



# **GAMBLE**

## **WP 6 Mid Term Review (Deliverable D8)**

### **Report on Error Budgets and Potential Solutions**

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## TABLE OF CONTENTS

1	Introduction .....	2
2	Sea Surface Height Features .....	3
2.1	Measurement Issues .....	3
2.2	Sea Level Measurement Requirements .....	3
2.3	Summary of SSH Requirements .....	6
3	Sea State Features .....	7
3.1	Feature Characteristics .....	7
3.2	Priority issues .....	8
3.3	Summary of User Requirements .....	9
4	Possible Technical Solutions.....	12
4.1	Mission Options .....	12
4.2	Altimeter Capabilities .....	13
4.3	Issues and Technical Solutions .....	13
4.4	Summary .....	17
5	References .....	18

## 1 Introduction

The purpose of this review is to provide a mid-term position report on:

- Altimeter measurement requirements/error budgets for resolution of features in sea surface height and sea state.
- The issues requiring technical solutions/developments that are raised through these requirements.
- An assessment of the solutions that are potentially available.

This report is based on work carried out under GAMBLE work packages 2, 3 and 4. We will not repeat here detailed information presented in other GAMBLE documents, so readers are referred to the WP2, WP3 and WP4 interim and final reports for greater detail and reference material.

In Section 2 of this report the major issues and requirements of the community making use of Sea Surface Height data will be summarised, followed by an equivalent presentation of Sea State requirements (winds, waves and air-sea fluxes) in Section 3. In Section 4 the various technical solutions will be assessed.

## 2 Sea Surface Height Features

### 2.1 Measurement Issues

#### 2.1.1 Mean Dynamic Topography

Currently available geoid models are not sufficiently accurate to provide a useful estimation of mean dynamic topography. New gravity missions (CHAMP, GRACE and GOCE) will improve the situation. After GOCE (launch 2006), an independent estimation of the geoid with an accuracy of 1-2 cm rms for scales larger than 100 km should be available. Meanwhile, the only solution is to estimate the mean dynamic topography from a combination of in-situ and model data and global geoids. The error on the resulting mean dynamic topography is typically of 5-10 cm rms; this should improve in the future with the Argo global array of profiling floats and with improved data assimilation methodologies as planned by GODAE.

#### 2.1.2 Mapping and merging of multiple altimeter missions

Merging of multi-satellite altimeter data sets is required to map the mesoscale variability. An effective methodology is to use the more precise missions (e.g. T/P, Jason-1) as a reference. This allows a reduction of orbit error for the other satellites to few cm rms even if the initial orbit errors are as large as 1 m.

When altimetric data have been homogenized and inter-calibrated, the Sea Level Anomaly (SLA) for the different missions must be extracted. These should be calculated relative to the same ocean mean using a common reference surface. The final step is to merge the SLAs from the different missions via a mapping or assimilation technique.

### 2.2 Sea Level Measurement Requirements

#### 2.2.1 Climate and mesoscale applications

A generally agreed baseline requirement for future altimeter missions is for at least two (preferably three) altimeter missions with one very precise long-term altimeter system. The long-term altimeter system provides the low frequency and large scale climatic signals and a reference for the other altimeter missions. The TOPEX/POSEIDON and Jason series were designed to meet these objectives. The other missions will measure the higher frequency signals, in particular the mesoscale signal, which cannot be well observed with a single altimeter mission. This does not require precise altimeter systems as most of the altimetric errors (in particular the orbit error) are at long wavelengths and do not impact significantly the mesoscale signal.

Studies have quantified the mesoscale mapping capability when combining various existing or future altimeter missions in terms of sea level anomaly (SLA) and zonal (U) and meridional (V) velocity. The main results are:

- There is a large improvement in sea level mapping when two satellites are included. Compared to T/P alone, the combination of T/P and ERS reduces mean mapping error by a factor of 4 and standard deviation by a factor of 5.
- The velocity field mapping is more demanding in terms of sampling. The U and V mean mapping errors are 2 to 4 times larger than the SLA mapping error. Only a combination of three satellites can provide a velocity field mapping error below 10% of the signal variance.

### 2.2.2 *Data Assimilation Perspective*

Data assimilation experiments have been conducted to examine how the mesoscale ocean circulation can be identified from multi-satellite configurations.

The comparison between error statistics calculated for various scenarios and other mission parameters such as altitude, allows a number of conclusions to be drawn:

- The addition of a second altimeter improves the reconstruction of the mesoscale circulation by 18% to 28%, depending of the mission parameters. The addition of a third satellite makes an additional improvement of 10% to 16% depending again of the flight configuration.
- A 3 day interval between successive analyses appears to better sample mesoscale features than other assimilation periods (intervals of 1, 3, 10 and 20 days were tested).
- With regard to mesoscale features, the observing scenarios optimising spatial sampling (interleaved tracks, or space offset) compete very well with those optimising temporal sampling (time offset). In contrast, the case of two satellites flying in parallel (with an offset of  $0.5^\circ$  between tracks) seems less effective.
- The “best” observing scheme may be dependant on whether the variable of interest is related to the surface circulation, or to deep ocean fields.
- Determination of dynamical modes with intensifications at intermediate depths will require more than two satellites. In a dynamical context, the lack of information concerning these modes might affect the global 3-D flow field, and therefore may also limit the quality of the estimation near the surface. The launch of 3000 Argo profilers will also make a significant contribution
- In a three satellite constellation at given inclination, the increase of altitude has a negative effect on performances

Overall, the results using three satellites confirm other studies indicating that a third satellite is required to control the mesoscale features satisfactorily. The choice of the optimal configuration is not trivial. Assimilation experiments are being extended over longer periods to refine these conclusions.

To further improve mapping (needed for some proposed scientific and operational applications), we need to resolve the high frequency and high wavenumber signals, i.e. sample the ocean with a time sampling below 10 days and 100 km. Such a sampling density would require a constellation of altimeter satellites and/or the development of different concepts for satellite altimetry (wide swath techniques).

### 2.2.3 *Measurement Errors*

Assuming the Jason series continue to provide a long term reference, additional measurement systems do not have to provide very precise measurements. Results derived from these systems will not be sensitive to very long wavelengths errors (wavelengths  $> 5000$  km/  $10\ 000$  km ) if the Jason satellites are used to constrain the large scale (climatic) signals.

The typical amplitude of the mesoscale signal is 4 to 8 cm rms in the open ocean. A 2 to 4 cm measurement noise (1 second average) is thus satisfactory but a smaller noise will allow a better estimation of the velocity fields and a detailed analysis of the eddy structure in the along-track direction.

Wet troposphere and ionospheric corrections impact on medium and large scale signals. In high precision missions these are measured by dedicated instrumentation (radiometer, dual

frequency). Studies could be undertaken quantify the degradation of results for altimeter missions without a radiometer or dual frequency capability.

#### *2.2.4 Coastal Applications*

Most of the SSH signal associated with energetic coastal currents have height differences ranging from 2-5 cm to 10 cm or more. 1-2 cm precision would thus provide a good resolution of these signals. Degrading that resolution to 5 cm would make the observation of many coastal features very difficult. The most demanding constraint results from the temporal resolutions needed to resolve most of the coastal features: the temporal revisit of a site must be 1-2 days for rapidly changing currents. Sampling at 10 km intervals will allow marginal detection of these features. Thus, it is in the coastal domain that we find the most strenuous requirements in terms of space/time resolution and accuracy, but it is in these regions that we also find such requirements most difficult to satisfy, particularly due to the contamination of land in the altimeter and radiometer footprints. It is concluded therefore that altimetry should be combined with other technologies that provide more detailed fields over shelves (SST and ocean colour observation from space, coastal radars, other in situ observation techniques), and through assimilation into coastal circulation models.

#### *2.2.5 Tidal Studies*

##### **Sun Synchronous Orbits**

With a sun-synchronous orbit, a satellite altimeter always observes the solar tides at the same phase of their period. The contribution to the altimeter signal is then just an unknown constant. This affects the main solar tide components S1 and S2.

S2 is now better known after analysis of T/P and ERS data, and progress in hydrodynamic modelling and data assimilation. For S2 the accuracy of recent solutions is at the cm level over the deep ocean. However, these solutions need to be improved over coastal and shelf regions where their accuracy is only of the order of 20 cm. Complementary studies are required for coastal areas, including satellite altimetry observation with higher space resolution on a non sun-synchronous orbit.

##### **Tides over mid ocean ridges**

To fully observe the 2D structure of short wavelength tidal characteristics due to mid ocean ridges, high-resolution altimetry is needed. Measurements must be at the level of accuracy of the on going altimeter missions T/P and ERS, with a (provisional) space resolution of the order of 10 km. The time resolution for tidal applications is not so crucial, so long as the tidal aliasing problem is considered with care (ERS and T/P have known problems).

##### **Barotropic tides over continental shelves and near the coasts**

Tidal amplitudes can increase by several meters over shelves and approaching the coast. Also, horizontal gradients can reach up to several cm per km, and the horizontal patterns in amplitude and phase of the main tidal components are strongly reduced.

High resolution altimetry can thus help to improve the mapping of the tidal characteristics in coastal areas, by resolving their 2D spatial structures and observing the strong horizontal gradients in amplitude and phase experienced along the coastlines. As above, T/P and ERS level of accuracy is required. Space resolution must be typically of the order of 5 km. The time resolution for tidal applications is not crucial, so long as tidal aliasing is considered.

### Non linear tides over continental shelves and near the coasts

In coastal areas, tides are also more complex because of non-linear dynamical processes, which distort the tidal waves. These nonlinear constituents can be order 10cm. Their patterns are also more complex as their frequency is higher.

Although long altimetric records now allow the amplitude and phase of these constituents to be extracted with an acceptable level of accuracy (2.5 cm), the short wavelength of these higher harmonic tidal waves render difficult the inter track interpolations. High resolution altimetry is needed to fully map these non linear high frequency tidal waves. The required accuracy and precision are the same as above (~cm height, 5 km horizontal resolution, no major constraint on the time sampling, bearing in mind aliasing requirements). Large swath altimeter satellite missions, like WSOA on T/P-Jason track, with 13 km resolution and 150 km swath will allow full coverage of areas such as the North Sea. Although the space resolution will be marginal, such measurements will help to map these non linear features.

## 2.3 Summary of SSH Requirements

Table 2.1 provides indicative SSH measurement requirements.

Application	Parameter	Indicative Measurement Requirements			
		Spatial Res	Time Res	Latency	Accuracy
Mesoscale variability	Sea surface topography	25-50 km	5 day	3 day	2-4 cm
Global mean sea level change	Sea surface topography	100 km	10 day	10 day	0.5 mm yr <sup>-1</sup>
ENSO – seasonal to interann. prediction	Sea surface topography	200 km	5 day	5 day	4 cm
Large scale variability	Sea surface topography	200+ km	10 day	3 day	2 cm
Tides (Sun synchronous)	Tidal constants – sea surface height	100 km	non sun synch. orbit	> 100 visits to each location	2 cm
Coastal features	Sea surface topography	10 km	1-2 day	1 day	1-2 cm
Tides near coasts & topography	Tidal constants – sea surface height	10 km	-	> 100 visits	1-2 cm
Barotropic tides	Tidal constants – sea surface height	5 km	-	> 100 visits	2 cm
Non-linear tides	Tidal constants – sea surface height	5 km	-	> 100 visits	1 cm

**Table 2.1. Indicative Measurement Requirements for Applications of Sea Surface Topography**

Priority issues are:

- Improve sampling in space and time.
- Identify preferred sampling regimes.
- Establish how to ensure satisfactory accuracy for micro-satellite, swath range measurements (ionosphere, troposphere corrections, accurate orbit knowledge).
- Identify preferred orbits.

### 3 Sea State Features

#### 3.1 Feature Characteristics

The distribution of wind and waves on the oceans is mainly characterised by the sharp distinction between the storm belt, at latitudes poleward of 40°-45°, and the tropical-equatorial zone. North/South of this zone 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 poleward position during the warmer months of the year.

The overall pattern reflects this distribution, with the strongest winds present at latitudes between 60°-70°. Local patterns exist close to the continents. 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 extremely large waves.

The distribution of wave heights closely follows the wind climate. The storm belt is characterised by frequently occurring 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 is 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, there is no special constraint on the accuracy of the time and location of a pass, or on time interval between passes and the spacing between adjacent passes. The scale of the processes is fairly wide, with variations on the scale of hundreds of kilometres. The choice is a compromise between the number of data at each location and the spatial density of the information. For individual storms, particularly 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. In these conditions a much higher density of information would be required, most likely beyond the practical possibilities of satellite altimetry alone. As for a detailed description of the open ocean climate, a step towards a solution lies in the parallel use of the information from the numerical models.

## 3.2 Priority issues

### 3.2.1 Sampling

Altimeter data are still relatively scarce on a global scale, with large gaps in space and time. An orbit with a return period of, e.g., ten days implies at each visited location less than forty data per year, with a gap of  $2.5^\circ$  between adjacent tracks. Most applications place the highest priority on increased sampling in time and space, some users have indicated an order of magnitude increase in sampling is desirable.

### 3.2.2 Accuracy

The accuracy of measurements is still an issue, more for wind speed than for wave height. Both the parameters have strong uncertainties in extreme conditions (wind speed  $> 15 \text{ ms}^{-1}$ .  $H_s > 10\text{m}$ ). This is precisely the area in which users are posing their most pressing demands, particularly for offshore operations.

### 3.2.3 Assimilation into Models

In application to forecast models, the altimeter has been the basic instrument for supply of wave height information. However, the impact of altimeter data is limited to a relatively narrow band either side of the ground track. The main drawback has been the inability to correct the individual wave systems that compose the two-dimensional spectrum at a given location. SAR data have been useful in this respect, boosting the development of techniques for the assimilation of the measured spectra. To date the assimilation of SAR data has required a priori knowledge of the spectrum, obtained from the model in which the data are to be assimilated.

### 3.2.4 Other Wave Parameters

Many offshore operational users have indicated that an accurate *wave period* parameter would be of significant benefit. In addition users have asked for *wave direction*, separate estimates of *height*, *period* and *direction* for *wind-seas* and *swells*. This leads to a need for full *directional wave spectra*.

### 3.2.5 Understanding of Wave Processes

One of the key issues for the improvement of the numerical wave model is a better knowledge, hence formulation, of the physics of waves, and of their interaction with the atmosphere. Waves are the interface that controls the fluxes between the two large systems, ocean and atmosphere, that in turn control the earth climate. A better knowledge of the involved processes is 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. 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. In addition 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.

### 3.2.6 Coastal Studies

The knowledge of the conditions in coastal areas present a particular challenge. To date the altimeter has not been able to 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). In addition it is

clear that the spatial variability that characterises the coastal environment cannot be adequately sampled by a single altimeter.

### 3.2.7 *Air-Sea Flux Climatologies*

Climatologies of air-sea fluxes (momentum, heat, gas, freshwater) are centrally important in climate studies. Dual frequency (or multi-frequency) altimeters offer a unique possibility for direct measurements of surface wind stress, and air-sea gas transfer velocities. The derivation from altimeter data of estimates for these parameters is the subject of ongoing research.

Presently available estimates of global mean air-sea gas transfer velocities vary by a factor of two. Any improvement on this resolution would be beneficial. An accuracy to aim for (in a climatology) could be 50% (or 10 cmhr<sup>-1</sup>) on a monthly 2° x 2° grid.

Also an estimate of rain rate can be derived from the differential radar backscatter for a dual frequency altimeter. Whilst other, specifically designed, satellite missions provide better sampling, altimeter estimates provide a valuable independent verification.

### 3.2.8 *Event and Process Studies*

There is a growing interest in the understanding of the physics of extremely severe conditions. Of course it is in these conditions when human and environmental safety are most at risk, but it is exactly in such situations when in-situ instrumentation are most vulnerable. Although the physical processes are different, satellite measurements are not vulnerable in the same way and so satellites offer an opportunity to measure extreme conditions.

There are two areas of specific interest.

- The study of wind and wave fields associated with events such as tropical storms or cyclones.
- The study of occurrences of and characteristics of so-called “Rogue” waves.

Joint use of altimeter/SAR and perhaps altimeter/optical data sets could provide important information by allowing profiles of individual severe events.

For detailed studies of ocean wave processes more sophisticated processing of the altimeter signal could be attempted.

## 3.3 **Summary of User Requirements**

Table 3.1 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). “Latency” is the delay from the time the measurement is taken to the availability of this measurement to the user. Note that the resolution requirements for offshore and coastal near-real time data (30 km and 1 hour) are requirements for a final product which may be derived from a number of sources, not only altimeters. For the GANDER constellation, SOS proposed an altimeter sampling regime of 400 km every 6 hours (equivalent to 100km each day).

Application	Altimeter Parameter	Indicative measurement requirements			
		Spatial res (km)	Time res	latency	accuracy
Climate Research	Sig. wave ht (Hs) <sup>1</sup>	100	1 mon	3 months	0.1 m
Offshore appls. (climate)	Hs <sup>1</sup>	1° x 1°	1 mon	Years	0.1 m
assimilation into models	Hs <sup>1</sup>	100	6 hr	3 hr	0.25 m
near real time - offshore	Hs <sup>1</sup>	30	1 hr	1-3 hr	0.25 m
near real time - coastal	Hs <sup>1</sup>	10	1 hr	1-3 hr	0.25 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>	1° x 1°	1 mon	Years	0.2 s
near real time- offshore	wave period <sup>1</sup>	30	1 hr	1-3 hr	0.5 s
near real time- coastal	wave period <sup>1</sup>	10	1 hr	1-3 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>	1° x 1°	1 mon	Years	±10°
near real time- offshore	wave dir. <sup>1</sup>	30	1 hr	1-3 hr	±10°
near real time- coastal	wave dir. <sup>1</sup>	10	1 hr	1-3 hr	±10°
Offshore appls. (climate)	dir. wave spectrum	100 km	1 mon	Years	15° dirn, 10% wavelen.
Near real time	dir. wave spectrum	30	1 hr	1-3 hrs	10% max energy
Surface wind stress (U*)	□□0 <sup>2</sup>	100	1d	1d	0.1 m s <sup>-1</sup>
Air sea gas transfer vel.	□□0 <sup>2</sup>	100	1d	1d	10 cm hr <sup>-1</sup>
Rain rate	□□0 <sup>2</sup>	250	30d	90d	10 mm mon <sup>-1</sup>
Event and feature studies	Hs	200	1d	3 hr	0.1m / 10%
	U10	200	1d	3 hr	2 ms <sup>-1</sup> / 10%
	□0	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. (□)□0, wave spectrum	Various, according to sea surface height requirements			< 1 cm

**Table 3.1. Indicative User requirements for altimeter derived sea state information.**

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

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

N.B. 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>.

Thus, 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,  $H_{max}/H_s$ ).
- 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.
- Improved estimation of sea state bias (information from the wave spectrum could help here).

## 4 Possible Technical Solutions

### 4.1 Mission Options

New concepts for altimeters address the issues of improving sampling and improving data provision through a wider range of ocean surface geophysical parameters, or improved reliability/accuracy in presently available parameters.

Briefly these new concepts are:

- Constellation of micro-satellite altimeters – the AltiKa and GANDER proposals exist as possible options. AltiKa has been designed as a range measuring altimeter with built in dual frequency radiometer, GANDER was designed as a Ku band wave measuring radar (no radiometer).
- Wide Swath altimetry would provide a range measurement in a ~100km swath on either side of the satellite, but does not provide sea-state information off-nadir.
- Use of GPS reflections. Potentially provides an order of magnitude improvement in sampling, but technology is not mature and further studies are required before it is possible to be confident that this technique offers a practical option. Significant averaging may be required to bring down random errors.
- “Wittex” - Small constellation of micro-satellites employing delay Doppler altimeters (these effectively sub-sample of the altimeter echo). Possible bi-static operation increases the ground tracks to  $2n-1$  (for  $n$  satellites).
- SWIMSAT – A wave measuring real aperture radar, with a possible height measuring capability at nadir.

Of course, these new options exist in addition to presently mature and operational altimeter missions, and those at advanced planning stages.

Operational Missions:

- JASON-1 – Accurate sea surface topography altimeter. Dual frequency (Ku/C band) Poseidon-2 solid state altimeter with radiometer and accurate orbit positioning. 10-day repeat,  $66^\circ$  inclination, orbit. Continues the 10+ year time series started with TOPEX. Launched December 2001. 5 year planned lifetime
- ENVISAT RA2 – Accurate dual frequency (KU/ S band) altimeter with radiometer and accurate orbit positioning. 35-day,  $98^\circ$  inclination repeat orbit. Continues the series started with ERS-1 (1991). Some enhanced tracking capabilities – better performance close to coasts. Launched March 2002, 5 year planned lifetime.
- Geosat Follow-On – Single frequency Ku band altimeter launched in 1998 on a 17 day repeat,  $108^\circ$  inclination, orbit. Initial problems with unplanned satellite resets now overcome.
- TOPEX/POSEIDON - Accurate, but 10 year old, sea surface topography altimeter. Dual frequency (Ku/C band) altimeter with radiometer and accurate orbit positioning. 10-day repeat orbit. Now in an orbit with interleaved tracks with JASON-1. Launched 1992.

- ERS-2 - Single frequency Ku band altimeter (launched 1995). On 35 day repeat orbit. Has experienced some problems maintaining accurate attitude due to failed gyroscopes. However this problem is now largely overcome, through the application of an updated on board algorithm.

#### Planned Missions:

- Jason-2/OSTM – Will operate Poseidon-2 dual frequency solid state altimeter as main instrument, and will continue TOPEX/Jason ocean monitoring mission. May carry wide swath altimeter as demonstration instrument. Scheduled for launch in 2007.
- NPOESS – Dual frequency (Ku/ S band) altimeter to be operated as part of the US National Polar-Orbiting Operational Environmental Satellites System. First launch expected 2013 at the earliest.
- CRYOSAT - The SIRAL altimeter (Synthetic aperture interferometric altimeter) designed for the Cryosat mission (planned launch 2005) should also be mentioned, although this is an ice monitoring mission. This makes use of interferometric techniques and uses the reflected doppler spectrum to sub-sample the echo, and can provide measurements at along track resolution of better than 1 km.

## 4.2 Altimeter Capabilities

Table 4.1 reviews the capabilities of various existing and proposed altimeter 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. Sea surface height accuracy is for single pass 1 Hz data (this includes errors due to orbit, troposphere, ionosphere and EM bias corrections, and range noise). Sources of information for these estimates (in addition to the Reports from WP2, WP3, and WP4) are given in the reference list at the end of this report.

## 4.3 Issues and Technical Solutions

Issues to be addressed include

- *Range Accuracy*  
Corrections (ionosphere, troposphere, sea-state bias).
- *Orbits and Tracking*  
Accurate knowledge of orbits - particularly for micro-satellites.  
Selecting best orbits to meet mission goals.
- *Sea State*  
Can the requirements for new wave measurements (period, directional spectra) be satisfied by developments to “standard” altimeters, or do they require specific instrumentation.  
Improve accuracy and reliability of measurements under severe conditions.
- *Sampling Regimes*  
Which sampling regimes are preferred for different applications?

	Parameter	Accuracy	Range of valid data	Spatial Res 1 day /climatol.	Comments
JASON (IGDR) <sup>1</sup>	SSH	4 cm	0-15m	1350 km/ 2° x 2°	
	H <sub>s</sub>	0.25 m	0-15ms <sup>-1</sup>		
	U <sub>10</sub>	1.5 ms <sup>-1</sup>	4-10 s		
	T <sub>z</sub>	0.5s	Not Available	Not Available	
	Dirn spectra, separate wind sea/swell				
	□□ <sub>0</sub> <sup>2</sup> (various applications)	0.1 dB		1350 km/ 2° x 2°	
GFO	SSH	6.5 cm <sup>3</sup>	as JASON	1350km / 2° x 2°	Single frequency, so no □□ <sub>0</sub> parameters.
	H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub> (not □□ <sub>0</sub> )	as JASON	as JASON		
JASON & TOPEX & ENVISAT / ERS-2 & GFO	SSH	4 –6.5 cm	as JASON	~350km <sup>4</sup> / 1° x 1°	4 <sup>4</sup> satellite sampling available <i>now</i> (from Sept. 2002 onwards)
	H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub> (also □□ <sub>0</sub> for JAS, TOP, & ENV)	as JASON	as JASON		
SIRAL	SSH, H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub> & □□ <sub>0</sub>	as JASON	as JASON	as JASON High resolution along track (< 1km)	Possibility to derive other sea state parameters
Swath altimetry	SSH	4-10 cm? (variable across swath)	as JASON	20km in 10 days	100km dual sided swath
	H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub> & □□ <sub>0</sub> (only at nadir)	as JASON (only at nadir)	as JASON	1350 km/ 2° x 2°	Sea state measurements only given at nadir
GANDER - "Basic" Ku altimeter Constellation (no radiometer)	SSH	Alt requires modification for range measurements	as JASON	3 sats ~350 km / daily	Single frequency, so no □□ <sub>0</sub> parameters.
	H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub> (not □□ <sub>0</sub> )	Original design specification 0.5 m, 2 ms <sup>-1</sup>		6 sats ~350 km / 12 hours	
AltiKa Constellation	SSH	5.5 cm <sup>5</sup>	as JASON	3 sats: ~350 km / 24 hours	Single frequency, so no □□ <sub>0</sub> parameters.
	H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub> (not □□ <sub>0</sub> )	Original design specification 0.5 m, 2 ms <sup>-1</sup>		6 sats: ~350 km / 12 hours	Ka less attenuated by ionosphere than Ku (but more attenuated by rain )
				~5 km footprint	
SWIMSAT	SSH	6 cm	Nadir – as JASON	Nadir – as JASON.	A single frequency Ku band nadir radar plus a rotating wave measuring real aperture radar. 100 km dual sided swath
	H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub> (not □□ <sub>0</sub> )	Nadir – as JASON	Nadir – as JASON	It may be possible to estimate H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub> off-Nadir.	
	Directional spectra	15° direction 10% wavelength		50-90km cells, 100km res. after 7 days	
	Separate wind sea/swell, long wave steepness	Possible			
WITTEX <sup>6</sup>	SSH	4 cm	as JASON	Various high res. along track (< 1 km)	Tracks may not be evenly separated.
	H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub> (not □□ <sub>0</sub> )	as JASON	as JASON		
GPS reflectometry	SSH	6cm after 10days <sup>7</sup>		estimated average track separation of 75 km over 1 day.	Feasibility under study, not available until 2010+.
	H <sub>s</sub> , U <sub>10</sub> , T <sub>z</sub>	To be determined			No □□ <sub>0</sub> parameters.

**Table 4.1 Measurement capabilities of existing and proposed missions.**

<sup>1</sup> The near real time data set (OSDR) will have lower accuracies.

<sup>2</sup> Various parameters derived from □□<sub>0</sub>, mostly experimental, and accuracy yet to be verified.

<sup>3</sup> Assumes a 5 cm orbit accuracy and 3 cm range noise.

<sup>4</sup> ERS-2 and ENVISAT effectively sample the same ocean signal (on the same ground track 30 minutes apart).

<sup>5</sup> Assumes a 5 cm orbit accuracy and 0.8 cm range noise.

<sup>6</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 provided 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).

<sup>7</sup> Averages of a number of measurements over a period of days may be required to bring down the errors.

#### 4.3.1 Accuracy of Range Measurements

##### Corrections

Wet troposphere and ionospheric corrections are generally associated with medium and large scale signals. However, under certain conditions and locations these sources of range delay can exhibit significant small scale variability (for instance close to coasts – for the wet troposphere, and at higher latitudes during ionospheric storms for the ionosphere.) Ideally the associated errors would be corrected by direct measurements made by dedicated instrumentation (radiometer, dual frequency). The subject deserves, however, to be revisited since most of the studies date from the GEOSAT period (1985-1990). Currently, the estimated the range error associated with (corrected) wet troposphere delay is 1.7 cm rms.

Geosat, Geosat Follow-On, ERS-1 and ERS-2 are/were single frequency altimeters, and so models are used to estimate a correction for ionospheric delay. Scharroo (2002) estimates this is the source of an additional 0.5 cm rms error (i.e. ionospheric associated range error of 1.0 cm rather than 0.5 cm).

Studies should be undertaken, in particular, to quantify the degradation of results for an altimeter mission without a radiometer on board (given continuous improvements of ECMWF wet tropospheric corrections).

#### 4.3.2 Orbits and Tracking

##### Tracking systems

Future high-accuracy altimeter satellites should carry either a GPS/Galileo or DORIS receiver for high-accuracy, near continuous tracking. In addition, a laser retroreflector is required for several purposes: for additional high-accuracy tracking, for validation of the radiometric tracking, for calibration of the altimetric range, and as a fail-safe backup tracking device,

The TOPEX/Poseidon and Jason missions have proven that each of the three available tracking devices (SLR, DORIS and GPS) adds unique valuable information to the computed orbits and to the improvement of force and measurement models. It is therefore recommended to take this combination into consideration for the follow-on missions of Jason and Envisat as well.

##### Cross-Overs with other Altimeters

For missions which have to rely only on SLR measurements for orbit determination, differences in sea-surface height at crossover points provide a powerful technique to reduce orbit error. A development of this technique is the use of dual-satellite crossovers. For example, radial orbit errors of a satellite such as ERS-1 or ERS-2 can be corrected by minimizing the sea-surface height differences between that satellite and TOPEX/Poseidon, under the assumption that the TOPEX/Poseidon orbit is much more accurate.

In the case that a GANDER-type constellation is able to provide accurate height measurements, the dual cross-over technique could be used to save costs on other more expensive orbit tracking solutions (DORIS, GPS). Presentations made to the GAMBLE workshop indicated that 5 cm radial orbit accuracy could be achieved through the use of dual crossovers even if the original orbits may be 50-100 cm in error. In this case the fitting of a laser retro-reflector should be a minimum, but perhaps sufficient, enhancement to the GANDER platform.

If real-time orbits are required, the DORIS/DIODE navigator system is a flight-proven technology. Onboard orbit determination at the same precision using GPS is more difficult, because of the need for auxiliary information. However, this might also become possible in the near future.

### **Orbit Choice**

The final recommendations concerning orbit choice shall be made under GAMBLE Work Package 8: Constellation optimization. At this stage, the following suggestions can be made:

In order to obtain multi-decadal time-series of altimetry data over the same ground tracks, the orbit choices of both TOPEX/Poseidon/Jason and ERS- 1/ERS-2/Envisat must be adopted for their follow-on missions. Solar activity will be at a minimum in its 11-year period around 2006. Still, if GRACE models have eliminated the gravity-induced radial orbit error, drag perturbations will likely remain a large error source at lower altitudes. The choice of a high altitude orbit is recommended.

Higher orbits are in theory preferable as the satellites experience less drag and orbits can be more accurately modelled. However, the cost of a higher orbit is the increased power required by altimeter. This may be an issue for microsatellite altimeters, where power may be limited. In addition, a higher orbit would imply a greater protection against solar radiation would be required – in turn implying a consequent increase in satellite mass.

### **Orbit Maintenance / repeatability**

It is anticipated that all the proposed missions can at least match the ENVISAT orbit repeatability specifications ( $\pm 2$ km of nominal orbit ) without modification. The specification for JASON is  $\pm 1$  km). There is a trade off to be determined between frequency of orbit manoeuvres, and the need to have long stable orbits for orbit calculations.

#### *4.3.3 Sea State*

##### **Wave Period**

New wave period algorithms are being developed. They promise an accuracy of  $\sim 0.5$  s, though further testing is required.

##### **Directional Wave Spectra / Separate wind sea /swell information**

Directional wave spectra (and separate wind sea swell information) can be provided only by more sophisticated instrumentation, capable of taking multiple looks at the same patch of ocean from a full range of angles. This can only realistically be achieved through synthetic or real aperture radar operations.

##### **Severe Conditions**

Further studies are required to develop improved algorithms and verify the accuracy of altimeter wave and wind measurements in extreme conditions. This may involve case studies of individual well monitored events.

#### *4.3.4 Sampling Regimes*

Studies investigating the effectiveness of different sampling strategies for monitoring mesoscale sea surface height features (reported in WP2) have indicated that the sampling provided by evenly spaced ground tracks (achieved through “interleaving” orbits of different missions) is to be preferred to that from more closely spaced parallel tracks (e.g.  $0.5^\circ$  proposed to provide continuous across track slope and so 2-D geostrophic velocity).

Intuitively the same result may be expected to hold for sea state applications. Two data sets on parallel tracks separated by 50km can be expected to contain highly correlated information, and so would provide less uncorrelated data (and so a smaller volume of independent sea state information) than would tracks separated by (say) 200km.

However, further simulations are required to provide a rigorous assessment of the relative benefits of different sampling scenarios offered by e.g. swath altimetry and microsatellite constellations, before one is adopted in preference to the other.

#### 4.4 Summary

Technical solutions exist to address many of the issues raised. Some solutions are relatively straight forward and could be easily applied, for instance the use of dual satellite cross-overs to improve orbit accuracy. Others have significant associated costs, indeed to satisfy some requirements would require specific missions.

- *Range corrections* – Further studies are required to investigate errors associated with using modelled wet troposphere corrections. The use of modelled ionospheric corrections has proved a satisfactory solution for single frequency altimeters, especially when using Ka band.
- *Orbit tracking* – Dual satellite cross-overs can be used to generate satisfactory precise orbits (5 cm radial accuracy). If real time orbits are required, DORIS seems a good option.
- *Orbit Choice* – There are conflicting requirements between higher altitude giving more accurate orbits, but also requiring more power from the altimeter.
- *Wave direction, Wave spectra, Separate wind sea / swell measurements* – Requires specific wave measuring instrumentation – most probably on a specific wave measuring mission
- *Wave period, Wave/wind measurements under severe conditions* – New / improved algorithms should be developed, as well as appropriate techniques for merging different sets of data into models which will improve our capacity of detecting and forecasting such events.
- *Improving Sampling* – What are relative benefits of different techniques by which sampling can be improved (swath measurements, constellations of microsatellites)? Further simulations are required to identify preferred sampling regimes for different applications.
- *Maturity of Technologies* - On what time scale will GPS reflectometry provide a practical measuring capability?

Many of these issues will be further addressed within GAMBLE. WP7 will identify recommended themes for further research, WP8 will assess the relative benefits of a number of possible mission scenarios, with a view to identifying satellite combinations preferred for specified mission aims.

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