hessner, J. C. Nieto Borge, and J. Dittmer, 1999, WaMoS II: A radar based wave and current monitoring system, Proceedings of the ninth ISOPE, Brest, France, may 30 – June 4, 1999, Vol III, pp139-143.

Rogers, J. C. 1990. Patterns of low-frequency monthly sea level pressure variability (1899-1986) and associated wave cyclone frequencies. *J. Climate*, **3**, 1364-1379.

Rogers, J. C. 1997. North Atlantic storm track variability and its association to the North Atlantic Oscillation and climate variabilty of Northern Europe. *J. Climate*, **10**, 1635-1647.

Rossby, C.-G. and Collaborators. 1939. Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semi-permanent centers of action. *J. Mar. Res.*, **2**, 38-55.

Srokosz, M. A. 1986. On the joint distribution of surface elevation and slopes for a nonlinear random sea, with an application to radar altimetry. *J. Geophys. Res.*, **91**, 995-1006, 1986.

Sterl, A., G.J. Komen and P.D. Cotton. 1998. Fifteen years of global wave hindcasts using winds from the European Centre for Medium-Range Weather Forecasts reanalysis: Validating the reanalyzed winds and assessing the wave climate. *J. Geophys. Res.*, **103**, 5477-5492.

Swail, V. R. and Cox, A. T. 2000. On the use of NCEP-NCAR reanalysis surface winds for a long-term North Atlantic wave hindcast. J. Atmos. & Oceanic Tech., 17,532-545.

Swail, V. R., A. T. Cox and V. J. Cardone. 2002. Analysis of wave climate trends and variability. *Advances in the Applications of Marine Climatology - The Dynamic Part of the WMO Guide to the Applications of Marine Climatology. WMO/TD-No.1081 JCOMM Technical Report No.13*. World Meteorological Organization. Geneva, Switzerland (in press).

Taylor, P.K. & M. J. Yelland. 2001. The dependence of sea suarafce roughness on the height and steepness of the waves. *J. Phys. Oceanogr.*, **31**, 572 – 590.

Tokmakian, R. and P.G. Challenor. 1999. On the joint estimation of model and satellite sea surface height anomaly errors. *Ocean Modelling*, **1**, 39-52.

The WASA Group. 1998. Changing waves and storms in the Northeast Atlantic? *Bulletin A.M.S.*, **79**, 741-760.

Voorrips A.C., V.K. Makin, and S. Hasselmann, Assimilation of wave spectra from pitch-and-roll buoys in a North Sea wave model, J. Geophys. Res., 102 (C3), 5829-5849, 1997

Voorrips, A. C., Mastenbroek C., Hansen B., Validation of two algorithms to retrieve ocean wave spectra from ERS-SAR, preprints KNMI, N99-23, 34 p, 1999

Wallace, J. and D. Gutzler. 1981. Teleconnections in the geopotential height field during the Northern hemisphere winter. *Mon. Wea. Rev.*, **109**, 784-812.

Wang, X.L. and V.R. Swail. 2001. Changes of extreme wave heights in Northern Hemisphere oceans and related atmospheric circulation regimes. *J. Climate*, **14**, 2204-2221.

Wang, X.L. and V.R. Swail, 2002. Trends of Atlantic wave extremes as simulated in a 40-year wave hindcast using kinematically reanalyzed wind fields. *J. Climate*, **15**, 1020-1035.

Witter, D.L. and D.B. Chelton. 1991. A Geosat altimeter wind speed algorithm and a method for altimeter wind speed algorithm development. *J. Geopyhs. Res.*, **96**, 8853-8860.

Woolf, D.K. and P.G. Challenor. 2002. Statistical comparisons of satellite and model wave climatologies. In *Ocean Wave Measurement and Analysis*, Ed.s B.L. Edge and J.M. Hemsley, ASCE, Virginia, Virginia, 640-649.

Woolf, D.K., P.G. Challenor and P.D. Cotton. 2002a. The variability and predictability of North Atlantic wave climate. *Journal of Geophysical Research* (in press).

Woolf, D.K., P.D. Cotton and P.G. Challenor. 2002b. Measurements of the offshore wave climate around the British Isles by satellite altimeter. *Philosophical Transactions of the Royal Society London, Series A* (in press).

Wyatt, L. R.,1999, HF radar measurements of the development of the directional wave spectrum, The Wind-Driven Air-Sea Interface, ed M L Banner, pub School of Mathematics, University of New South Wales, Australia, 433-440.

Young, I.R. 1999a. An intercomparison of GEOSAT, TOPEX and ERS1 measurements of wind speed and wave height. *Ocean Engng*, **26**, 67-81.

Young, I.R. 1999b. Seasonal variability of the global ocean wind and wave climate. *Int. J. Climatol.*, **19**, 931-950.

Young, I.R. and G.J. Holland. 1996. *Atlas of the oceans: wind and wave climate*. Pergamon, Oxford, 241pp.

Zveryaev, I. I. 1999. Decadal and longer changes of the winter sea level pressure fields and related synoptic activity over the North Atlantic. *Int. J. Climatol.*, **19**, 1177-1185.