



# **GAMBLE**

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

**Final Report**

January 2003

**Edited by: Luigi Cavaleri**  
**Istituto per lo Studio della Dinamica delle Grandi Masse,**  
**Consiglio Nazionale delle Ricerche - ISDGM/CNR,**  
**Venice, Italy**

**Written Contributions from:**

David Cotton (Satellite Observing Systems - SOS, UK)  
Daniele Hauser (Centre d'Etude des Environnements Terrestre et Planétaires -CETP, France)  
Yves Menard (Centre National D'Etudes Spatiales – CNES, France)  
Laurent Phalippou (ALCATEL, France)  
David Woolf (Southampton Oceanography Centre - SOC, UK)

**Further Contributions from:**

Johannes Guddall (Det Norske Meteorologiske Institutt - DNMI, Norway)  
Jim Gunson (United Kingdom Meteorological Office – UKMO, UK)  
Peter Janssen (European Centre for Medium Range Weather Forecasting – ECMWF, UK)  
Jean-Michel Lefèvre (Météo France, France)  
Susanne Lehner (Deutsches Zentrum für Luft- und Raumfahrt - DLR, Germany)  
Francisco Ocampo-Torres (El Centro de Investigación Científica y de Educación Superior de Ensenada - CICESE, Mexico)

# TABLE OF CONTENTS

1	Introduction .....	4
2	Satellite altimetry and sea-state .....	5
2.1	Priority issues.....	5
2.2	Feature Characteristics.....	6
2.3	Supporting information.....	7
2.4	Summary of User Requirements.....	7
2.5	Altimeter Capabilities.....	9
2.6	Suggested Research / Recommendations from the GAMBLE Sea State Workshop .....	10
2.7	Possible Mission Scenarios.....	11
3	Wind and Waves.....	12
3.1	Background and Key Issues.....	12
3.2	Measurement Principles.....	13
3.3	Expectations and Current Performance.....	15
3.4	Mission Characteristics.....	18
3.5	Future Developments.....	19
4	Satellite altimeter sea state measurements for offshore operations.....	20
4.1	Introduction.....	20
4.2	Near Real Time Applications.....	20
4.3	Climatological Applications .....	24
4.4	Conclusions.....	27
5	SWIMSAT – the use of altimeter for the measurement of the 2-D wave spectrum.....	29
5.1	Objectives .....	29
5.2	Basic principles and characteristics .....	29
5.3	Expected geophysical parameters.....	33
5.4	How SWIMSAT will contribute to answer to the key issues .....	33
5.5	Relation with other missions concerned by the GAMBLE project.....	38
6	JASON-1 .....	40
6.1	The Jason-1 mission.....	40
6.2	Jason-1 products and ground segment .....	40
6.3	Jason-1 CALVAL phase.....	42
6.4	The Jason 2/OSTM mission to follow up Jason-1 .....	43
7	Radar state of the art and new concepts for GAMBLE .....	44
7.1	Introduction.....	44
7.2	State of the art in radar altimeters .....	44
7.3	New altimeter concepts.....	47
7.4	Mission reviews.....	53
7.5	Instrument complexity .....	59
8	Appendices .....	67
8.1	Appendix A. Offshore Operator’s Requirements - EUROGOOS questionnaire .....	67
8.2	Appendix B. Presentations made to the GAMBLE Sea State Workshop .....	68

## Glossary

ADC:	Analogue to Digital Converter
AGC:	Automatic Gain Control
ALTIKA:	Ka band altimeter, proposed by CNES
ASAR:	Advanced Synthetic Aperture Radar (carried on ENVISAT)
CETP:	Centre d'Etude des Environnements Terrestre et Planétaires, France
CHAMP:	Challenging Mini-Satellite Payload, Research satellite. Will support improved gravity field mapping.
CNRS:	Centre National de la Recherche Scientifique, France
CRYOSAT:	A satellite altimeter mission to monitor ice sheet thickness.
DORIS:	Precise Orbit Determination system
ENVISAT:	European Environment Monitoring Satellite.
ERA:	ECMWF Re-Analysis. 15 year atmospheric hindcast
ERS-1:	1 <sup>st</sup> European Remote Sensing Satellite (launched 1991)
ERS-2:	2 <sup>nd</sup> European Remote Sensing Satellite (launched 1995)
ESSC:	Environmental Systems Science Centre, Reading, UK .
EUMETSAT:	European Agency to provide operational meteorology measurements from satellites
EUROGOOS:	European Contribution to the Global Ocean Observing System.
fft:	Fast Fourier Transform
GANDER:	Proposal for a constellation of wave measuring Microsatellite altimeters
(I)GDR:	(Interim) Geophysical Data Records
GEOSAT /GFO:	US Navy Altimeter Satellite (1985-90) / Geosat Follow-On - Follow on to Geosat (1998-)
GNSS:	Global Navigation Satellite System
GPS:	Global Positioning System.
GRACE:	Satellite mission to improve mapping of the Earth's gravity field, launched by NASA in 2002.
GTS:	Global Telecommunications System.
GWS:	Global Wave Statistics (Wave Climate data base).
HF Radar:	Surface High Frequency Radar, for remote sensing of waves and surface currents.
IAP/RAS:	Institute of Applied Physics/ Russian Academy of Science
IMDSS:	Integrated Marine Decision Support System (Wave Climate data base).
IODR:	Integrated Operational Requirements Document (for NPOESS).
JASON-1:	Ku/C band altimeter launched in 2001 by CNES/NASA
JASON-2/OSTM:	Successor to JASON-1, Planned launch 2007 (Ocean Surface Topography from Space Mission)
JPL:	Jet Propulsion Laboratory (NASA Laboratory).
LEO:	Low Earth Orbit.
NAO:	North Atlantic Oscillation
NASA:	National Aeronautics and Space Administration
NCEP:	(US) National Center for Environmental Prediction
NOAA:	(US) National Oceanographic and Atmospheric Administration
NPOESS:	National Polar-Orbiting Operational Environmental Satellite System
OSDR:	Operational Sensor Data Record
OWS:	Ocean Wave Statistics (Wave Climate data base)
pdf:	Probability Density Function
POSEIDON:	A solid state Ku band altimeter carried as an experimental instrument on TOPEX.
POSEIDON2:	Upgrade of POSEIDON adopted as the main altimeter on JASON.
PRF:	Pulse Repetition Frequency
PROTEUS:	ALCATEL mini satellite platform.
RESSAC:	Airborne Wave Measuring Radar
RMS:	Root Mean Square (a measure of data scatter)
SAR:	Synthetic Aperture Radar
Scatterometer	Satellite radar instrument to measure ocean surface wind
SIRAL:	Advanced interferometric, synthetic aperture radar altimeter, developed for Cryosat.
$\sigma_0$	Surface Radar Backscatter
SSB:	Sea State Bias. A sea state dependant error (overestimate) in the altimeter height measurement.
SWH, $H_s$ :	Significant Wave Height.
SWIMSAT:	A proposal for a satellite -borne Wave Measuring Radar.
TOPEX:	Ku/C band altimeter launched in 1992 by CNES/NASA
WAM:	A widely used computer model for wave generation, propagation and dissipation
WAM-ERA	A global wave hindcast, gained from running WAM on the ERA output.
WSOA:	Wide Swath Ocean Altimeter – a proposed swath measuring altimeter
U10:	Wind speed referenced to 10m above the ocean surface

## **1 Introduction**

This is the final report for the 3<sup>rd</sup> work package WP3 of the GAMBLE project. It provides a 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, preceded by a section where the background of the problem and the present state of the art are summarised. 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 provides an overview of the main points discussed and of the information available in the overall report. It provides also summary tables where needs and present capabilities are quantified for a better assessment of the practical future possibilities. This information is justified and expanded in the following sections highlighting the problems connected with satellite altimetry from different points of view. 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. In section 7 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 Satellite altimetry and sea-state

### 2.1 Priority 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., Young and Holland, 1996, and Barstow et al., 2000). 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. Altimeter data are an especially important resource for countries who have an interest in monitoring offshore ocean conditions but are unable to support networks of in-situ measuring instrumentation (Ocampo-Torres, pers. comm.2002).

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. At “cross-over” points (where ascending and descending tracks intersect) this sampling rate is doubled, but these points are widely spaced. Of course the data are more dense along the track (one every 7 km), but in practice the sampling variability requires that these data are averaged over 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 only in a relatively narrow band on the sides of the ground track. The main drawback has been the lack of capability to singularly correct, with data assimilation, the single wave systems that compose the two-dimensional spectrum at a given location. SAR data have been used 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 SAR signal requires an a priori knowledge of the spectrum, which is obtained from the model where the data are to be assimilated. More recent techniques promise to bypass this limitation.

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 away from the coast. (N.B. Early results from ENVISAT promise improved performance in this respect). 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 models is 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 ocean and atmosphere systems, which in turn control the earth climate. A better knowledge of the processes involved is clearly highly desirable. However, the basic difficulty in studying the physics of waves, e.g. 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 may be hampered by the coarse resolution at which 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.

## 2.2 Feature Characteristics

The distribution of wind and waves on the oceans is mainly characterised by the sharp distinction between the storm belt, at latitudes north of  $40^\circ$ - $45^\circ$ , and the tropical-equatorial zone. North of this zone (symmetrical conditions exist in the southern hemisphere) a permanent west to east atmospheric flow brings with it a steady flow of storms. The border between the two areas depends on the season, with a shift to a more northern position during the warmer months of the year.

The overall pattern reflects this distribution, with the strongest winds present at latitudes between  $60^\circ$  and  $70^\circ$ . Obviously local patterns exist close to the continents, where orography can play a major role (see Figure 3.4). An exception to the above pattern are the hurricanes, which are generated only in the sub-tropical belt. Their dimension is limited, at least with respect to the extra-tropical storms, but the extremely high winds still lead to record wave heights.

The distribution of wave heights follows closely the wind climate (see Figure 3.1). The storm belt is characterised by frequent very active sea conditions, with wind generated, steep breaking waves. In the tropical-equatorial zone the climate is characterised mainly by swell, when the long waves generated by the northerly storms propagate out of the stormy area. Because of the very limited attenuation with distance, an energetic swell can propagate for thousands of kilometres.

These different characteristics are relevant for satellite altimetry. The different physics associated with the different wind and wave conditions affect the altimeter output and the quality of the results. The higher and steeper the waves, the higher is the sea-state bias affecting the accuracy of sea surface height. There are strong doubts about the validity of altimeter wind data at extremely high wind speeds. In these conditions the physics of the surface changes dramatically, and are still largely not understood.

The different time scales and spatial gradients present in different situations set different constraints on the desired altimeter sampling strategy. For climate purposes, i.e. to provide a general outline of the distribution of the main characteristics of wind and waves, there is no special constraint on the accuracy of the time and location of a pass. The scale of the processes is fairly wide, with variations on the scale of hundreds of kilometres. Nor is there is a special restriction on the time interval between passes, or, conversely, on the spacing between adjacent passes. The choice is a compromise between the number of data at each location and the spatial density of the information.

Things change substantially when we move to practical applications. Dealing with the single storms, or even more with hurricanes, the time and space scales shrink dramatically. However, no particular optimum satellite orbit configuration can be chosen in advance because of the almost random (within the storm belt) distribution of the storms.

All this holds for the open oceans. Close to the coasts we find much larger spatial gradients, both for the geometry of the coast and for the effect of orography on the driving wind fields. In these conditions a much higher density of information would be required, but most likely beyond the practical possibilities of satellite altimetry. As for a detailed description of the open oceans climate, a step towards a solution lies in the parallel use of the information from the numerical models.

### **2.3 Supporting information**

Satellite data are by far the largest source of marine measured data. During the last ten years an unprecedented volume of data has been made available, providing information at a level inconceivable only 15 years ago. Notwithstanding this, the information is still not up to the level believed as necessary for a continuous, reliable and detailed application. As already mentioned in sub-section 2.1, an altimeter with a return period of ten days provides at each location less than forty data per year.

Complementary measured data, measured from buoys and platforms, are dismayingly limited in number, and mostly concentrated close to the coasts. These data are extremely useful for the validation and calibration of satellite data, but they cannot contribute significantly to the definition of the ocean climate.

As it is often the case, the solution does not come from a single source, but from the combined use of several of them. Meteorological and wave models provide wind and wave information on a global scale with high resolution and on a continuous basis. In principle, this should be the optimal solution in itself. However, although highly refined, these are just models, and as such they bring with them all the implied limitations. The solution lies in the combined use of satellite and model data. In general, within the uncertainty of the single estimates, the model errors tend to be systematic. In statistical terms and on a percent basis, they do not vary much in space and time. Therefore a comparison with satellite data will reveal which corrections are required. The clue is that, because the long term model errors do not vary rapidly in space, the model corrections at one or more locations can be readily extended to the whole neighbouring area.

The overall picture we can derive is on the combined use of buoys (ground truth) – satellite – models. The buoys are used to validate the satellite data. In turn these will provide the necessary widely distributed information to validate and, where necessary, calibrate the model results. Given that the model data have been available with high spatial and temporal density for many years, this provides an extremely large data-base to be used for any practical application.

All this holds in the open oceans, where the gradients are limited, and the information can be transferred in space. As already mentioned at the end of the previous sub-section, the conditions change substantially close to the coasts. There is no straightforward solution in this area. Additional sources of information are required, their density being proportional to the local gradients. Local measuring systems, e.g. radars, and high resolution limited area models, nested in the large scale ones, are obvious suggestions.

### **2.4 Summary of User Requirements**

Table 2.1 provides summary user requirements, from the research and offshore operator communities, for “Sea State” information that can be derived from altimeter measurements. In this instance “Sea State” is defined to include wind and wave measurements, and air sea fluxes (including rain). In Table 2.1 “Threshold Requirements” indicate requirements that represent a “practically useful” improvement on the present capability, “Optimum Requirements” represent the measurement characteristics beyond which no improvement would have practical value. “Latency” is the delay from the time the measurement is taken to the availability of this measurement to the user.

The exact requirements of course vary from user to user, also the requirements reflect the necessary precision / resolution in the final product as received by the user, they do not necessarily indicate the specifications for the original altimeter measurement. Thus Table 2.1 represents a “synthesis “ of several sets of requirements, differing in individual detail.

Application	Altimeter Parameter	Optimum requirements				Threshold requirements			
		Spatial res. (km)	Time res.	latency	accuracy	Spatial res (km)	Time res	latency	accuracy
Climate Research	Sig. wave ht (Hs) <sup>1</sup>	50	6hr	months	0.1 m	100	1 mon	3 months	0.1 m
Offshore appls. (climate)	Hs <sup>1</sup>	10	6 hr	years	0.1 m	1° x 1°	1 mon	Years	0.1 m
assimilation into models	Hs <sup>1</sup>	25	3 hr	1hr	0.1 m	100	6hr	1hr	0.1 m
near real time - offshore	Hs <sup>1</sup>	10	20 min	1 hr	0.1 m	30	1 hr	3 hr	0.5 m
near real time - coastal	Hs <sup>1</sup>	<5	20 min	1 hr	0.1	10	1 hr	3 hr	0.1 m
Joint U10/ Hs pdfs	U10/Hs					1° x 1°	1 mon	Years	0.1 m / 2 ms <sup>-1</sup>
Climate Research	wave period <sup>1</sup>					100	1 mon	3 months	0.5 s
Offshore appls. (climate)	wave period <sup>1</sup>	10	6 hr	years	0.1 s	1° x 1°	1 mon	Years	0.2 s
near real time-offshore	wave period <sup>1</sup>	10	20 min	1 hr	0.1 s	30	1 hr	3 hr	0.5 s
near real time-coastal	wave period <sup>1</sup>	<5	20 min	1 hr	0.1 s	10	1 hr	3 hr	0.1 s
Joint Hs / period pdfs	Hs/T					1° x 1°	1 mon	Years	0.1 m / 0.2 s
Offshore appls. (climate)	wave dir. <sup>1</sup>	10	6 hr	years	±5°	1° x 1°	1 mon	Years	±10°
near real time-offshore	wave dir. <sup>1</sup>	10	20 min	1 hr	±5°	30	1 hr	3 hr	±10°
near real time-coastal	wave dir. <sup>1</sup>	10	20 min	1 hr	±5°	30	1 hr	3 hr	±10°
Offshore appls. (climate)	dir. wave spectrum					100 km	7d	3hr	15° dirn, 10% wavelen.
Near real time	dir. wave spectrum	10	30 min	1 hr	1% max energy	30	1 hr	3 hrs	1% max energy
Surface wind stress (U*)	Δσ <sup>02</sup>	25	1d	1d	1 cm hr <sup>-1</sup>	100	1d	1d	1 cm hr <sup>-1</sup>
Air sea gas transfer vel.	Δσ <sup>02</sup>	25	1d	1d	1 cm hr <sup>-1</sup>	100	1d	1d	10 cm hr <sup>-1</sup>
Rain rate	Δσ <sup>02</sup>					250	30d	90d	10 mm mon <sup>-1</sup>
Event and feature studies	Hs	< 10	<1d	1 hr	0.1m / 10%	200	1d	3 hr	0.1m / 10%
	U10	< 10	<1d	1 hr	2 ms <sup>-1</sup> / 10%	200	1d	3 hr	2 ms <sup>-1</sup> / 10%
	σ <sub>0</sub>	< 10	<1d	1 hr	0.1 dB	200	1d	3 hr	0.1 dB
Global Mapping of “Extreme” Waves	Joint Alt/SAR data sets.	Requirements to be determined through research							
Extreme Event Warning Systems	Combined Hs/ sea level: alt/model/in-situ systems					kms	hours	hours	threshold to be determined
Sea State Bias	Hs, (Δ)σ <sub>0</sub>					Various, according to sea surface height requirements			< 1 cm

<sup>1</sup> Separate wind sea and swell information desirable

<sup>2</sup> Dual frequency altimeter required.

NB Altimeter wave heights and wind speed measurements should ideally be accurate to the maximum of the expected range. Wind speeds are known to be inaccurate above 15 ms<sup>-1</sup>.

**Table 2.1. User requirements for altimeter derived sea state information.**

## 2.5 Altimeter Capabilities

Table 2.2 reviews the capabilities of various existing and proposed altimeter missions (see Section 7 for technical details of the missions). Two spatial resolutions that can be achieved are given, the first being the effective track separation over a period of 1 day, the second the best resolution for a climatology averaged over a period of 1 month.

	Parameter	Accuracy	Range of valid data	Spatial Res 1day /climatol.	Comments
JASON	$H_s$	0.15 m / 6%	0-15m	1350 km/ 2° x 2°	
	$U_{10}$	1.5 ms <sup>-1</sup> / 10%	0-15ms <sup>-1</sup>	1350 km/ 2° x 2°	
	$T_z$	0.5s	4-10 s	1350 km/ 2° x 2°	
	Dirn spectra	Not Available			
	Separate wind sea/swell	Not Available			
	$\Delta\sigma_0^1$ (various applications)	0.1 dB		1350 km/ 2° x 2°	
GFO	$H_s, U_{10}, T_z$ (not $\Delta\sigma_0$ )	as JASON	as JASON	1350km / 2° x 2°	Single frequency, so no $\Delta\sigma_0$ parameters <sup>1</sup> .
JASON & TOPEX & ENVISAT & GFO	$H_s, U_{10}, T_z$ (also $\Delta\sigma_0$ for JASON, TOPEX, & ENVISAT)	as JASON	as JASON	~350km / 1° x 1°	4 satellite sampling available <i>now</i> (from Sept. 2002 onwards)
NADIR altimetry with SAR and interferometry	$H_s, U_{10}, T_z$ & $\Delta\sigma_0$	as JASON	as JASON	as JASON High resolution along track (< 1km)	Possibility to derive other sea state parameters
Swath altimetry	$H_s, U_{10}, T_z$ & $\Delta\sigma_0$ (only at nadir)	as JASON (only at nadir)	as JASON (only at nadir)	1350 km/ 2° x 2°	Sea state measurements only given at nadir
“Basic” Ku altimeter Constellation (no radiometer)	$H_s, U_{10}, T_z$ (not $\Delta\sigma_0$ )	Original design specification 0.5 m, 2 ms <sup>-1</sup>	as JASON	3 sats ~350 km / daily 6 sats ~350 km / 12 hours	Single frequency, so no $\Delta\sigma_0$ parameters <sup>1</sup> .
AltiKa Constellation	$H_s, U_{10}, T_z$ (not $\Delta\sigma_0$ )	Original design specification 0.5 m, 2 ms <sup>-1</sup>	as JASON	3 sats: ~350 km / 24 hours 6 sats: ~350 km / 12 hours ~5 km footprint	Single frequency, so no $\Delta\sigma_0$ parameters <sup>1</sup> .  More attenuated by rain than Ku band
SWIMSAT	$H_s, U_{10}, T_z$ (not $\Delta\sigma_0$ )	Nadir – as JASON	Nadir – as JASON	Nadir – as JASON. It may be possible to estimate $H_s, U_{10}, T_z$ off-Nadir.	A single frequency Ku band nadir radar plus a rotating wave measuring real aperture radar
	Directional spectra	15° direction 10% wavelength		50-90km x 50-90km cells, ± 100km swath 100km res. after 7 days	
	Separate wind sea/swell	Possible			
	□□□□□□□□□□ □□□□□s□				
WITTEX <sup>2</sup>	$H_s, U_{10}, T_z$ (not $\Delta\sigma_0$ )	as JASON	as JASON	Tracks may not be evenly separated. Potential high resolution along track (< 1 km)	Single frequency, so no $\Delta\sigma_0$ parameters <sup>1</sup> .
GPS reflectometry	$H_s, U_{10}, T_z$	To be determined		estimated average track separation of 75 km over 1 day.	Feasibility under study, not available until 2010+. No $\Delta\sigma_0$ parameters <sup>1</sup> .

Table 2.2. Measurement Capabilities of existing and proposed missions.

<sup>1</sup> Various parameters derived from  $\Delta\sigma_0$ , mostly experimental, and accuracy yet to be verified

<sup>2</sup> The Wittex proposal includes a number of possible orbit configurations, including tracks separated by ~30km to provide across track slope and hence full 2D geostrophic velocities. Such a configuration would provide highly correlated sea state information on the two tracks, and so would be of limited interest in sea state applications. However, it could be of interest for studies into features with high small scale variability (e.g. close to coasts, and across intense storms).

## 2.6 Suggested Research / Recommendations from the GAMBLE Sea State Workshop

### 2.6.1 Quantifying Benefits

It is difficult to quantify in detail the improvements in knowledge that may flow from the various proposed missions. By the very nature of the problem, it is proposed to provide information on phenomena at a resolution and/or scale and/or accuracy not currently available. Thus it is not possible to know in advance the significance of what may be found. Take, for instance, the case of air-sea gas transfer velocities. The rate of air-sea CO<sub>2</sub> transfer is one of the largest unknowns in climate modelling. Presently the only way to estimate this quantity is through a parameterisation of secondary modelled quantities – the uncertainties associated with these estimates are large. Thus *any* direct estimate of this quantity will be of significant value, but, until comparisons of altimeter derived measurements against in-situ data have taken place, it is not possible to quantify exactly what improvements may be possible.

In the case of ocean wave forecasting it is possible to use models to estimate the possible impact of the assimilation of altimeter data (bearing in mind the limited knowledge of sea state variability scales in the open ocean). In Section 4 we note the work of Guillaume and Hansen, (1993) who found an impact of assimilating wave height data from a single altimeter up to 5° either side of the satellite track. Also, in Section 5, the results of studies investigating the potential impact of assimilating wave spectra from the proposed SWIMSAT mission are presented. It is seen that the impact of assimilating spectra has a impact on the model of longer duration and wider spatial impact than seen from the assimilation of altimeter data only (from one satellite). We note that in the summer of 2003 Météo France plan to model the impact of assimilating data from up to 5 satellite altimeters in their wave model.

### 2.6.2 Recommendations

A workshop to discuss future requirements for altimeter derived sea-state data was held at ISDGM, Venice on 30th September 2002 (see Appendix B, section 8.2). Recommendations derived from this workshop, and following from subsequent discussions, are presented in this section.

#### Measurement Priorities

From the perspective of users (research and commercial) priorities are:

- Improved sampling in space and time (uniformly distributed, so far as is possible)
- Availability of wave directional and wave period information – also separate wind sea and swell parameters (height, period and direction), wave steepness and joint distributions (e.g. of wave height / period, Hmax/Hs).
- Better combination of ocean / coastal monitoring resources (satellite, in-situ, models) to provide improved warning of severe events with high impacts on vulnerable populations.
- Implementation of a (new) wind speed algorithm valid for higher wind speeds.
- Validation of measurements at higher wave heights and wind speeds.
- Improved performance at coasts (higher along track resolution, quicker gain of ocean surface when the track comes from land to sea).
- Near real time availability of data (< 3 hours) .
- Joint climatologies of altimeter and SAR data - e.g. groupiness, expected maximum wave heights, crest length.

- Climatologies of air-sea fluxes (momentum, heat, gas, freshwater) are important for climate studies. Dual frequency altimeters offer the possibility for direct measurements of surface wind stress, and air-sea gas transfer velocities.

#### **Further Research**

Possible directions for further research include:

- Simulations with wave models to investigate the impact of a system combining SWIMSAT and Altimeters on a global scale wave model.
- A combined study with SAR wave mode and altimeter (and optical?) data to map characteristics and occurrences of possible rogue waves.
- Investigate validity of altimeter wave height measurements for significant wave heights above 10m.
- Develop and test new wind speed algorithms for high wind speeds.
- Further testing and development of altimeter wave period algorithms.
- Test validity of altimeter derived estimates of air sea gas transfer velocity and if appropriate generate climatologies.
- Provide an objective assessment of the relative benefits to wave modelling of improving the sampling of the wind field or improving the sampling of the wave field.
- Analysis of the waveform shape (averaged if necessary) could provide estimates of: Kurtosis/skewness, pdf of surface elevation,
- Develop algorithms to estimate wave steepness, of use to offshore operators and for better estimates of sea state bias.
- Cryosat altimeter data over the ocean should be requested, to allow:
  - Analysis of phase information from Cryosat altimeter
  - Analysis of returns from altimeter “sub-cells”, possible from ISAR mode of Cryosat

## **2.7 Possible Mission Scenarios**

Bearing in mind the requirements for altimeter sea surface height (SSH) information, and the recommendations from the SSH community (see GAMBLE WP2 report), possible future scenarios that could be investigated with respect to sea state information in the second phase of GAMBLE are:

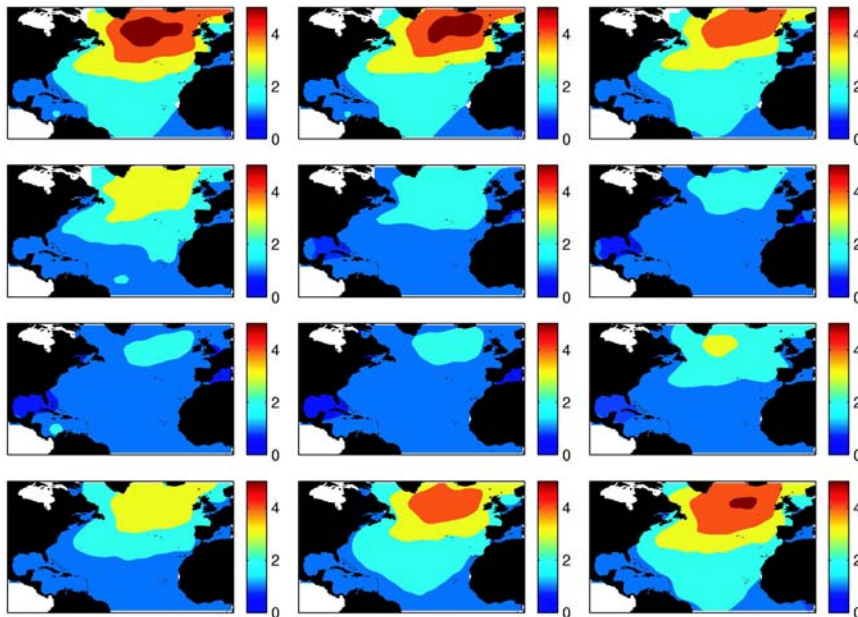
- Basic requirement for 2007-2011 (to ensure continuity of coverage by 2 satellite altimeters)
  - JASON-2, + 1-3 single frequency microsatellite altimeters**
- Further development for 2011 timescale
  - JASON-2, + NPOESS, + SWIMSAT + 1-3 (or more?) single frequency microsatellite altimeters**
- Possible long term scenario for 2015+ timescale
  - JASON series , + NPOESS series , + single frequency microsatellite constellation OR GPS reflectometry system, + ? SWIMSAT successor**

### 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

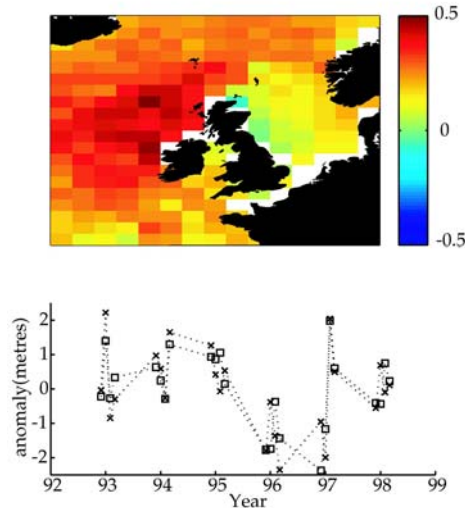
The oceans are essential to mankind both for everyday commerce and for their role in moderating climate. Wind and waves directly affect both commerce (e.g., disruption of trade, oil production and fishing by storms) and climate forcing (through their relationship to atmosphere-ocean fluxes [Jones and 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 3.1 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 3.1. 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 3.2: 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°-58°N, 8°-10°W). [Woolf et al. 2002b]**

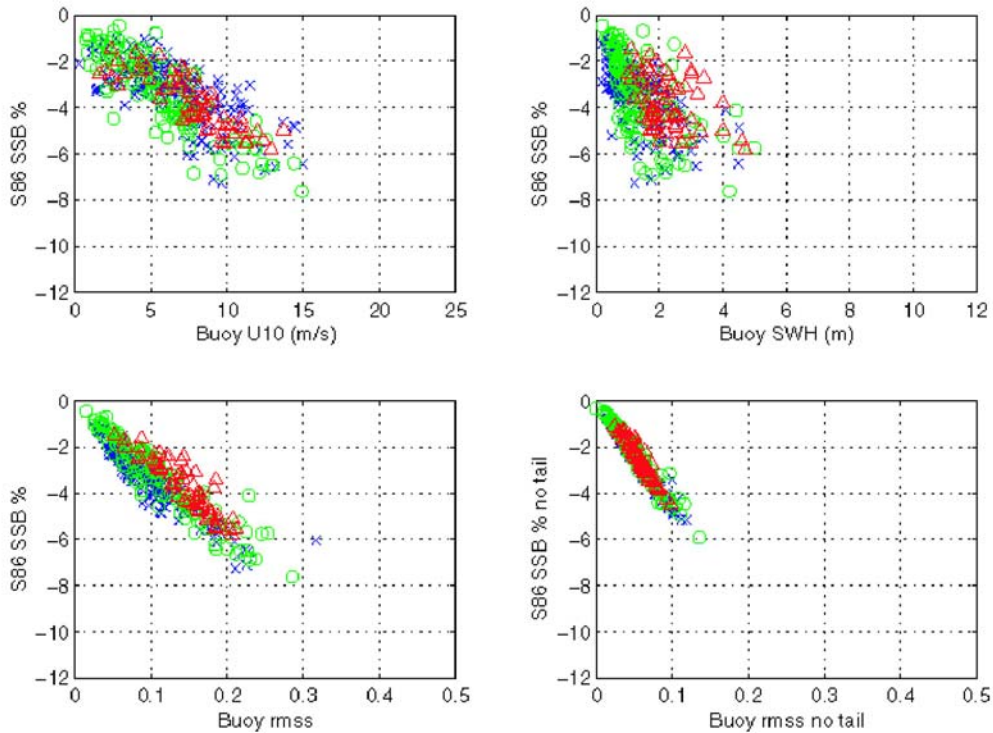
Where long-term altimeter records exist, e.g., the continuous 10 years dataset from Topex/Poseidon, altimeter wind and wave information can also serve to monitor inter-annual and decadal variability of the atmospheric forcing and the response of the ocean. As well as monitoring its temporal variability, the global capabilities of spaceborne altimeters allow changes in spatial distribution to be detected. Thus, it is possible (see Figure 3.2) 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,  $\sigma_0$ , from the sea surface is mainly sensitive to small scale surface roughness (short ocean waves), and since these respond rapidly to the local wind,  $\sigma_0$  is the primary variable used in estimating wind speed [e.g., Witter and Chelton 1991] or wind stress. However,  $\sigma_0$  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.

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 3.3) 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].

Theo. ssb coeff with  $f^{-5}$  tail



**Figure 3.3** 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).

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 [Quarty 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  $\approx 0.3$  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.

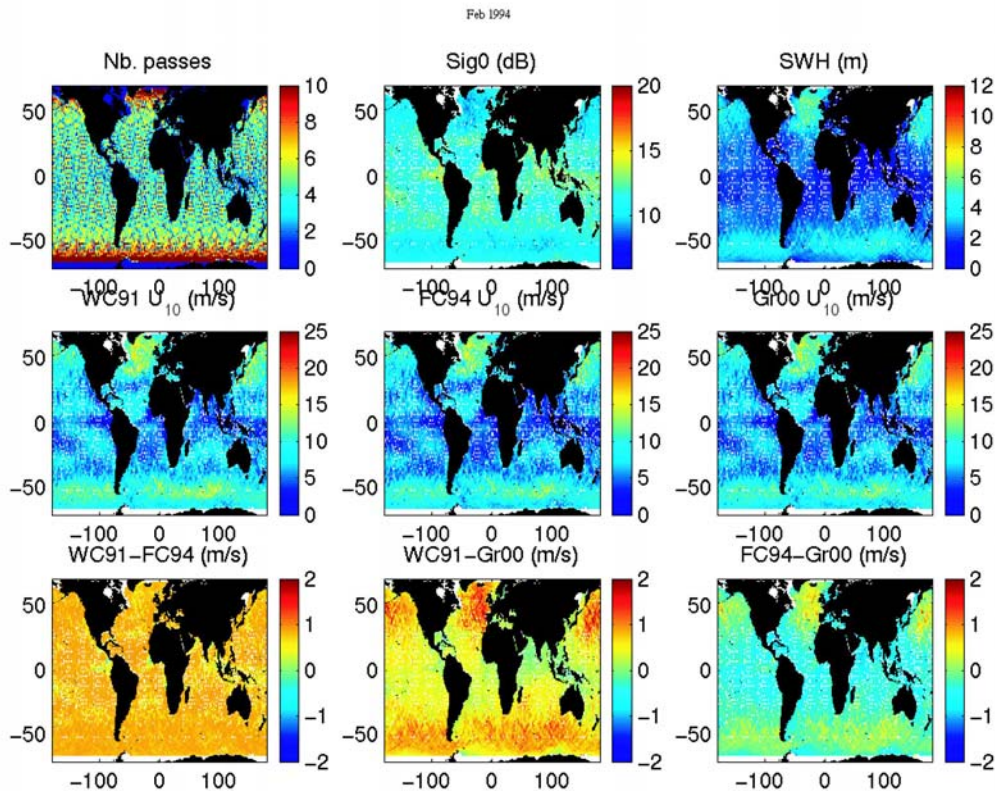
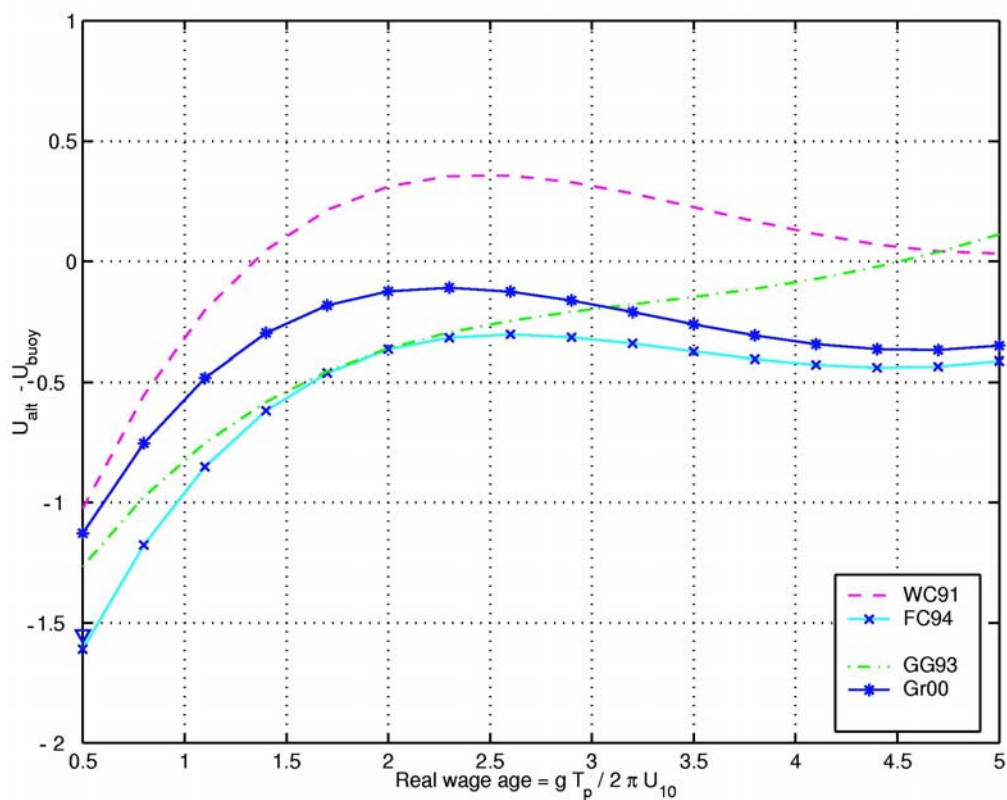


Figure 3.4 Global monthly (February 1994) averaged altimeter wind speed gridded over  $1.5 \times 1.5$  degree boxes. Subplots from top left to bottom right show respectively (a) number of Topex passes, (b) altimeter backscatter at Ku-band,  $\sigma_{Ku}^0$ , (c) altimeter significant wave height at 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  $\sigma_{Ku}^0$ -only model by Freilich and Challenor and the  $(\sigma_{Ku}^0, SWH)$  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 3.5. [Gommenginger et al. 2002c].

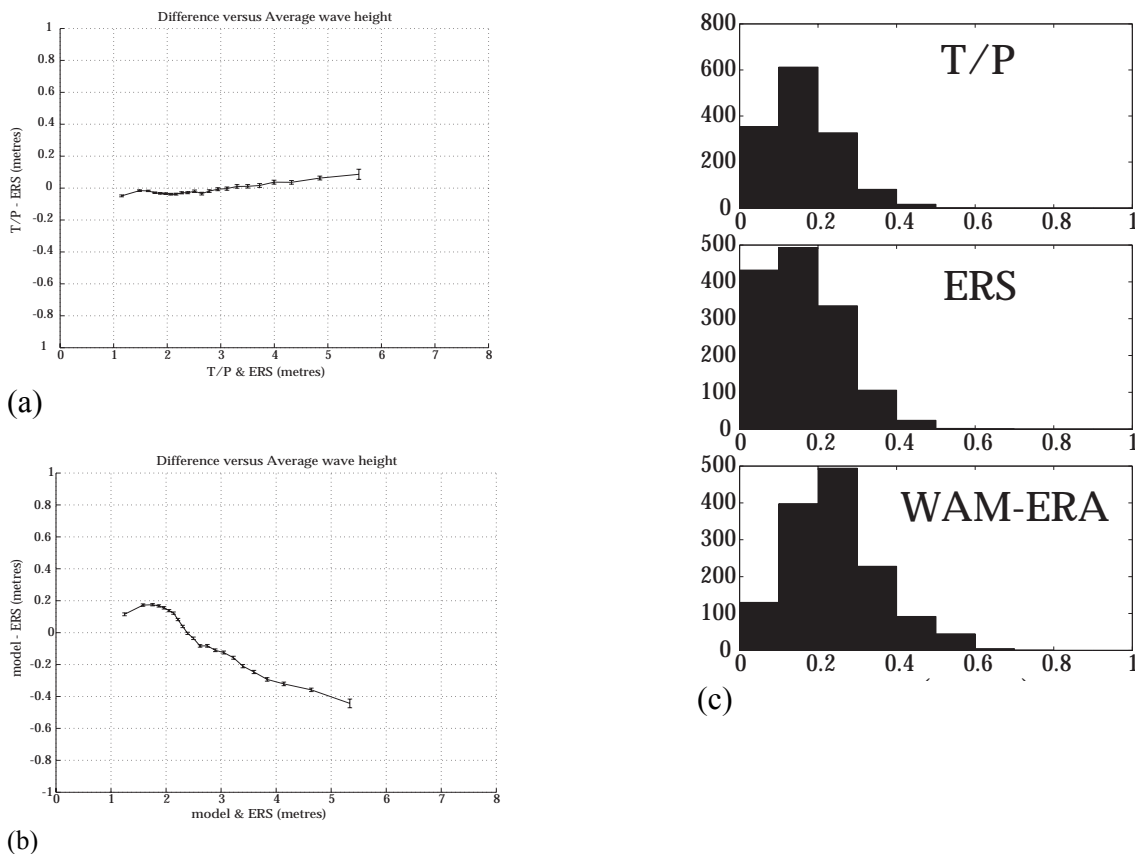
Estimated errors in wind speed or wind stress retrieval from the altimeter remain stubbornly high. There are two main reasons why the accuracy of altimeters is generally poorer than for scatterometers. Firstly, there is less calibration data for altimeters. Secondly, altimeter back scatter is far more 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  $\approx 0.3$  metres/second and RMS errors for individual passes  $\approx 1.5$  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  $\approx 1.3$  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 3.4). Even recently proposed altimeter wind speed models that include SWH [Gourrion et al. 2000] nevertheless display a residual dependence on wave age (Figure 3.5). 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 [Quarty 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 3.5 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.**

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 3.6 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].**

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  $4.5 \times 4.5$  degree grid squares from a single satellite is typically  $\approx 0.2$  metres (Figure 3.6), 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 3.7). 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.

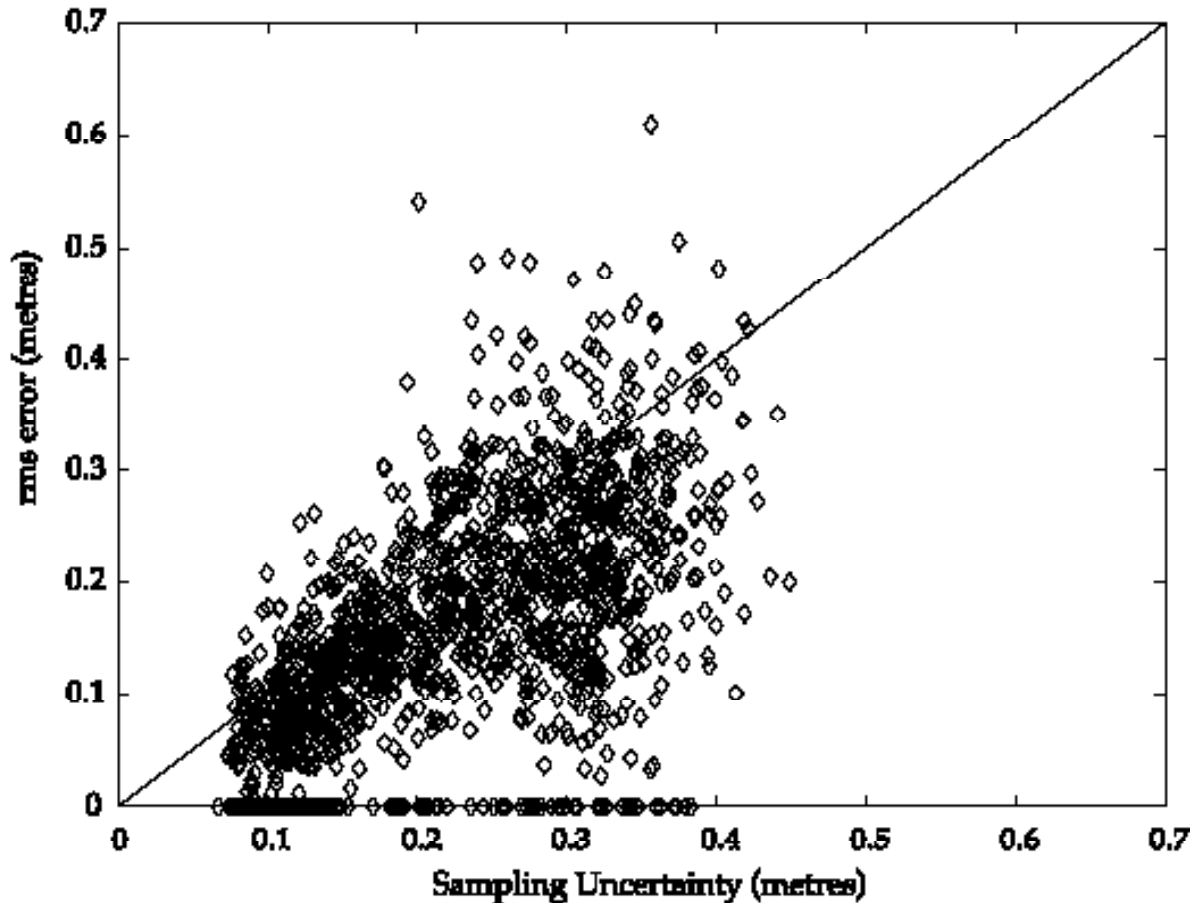


Figure 3.7 Estimates of root-mean-square error in ERS-1 values of mean monthly significant wave height in each grid square plotted against an estimate of "sampling uncertainty" calculated from the measured variability within each month and the number of samples of the particular grid square in each month. 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. Table 3.1 summarises the mission characteristics desirable from the point of view of wave/wind climatology studies.

Parameter	Auxiliary Data	Relevant Future Developments	Main Freq.	2nd Freq	Altimeter Type	Number of satellites	Repeat cycle	Accurate & repeatable orbit
Wind speed, wind stress, significant wave height, wave period, wave power	In situ validation data	Improvements in waveform. Validation networks. Bistatic. Directional capability.	1 <sup>st</sup> pref Ku 2 <sup>nd</sup> pref Ka	Not required for waves  C or S OK for wind stress.	“Basic” altimeter OK for waves Dual Freq required for wind stress	Most Important – higher spatial /temporal sampling a priority	Compromise of spatial and temporal resolution	Only important near coasts

**Table 3.1 Mission Characteristics suitable for wind and wave climatology studies**

### 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 Satellite altimeter sea state 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 COMKISS 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 ( $T_z$  (Zero upcrossing period) and  $T_p$  (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.

The EuroGoos Requirements Survey (Fischer and Flemming, 1999 – also see Appendix 1) identified surface currents as the “most requested” oceanic parameter, and wave information was 2nd highest on the list of priorities. Later in this section Table 4.2 summarises operational users’ requirements for real time data (and climatological data).

#### 4.2.1 *Satellite data in Operational Wave models*

Many operational wave models now incorporate altimeter wave data through assimilation schemes – e.g. UKMO, ECMWF, Météo-France and NCEP (USA). See various papers by Bauer et al. (1992), Guillaume and Hansen(1993), Hauser(2001), Komen et al. (1994), Lefèvre 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.

Lefèvre (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  $\sim 5^\circ$  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).

#### 4.2.2 *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

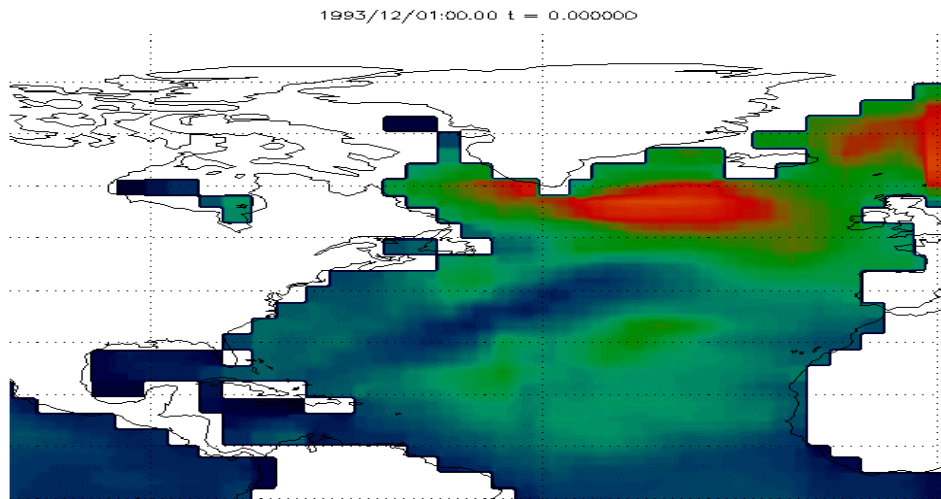


Figure 4.1 ECMWF 1 degree 6 hourly modelled wave height data. Regions of significant wave heights >5m are shown in red.

### Sampling Patterns

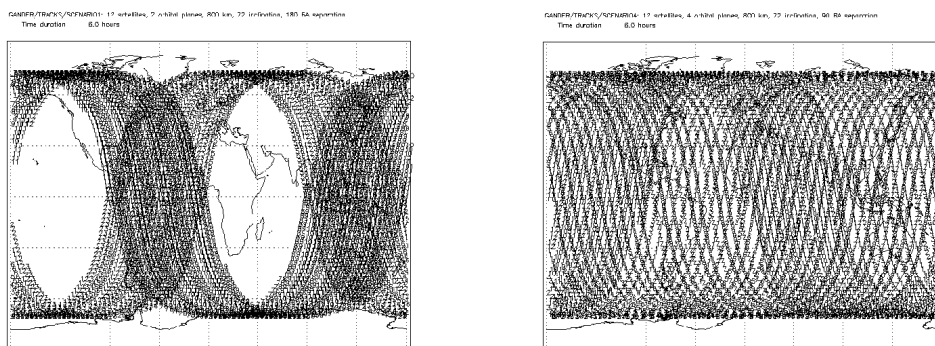


Figure 4.2 (a) 6 hour propagation of scenario 1, 2 planes, 6 satellites in each, (b) 6 hour propagation of scenario 4, 4 planes 3 satellites in each.

Figure 4.1 gives an example of the significant wave height field at one model forecast time step. General characteristics are:

- High significant wave heights ( $> 5\text{m}$ ) 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  $40^\circ$ - $60^\circ$  latitude band.
- Winter storms are more intense and quicker moving (but not more numerous).

Figure 4.2 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 4.1 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 $45^\circ$	Mean time between planes
1	12	$360^\circ$	$2.1^\circ$	233 km	163 km	12 hrs
2	6	$90^\circ$	$4.2^\circ$	466 km	326 km	6 hrs
4	3	$45^\circ$	$8.3^\circ$	921 km	645 km	3 hrs
6	2	$30^\circ$	$12.5^\circ$	1387 km	971 km	2 hrs
12	1	$15^\circ$	$25^\circ$	2775 km	1943 km	1 hr

**Table 4.1 Indicative ground track spacing characteristics for a 12 satellite constellation**  
Satellite spacing assumes  $\sim 100$  min orbital period.

We note from Figure 4.2 and Table 4.1:

- 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,  $\sim 90^\circ$  apart, with an inclination of  $\sim 80^\circ$

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  $4^\circ$  over the globe (see Table 4.1). 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 a continuous 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.

#### *4.2.3 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.

#### *4.3.1 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.

Perhaps the state of the art hindcast derived data base is IMDSS (Integrated Marine Decision Support System, OceanWeather), generated from a 40 years re-analysis wind field (see Swail and Cox, 2000). The grid is  $2.5^\circ \times 2.5^\circ$ , 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.

#### 4.3.2 *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.

#### 4.3.3 *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!)?

#### 4.3.4 *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). Table 4.2 provides a summary of requirements for ocean waves. It has been generated from discussions with representative members of the operational offshore community, from the EuroGoos Requirements Survey (Fischer and Flemming, 1999), GANDER studies, COMKISS, a study carried out for ESA (Cotton et al., 2002) and from direct questionnaires to users. “Threshold Requirements” indicate requirements that represent a “practically useful” improvement on the present capability, “Optimum Requirements” represent the measurement characteristics beyond which no improvement would have practical value.

Applica-tion	Parameter	Optimum requirements				Threshold requirements			
		Spatial res (km)	Time res	latency	accuracy	Spatial res (km)	Time res	latency	accuracy
near real time	sig. wave ht. <sup>A,B</sup>	10	20 min	1 hr	0.1 m	30	1 hr	3 hr	0.5 m
climate	sig. wave ht. <sup>A,B</sup>	10	6 hr	years	0.1 m	1° x 1°	1 mon	Years	0.1 m
near real time	wave period <sup>1A,B</sup>	10	20 min	1 hr	0.1 s	30	1 hr	3 hr	0.5 s
climate	wave period <sup>1A,B</sup>	10	6 hr	years	0.1 s	1° x 1°	1 mon	Years	0.2 s
near real time	wave dir. <sup>A,B,C</sup>	10	20 min	1 hr	±5°	30	1 hr	3 hr	±10°
climate	wave dir. <sup>A,B</sup>	10	6 hr	years	±5°	1° x 1°	1 mon	Years	±10°
near real time	swell swh <sup>A,B</sup>	10	30 min	1 hr	0.1 m	30	1 hr	3 hr	0.5 m
climate	swell swh <sup>A,B</sup>	10	6 hr	years	0.1 m	1° x 1°	1 mon	Years	0.1 m
near real time	swell period <sup>A,B</sup>	10	30 min	1 hr	0.1 s	30	1 hr	3 hr	0.5 s
Climate	swell period <sup>A,B</sup>	10	6 hr	years	0.1 s	1° x 1°	1 mon	Years	0.5 s
Near real time	swell dir. <sup>A,B</sup>	10	30 min	1 hr	±5°	30	1 hr	3 hr	±10°
Climate	swell dir. <sup>A,B</sup>	10	6 hr	years	±5°	1° x 1°	1 mon	Years	±10°
Near real time	dir. wave spectrum <sup>2</sup> <sub>A,B,C</sub>	10	30 min	1 hr	1% max energy	30	1 hr	3 hrs	1% max energy
Climate	dir. wave spectrum <sup>3,D</sup>					100 km	7d	3hr	15° dirn, 10% wavelength
Joint swh/period prob. dist fns. <sup>4,E</sup>						1° x 1°	1 mon	Years	0.1 m / 0.2 s
Joint wind/wave prob. dist fns. <sup>4,E</sup>						1° x 1°	1 mon	Years	0.1 m / 2 ms <sup>-1</sup>

**Table 4.2. Offshore industry data requirements for ocean waves and currents.**

**Footnotes:** Requirements are derived from Fischer and Flemming<sup>A</sup>, questionnaires sent to representative users<sup>B</sup>, IORD II<sup>C</sup>, Hauser et al (2002)<sup>D</sup> and Grant and Shaw (2001)<sup>E</sup>

<sup>1</sup> Average wave period, T<sub>a</sub>– or equivalent (e.g. zero up-crossing period T<sub>z</sub>)

<sup>2</sup> Accuracy requirement for maximum energy in spectrum.

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

<sup>4</sup> Joint probability distributions functions (pdfs) require the different parameters to be gathered simultaneously at the same location.

#### 4.4.1 *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 (  $\sim 5$  km) data are required close to the coast.

A constellation of 12 satellites, distributed evenly across two orbital planes, would provide measurements within  $\pm 233$  km of any ocean location every 6 hours.

## 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

#### 5.2.1 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).

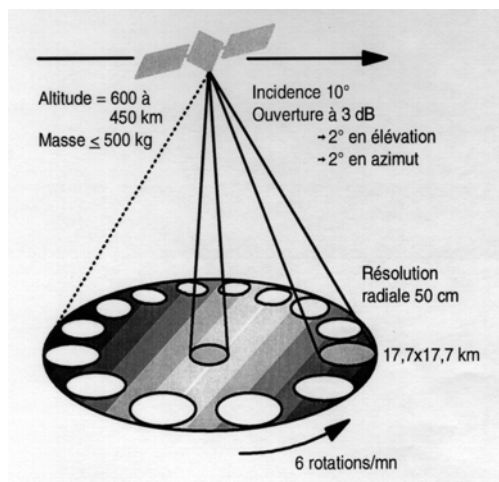
The repeat cycle is still an open choice. Presently, the proposal is to get a global coverage of the ocean for latitudes higher than 35° (N or S). A cycle of 8 days is thus proposed, but this choice remains open. Indeed, for operational objectives (wave forecast) the impact of assimilation will be basically 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.

### 5.2.2 Instrument characteristics

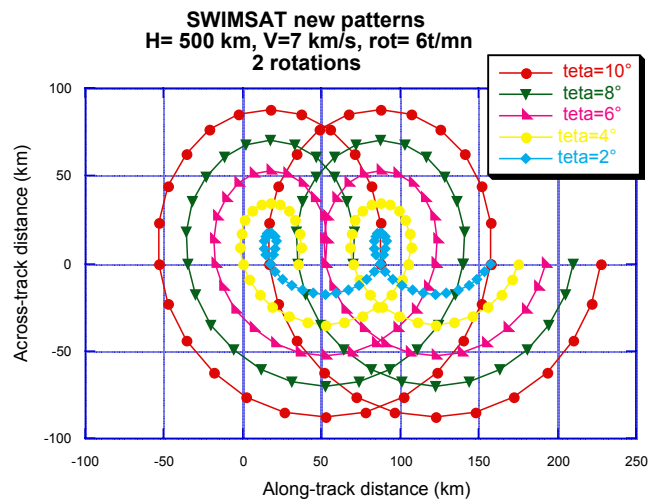
The nadir looking mode of the instrument has characteristics and requirements similar to radar altimeters used in the standard altimeter missions in terms of range resolution, and accuracy on significant wave height and wind speed. The observations at nadir will be used in a way similar to other radar-altimeters (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 5.1 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 5.2 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 5.1: Geometry of observations of SWIMSAT for 2 incidence beams (0 and 10°)**



**Figure 5.2: 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.**

### 5.2.3 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  $\sigma_0$  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:

$$P_m(k,\phi) = \frac{\sqrt{2\pi}}{L_y} \alpha^2 k^2 F(k,\phi) \quad (5.1)$$

where  $L_y$  is the width of the footprint in the azimuth direction,  $k$  is the wave number of the waves,  $\phi$  their travelling direction, and  $\alpha$  is related to the fall-off of the normalised radar cross-section  $\sigma_0$  with incidence angle  $\theta$ :

$$\alpha = \cot g\theta - \frac{1}{\sigma_0} \frac{\partial \sigma_0}{\partial \theta} \quad (5.2)$$

In  $\alpha$ , the derivative of  $\sigma_0$  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  $\phi$  can be inverted from the modulation spectrum  $P_m(k,\phi)$  using Equation (5.1). To retrieve the full spectral information, scanning of the radar beam over 360° in azimuth provides the wave spectrum  $F$  in all directions  $\phi$  (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:

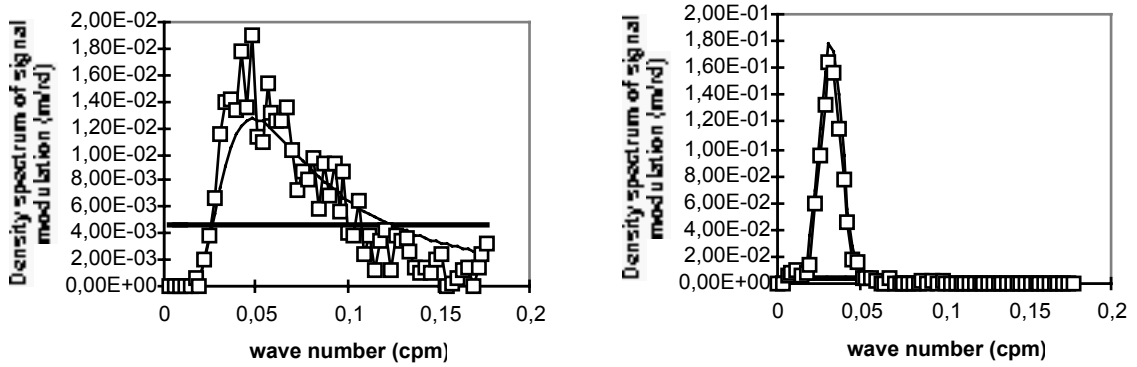
$$P_m(k) \approx P_c(k) + P_s(k) \quad (5.3)$$

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:

$$P_s(k) = \frac{1}{N_{\text{int}} \sqrt{2\pi}} \cdot \frac{\Delta x}{2\sqrt{2\ln 2}} \quad (5.4)$$

where  $N_{\text{int}}$  is the number of independent samples (of the order of 100 for SWIMSAT) and  $\Delta x$  is the intrinsic horizontal resolution (3 to 14 m depending on the incidence angle). After subtracting the speckle contribution, Eq. (5.1) can be used to retrieve the energy density of the waves, for wave-numbers  $k$  smaller than a certain threshold. This threshold corresponds to the wave number where the density spectrum of speckle is of the order of that of the modulation spectrum.

Figure 5.3 illustrates the expected performance at incidence  $10^\circ$ , 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  $\lambda_{\text{peak}}=200$  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 5.3: 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  $H_s=4$  m,  $\lambda_{\text{peak}}=200$  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 over 16 individual samples. Heavy horizontal line: Speckle noise level.**

As concerns the  $180^\circ$  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 and 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  $50 \times 50$  km to  $90 \times 90$  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 ( $2-6^\circ$ ) and larger ( $8-10^\circ$ ) 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**

#### *5.4.1 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.

#### 5.4.2 *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 cut-off 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 Voorrips 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 Voorrips (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 Gaussian and 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, Voorrips 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.

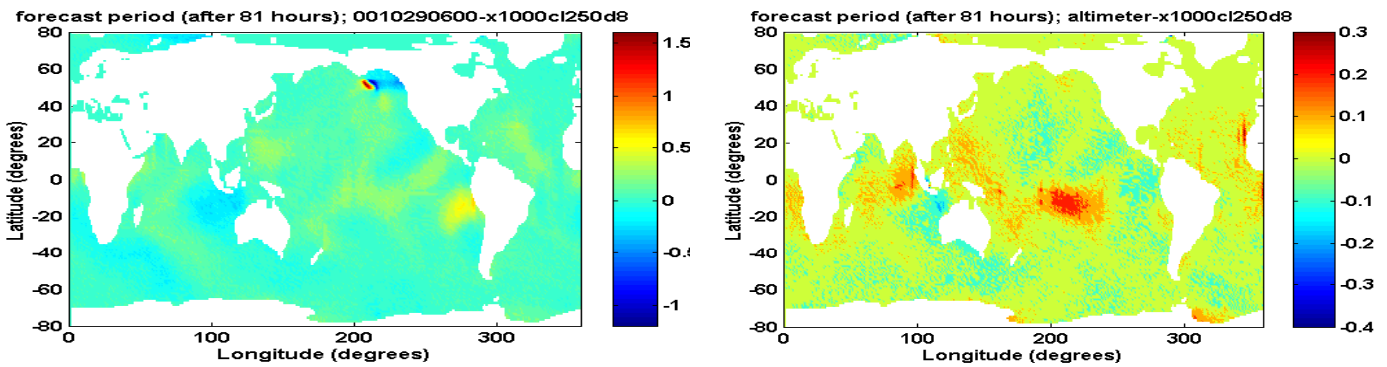
The main results are summarised as follows :

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 1m (Fig 5.4a) and decreases progressively until it reaches about 0.3 m, 6 days after the end of assimilation (Fig 5.5).
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 Fig 5.4a and 5.4b).
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 5.7). This analysis also confirms the larger impact of the

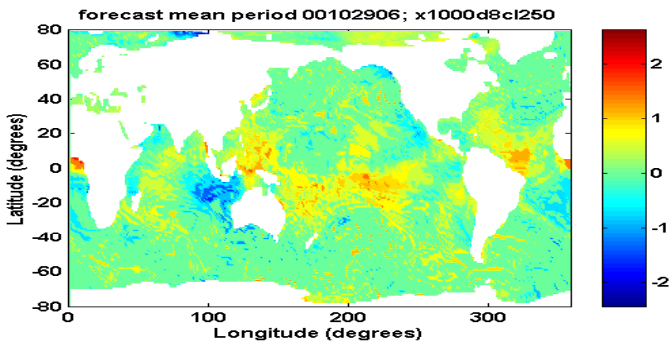
assimilation of spectral data with respect to the assimilation of significant wave height only. Results obtained on the mean period (not shown) indicate that the impact of assimilation in the forecast period decreases less rapidly for the mean wave direction than for the wave height.

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.

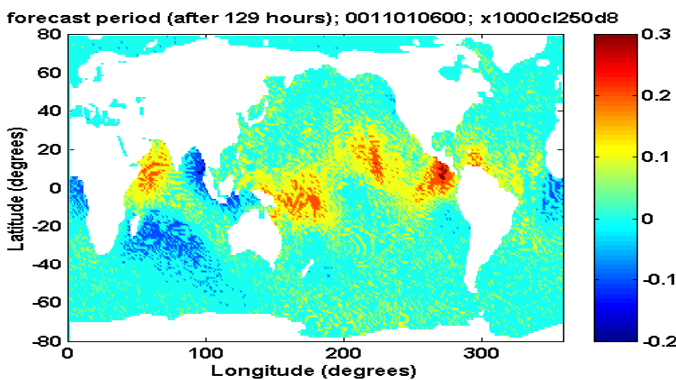
In summary, this assimilation study, (based on synthetic data) has shown that there is a significant impact of assimilation and that this impact is larger when parameters derived from the full spectral information (wave height, mean period, mean direction for several wave trains) are used, compared to 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.



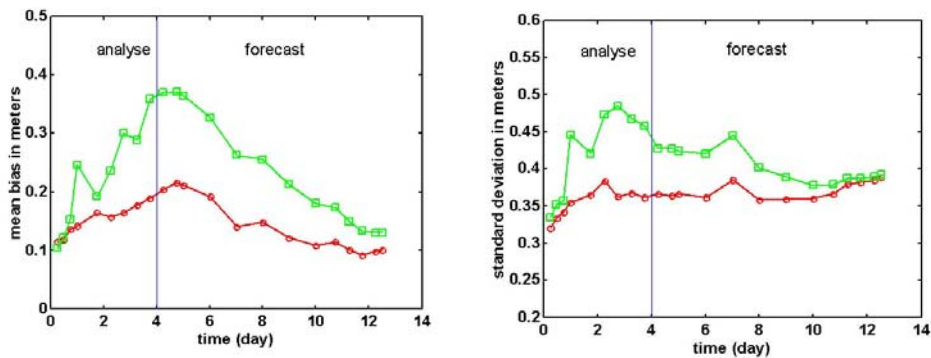
**Figure 5.4: Difference in the forecasted significant wave heights (in meters) between the cases with and without assimilation, 81 hours (3.375 days) after the end of assimilation. (a) with assimilation of spectral data (b) with assimilation of significant wave height only.**



**Figure 5.5: 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 5.6: 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 5.7: Mean bias (left plot) and standard deviation (right plot) for the significant wave height between forecast (or analysis) and synthetic observations. Green squares: assimilation of significant wave height only; Red circles: assimilation of the spectral information. The analysis period (with assimilation) lasts for 4 days. Then the model fields evolve without assimilation.**

#### 5.4.3 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.

#### 5.4.4 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 bias.

#### 5.4.5 *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.

### 5.5 **Relation with other missions concerned by the GAMBLE project**

#### 5.5.1 *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 than 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.

#### 5.5.2 *Complementarity in terms of orbit and sampling*

As mentioned 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). Increasing 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.

### *5.5.3 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 developed 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 6.1). The instruments (figure 6.1) provided by CNES include a solid state bi-frequency (Ku and C bands) altimeter (developed by Alcatel Space Industries) and a DORIS Precise Orbit Determination system (developed by Thales) (Escudier et al., 2000). The payload provided by NASA includes the TRSR/GPS receiver (developed by JPL, built by Spectrum Astro Inc.) and the laser retro-reflector (from ITE inc.) for POD support, and the JMR radiometer (developed by JPL). The new mini-satellite (500 kg) platform, named PROTEUS, has been jointly developed 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 6.1. 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  $66^\circ$  and an altitude of 1336 km. This makes the orbit repeating on the same ground-tracks at exactly 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 for 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 6.1, 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 Data 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 6.2). 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 6.1 for GDR products. The improvement for significant wave height, sigma-naught and wind speed should be significant (specially for wave-height).

Measurement	3 hours (OSDR)	3 days (IGDR)	30 days (GDR)	30 days (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
<b>Significant wave height (cm), whichever is greater</b>	<b>50 or 10%</b>	<b>50 or 10%</b>	<b>50 or 10%</b>	<b>25 or 5%</b>
<b>Sigma-naught (dB)</b>	<b>0.7</b>	<b>0.7</b>	<b>0.7</b>	<b>0.5</b>
<b>Wind speed (m/s)</b>	<b>2</b>	<b>1.7</b>	<b>1.7</b>	<b>1.5</b>

Table 6.1 JASON-1 Performance as a function of latency and products.

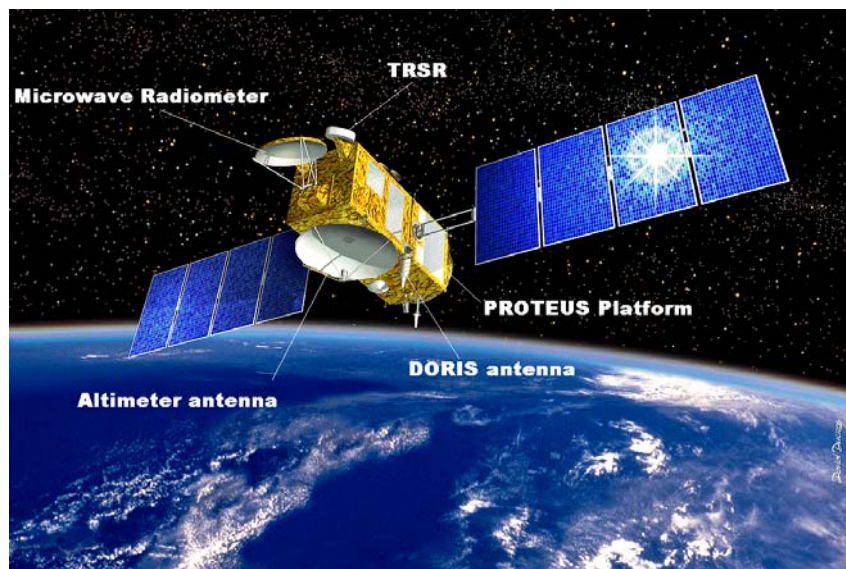
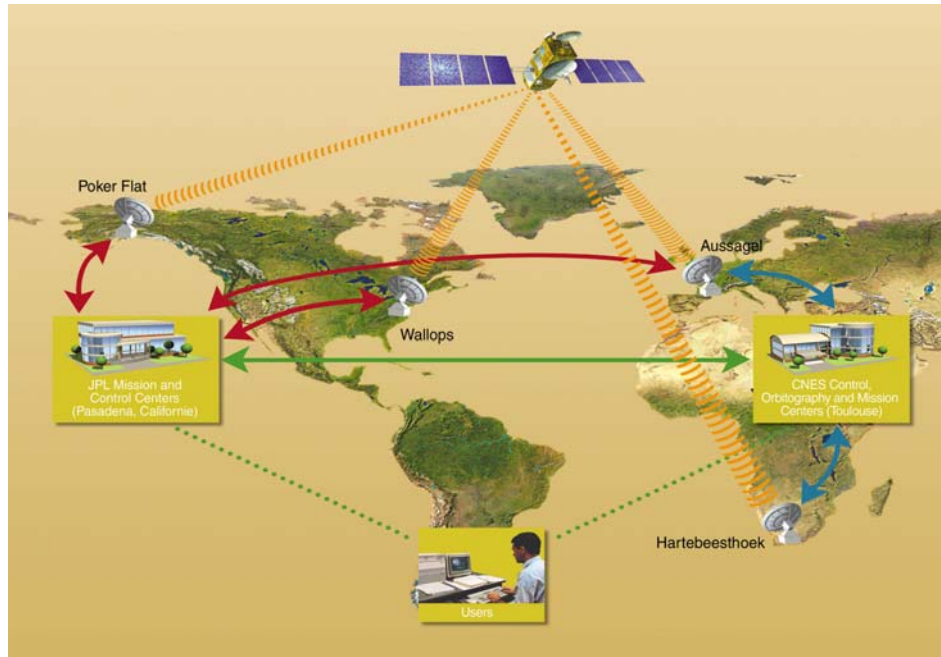


Figure 6.1: The Jason-1 satellite on its orbit



**Figure 6.2: The Jason-1 ground segment**

### 6.3 Jason-1 CALVAL phase

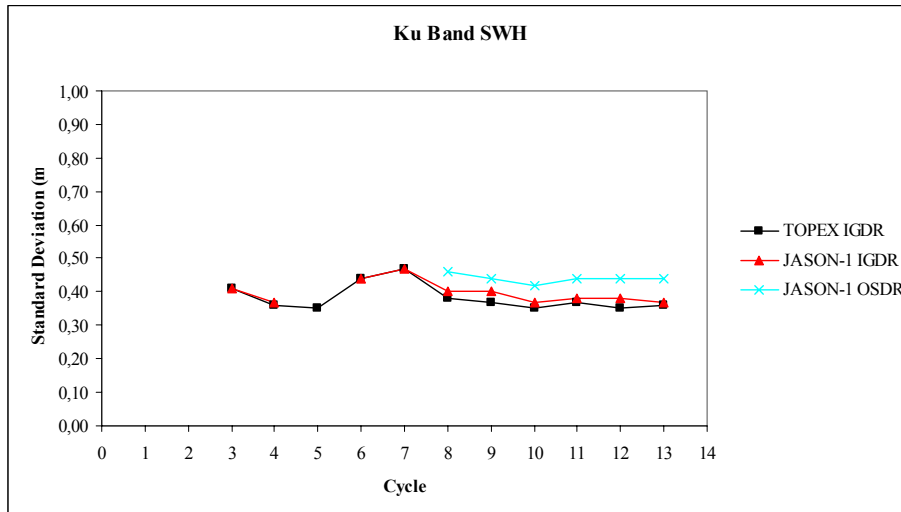
Soon after the launch of the Jason-1 satellite, end of March 2002, the first IGDR data have been released to the Principal and Co-investigators of the mission for calibration and validation purpose (cf. Jason-1 Cal Val plan). On June 10-12, 2002 in Biarritz, at mid-term of the verification phase, the 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. Lefèvre et al., D. Cotton et al., P. Queffeuilou et al., presented at the June 2002 SWT meeting). As illustrated in Figures 6.3 and 6.4, 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 addition to IGDR, and the near-real time release of the OSDR.

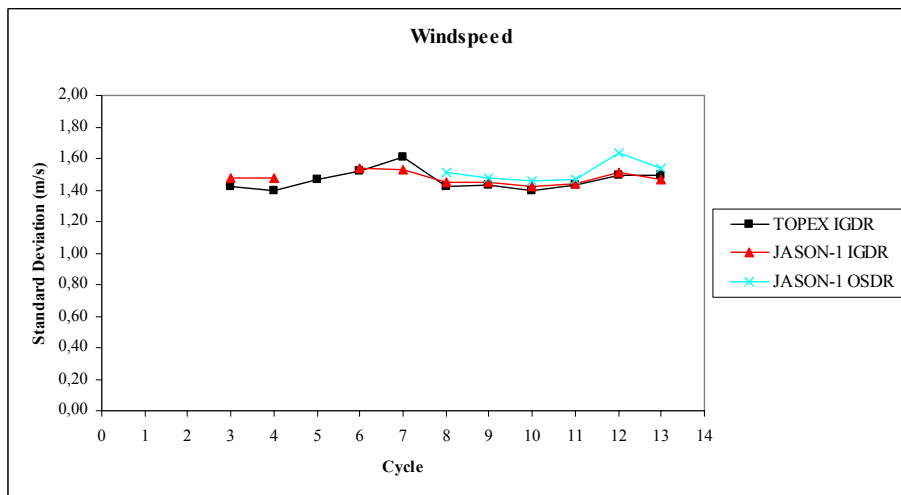
## 6.4 The Jason 2/OSTM mission to follow up Jason-1

In order to maintain the continuity of the Jason mission beyond 2006, the CNES and NASA space agencies have proposed the follow-on Jason-2 (part of the US Ocean Surface Topography Mission). 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 developed 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 entirely 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.



**Figure 6.3 : Comparison of SWH measured by T/P (IGDR), Jason-1 (IGDR and OSDR) with WAM model for 11 simultaneous cycles (Lefèvre 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 6.4 : Comparison of wind speed measured by T/P (IGDR) and Jason-1 (IGDR and OSDR) with ECMWF model, for 11 simultaneous cycles (Lefèvre 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

## 7 Radar state of the art and new concepts for GAMBLE

### 7.1 Introduction

The purpose of this document is two fold:

- to give an overview of the state of the art in radar altimeters design and performances
- to provide a status on new altimeters and other radar concepts, under study or developments

### 7.2 State of the art in radar altimeters

Current radar ocean altimetry missions are based on a nadir looking altimeter as it can be shown that this geometrical configuration leads to better elevation budget error. Although the nadir altimetry principle is well known we recall first the basics for completeness. A summary of the most recent altimeter instrument and geophysical performances are also reported in this Chapter.

#### 7.2.1 Nadir altimeters

##### Operating principle – radar waveform

Radar altimeters are microwave instruments, which transmit pulses at the pulse repetition frequencies (PRF). The pulses are subject to linear frequency modulation (chirp) with a large bandwidth, typically from 320 MHz to 500 MHz. The vertical resolution of the radar is inversely proportional to the radar bandwidth. However, the ultimate resolution is obtained after processing of the radar echo and is generally more than an order of magnitude smaller than the radar vertical resolution.

With such large transmitted bandwidth, the altimeter operates in the so-called pulse limited mode. It can be shown that the requirements on the instrument pointing control and knowledge are generally relatively easy to meet. This is not the case of beam limited configuration.

Each pulse is reflected by the surface and is returned to the altimeter a few milliseconds ( e.g. 5 ms at 800 km) after its transmission.

At the assumed instant of reception, a second (reference) pulse is generated within the altimeter but is not transmitted. Instead, it is mixed with the returned pulse. This technique is known as Full Deramp technique, and it enables to reduce dramatically the processed (e.g. 1.2 MHz instead of 320 MHz for Poseidon 2). For large range window, e.g. in the case of swath altimeter, the deramp technique may not be appropriate.

The altimeter's operating principle is shown in Figure 7.1

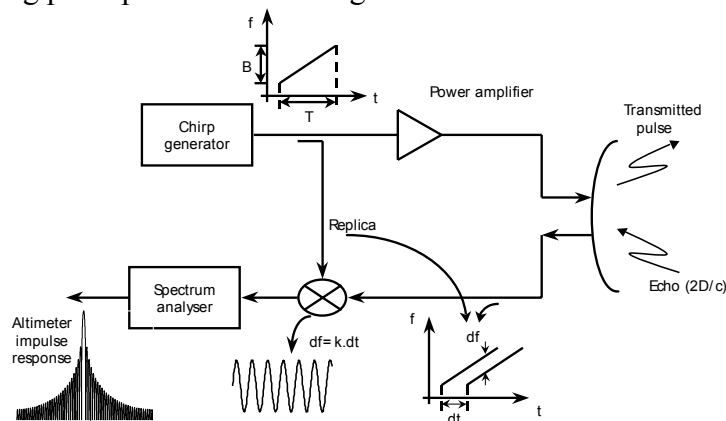


Figure 7.1: Altimeter operating principle

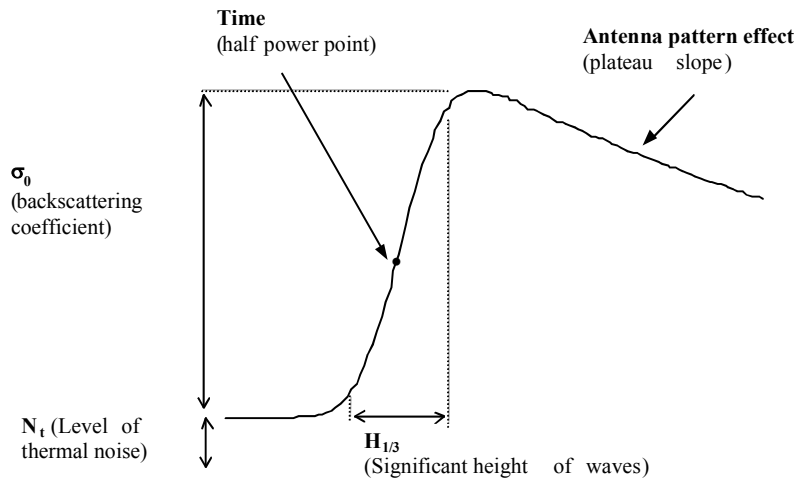
As the pulse phase is parabolic, after mixing, on the signal's return from a point target, we obtain a pure frequency signal proportional to the satellite/target range ( $d$ ). This is called the range impulse response. The signal is then processed by spectral analysis using a Fast Fourier Transform (FFT).

**Power waveforms**

The power waveform is the change of the power of the echo as a function of time (after complete deramp). It can be shown that it is a composite signal corresponding to the convolution of the three following terms:

- the sea response to a Dirac radar pulse,
- the altimeter response to a point target (impulse response),
- the distribution of heights of zero-gradient surface points (or wave distribution).

The sea echo can be modelled by analytical formula, (using some approximation). The most used model has been formulated by Brown, and is known as the Brown's model.



**Figure 7.2: Brown Echo for a sea surface**

After receiving the thermal noise from the instrument, the reflection of the radar wave from the sea surface gives rise in power, with a rapid leading edge.

- The maximum amplitude of the power is a function of the backscattering coefficient of the ocean surface ( $\sigma_0$ ), which in turn is a (not-unique) function of the wind speed.
- The time corresponding to half the maximum power in the leading edge provides the distance between the radar and the sea surface (the range).
- The slope of the leading edge is related to the roughness of the sea i.e. to the height of the waves. The trailing edge of the echo depends mainly on the antenna gain pattern and the pointing of the radar antenna.
- In fact, speckle must be added to the average Brown echo, with an exponential probability at each range gate and for each elementary pulse.

Over flat ice-surfaces like sea-ice the power waveforms deviate dramatically from the ocean echo due to the specular nature of reflection, and they become very peaky. The shape of the echo can become very complex over the ice sheet margins due to the combination of the topography and  $\sigma_0$  variation.

### Definition of the fine estimation processing

During the range measurement phase, the fine estimation of the backscattering coefficient  $\sigma_0$ , significant wave height (SWH or  $H_{1/3}$ ), range, pointing error ( $\xi$ ), and thermal noise ( $N_t$ ) is performed by a Maximum Likelihood Estimator (MLE) algorithm. This processing is known as re-tracking which allows an estimation of the range with an accuracy (random noise) much smaller than the resolution of the compressed pulse (typically few cm for a compressed pulse length of 50 cm).

### Operation principle

The altimeter operation is based on 3 main functions:

- Acquisition
- Tracking in measurement mode
- Calibration 1 and 2.

These functions are described hereafter:

Before reaching the tracking phase (used to keep the radar echo at a set position in the FFT analysis window), it is necessary to bring the signal into this window. The acquisition phase positions the radar echo inside this window and initializes tracking loops.

The tracking algorithm is used during the range measurement phase and is a closed loop system.

The tracking is designed to:

- keep the rising front of the returned signal at a determined position in the FFT analysis window (range processing),
- keep the signal at a given amplitude using an Automatic Gain Control loop (AGC). The instruction generates a digital gain control (CNG) value, which drives a variable-gain amplifier.

The tracking processing requires the computation of the mean of several echo signals. Computation of the mean takes into account any range rate variation using a step by step shift (fine altitude correction).

The measurements are delivered to ground while the instrument is tracking.

### Definition of calibration processing

In order to know the instrument contribution to the measurement, internal calibration is necessary. The internal calibration is of primary importance to monitor and correct of the instrument transfer function and of its drift if any. There are two types of calibration:

- Calibration 1: Measuring the impulse response. This processing mode gives the altimeter impulse response. The transmission channel is looped back to the corresponding receiver input via calibration couplers. The spectrum obtained is the radar impulse response.
- Calibration 2: measuring the reception channel profile. The calibration 2 processing mode is designed to measure the altimeter transfer function. It measures within the useful echo band the thermal noise spectrum filtered by the radar's baseband / intermediate frequency cross-section. It is also designed to check that there is no interference in the spectrum by analyzing the thermal noise of the reception channel over a long period while the altimeter reception windows are positioned at a programmed range value guaranteeing the absence of return echoes.

### Dual-frequency operation

As any radar the altimeter measures range through a time measurement. The time delay due to the ionosphere (varying as  $1/f^2$ ) and to the troposphere needs to be corrected for in order to have accurate measurement of true range. The ionospheric contribution is corrected by making range measurement at two different frequencies typically chosen between S or C and Ku band.

For instance the Poseidon 2 dual-frequency (C+Ku) altimeter is based on the principle described above for each frequency band. C and Ku-band pulses are not transmitted simultaneously but interlaced. This simplifies the hardware, some sub-assemblies thus being common to both bands.

Other frequency combination are possible such as for instance a Ku and Ka, for correcting the ionospheric path delay.

### 7.2.2 Nadir altimeter performances

The following Table gives an overview of the most recent flying altimeters characteristics. Note that, the Alti-Ka altimeter is being studied in a phase B by Alcatel for CNES.

	<b>Poseidon 2</b>	<b>RA-2</b>	<b>GeoSat-FO</b>	<b>Alti-Ka</b>
Mission	Jason-1	Envisat	GFO	Alti-Ka
Altitude (km)	1330	800	800	Up to 800 km
Frequency (GHz)	13.6 (Ku) / 5.3 (C)	13.6 (Ku) / 3.2 (S)	13.5 (Ku)	35.5 (Ka)
Tx Bandwidth (MHz)	320 / 100-320	320-80/160	320	480
Pulse width	105.6 $\mu$ s	20 $\mu$ s	102.4 $\mu$ s	105.6 $\mu$ s
PRF (kHz)	1.8/0.3-0.45	1.8/0.45	1 (Geosat)	4
Best Vertical Resol. (cm)	46	46	46	30
Pulse Limited	yes	yes	Yes	yes
Tx power (W)	7 / 19 (SSPA)	60 (TWT) / 63 (SSPA)	7 (SSPA)	2 (SSPA)
Range noise over ocean	2.2 cm (C+Ku) SWH=2m Rate=1Hz	<4.5 cm	$\leq$ 3.5 cm SWH=2m Rate=1Hz	0.8 cm SWH=2m Rate=1 Hz
Significant Wave Height	10 cm @ SWH=2 m	??	??	??
Wind speed/ sigma0 noise	1.5 m.s <sup>-1</sup> / 0.7 dB	??	??	??
Power consumption (W)	69	161	71	56 (including radiometer)
Total Mass (kg)	58 with redundancy	110 with redundancy	28 partial redundancy	26 (including radiometer)
Data rate	20 kb/s	100 kb/s	?	21 kb/s

**Table 7.1: System characteristics of present and future conventional altimeters**

### 7.3 New altimeter concepts

Several new altimeter concepts, with respect to nadir altimetry, have been proposed in the last ten years. They mainly pursue some of the following objectives:

- to improve the spatial/temporal sampling: this can be achieved either by off-nadir altimetry (swath) or by a constellation of nadir altimeters,
- to access to the bi-dimensional height distribution of the ocean surface: again off-nadir altimeters combined with SAR and interferometry techniques is a possible solution and has been

proposed by the JPL for the WSOA instrument. A constellation of nadir altimeters such as Wittex has also been proposed,

- to improve the vertical resolution, by increasing the transmitted bandwidth as for the Alti-Ka altimeter,
- to improve the along track spatial resolution, by a combination of the altimetry technique with SAR and interferometry such as for the SIRAL instrument of the Cryosat mission, or by having a smaller antenna footprint (Alti-Ka),
- to measure ocean and ice surfaces with a single instrument,

Section 7.3.1 deals with the fairly new concepts of SAR interferometric altimetry. It is divided in two sections, the first one dealing with Interferometric SAR altimeter at nadir and the second one with swath radar altimeter.

The Alti-Ka instrument concept and the radar of the SWIMSAT mission for the observation of the ocean surface wave spectra are briefly described in section 7.4.2

### *7.3.1 Nadir altimetry with SAR and interferometry*

#### **The concept**

The concept, is based on a nadir-looking radar which can be operated in the pulse-limited conventional mode over relatively flat surface such as ocean and Antarctica interior, and in the high spatial resolution mode over topographic areas such as coastal zones (ice margins) and sea-ice.

The high spatial resolution mode (SAR) is based on Doppler processing and therefore it allows for an improvement of the resolution in the along-track direction only.

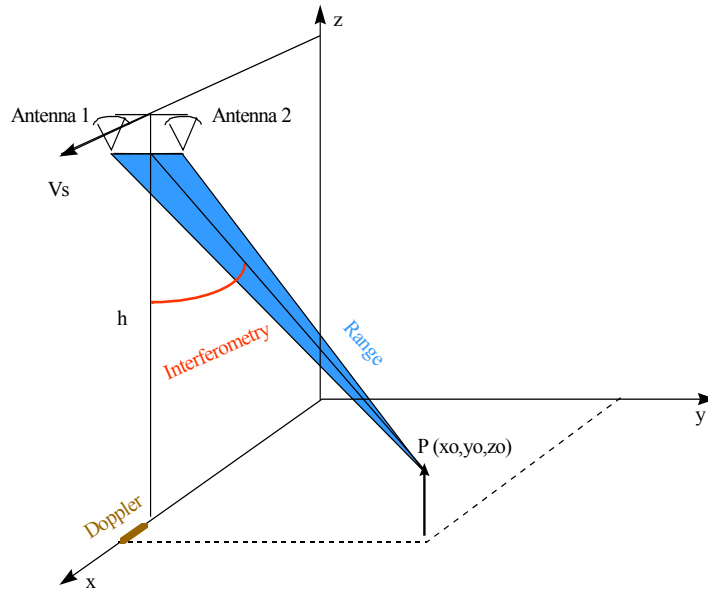
The across-track interferometric mode (SARIn) combines SAR and interferometry, and it is used for determining the angle of arrival of each resolution cells in the across-track direction.

This concept is used for the SIRAL (SAR Interferometric Altimeter) instrument of the CryoSat mission (see section 7.4.1)

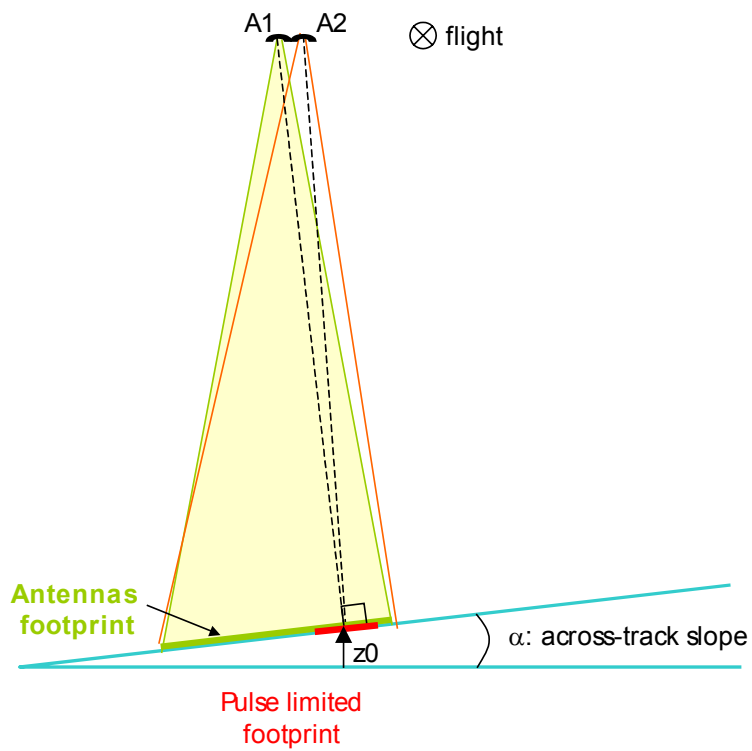
The principle of interferometric SAR in a mono-pass configuration (i.e. two antenna mounted on the spacecraft) is given in Figure 7.3

Some modifications with respect to conventional interferometric SAR are inherent to this system: Doppler filtering is used for the enhancement of the along-track resolution. This requires the transmission of coherent pulses at a PRF larger than the Doppler bandwidth. However because the required resolution is generally much smaller than the antenna size (ultimate resolution achievable with a SAR is half of the antenna size) the coherent integration time is smaller than the antenna dwell time. The processing for focusing the Doppler beam can therefore be achieved by using a simple Fourier transform. This is done for SIRAL where the along track resolution is typically 200 m. For the same reason the number of looks for each resolution cells can be very large (typically from 60 for 180 for SIRAL) while keeping the along track resolution constant. In addition, if a larger number of looks were needed an averaging in the along and across track direction could be done but to the detriment of the spatial resolution.

A second antenna provides a second take of the scene, which is used for surface height retrieval (as for SAR interferometry) and quality control of ambiguities due to overlapping signals. The interferometric baseline is orthogonal to the satellite velocity and to the nadir direction.

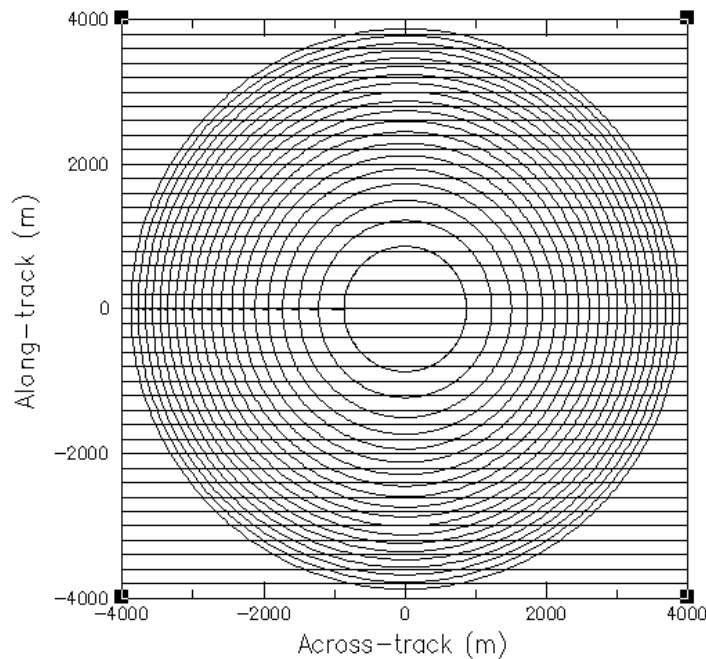


**Figure 7.3 : Principle of interferometric SAR**



**Figure 7.4: Principle of measurement of a SAR interferometric altimeter at Nadir**

After range and Doppler processing, the resolution cells mapped on a flat earth surface are shown in Figure 7.5 for a 220 m along-track resolution (64 pulses). Each ring represents an iso-range cell and each ‘horizontal’ band represents a Doppler bin (i.e. along track position).



**Figure 7.5 : Resolution cells on a flat surface for a nadir looking altimeter with Doppler focusing**

The advantages of a nadir looking radar with respect to off-nadir are twofold:

- Compatibility with conventional pulse limited altimetry (ocean or relatively flat surface)  
This configuration allows to minimise the vertical accuracy ( $\sigma_z$ ) of the retrieved surface height.

As shown from Figure 7.5, a limitation of the nadir configuration is that, as for conventional altimetry, the ‘point of first return’ corresponding to the pulse limited footprint plays a fundamental role in the interpretation of the data. Indeed, we see that all other cells are ambiguous for a non-tilted surface. In other words this configuration does not provide a swath over surfaces which are not strongly tilted (i.e. slope larger than the antenna beam, say more than 2 degree).

#### **Processing scheme**

The processing flow chart is more complex than for conventional altimeters as it requires the Doppler focusing and the interferometric processing, prior to echo-retracking. A schematic is given in shown in Figure 7.6. This chart does not presume whether the processing is done on ground or on board. For instance, for SIRAL, raw data (i.e. after the ADC) in the SAR and SAR interferometric modes are downlinked to ground for processing. However it is to be noted that the data rate of SIRAL is about three order of magnitude larger Poseidon 2 data rate (20 kb).

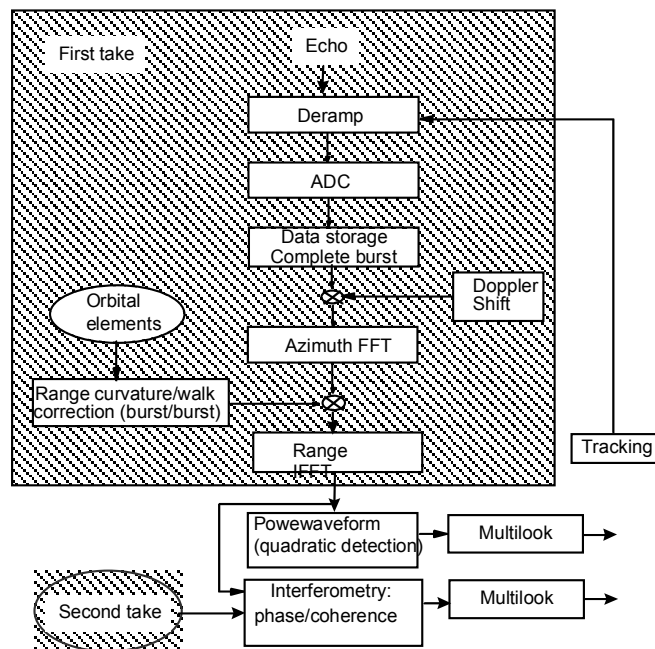
The radar echoes are first deramped, digitized and stored in a memory. At this stage the range compression is not completed, and range (or delay) has simply be transformed into frequency.

As mentioned earlier focusing techniques are not needed as the required along-track resolution for the altimeter only requires short integration time, i.e. the azimuth phase law is almost constant. The azimuth FFT is then performed on a set of  $N_p$  pulses referred to as a burst. The azimuth impulse response characteristics (PSLR, ISLR) are close to those of an ideal sine function.

Prior to the azimuth FFT a linear phase ramp is used to co-locate the reflected signals from the two antennae.

The range curvature during the integration time depends on the relative satellite-target along-track position and on the azimuth resolution. The range curvature is null for a target located at nadir and maximum at the edge of the antenna beam. For SIRAL for instance, the maximum range curvature within a burst is about 0.35 m for a 220 m azimuth resolution, i.e. less than the range resolution. In that case range cell migration can be left non-corrected without too big a loss on the performances of the impulse response. However, burst to burst range-migration must be corrected in order to perform multilooking.

The range compression is completed by taking the inverse Fourier transform (IFFT). The same processing is applied to the echoes received by the second antenna, which provides the second take for the interferogram computation. The power waveform and the interferogram obtained for successive bursts are multilooked for reducing the speckle.



**Figure 7.6 : Typical processing flow chart for a SAR Interferometric altimeter**

**Off nadir altimetry: swath altimeter**

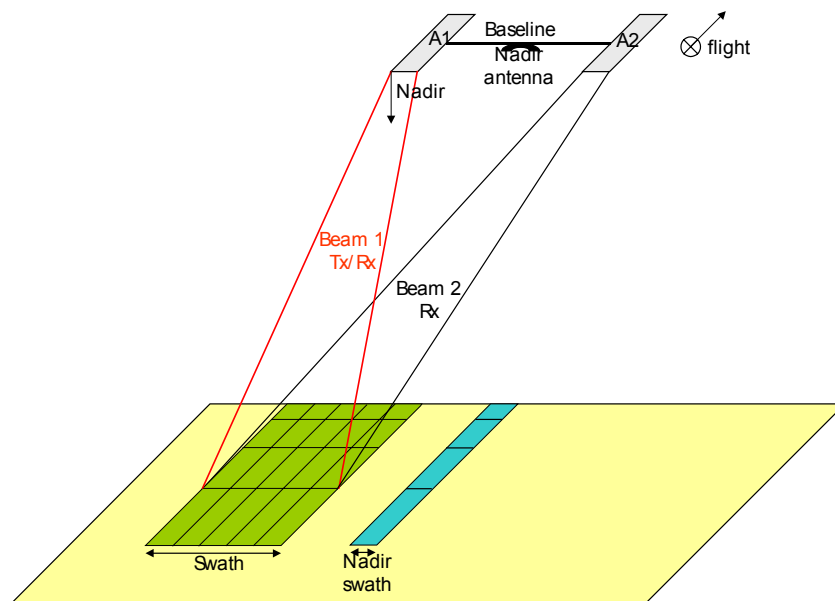
Off nadir altimetry using the SAR interferometric technique is similar to the SIRAL concept with the difference that the antennas illuminate a swath off-nadir as show in Figure 7.7. The motivation is obviously to acquire a non-ambiguous swath and therefore to have access to the bi-dimensionnal distribution of heights and to the ocean currents. The size of the swath is typically determined by considerations on the spatial coverage, temporal repeatitivity and by the scale of the ocean eddies to be observed. Typically swath around 50 to 100 km could be achievable.

A double swath concept, symmetrical with respect to nadir can also be envisaged in order to improve the spatial and temporal sampling.

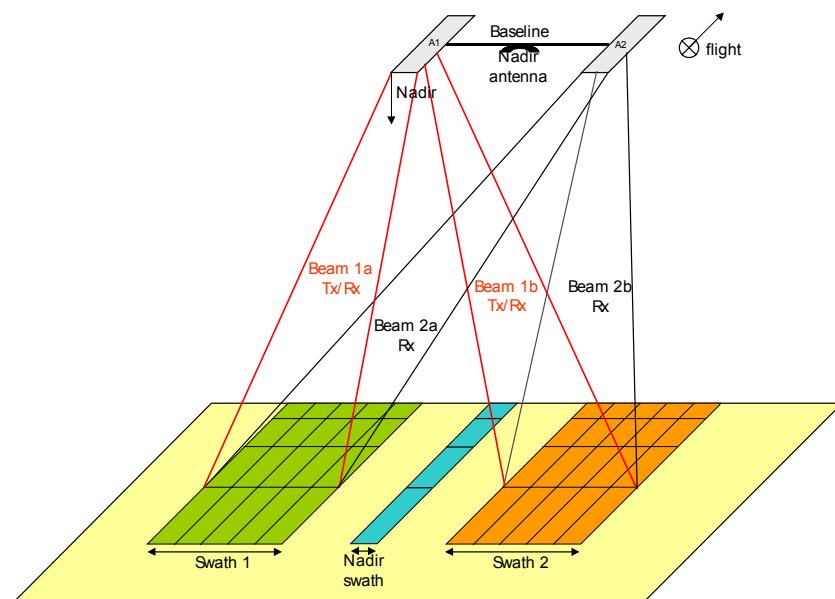
The inclination of the baseline would depend on the single or double swath selection. It can be shown that the baseline should ideally be orthogonal to the boresight at the middle of the swath if one wants to minimise the height error due the interferometric phase error [Rodriguez, 92]. For a double swath configuration symmetrical with respect to nadir, the interferometric baseline should be oriented orthogonal wrt to nadir if equal performances are desired for each side.

The major technical challenge for such an instrument remains the antenna subsystem and the required accuracy in the interferometric phase measurement. The mast length is around 5-10 m, and must be deployable to allow the accommodation under the launcher fairing. The dimension of the antenna themselves (say around 3 m\* 0.3 m) should also be deployable. The stringent accuracy in antenna phase centre stability and knowledge of the attitude baseline (typically tenth of arcsec) combined with deployment constraints makes such a system particularly critical for Europe. The US claims extremely good performance of the antenna subsystem thanks to the heritage acquired in the SRTM (Shuttle Radar Topographic Mission) which used a 60 meter boom.

Other critical points to be assessed are the internal and external calibration of this instrument, again regarding the interferometric phase and the antenna baseline attitude.



**Figure 7.7 : Off-nadir SAR Interferometric Altimeter (single swath)**



**Figure 7.8 : Off-nadir SAR Interferometric Altimeter (Double swath)**

## 7.4 Mission reviews

### 7.4.1 Past and present missions

#### ENVISAT

The European Space Agency's earth observing satellite ENVISAT is due for launch beginning of 2002. Among other instruments, this satellite will carry an advanced dual frequency radar altimeter, the RA-2, which will build upon the success of the altimeters on the ERS-1 and ERS-2 satellites, and the Doris positioning system. As for ERS missions, ENVISAT will generate highly accurate ocean topography measurements, and also will provide near real time sea state data to the Global Meteorological Transmission network. ENVISAT measurements, jointly with Jason-1 data (and ERS and T/P data), will be invaluable in describing, understanding and forecasting the ocean dynamics at short to long scale. Because of their early launch in 2001, these two data sets will be extensively used in preparing and assessing the potential synergy between future altimetric missions, as advocated in this GAMBLE thematic network proposal.

#### JASON-1

JASON-1, a joint US/France mission designed as a follow-on to the phenomenally successful TOPEX/POSEIDON (T/P) mission, will be launched end of 2001. During most of this decade T/P has delivered very precise measurements of the variations in the level of the ocean surface to the ocean and marine research community. This data set has permitted tremendous progress in research on ocean circulation, specially for the low frequency part, and in studying its impact on climate. The contribution of T/P data has been essential in many other domains (tides, mean sea level, seasonal and intra-seasonal signal, planetary wave propagation etc.). The early recommendation from the scientific community arguing the necessity for continuing such dedicated altimetric missions proved strong enough to convince of the need for a follow-on to T/P.

The Jason-1 satellite payload is as for T/P except for the mass, volume and power consumption, which have been reduced by a factor of 3 to 4, due to miniaturisation of the instruments. Mounted on-board will be the Poseidon 2 dual frequency altimeter (Ku and C bands for ensuring accurate ionospheric corrected range measurements), the Doris system, a GPS receiver and a laser retro-reflector (for precise orbit determination) and a radiometer (to accurately measure the troposphere water vapour content). Despite a reduced total mass of about 500 kg, the Jason-1 satellite will deliver sea surface height measurements with the same accuracy as T/P along the same ground tracks (identical 10 days repeat orbit).

Jason-1 will continue the T/P research mission but will also support the development of emerging operational oceanography by providing usual Interim Geophysical Data Records (within 3 days) and near-real time products (within 3 hours). These new real time products will include not only on-board computed range measurement and Doris orbit, but also wind speed and wave-height, as derived from altimeter signal, to be used in particular in forecast sea-state models. It is already planned that Jason-1 will be succeeded by Jason-2 in 2005, at a time when global ocean forecasting systems are planned to start running in an operational way.

#### CRYOSAT

The purpose of the CryoSat mission is to determine trends in the ice masses of the Earth. Of principal importance is to (a) test the prediction of thinning perennial Arctic sea ice due to global warming, and (b) reduce uncertainty in the contribution to sea level of the Antarctic and Greenland Ice Sheets. These questions provide the primary mission goals. CryoSat will provide observations for:

- The determination of regional and basin-scale trends in perennial Arctic sea ice thickness and mass.
- The determination of regional and total contributions to global sea level of the Antarctic and Greenland Ice Sheets.

Trends determined by CryoSat within its lifetime will be limited by the natural variability of ice thickness. The importance of its measurements will be increased by a future flight of an equivalent mission two decades or so later. Nonetheless, the actual performance will allow CryoSat in its own lifetime to determine whether the observed changes in sea ice signal important trends in Arctic climate or merely the ephemera of inter-annual variability at short spatial scales, and to reduce the uncertainty in the ice sheet contribution to sea level to a magnitude similar to that associated with other sources of sea level rise.

The secondary mission goals of CryoSat are to make observations of:

- The seasonal cycle and inter-annual variability of Arctic and Antarctic sea ice mass and thickness;
- The variation in thickness of the world's ice caps and glaciers.

To address the above objectives, the CryoSat payload comprises an enhanced altimeter system for the ice sheet interiors, for sea ice and for ice sheet margins and other topography. Three operative modes are foreseen:

- Conventional pulse limited operation for the ice sheet interiors (and ocean if desired).
- Synthetic aperture operation for sea ice.
- Dual-channel synthetic aperture/interferometric operation for ice sheet margins.

A full description of the detailed objectives, mission and system requirements may be found in Wingham et al. (1999).

#### *7.4.2 Review of proposed mission concepts*

##### **A large constellation concept based on low-cost instruments: GANDER**

The GANDER concept is to launch a number of microsats where the primary payload is probably limited to a single frequency radar altimeter and a precision navigation system in order to fill the gaps created by Envisat and JASON. The number depends on the requirements. For the resolution of eddies requested in the 1987 report to NASA it was thought that 4 would be enough to provide a 50km spatial resolution over a 15-day sampling period. As one moves more towards the requirements of day-to-day marine operations, timeliness of delivery - or the need for near real-time information on fast changing events such as storms at sea - assumes an ever increasing importance. Somewhere in between the research needs for increased knowledge on ocean heat transfer and the operational requirement to locate and track the passage of storms at sea, lies an area where an increased number of altimeters would generate information on currents (updated say at weekly intervals) which would benefit transocean shipping and offshore operations as well as climate research.

The frequency of the altimeters to be carried - C, Ku or Ka band or a suitable mix - has yet to be determined as has the navigational systems (DORIS, GPS, Galileo, laser ranging etc.). Each carries advantages and disadvantages according to the requirements of a particular client community. Several of these application areas were identified in the ESA Call for Proposals including improved predictability of ocean weather in both the short and long-term.

#### **A delay Doppler altimetry system for high resolution: WITTEX**

The Applied Physics Laboratory of Johns Hopkins University has proposed a method of increasing the efficiency of a radar altimeter by making use of the Doppler spectra of the returned signal. The technique effectively combines the sampling of small cells within the altimeter footprint from a number of different pulses.

The WITTEX Proposal, also from Johns Hopkins University, builds on the miniaturisation allowed by the Delayed Doppler Altimeter (DDA). It suggests that 3 mini satellites equipped with DDA's are launched together in the same orbit (separated by 200 - 900km) so that they sample the ocean on closely parallel ground tracks (12 - 50km).

#### **Wide swath sampling for ocean circulation: the Wide Swath Ocean Altimeter (WSOA)**

In order to map ocean mesoscale phenomena adequately, it is necessary to be able to resolve phenomena which are on the order of the Rossby radius of deformation (a conservative value would be on the order of 30km) and have a typical lifetime on the order of a month. It is not possible to reconcile both of these requirements with a single nadir looking altimeter: the TOPEX altimeter has a repeat cycle of 10 days, but an equatorial separation of 310 km. Given a sufficient number of satellites, it is possible to meet these requirements, but at the cost of coordinating and launching multiple platforms, as well as cross-calibrating different systematic errors due to orbit and instrument biases.

The Wide Swath Ocean Altimeter (WSOA) concept is an attempt to meet the requirements using a single platform. The WSOA consists of a suite of instruments: a conventional nadir altimeter (Ku and C-band nadir altimeters, 3-frequency radiometer, and GPS receiver) supplemented by a Ku-band radar interferometer [Rodriguez and Martin, 1992] [Rodriguez et al., 2001]. The nadir altimeter is used for high precision basin scale measurements, for the estimation of ionospheric and tropospheric delays, and for the calibration of the interferometer.

The radar interferometer illuminates 100 km swaths on either side of the nadir track using right and left-looking beams. The intrinsic cross-track resolution varies from approximately 670 m in the near range to about 100 m in the far range. The along-track resolution is given by the azimuth beamwidth, and is approximately 13.5 km. In order to have spatially uniform resolution cells, and to reduce random measurement error, the final measurements are averaged to 15 km resolution cells. The 200 km swath enables the WSOA to achieve near global coverage with a single instrument.

Another advantage of the 200 km swath is that, in contrast with a nadir looking altimeter, a typical point on the ocean surface will be imaged at least twice within a 10-day repeat period, and often more frequently. The multiple looks at the same point can be used to improve temporal sampling, but, perhaps more importantly, to reduce random measurement errors by averaging, optimal interpolation, or assimilation. The high accuracy of requirements for ocean topography measurements implies that the measurement error budget must be thoroughly understood. The errors for interferometric measurements and for the WSOA in particular are described in detail in [Rodriguez and Martin, 1992] [Rodriguez et al., 2001]. The WSOA errors can be derived into three components: random errors, media errors, and platform roll errors. The random error contribution depends on the system signal to noise ratio (SNR), on the length of the interferometric baseline, and on the processing used. The WSOA interferometer does not directly measure tropospheric, ionospheric, and EM bias corrections, but uses the corrections from the nadir altimeter. Spatial variability of the ionosphere, troposphere, wave and wind fields over the scales of the swath will induce residual height errors.

Finally, the lack of knowledge in the spacecraft roll angle induces height errors. In order to remove these errors a calibration scheme has been designed which uses ascending and descending WSOA data at crossover regions to estimate and remove the roll error.

One of the principal advantages of the WSOA measurements is that one can obtain the two-dimensional sea surface, rather than just the traditional along-track profiles measured by nadir altimeters. The availability of a two-dimensional height field allows the calculation of surface topography derivatives in the zonal and meridional directions. This means that it is possible to estimate the full vector geostrophic velocity everywhere WSOA measurements are available, rather than the single component of the velocity measured by a nadir altimeter.

Similarly, the Laplacian of the height field can be used to estimate the geostrophic relative vorticity.

**A low-cost ocean/ice multi-objective concept: The Ka-band integrated altimeter/radiometer.**

The objectives of Ka-band altimetry as reported in an above dedicated section were translated into some main features of the Ka-band payload:

- get an altimeter instrument whose range noise performance may be so that the recovery of the ocean short wavelength features is improved,
- get an altimeter instrument with an improved space resolution along-track and a better performance when approaching or leaving coastal boundaries,
- get an altimeter instrument that will minimise the penetration effects over media such as continental ice,
- embark an orbitography system that will ensure a high level of accuracy in terms of orbitography and that will ease the connection of historical altimetry series within a common well surveyed geodetic reference frame,
- embark a microwave radiometer that will help correcting altimeter measurements for wet troposphere effects.

To answer the previous requirements, it has been proposed to compose an AltiKa payload with:

- \* A single frequency Ka-band (35 GHz) altimeter instrument
- \* A two-frequency radiometer,
- \* A DORIS receiver,
- \* A passive laser retroreflector array.

To comment on some aspects of the Ka-band system, we can add the following:

- At Ka-band, the ionosphere effects are much lower than at Ku-band and maybe considered as negligible, except for some exceptional ionospheric situations (in the latter cases, the embarkment of DORIS may provide a backup solution to retrieve the ionospheric correction). This is one reason for the choice of such a frequency band for a single frequency altimeter.
- The decorrelation time of sea echoes at Ka-band is shorter than at Ku-band. This gives the possibility to significantly increase the number of independent echoes per second compared with Ku-band altimeters. The instrument is designed for a high Pulse Repetition Frequency (PRF) around 4000 Hz.
- The antenna beamwidth is smaller for the Ka-band altimeter than for Ku-band POSEIDON 2. This gives a Brown echo, which is sharper than the echo obtained with altimeters such as POSEIDON 2; the echo power is also lower due to larger gain variation in the pulse limited footprint.
- The 480 MHz bandwidth that may be used at Ka-band will provide a high vertical resolution (0.3 m) which is improved with respect of all flying altimeters (including Jason and ENVISAT)
- It is known that Ka-band EM waves are sensitive to rain. In addition to attenuation effects, perturbation of echoes by rain has to be analysed in terms of the retrieval of the 3 geophysical parameters to be estimated from waveforms.

The selection of the radiometer type has been driven by:

- The basic science requirement, that is to perform the measurements necessary to get the wet troposphere correction with a sufficient accuracy;
- The willingness to embark the AltiKa payload on a microsatellite, which requires a compact and simple instrument.

Frequencies have been selected to be optimal for the case of a dual frequency radiometer, that is 23.8/36.5 GHz. A three-frequency radiometer would be more difficult to embark because the lowest frequency (19 GHz) would impact the system on the microwave and antenna point of views. In addition, it is possible to overcome this drawback by adapting a wet troposphere retrieval algorithm incorporating the relationship between the wind and the altimeter backscatter coefficient (for instance, such a solution is used for the ENVISAT altimetry).

The 23.8 GHz frequency will use the full width of the allocated bandwidth, that is 400 MHz. Concerning the 36.5 GHz frequency, the fact that it is near from the altimeter frequency does not allow the use of the whole allocated bandwidth which is 1 GHz. In addition, the accuracy of the wet tropospheric correction does not much depend on this bandwidth. Then, it is envisaged to use a 400 to 700 MHz bandwidth with a high probability to select a 400 MHz band (so that the high frequency of the radiometer is centred at 36.8 GHz).

After comparing the known radiometer concepts, a so-called “Total Power” radiometer was selected because it has the simplest architecture and also provides the best radiometric sensitivity. The counterpart is the necessary frequent radiometric calibrations because of the high sensitivity to the gain variations.

One of the initial requirements to design the AltiKa payload was that it should be possible to embark it on a microsatellite and that it could also be provided as a whole to become a passenger on an opportunity platform.

This has lead to the definition of an integrated instrument that allows for interface optimisation and reduction of the number of units (boxes). Indeed, the integrated instrument is composed of:

- One microwave unit that gathers all microwave functions of the altimeter and the radiometer, including the calibration functions of the radiometer and the sources of the antenna.
- One processing unit that gathers all functions dedicated to the altimeter and radiometer processing, as well to a global management unit.

The payload is identical for each microsatellite of the constellation, when considering 3 AltiKa satellites to answer high resolution ocean topography requirements.

**A concept focused on wave height and wave spectra: SWIMSAT (See also Section 5)**

Presently, assimilation of satellite altimeter data in wave prediction models is based upon observations of the total energy (or significant wave-height) of the wave spectrum, ignoring spectral properties. Assimilation of spectral properties of the waves is important since the assimilation of only significant wave height requires assumptions on the characteristics of the wave field, in particular on the separation between wind-sea and swell, which causes errors or weak impact of the assimilation. Attempts to include spectral information in the assimilation process have been mainly limited to regional areas, e.g. the Atlantic Ocean, but they have shown encouraging results, and have demonstrated the value of spectral wave data for sea-state prediction models. The same added value will also contribute to wave climate and coastal applications. Also, the estimate of sea-state bias affecting range altimeter measurements should be considerably improved when the spectral properties of the wave field are taken into account. This has lead German/French groups to propose the SWIMSAT concept, which will use real-aperture rather than the synthetic aperture radar techniques. The measurement principle is to use a dual-beam radar at Ku-band (13.6 GHz). One of

the beams is pointed towards nadir, the other is pointed at a 10 degree incidence angle and scans around the vertical axis over 360 degrees in azimuth. Such a technique has already been developed and validated using airborne radar systems in France and USA. Feasibility studies of the spaceborne concept have proved very positive, so that instrument and mission characteristics are now well defined. In terms of orbit, an inclination between 65 and 115 degrees is acceptable to cover the whole ocean, whereas sun-synchronism will allow minimising constraints on the electric power supply by the satellite, even if not mandatory. The altitude of the orbit is partly constrained by geometrical considerations. The requirement is that the swath of the radar beam (swept during one rotation of the 10 degree incidence beam) be comparable to grid mesh sizes of wave prediction models and be compatible with reasonable assumptions concerning the homogeneity of the surface within the swath. An altitude ranging between 450 and 600 km is acceptable. However, optimising orbit parameters for one or several SWIMSAT satellites within a GAMBLE constellation (including GANDER satellites, Jason-2, AltiKa and SWIMSAT) is of course different from optimising them for a sole SWIMSAT mission. SWIMSAT is proposed in 2001 to ESA in the context of "Opportunity Missions" of the Earth Explorer Program, for an expected launch in 2006.

For sake of completeness, we should also notice that there is Russian proposal from IAP/RAS (Russia) to fly a rotating 'knife-beam' altimeter, primarily for measuring ocean wave spectra.

#### **An altimetry concept for the far-future: GPS altimetry**

There is also some interest in an alternative system to radar altimeters, which depends on the analysis of the return of GPS transmission received by satellites in LEO in terms of the dynamics of the reflecting sea surface. Satellite altimeters and scatterometers transmit radar pulses and record the return - specular reflection from the nadir path of the altimeter, and back-scatter from oblique incidence angles for the scatterometer. The concept of bistatic radar is to use different satellites to transmit and to receive the radar pulse - in particular to make 'parasitic' use of transmissions from the 24 GPS satellites - to obtain estimates of the parameters provided by the altimeters and scatterometers; surface elevation, wave height and near-surface wind velocity.

The concept has been discussed for about 15 years, eg Hall & Cordey (1988), Garrison et al. (1997). The USA has an on-going programme investigating the detection and interpretation of reflected GPS by airborne receivers. ESA's 'PARIS' project has been studying the possibilities - and problems - of satellite receivers since 1993 (Martín-Neira, 1993).

The first report of a spaceborne observation of GPS reflections was from the space shuttle, reported by LaBrecque et al. (1988). To our knowledge, no reflections have yet been obtained by an unmanned satellite. A secondary mission of the satellite 'CHAMP' launched in July 2000 (a small satellite project led by GeoForschungsZentrum Potsdam) is to test its nadir GPS antenna but this experiment is still pending.

From the studies that have analysed preliminary GPS data for such altimetric measurements, it shall already be stated that the GPS altimetry technique is the less mature of techniques reported here and that it should not be envisaged for a 2006 mission. Moreover, the GPS technique is not based on radar instrument and will not be addressed in the study.

The historical and present missions were recalled because a large inheritance from them comes into the definition of near-future missions.

## 7.5 Instrument complexity

It is already anticipated that the main driver for the instrument complexity, and for the satellite will be:

- The selection of the orbit as it affects many of the radar system parameters (SNR, resolution, etc...) and the design of the altimeter
- The selection of a single satellite configuration, or a constellation. This will be driven by the user requirements in particular the need for space/time repeatability of the measurement and instrument coverage capability.
- The stability and the calibration of the interferometric baseline if a swath instrument with a large baseline is used (typically from 5 to 10 m),.
- The accommodation of a swath altimeter instrument.

Table 7.2 gives an overview of the ranking of the complexity/criticality of the different instrument alternatives, based on Alcatel expertise. The conventional nadir altimeter and off-nadir SAR interferometric altimeter expertise are based on Poseidon 2 on board Jason 1, Alti-Ka (phase B), and SIRAL (C/D phase).

	Conventional nadir Alt.	SAR Interfero Nadir	SAR Interfero Swath
Demonstrated	Yes	Should be in 2004 with Cryosat	No with the required accuracy
RF Unit	Low	Medium	Medium
Digital Unit	Low	Medium	High (OB processing)
Antenna Subsystem	Low	Medium	High (mast)
External Calibration	Low	Medium	High
Size	Small	Medium	Large
Accommodation complexity	Small	Medium	High

**Table 7.2 : Complexity / Criticality of altimeter concepts.**

## References

- 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.
- Caubet, E., L. Phalippou, and L. Thouvenot, 2001, Design stage of a ka-band combined altimeter/radiometer, IGARSS'01, July 2001, Sydney, Australia.
- 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
- Cotton, P.D. 2002. Study of Innovative Altimeter Concepts: WP100 Review of Products and Requirements, ESA Contract Report.
- 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. Wilson, S. De Margerie, and R. Lalbehrry, The effect of assimilating ERS-1 fast 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 hydrodynamic modulations, *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.unesco.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 cross-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 observations 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 2001
- Fischer, 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.
- Lefèvre, 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.
- Lefèvre, 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..
- Lefèvre, 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
- Maurocordato, C., S.Gouenard, and J.Richard, 1994, A compact dual frequency altimeter for TPFO, IGARSS'94, August 1994, Pasadena, Cal., US.
- 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 .
- Phalippou, L., and D.J. Wingham, 1999, HSRRA: an advanced radar altimeter for ocean and cryosphere monitoring, CEOS'99, 1999.
- Phalippou, L., P. Piau, D.J. Wingham, and C. Maurocordato, 1998, High spatial radar altimeter for ocean and ice-sheer monitoring, IGARSS'98, July 1998, Seattle, Wash., US.
- Phalippou, L., E. Caubet, and E. Thouvenot, 1999, A Ka-band altimeter for future altimeter missions, IGARSS'99, 1999, Hamburg, Germany.
- Phalippou, L., E. Caubet, and E. Thouvenot, 2000, Preliminary design of a combined Ka-band altimeter and dual frequency radiometer, IGARSS'00, July 2000, Hawaii, US.
- Phalippou, L., L. Rey, T. de Chateau, E. Thouvenot, N. Steunou, C. Maurocordatos, and R. Francis, 2001, Overview of the performance and tracking design of the SIRAL altimeter for the CRYOSAT mission, IGARSS'01, July 2001, Sydney, Australia.
- 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.
- Queffeuilou, 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.
- Rey, L., N. Suinot, and E. Thouvenot, 1995, preliminary design of VAGSAT wave scatterometer, EUROPTO, September 1995, Paris, France.

- Rey, L., N. Suinot, P. Oudart, and G. Carayon, 1996, Phase B and breadboard results for the Topex-Poseidon follow-on mission, IGARSS'96, May 1996, Lincoln, US.
- Rey, L., T. de Chateau, Y. Jaulhac, and G. Canayon, 1999, Poseidon 2: the new generation altimeter for the CRYOSAT mission, IGARSS'99, 1999, Hamburg, Germany.
- Richard, J., C. Maurocordato, and P. Raisonville, 1993, Poseidon altimeter, a satellite-based radar altimeter compatible with small satellite missions features and in-orbit performance, SPE Symposium on Aerospace and Remote Sensing, April 1993, Orlando, FL., US.
- Richard, J., L. Rey, and A. Faure, 1998, Jason (Topex-Poseidon follow-on) altimeter – Technologies and Performances, IGARSS'98, July 1998, Seattle, Wash., US.
- 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 variability 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 surface 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.
- Verron, J., P. Bahurel, E. Caubet, B. Chapron, J.F. Cretaux, L. Eymard, C. le Provost, P.Y. le Traon, L. Phalippou, F. Remy, E. Thouvenot, L. Tournadre, and P. Vincent, 2001, A micro-satellite Ka-band altimeter mission, IAF01, October 2001, Toulouse, France.
- 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. Geophys. 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.

## 8 Appendices

### 8.1 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.

Variable	Most chosen		Ranked by no of sectors, then by no of respondents		Research	Transport	Environment	Building	Defence	Food	Energy
	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. 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.

## 8.2 Appendix B. Presentations made to the GAMBLE Sea State Workshop

A workshop to discuss future requirements for altimeter derived sea-state data was held at ISDGM, Venice on 30th September 2002. To provide additional material to the papers included in this report, the following extra presentations were invited. Where available, links are provided to pdf documents containing the presentation material (located on the GAMBLE web-site):

**Peter Janssen (ECMWF) :** Error estimation of model, buoy and altimeter wave height.  
Benefit of flying an additional altimeter on wave height analysis.  
Sea State Bias

**Jean-Michel Lefèvre (Météo-France):** [Wave forecasting and Satellite data:](#)  
Research and Development Activities at Météo-France

**Johannes Guddal (DNMI):** Suggested use of altimetry in Storm Surge Forecasting connected with Tropical Cyclones. (see 8.2.1 below)

**Susanne Lehner (DLR):** [Radar Remote Sensing of the Sea Surface:](#) Synthetic Aperture Radar and “Rogue” Waves.

**Francisco Ocampo-Torres, CICESE (Mexico):** Wave measurements and Satellite Data Requirements from CICESE.

**Jim Gunson (UKMO):** Statement of UKMO Priorities with Respect to Wave Prediction and Modelling. (see 8.2.2 below)

The [Workshop Minutes](#) are also available on-line

### 8.2.1 *Altimetry in Storm Surge Forecasting connected with Tropical Cyclones (Johannes Guddall, DNMI)*

#### **Introduction**

Storm surges connected with landfalls of Tropical Cyclones are perhaps the most dramatic, damaging and suddenly occurring between natural disasters. Up to half a million people are believed to have perished only through one night with a storm surge hitting Bangladesh. The prominent drivers of extreme storm surges in the tropics are the tropical cyclones and their wind fields. These are intensive atmospheric cyclones, with sustained wind speeds even beyond 100kts, and propagating rapidly over large distances. Conventional forecasting of cyclone developments seeks to predict the intensity and movement track of the cyclone, with a rough parameterization of the wind/pressure fields around the eye of the cyclone. Wind/pressure fields are necessary forcing fields for the numerical models to predict storm surges. The state-of-art leaves much to be improved regarding the quality of such forecasting. This document suggests the inclusion of global tropical altimetry, and, optionally scatterometry, to improve the accuracy of storm surge forecasting.

#### **Possible inclusion of altimetry and scatterometry.**

The operational mode of a storm surge forecasting model has the following phasing:

1. Initialization, which normally means using the prognostic fields from a previous prognosis or a ‘warming up’ of the model with analytical wind/pressure fields.
2. Provision of forcing fields for wind/pressure, normally from a large responsible computer center such as the Japan Meteorological Agency.
3. Ocean Model operation 2 – 5 days, predicting future development of sea level including tides in a region such as the South China Sea.

#### 4. Performing verification statistics by comparison with tidal gauges etc.

It is strongly believed that inclusion of altimetry (and scatterometry) becomes beneficial under phase 1 and 4, perhaps in phase 2 as well. Much of the lack of accuracy in sea level forecasting is due to inadequate initialization, as well as a too rough description of the acting wind fields.

##### **Altimetry/scatterometry products that may help in storm surge forecasting.**

Near real time gridded sea level and wind fields could be ‘sold’ to responsible centers in the Tropical Cyclone Programme, or to regional/national forecasting agencies in closer contact with disaster mitigation mechanisms. These would again be used to update the corresponding numerical fields, and thereby have a positive impact on the forecasting accuracy.

#### *8.2.2 Statement of UKMO Priorities with Respect to Wave Prediction and Modelling (Jim Gunson, UKMO)*

The Met Office runs a spectral wave model to provide sea-state forecasts and hindcasts for a variety of customer needs. The model is run both globally and regionally for the European and UK waters. An important need is the accurate representation of long-period swell propagation. Good quality satellite observations of wave height and wind speed from an altimeter, and the two-dimensional wave energy spectra from the SAR, are highly desirable. A synergy of the wave model with the satellite observations over regions of swell generation would greatly improve the sea-state forecasts.