GAMBLE
WP2 –Scientific/Technical theme 1 – sea surface height error budgets, and recommendations for future missions

Summary Report
December 2002

1. Introduction

This is a summary of the interim report for GAMBLE WP2 (Sea Surface Height), and provides an overview of information that will be presented in the final report. The objective of the final report is to present a summary of understanding of future requirements for altimeter sea surface height data. What are the space/time sampling and error budget requirements for the different scientific and operational applications?

WP2 contributions have been gained from a wide variety of sources (see appendix). A GAMBLE workshop was held in Delft in November 2002 where many of the key issues were debated.

Until the final report is completed (due in April 2003) readers who desire further detail are directed to the WP2 interim report and Delft Workshop submissions.

2. Sea Level Measurement Issues

Mean Dynamic Topography

The mean dynamic topography <□> can be obtained from the difference between an altimeter Mean Sea Surface (MSS) and a geoid. To get a precise estimation of instantaneous absolute dynamic topography, <□> must be known with a resolution of 100-200 km and an accuracy of a few cm. 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.

Mapping and merging of multiple altimeter missions

Merging of multi-satellite altimeter data sets is required to map the mesoscale variability. This requires homogeneous and inter-calibrated data sets. An effective methodology is to use the most precise mission (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.

3. Sea Level Measurement Requirements

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.

Data Assimilation Perspective

Data assimilation experiments have been conducted to examine how the ocean circulation can be identified from multi-satellite configurations. A dynamical data assimilation scheme can interpolate data in space and time, taking the non-linear dynamics of mid-latitude oceans into account and estimating data fields at the surface and in the deep ocean.

The comparison between error statistics calculated for various scenarios (time offset only, space offset only, space/time offset, parallel flights) 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 be better than other assimilation periods (intervals of 1, 3, 10 and 20 days have been tested).
- 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° 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 <u>and</u> 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).

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.

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. 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.

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.

4. Summary of SSH requirements and recommendations

Based on this overview and on GAMBLE workshop discussions, the following requirements can be made for future altimeter missions (Table 1 also provides an overview of *indicative* measurement requirements – but please note the results of the studies referred to in the summary text)

1. <u>Minimum</u> requirement

- Continue the Jason series for long-term, precise altimeter system
- <u>Fly a post-ENVISAT mission</u> to continue the Jason-1+ENVISAT configuration after 2006.

2. Sampling Requirements for Mescoscale Features and Tides

Higher sampling in space than provided by the above minimum requirement would be necessary to monitor these features. Possible options for *additional* missions are:

- A “constellation” of altimeter (micro)satellites.
- A Wide Swath Ocean altimeter

Later work in GAMBLE will consider the relative merits of these two approaches.

Table 1. *Indicative* Measurement Requirements for Applications of Sea Surface Topography

Application	Parameter	Indicative Measurement Requirements			
		Spatial Res	Time Res	Latency	Accuracy
Mesoscale variability	Sea surface topography	50 km	10 day	3 day	2-4 cm
Large scale variability	Sea surface topography	100 km	10 day	3 day	2 cm
Global mean sea level change	Sea surface topography	100 km	10 day	10 day	0.5 mm yr^{-1}
ENSO – seasonal to interann. prediction	Sea surface topography	200 km	5 day	5 day	4 cm
Tides (Sun synchronous)	Tidal constants – sea surface height	100 km	non sun synchronous 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

Appendix – Contributors to the GAMBLE Sea Surface Height Work Package

Contributor	Topic
P.Y. Le Traon (CLS, Toulouse, France)	Mescoscale features, model and assimilation studies, GODAE, (GAMBLE WP2 Leader)
Y. Ménard, P. Vincent (CNES, Toulouse, France)	TOPEX Poseidon, JASON technical and scientific studies. AltiKa, Cryosat.
E Thouvenot (CNES)	Swath Altimetry
R. Scharroo (DEOS Tu Delft, The Netherlands)	Precise Orbits, data processing. altimeter expertise.
P. Challenor (SOC, Southampton, UK)	Feature modelling
P Bahurel et al. (SHOM, Toulouse)	Operational ocean models (Mercator) data assimilation
Laurent Phallippou (ALCATEL Space, Toulouse)	New altimeter technology
C Le Provost (LEGOS, Toulouse)	Tidal studies
P Woodworth (POL, Bidston, UK)	Tidal Studies, Coastal Applications
J Verron et al. (LEGI, France)	Assimilation into ocean Models, simulations of present and future missions.
D Muller (MPI, Germany)	Primitive Equation Modelling of Mescoscale Variability
J. Johannessen (NERSC , Norway)	Operational Oceanography
David Cotton (Satellite Observing Systems, UK	GANDER studies