



GAMBLE

EVRI-CT-2001-20009

SEA SURFACE HEIGHT ERROR BUDGETS AND RECOMMENDATIONS FOR FUTURE MISSISON

GAMBLE WP2

Final Report

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April 15, 2003

1 Introduction

Satellite altimetry has made a unique contribution to the observation and understanding of the global ocean circulation both at large scale and at the mesoscale (see Fu and Chelton, 2001; Le Traon and Morrow, 2001; Picaut and Busalacchi, 2001, for a recent review). The surface dynamic topography as measured by satellite altimetry also provides a strong constraint to estimate and forecast the three-dimensional ocean state through data assimilation. Satellite altimetry is thus considered as one of the most important input data sets of the forthcoming Global Ocean Data Assimilation Experiment (GODAE) and its envisioned scientific and operational applications (The International GODAE Steering Team, 2001).

The objective of the 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 scientific and operational applications of satellite altimetry ?

An overview of sea level measurements from altimetry is first given. We then discuss the main requirements for sea level measurements for climate, mesoscale and operational oceanography applications. The error budget requirement is also discussed, in particular, for the Gander concept (no radiometer on-board, single frequency radar). Specific requirements for coastal and tidal applications are discussed. A summary of main requirements and recommendations is given in the conclusion.

2 Sea level measurements from altimetry

2.1 *Measurement principle*

The principle of altimetry measurement is simple (although the system is complex). The altimeter measures the range from the satellite to the ocean surface by determining the time taken by the radar pulse to travel from the satellite to the ocean surface. Using a precise orbitography system, we can determine the position of the satellite relative to a reference ellipsoid. Combining these two measurements yields an estimation of the sea level relative to a reference ellipsoid. This estimation comprises the geoid (an equipotential of the earth gravity field to which a motionless ocean would exactly conform) and the ocean dynamic topography. The geoid can vary as much as 100 m for only 1 m for the dynamic topography (the parameter of interest here).

The satellite repeats exactly the same ground track every cycle. For T/P and Jason-1, this cycle is 10 days, for ERS-1/2 multi-disciplinary phase and for ENVISAT it is 35 days, and for GEOSAT and GFO 17 days. Every cycle, it thus observes the same geoid signal (which does not vary over time) and the dynamic topography (which varies over time).

2.2 *Signal extraction*

The altimetric observation of the sea surface topography S can be described by $S = N + \eta + \varepsilon$ where N is the geoid, η the dynamic topography and ε the measurement errors (orbit error, propagation effects in the troposphere and ionosphere, tides, electromagnetic bias, inverse barometer effect, altimeter measurement noise).

Present geoids generally are not accurate enough to estimate the absolute dynamic topography η globally, except at very long wavelengths (> 2000 km) (see next section). The variable part of the dynamic topography η' ($\eta' = \eta - \langle \eta \rangle$) (or Sea Level Anomaly, hereafter SLA) is, however, easily extracted since no prior knowledge of the geoid height is needed. The most commonly used method is the so-called repeat track method (collinear analysis), suitable for satellites whose orbits repeat their ground tracks (to within ± 1 km) at regular intervals. For a given track, the variable part of the signal is thus obtained by removing the mean profile, which contains the geoid and the quasi-permanent dynamic topography, from each profile.

2.3 *Measurement errors*

Altimeter measurements of sea surface topography are affected by a large number of errors. These include errors on the range measurement due to propagation effects in the troposphere and ionosphere; electromagnetic bias; errors due to inaccurate ocean and terrestrial tide models; cross-track geoid errors, and inverse barometer effect. Most are large-scale, and do not limit the use of altimetry for ocean mesoscale studies. For studies of large-scale oceanic variability, most of these corrections must be taken into account, however, since they can significantly contaminate the oceanic signal. Some of these errors can be corrected with dedicated instrumentation (dual-frequency altimeter for ionospheric corrections, microwave radiometer for wet tropospheric corrections). Electromagnetic bias can be deduced by analyzing altimeter data but it remains a significant contribution to the total error budget for precise altimeter missions such as the T/P and Jason series.

The inverse barometer effect is actually a large, real oceanic signal which reflects the response of the sea level to changes in atmospheric pressure. The static response assumes a non-dynamic adjustment of the ocean due to atmospheric pressure (about 1 cm for 1 mb change in atmospheric pressure). Recent numerical and empirical studies suggest that the ocean generally responds as an inverted barometer except over very short time scales and in semi-enclosed seas. This correction should thus be applied when studying the dynamic response of the ocean. A major research area today is to derive more precise corrections based on barotropic models (Tierney et al., 2000; Hiroshi et al., 2001); these corrections that could also include wind effects would allow us to remove the large scale high frequency signals that are aliased in altimeter data. Another complementary approach is to extract them from the altimeter data themselves (Schaeffer et al., 2002).

The tidal signal is the most important variable signal in altimetric data. This signal is only partially corrected using global ocean tide models. The residual errors are then aliased at certain periods depending on the repeat-period of the satellite. The satellite repeat-period should be chosen to avoid aliasing near dominant oceanic periods (e.g. annual or semi-annual periods). The M2 tide is thus aliased near 60 days for T/P. This is much less of a problem than the GEOSAT 317-day aliasing period which can cause major problems for the interpretation of altimetric signals. More accurate global tide models based on hydrodynamic models and/or altimeter data are now available and used. Still, aliasing may occur and this has to be taken into account when interpreting the data. Note also that the tidal aliasing can come and go, i.e. that tidal 'constants' are not constant (due to internal tides or interactions with the weather).

Last, but not least, comes the orbit error. This error is caused by imperfect knowledge of the spacecraft position in the radial direction. It is actually the largest error on altimetric

measurements of sea surface topography. It depends on the quality of the satellite tracking system. For T/P and Jason-1, precise orbit determination is achieved via three distinct tracking systems (DORIS, Laser, GPS) providing almost global coverage of satellite orbits. ENVISAT orbits (thanks to DORIS) are likely to (almost) reach a similar accuracy. The radial orbit error obtained is thus accurate to about 2 cm, compared to 5-10 cm accuracy for the most recent GEOSAT, GEOSAT Follow On and ERS-1/2 orbits available. Orbit errors are long-wavelength errors (about 40 000 km) that can be reduced by analyzing the altimeter data. Global crossover minimization can thus be used to estimate the orbit error without removing too much of the large-scale oceanic signal (e.g. Le Traon and Ogor, 1998). More generally using inverse techniques, the orbit error signal could be obtained through a global adjustment taking into account not only the spatial but also the temporal characteristics of the orbit error and oceanic signal (Le Traon et al., 1998).

2.4 Mean dynamic topography

Satellite altimetry provides Sea Level Anomaly ($SLA = \eta - \langle \eta \rangle$) with good accuracy (a few cm) and high resolution. In practice the best procedure to get an estimation of the absolute dynamic topography ($\eta = \langle \eta \rangle + \eta'$) from altimetry is :

- Estimate a mean dynamic topography (MDT) ($\langle \eta \rangle$). The mean should correspond to a mean over a precise time period determined by the sea level anomaly calculation (typically several years or the duration of an altimetric mission).
- Add this MDT to sea level anomaly (η') derived from repeat-track analysis.

The mean dynamic topography $\langle \eta \rangle$ 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, $\langle \eta \rangle$ must be known with a resolution of 100-200 km and an accuracy of a few cm (e.g. Le Provost et al., 1999). It must also correspond to a specified time period.

Geoid models currently available to the oceanographic community are not sufficiently accurate to provide a useful estimation of mean dynamic topography. Typical accuracy is of 10 to 20 cm rms for a spherical harmonic development of the order of 20 (i.e. wavelengths larger than 2000 km) (e.g. Lemoine et al., 1998). This is of the order or larger than the existing ocean models or in-situ data derived MDT accuracy. In addition, most of these geoids are not independent from altimetric data and have absorbed part of the oceanic signal. In particular, they contain the oceanic signal that is above the cut-off dynamic topography expansion degree used in the geoid model representation. New gravity missions (CHAMP and mainly GRACE and GOCE) will dramatically improve the situation. When GOCE is flown (2006), we should thus be able to get an independent estimation of the geoid with an accuracy of 1-2 cm rms for scales larger than 100 km. Meanwhile, the only solution is to estimate the mean dynamic topography from 1/ in-situ data, 2/ from model data, 3/ from exiting global geoids and from the combination of 1/, 2/, and 3/ through data assimilation or inverse modeling. The error on the resulting mean dynamic topography is typically of 5 to 10 cm rms; this should improve in the future with the Argo global array of profiling floats and the development of improved data assimilation methodologies as planned by GODAE.

2.5 Mapping and merging of multiple altimeter missions

The mapping can be done using optimal interpolation methods which use an a priori knowledge of the space and time scales of the ocean signal. When data are mapped onto a

regular space/time grid using such interpolation methods, the along-track long wavelength errors (or high-frequency ocean signals) can induce artificial cross-track gradient at smaller scales and thus spurious eddy signals (Le Traon et al., 1998). The effect is particularly important in low eddy energy regions and when several altimeter data sets are merged. Along-track long wavelength errors can also lead to other serious problems. A well-known example comes from GEOSAT for which errors in the tide correction were aliased to produce spurious Rossby wave like signals in the mapped data (Chelton and Schlax, 1994). To minimize these problems, the mapping method should either take into account an along-track long wavelength error (i.e. a correlated noise due to orbit, tidal or inverse barometer residual errors) or the long wavelength errors should be removed before the mapping (Le Traon et al., 1998).

The merging of multi-satellite altimeter data sets is generally necessary to map the mesoscale variability. This is not an easy task. To merge multi-satellite altimetric missions, it is first necessary to have homogeneous and inter-calibrated data sets. Homogeneous means that same geopotential model and reference systems for the orbit and same (as far as possible) instrumental and geophysical corrections should be used (e.g. same tidal models, same meteorological models, etc). Inter-calibrated means that relative biases and drifts must be corrected and also that the orbit error must be reduced. An effective methodology is to use the most precise mission (T/P, Jason-1) as a reference for the other satellites (Le Traon et al., 1995; Le Traon and Ogor, 1998). 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 rms (see Le Traon et al., 1995).

When altimetric data have been homogenized and inter-calibrated, the next step is to extract the SLA for the different missions. It is preferable that the SLAs from different missions are calculated relative to the same ocean mean using a common reference surface (e.g. either a very precise mean sea surface or mean profiles consistent between the different missions). The final step is to merge the SLAs from the different missions via a mapping or assimilation technique. Ducet et al. (2000) provide a detailed analysis of the merging of T/P and ERS-1/2 over a five year period, in particular to quantify the contribution of merging for the description of the ocean mesoscale circulation.

3 Requirements for sea level measurements

3.1 Main requirements for climate and mesoscale applications

The agreed main requirement for future altimeter missions is that at least two (and preferably three) altimeter missions with one very precise long-term altimeter system are needed (e.g. Koblinsky et al., 1992). The long-term altimeter system is supposed to provide the low frequency and large scale climatic signals and to provide a reference for the other altimeter missions. It requires a series of very precise (centimeter level) and inter-calibrated missions. TOPEX/POSEIDON and later on the Jason series have been designed to meet these objectives. The role of the other missions is to provide the higher wavenumbers and frequencies and, in particular, the mesoscale signal (see Le Traon and Morrow, 2001 for a recent review), 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 they do not impact significantly the mesoscale signal.

Such a requirement for future altimeter missions is partly based on several studies on the sampling characteristics of single and multiple altimeter missions. Le Traon and Dibarboure (1999) (hereafter LD99), Le Traon et al. (2001) (hereafter LDD01) and Le Traon and Dibarboure (2002) (hereafter LD02) have, in particular, quantified the contribution of single and multiple altimeter missions for the mapping of mesoscale variability. In the following section, we summarise the main findings of these studies. These studies are then used to provide refined requirements for future altimetry missions.

3.2 Summary of LDD99, LDD01 and LD02 studies

LD99 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. Their main results are as follows :

- There is a large improvement in sea level mapping when two satellites are included. For example, compared to T/P alone, the combination of T/P and ERS has a mean mapping error reduced by a factor of 4 and a standard deviation reduced by a factor of 5.
- The velocity field mapping is more demanding in terms of sampling. The U and V mean mapping errors are two to four 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.

LDD01 have shown that sea level mapping errors were larger than the ones derived from LD99 formal error analysis (by a factor of 1.5 to 2). This is mainly due to high frequency signals (periods below 20 days). In areas with large mesoscale variability, these signals represent 5 to 10% of the total sea level variance (see also Minster and Gennero, 1995) and are associated with high wavenumbers. They account for 15 to 20 % of the total velocity variance. In shallow and high latitude regions, these high frequency signals account for up to 30-40% of the total sea level and velocity variance; there, part of these signals correspond to large scale barotropic motions.

To better analyze the impact of the high frequency signals on the sea level and velocity mapping, LD02 systematically computed for all analyzed configurations the mapping errors on the instantaneous fields and on 10-day averaged fields. Results for the different configurations are summarized in table 1.

| | H | U | V |
|---------------------------|-----------|------------|-------------|
| T/P + ERS | 7.2 / 3.2 | 26.3 / 9.9 | 35.0 / 13.5 |
| T/P + Jason-1 | 5.0 / 2.0 | 21.6 / 7.4 | 24.2 / 8.9 |
| T/P+Jason-1+ENVISAT | 4.2 / 1.8 | 19.6 / 6.9 | 22.3 / 8.3 |
| Three interleaved Jason-1 | 3.7 / 1.5 | 17.9 / 5.3 | 20.6 / 6.3 |
| Four interleaved Jason-1 | 3.4 / 1.0 | 16.9 / 3.9 | 20.1 / 4.5 |

Table 1: Sea Level (H), zonal (U) and meridional (V) velocity mean mapping errors for regions with rms sea level variability larger than 15 cm. Errors expressed in percentage of the mean sea level and velocity variance. They are given both for “instantaneous” and 10-day averaged signal mapping.

The main finding of these studies is thus the role of high frequency signals. Since these signals cannot be resolved with any of the analyzed configurations, they strongly limit the mapping accuracy. This explains, in particular, why the velocity mapping errors remain larger than about 15-20% of the signal variance even for the four satellite configurations. The aliasing of high frequency signals is also a serious issue (see discussion in LD02).

The requirements presented in this section thus do not take into account model contribution as a dynamic interpolator of sparse measurements. They take, however, into account an a priori knowledge of the space and time scales of the mesoscale variability as well as the noise characteristics. They can be considered as a robust estimation of the contribution of the data themselves.

3.3 Data assimilation perspective

The best use of altimetry data will be when they are assimilated with in-situ and other remote sensing data into global eddy resolving models (and nested shelf/coastal models). Data assimilation is a powerful means for a dynamical interpolation of data and may be used to assess the spatial and temporal requirements of a satellite system (e.g. using a model forecast as an a priori knowledge instead of climatology). Demonstrating the value of data assimilation is the central objective of GODAE, the Global Ocean Data Assimilation Experiment (GODAE IGST, 2000). Providing general requirements from a data assimilation perspective is, however, today a difficult issue. Since first steps in these directions (e. g. Kindle, 1986; Verron, 1990; Verron et al., 1996), many progresses have been made, and much more consistent results are today seen regardless of the data assimilation techniques or/and the numerical models used.

Here, data assimilation experiments have been conducted to examine how the ocean circulation can be identified from multi-satellite configurations. A dynamical data assimilation scheme has the advantage to interpolate the data in space and time, taking the non-linear dynamics of mid-latitude oceans into account and estimating data fields of not only at the surface but also in the deep ocean.

The assimilation algorithm that has been used in the framework of the project is based on the SEEK (Singular Evolutive Extended Kalman) filters, a family of reduced order Kalman filters in which the estimation error is expressed in terms of a sub-space (or, simplification operator) that evolves with time according to the ocean dynamics (Pham et al., 1999; Brasseur et al., 1999; Verron et al., 2000). The model configuration is that of a simplified double-gyre system driven by surface wind, which includes a western boundary current zonally propagating across the ocean basin and generating mesoscale eddies. This mimics with a very good statistical similarity the eddy-active general circulation of the ocean in the mid-latitudes, such as the Gulf-Stream system for example. The general strategy of the numerical experiments that have been conducted, is that of the Observing System Simulation Experiments (OSSE) quite familiar in meteorology. Twin assimilation experiments are realized using several observing systems based on one, two and three altimeters flying simultaneously. The assumed satellite mission parameters are those of Topex/Poseidon, Jason, ERS and AltiKa. The data collected along tracks are pooled together at regular interval (typically a few days) to perform the analyses synoptically. Observation errors consistent with those of real data are added as a random signal to the pseudo-observations.

The comparison between error statistics calculated for the various phasing scenarios (time offset only, space offset only, space/time offset, parallel flights) and other mission parameters such as altitude, allows us to draw a number of conclusions:

- The addition of a second altimeter improves the reconstruction of the mesoscale circulation by an amount comprised between 18% and 28% depending of the mission parameters. (For example, flying T/P and Jason1 with a space offset gives better result than flying T/P and AltiKa.) The addition of a third satellite makes an additional improvement which is between 10% and 16% depending again of the flight configuration.
- A three-day interval between successive analyses appears to be better than smaller or longer assimilation periods (assimilation periods of one, three, ten and twenty days have been tested).
- The observing scenarios in favor of the spatial sampling (interleaved tracks, or space offset) compete very well with those in favor of the temporal sampling (time offset) ; by contrast , the case of two satellites flying in parallel (with an offset of 0.5 deg between tracks) seems less effective.
- The “best” observing scheme may be different if the variable of interest is related to the surface circulation, or to the deep fields.
- The dynamical modes intensified at intermediate depth require more than two satellites to be determined without ambiguity ; in a dynamical context, the lack of information concerning these modes might affect the three-dimensional flow field globally, and therefore limit the quality of the estimation near the surface as well.
- In a three satellite constellation at given inclination, the increase of altitude has a negative effect on the performances.

Overall, the results using three satellites confirm other studies indicating that a third satellite seems necessary to control the mesoscale features satisfactorily. But the choice of the optimal configuration is not trivial. The assimilation experiments are being extended over longer periods to refine these conclusions and to examine all the dynamical understanding behind the transfer the surface information at depth by adaptive accumulation of information.

3.4 Refined requirements for sea level measurements

From these and other (e.g. Jacobs, 1999; Jacobs et al., 2001) studies, we can derive the following refined requirements for mesoscale applications :

1. The minimum requirement will be to continue flying a two satellite configuration (after Jason-1 and ENVISAT) with one long-term precise mission (Jason series). A two-satellite configuration provides already a good representation of the mesoscale variability (sea level mapping errors of the order of 10% of the signal variance). It cannot provide, however, a sufficiently accurate estimation of the velocity field (e.g. below 10% of the signal variance) and will not allow us to track small eddies (e.g. diameter below 100/150km).
2. This can be very significantly improved with an optimized three satellite configuration. Compared to Jason-1 and ENVISAT (or T/P+ERS), these 3-satellite configurations should allow a reduction of sea level and velocity mapping errors by a factor of about 2 to 3. It is also likely to partly resolve the large scale high frequency barotropic motions (e.g. Tierney et al., 2000). Possible configurations could be a TP/Jason orbit with interleaved ground-tracks (which would yield a track separation of about 100 km at the equator and a

repeat period of 10 days) or an ENVISAT/ERS orbit with the same ERS/ENVISAT ground tracks (which would yield a track separation of about 80 km at the equator and a repeat period of 35/3 days). These two configurations have similar performances (Le Traon and Dibarboure, 2001). The TP/Jason scenario is slightly better for mapping the meridional velocity field but the ERS/ENVISAT scenario has the advantage of providing measurements at high latitudes; tidal aliasing is also not the same and only the TP/Jason orbit is optimized to reduce tidal aliasing problems (in the future, however, this should no more be an important selection criterion as tidal solutions are now very accurate; in addition, if –as required- a Jason type satellite continues to provide a long-term reference, the impact of tidal aliasing for the other missions is no more a serious problem).

3. To further improve the mapping (which is needed for some of the envisioned 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. This is likely to require constellation of more than six satellites and/or use different concepts for satellite altimetry (wide swath techniques).

3.5 Measurement errors

This analysis only deals with sampling requirements. As far as measurement errors are concerned, the following requirements can be made :

1. Assuming the Jason series continue to provide a long term reference, the 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.
2. Typical amplitude of mesoscale signal is 4 to 8 cm rms in the open ocean and 20 to 40 cm rms in the high eddy energy regions. 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 (i.e sea level gradients) and a detailed analysis of the eddy structure in the along-track direction.
3. Wet troposphere and ionospheric corrections are associated to medium and large scale signals. They should be corrected for with a dedicated instrumentation (radiometer, dual frequency). The subject deserves, however, to be revisited since most of the studies date from the GEOSAT period (1985-1990). Studies could 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).

3.6 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. Solar tides have two origins: astronomical and radiational (forced by the atmosphere). They very significantly contribute to the sea level variability: the main solar S2 is about half the contribution of the major lunar component M2, and the diurnal solar radiational component S1 is also significant. Besides, these radiational contributions have a time variable component, linked to the variability of the atmospheric forcing (pressure and wind). They cannot thus be ignored. S2 is now better known after the recent studies on T/P and ERS data analysis, the progress in hydrodynamic modelling and data assimilation (Le Provost, 2001 for a review). For S2, including the astronomical and the climatological

constant part of the radiational contribution, the accuracy of the new available solutions is at the cm level over the deep ocean. But these solutions need to be improved over coastal and shelf regions where their accuracy is only of the order of 20 cm. Complementary studies need thus to be done for the coastal areas, including satellite altimetry observation with higher space resolution on non helio-synchronous orbit.

Concerning the variable part of the solar radiational components (S2, S1, and their longer term modulations including semi-annual and annual), they were primarily included up to now in the IB correction. An alternative to the IB correction has been developed recently, based on barotropic hydrodynamic models of the global ocean, forced by pressure and wind fields. These new « IB corrections » are under evaluation: it appears that their use allow to significantly reduce the altimeter variance in T/P and Jason data, especially over the continental shelves and coastal areas. The use of these model outputs can thus be a solution to take into account these contributions in the analysis of sea surface topography measured by altimeters on heliosynchronous orbit.

3.7 Gander specific issues

Gander was originally proposed as a mission to provide near real time global monitoring of sea-state, primarily for offshore operations. The service specifications were to provide measurements of significant wave height and wind speed, within 200 km of any ocean location once every 6 hours

Accurate sea surface height data were not a mission priority. The mission and satellite specifications were tailored to meet the service requirement, and to provide the mission specification that was most economically feasible. Thus priorities were not to provide the most accurate and reliable data product, but to provide the most economic solution to generate a data product which met the specifications.

Technical and economic feasibility studies ending in the year 2000 established the following baseline specifications:

Mission / Platform

- 10 operational microsattellites deployed in 2 orbital planes.
- Truncated pyramid platform: 0.55m tall; Upper facet: 0.4m x 0.4, Lower facet: 1.0m x 1.0 m
- Micro-Satellite wet mass 85kg,
- 4 Si solar panels delivering 85W peak power.
- Orbit height 650 km, repeating orbit not necessary.
- Orbit determination: Ranging and NORAD, accurate to ~ 5km.
- Orbit maintenance through “OCK”
- Pointing control to $< 0.7^\circ$, pointing knowledge 0.1°

Instrumentation

- Single frequency Ku band radar altimeter (mass < 15 Kg, power < 35 W).
- Pulse limited, Pulse Repetition Frequency 500Hz
- Antenna, 1m diameter, Cassegrain parabolic dish.
- Range resolution +/- 4 cm
- Product averaged over 2 seconds

- Duty Cycle 75%
- No on board radiometer.

Data Handling

- S Band communications: 64 kbs uplink and 64 kbs downlink.
- Product size: 2 Mbit / orbit
- Product latency: 45-100 minutes.

If the GANDER satellites were to be used, in addition, to produce scientifically and operationally useful sea surface height data, then some of the mission specifications imply reduced accuracy in range measurements. Issues are:

Single frequency altimeter – no direct estimates of ionospheric delay.

No planned radiometer - no direct estimates of (wet) troposphere delay.

Orbit maintenance and determination - are NORAD/ranging and “OCK” sufficient?

Orbit height and orbit pattern – Are there preferable options (e.g. repeatable orbit)?

Instrument capability – What is consequence of e.g. 500 Hz PRF?

Some of these issues are discussed in more detail below:

3.7.1 Orbit knowledge

More accurate orbit information is essential. Current specifications would give location to ~5km, a preferred specification for useful range measurement would be < 1 km. Potential modifications are :

Laser Retro reflector

Pros – No power implications, low cost

Cons – May be problems in engaging necessary effort from tracking community – especially for a large number of micro-satellites.

Platform space implications

Comments: Mass ~ 2 kg, platform space OK, cost uncertain. Because of need for commitment from tracking community cannot rely on this for primary source of orbit information. However, would be useful to provide occasional confirmation of orbit.

GPS

Pros – Accurate reliable, internal, orbit measurements. No external effort required.

Cons – Power, volume, mass, data, cost, implications.

Comments: GPS systems which provide orbits to within +/- 15 m (3σ) are available for < 200k€ per installation . Could host 1,2 or 4 antennas on upper surface of GANDER.

Power ~5W, mass ~2kg, extra data rate minimal (<< 1 kbps). Can provide time information to satellite.

DORIS

Pros – Accurate reliable, internal, orbit measurements. Also ionospheric corrections

Cons – Power, volume, data, mass, cost, implications.

Comments: The version of DORIS installed on JASON version requires 27W and is 39kg, and this would not fit on GANDER. A second generation DORIS is being developed with smaller mass and lower power requirements, which may be accommodated on GANDER

platform. Ground station coverage is now effectively global. May need external time information.

Cross-Over Analysis

Analysis of cross-overs with other satellite altimeters (JASON-1, ENVISAT, GFO) would also provide a way of reducing orbit error. Modelling is required to determine what might be achieved by such analysis and what impact that would have on the requirement for extra on-board instrumentation.

Conclusion: GPS or DORIS would be a necessary addition to enable GANDER to make useful topographic measurements. GPS could be accommodated on the GANDER platform, but the power implications need to be investigated. Extra data rate not significant. DORIS only feasible if new DORIS design has much lower power and mass than version installed on JASON. A Laser retro-reflector would be a desirable, rather than necessary addition. There are no power or data rate implications, and one could be accommodated within the existing GANDER basic design.

3.7.2 Orbit Maintenance / repeatability

The original specification did not envisage regular manoeuvres to maintain an accurate and repeatable orbit. : ENVISAT spec. is +/- 2km of nominal orbit, JASON is +/- 1 km. Requirement for more frequent orbit maintenance manoeuvres might require higher fuel load.

Comments: The baseline is to operate the OCK (Orbit Control Kit) package. The capability of this package to maintain microsattellites within specified orbit constraints has been demonstrated. The GANDER platform would have this capability, and no significant extra fuel load is implied.

Conclusion: Existing GANDER design can match requirements without modification through operation of OCK. There is a trade off to be determined between frequency of orbit manoeuvres, and the need to have long stable orbits for orbit calculations.

3.7.3 Orbit Height

The nominal orbit height (650 km) may not be best for height measurements, for instance with regard to ionospheric/ atmospheric corrections, and the need to maintain an accurate and stable orbit.

Potential Modifications – Higher Orbit (~800km)

Pros: Reduced drag, easier to maintain accurate orbit, also more stable orbit

Cons – Altimeter power implications. Platform uplink/downlink budgets

More fuel required to decay orbit at end of life.

Implications for launch

Conclusion: An orbit of ~ 800km would be preferable. However, more work is needed to establish the benefits of higher orbits against cost of increased power required by altimeter.

3.7.4 Ionospheric Corrections

Ionospheric corrections cannot be derived from single frequency altimeter and a micro-satellite platform could not host a dual frequency altimeter. Can sufficiently accurate ionospheric corrections be obtained from models / other satellite data ?

Potential Modifications -DORIS

Pros – Medium accuracy ionospheric corrections , also provides orbit measurement capability.

Cons – Power, mass, volume, data, cost.

Conclusion: Direct GANDER measurements of ionospheric delay are not possible (except with a Ka altimeter). The accuracy of alternative sources of information (models, together with ENVISAT, JASON and GPS) should be investigated.

3.7.5 Atmospheric Corrections

Corrections must be made for wet tropospheric attenuation/delay. On previous altimeters this was achieved by a micro-wave radiometer.

Potential Modifications*Microwave radiometer*

Pros – Accurate reliable, internal, atmospheric corrections

Cons – Power, mass, volume, data, cost

Models

Pros – No power, mass, cost implications

Cons – Corrections not sufficiently accurate?

Comments: Flight proven designs of Microwave radiometers have significant mass and power requirements > 20Kg, > 20W, (plus need for antenna) which could not be accommodated on present GANDER design. However, for AltiKa it is planned to make dual use of the Ka band antenna for both the altimeter and MWR.

Conclusion: If model corrections are insufficiently accurate, and result in unacceptable error, dual use of altimeter antenna should be considered.

3.7.6 Altimeter Range Measurement.

The current altimeter specification is to enable it to provide wind and wave data only. Nominal Pulse repetition frequency is 500Hz. Enhancements may be necessary (pulse rate, processing, waveform fitting, tracking) to the altimeter specification.

Comments: The implications of the proposed specification for the GANDER altimeter require further investigation to establish power and other implications of uprating the design to a range measuring altimeter.

3.7.7 Altimeter Range and waveform Data IO

Data rates are presently defined for wind/wave data, plus some housekeeping and diagnostic data. The provision of range and (especially) waveform data will imply higher data levels

Nominal altimeter/OB computer data rate is currently 2kbps, 1Mbps raw for diagnostics

OB memory requirement is 2 Mbits/orbit

Currently specified minimum Uplink / downlink rate is 64 kbps.

Comments: Downloading extra range data only would not cause any significant increase in data rates or memory requirements. However, if 50Hz averaged waveforms were required extra capacity would be required, as follows:

128 bytes at 50 Hz -> 51.2 kbps (6.4 kbytes / sec) -> 1 Mbps alt to OB computer

60 mins ocean data per orbit -> 23 Mbytes / orbit (~330 Mbytes/day)

Present on board memory is 128 Mbytes (< 6 orbits, 10 hours)

For one ground station, with 4 passes / day at 10 mins (600 s), required downlink rate is:
1.1 Mbps

Conclusion: If range data only are required there are no implications on data rate and storage. If wave form data are required, there may be a need for increased on-board memory, and will be a requirement for improved downlink capabilities. This could be achieved through increased downlink rates, or more frequent downloads (implying more than one primary ground station).

3.7.8 Orbit Specification

An orbit specification which suits operational mapping of large scale, but quickly moving wave fields - requiring satellites evenly spaced over orbit - may not suit the need to map mesoscale (sub 100km), but slower moving ocean topography fields (eddies etc) – which may be better measured by closely spaced orbits.

Conclusion: From orbit acquisition considerations, the fewest possible number of orbit planes is to be preferred. Unless a very strong argument emerges, the specification will remain for GANDERS to be evenly spread on each of 2 orbit-planes.

3.7.9 Pointing accuracy

Presently specified at 0.2° (1σ or 3σ) The effect of mispointing is more severe on σ_0 than on H_s . If mispointing can be restricted to within $\pm 0.2^\circ$ (as for ERS-1/2) then no corrections are necessary. Otherwise, maximum mispointing must be restricted to less than 1.0° , and corrections must be applied to σ_0 and H_s . In this case it is required that estimates of mispointing are generated (to an accuracy of at least 0.1° , if excursions of up to 1.0° are expected), either from on board platform information or from waveform analysis.

Conclusion: No implications for pointing accuracy

3.7.10 On board Clock

Range measurement will require a highly accurate on board clock for time tagging the height data. The baseline GANDER design may not provide a sufficiently accurate USO. GPS may be able to provide a time signal of sufficient accuracy.

3.7.11 Orbit repeat period

The current specification is for a non-synchronous orbit, at $\sim 80^\circ$ inclination, but no repeat interval is specified. There may be exciting possibilities for tidal studies. An exactly repeating orbit (In the range 10-35 days?) is to be preferred to a slowly drifting orbit.

Conclusion: An exactly repeating orbit requirement could in principle be accommodated, though the full implications would have to be investigated.

3.7.12 "High Level" Modification Options

Options of creating more capability within the platform could be:

Higher performing solar panels

The baseline specification employs Silicon panels which will provide ~48 W orbit averaged power. Alternatives are GaAs panels which could provide ~70W orbit averaged power – however the cost is more than four times that of Silicon panels.

Ka band altimeter

Better height resolution, smaller antenna and footprint, smaller power requirements.

35.75 GHz, 480 MHz bandwidth gives high vertical resolution (0.3m)

0.7m antenna. shared by altimeter and radiometer

35 W average operating power, mass < 20 Kg.

These characteristics compare to the GANDER Ku band altimeter (wind/wave only) -

45W average operating power, mass 21 kg,

Antenna, 10kg, 1m diameter

3.8 Specific requirements for coastal applications and tidal studies

Coastal studies concern the circulation over the shelves, from the coast to the shelf break (typically ranging from a few 10 km to a few 100 km off the coasts). In most cases, the onshore-offshore spatial scales are smaller than the alongshore scales. The time scales are also generally shorter than in the deep ocean, and dominated in many regions by tides and high frequency response to meteorological forcing. Non linear physical processes and their coupling generate very specific dynamics. In particular, the presence of the coast, the shallow depths or the fresh water inflows are responsible for this complexity. Application of altimetry in these areas is thus much less developed, linked to these specific difficulties in terms of sampling space and time sampling.

Moreover, altimeter measurement next to the coast is also limited because of technological issues. The altimeter range and the necessary tropospheric correction are contaminated by the presence of continents, so that sea level measurements closer than about 20 km to the coast are today unusable. Presently, the limiting factor is the size of the radiometer footprint, from which the tropospheric correction is calculated. Therefore, coastal altimetry requires specific instrumental specifications not only in terms of sampling but also of footprint reduction.

The scientific issues related to coastal circulation include the processes that create the three-dimensional structure of these circulation, enhancing or inhibiting cross-margin transports, with strong topographic control, and complex interactions with both the low frequency deep ocean circulation on the shelf break, including its mesoscale variability, and the high frequency response to meteorological forcing (wind and pressure), and tides. Examples of particularly energetic coastal systems have been given in a recent report by Strub (2001), describing the presence of complex 2D meandering jets and eddy systems, wind-driven upwelling and downwelling, coastal-trapped waves, etc...

Most of the SSH signal associated with these energetic coastal currents have height differences ranging from 2-5 cm to 10 cm or more. The 1-2 cm precision generally required for future altimeter missions thus provide a good resolution of these signals. Degrading that resolution to 5 cm would make the observation of many coastal features very difficult. But the most demanding constraint results from the temporal resolutions needed to accurately resolve

most of the coastal circulation features: the temporal revisit of a site must be 1-2 days for rapidly changing currents. Gaps of 10 km and independent sampling separated by 10 km will marginally allow to detect these features. However, the situation can improve by combining altimetry with other technologies that provide more detailed fields over shelves (SST and ocean colour observation from space, coastal radars, other in situ observation techniques), especially when assimilated into coastal circulation models De Mey (2001).

Altimetry can of course provide important boundary conditions (either tidal or topography) in the deep ocean off-shore of the coastal area, but in general a single nadir-pointing satellite with a long repeat (e.g. 10 days) cannot provide the information needed for coastal studies, although the data can be assimilated so far as it goes into coastal schemes (there have been examples of people using altimetry in coastal areas for special studies but nothing 'routine') For example, one storm surge assimilation study long ago, which is still valid, concluded that a single tide gauge on an oil rig in the North Sea would be more use than ERS-1. The situation would change dramatically with the availability of swath altimetry as long as the cross-track gradient error was not significantly worse than present-day along-track gradient error. In coastal applications (e.g. storm surges) there is also a need for data faster than the 'real time' usually studied at the moment (which usually has an ocean circulation perspective). That implies investment in data links and processing.

3.8.1 Tides Over Ridges, Shelves and Near the Coasts

T/P and ERS satellite altimetry, together with improved hydrodynamic models, has allowed to map the characteristics of the ocean tides over the global ocean. Over the deep ocean, it is commonly agreed that the barotropic tides are now known and predictable with an accuracy of the order of 3 cm. The more recent solutions (for example GOT00 and FES2002) are very close to each other. As a typical example, for the major M2 tide, the maximum differences are of the order 2.5 cm in a very limited number of locations. The major uncertainties remain over the shelves and in coastal areas. Some improvements are also expectable over mid ocean ridges and seamounts where shorter wavelength signals are locally forced by topography and internal tides.

3.8.2 Tides over mid ocean ridges

Most of the state of art global ocean tide models derived from altimetry have been generated by applying long wavelength corrections to a priori hydrodynamic model results. The short wavelengths in these solutions are thus the ones of the hydrodynamic models. However, with the accuracy of the last altimeter missions (mainly T/P, but also ERS), and the amount of data available, it is possible to get accurate tidal estimates from along track altimetry. By analyzing only 3 years of T/P data along track, Ray and Mitchum (1996) showed that M2 baroclinic signal could be found in the altimetric measurements, phase locked with the barotropic tides. Also, Tierney et al (1998) have carefully investigated the potential and limiting factors of along track tidal analysis with 4.5 years of T/P data. They have, among other points, clearly shown that along track analysis allows to catch short wavelength tidal signals, which are not baroclinic tides. These short wavelength signatures are due to mid ocean ridges: they are also recovered in the purely hydrodynamic barotropic solutions FES 94 Le Provost et al (1994) and the more recent ones FES95 Le Provost et al. (1998) and FES 98 Lefevre et al, (2000-b). Maps of the amplitude of the M2 tidal velocities can be used as a proxy to illustrate the expected location of these short wavelength signatures. To fully observe the 2D structure of these 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 space resolution to be defined more specifically, but typically of the

order of 10 km in 2D on the horizontal. The time resolution for tidal applications is not so crucial, as far as the tidal aliasing problem is considered with care, except for well known limitations for a few constituents such as K1 with the T/P sampling, and the solar tides with the ERS sampling.

3.8.3 Barotropic tides over continental shelves and near the coasts

Over shelves and when approaching the coasts, tidal amplitudes can increase up to several meters. Also, the horizontal gradients can reach up to several centimeters per km, and the horizontal patterns in amplitude and phase of the main tidal components are strongly reduced. The typical wavelength of the shallow water gravity wave are indeed controlled by the local bathymetry as $(gh)^{1/2}$. By 50-m depth, the semi-diurnal wavelength is typically 1000 km. By 20 m, it reduces to 600 km. Illustrations of the complexity of the co-tidal patterns can be found over areas where regional high resolution numerical hydrodynamic models have been developed: the European continental shelf (Flather, 1981), the Patagonian shelf (Glorioso and Flather, 1997) and the Yellow Sea (Lefevre et al, 2000-a). The information coming from T/P observations over continental shelves, where the tidal characteristics are complex, are clearly too limited. This is the reason why even now, high precision altimetry has not allowed to correctly map the characteristics of the major tidal components over the shelves and in coastal areas. Recent attempts to merge T/P and ERS data are on going (Andersen, personal communication, Ray, personal communication) but they are facing big trouble when approaching the coasts, because of lack of altimetric data, and because of too coarse inter-track resolution. Besides, the hydrodynamic models, which can help to fill the gaps and extrapolate up to the coast, are very dependent on the bathymetry, which accuracy is still poor in many areas. The analysis of long enough records of along track T/P and ERS data has demonstrated the feasibility to extract the characteristics of the major tidal waves, at the 2 cm level accuracy (Andersen, 1999) even in coastal areas. High resolution altimetry can thus help to improve the mapping of the tidal characteristics of the major constituents in coastal areas, by allowing to resolve their 2D spatial structures and observe the strong horizontal gradients in amplitude and phase observed along the coastlines. As above, the level of accuracy must be the one of the on going altimeter missions T/P and ER. The space resolution must be typically of the order of 5 km in 2D on the horizontal. The time resolution for tidal applications is not crucial, as far as, again, the tidal aliasing problem is considered with care.

3.8.4 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. The dynamical mechanisms at work are well known (Le Provost, 1991). They are due to wave propagation sensitivity to difference in depth between high and low tides, spatial acceleration of the flows around capes, and non linear bottom friction. In term of harmonic description of the tides, these non linear distortions lead to the generation of harmonic and compound tides, in all the frequency species: diurnal, semi-diurnal, but also quarter diurnal, six diurnal, ... These nonlinear constituents can reach several tens of centimeters. And their patterns are the more complex as their frequency is higher. Illustrations of the complexity of the co-tidal maps of these constituents can be found over areas where the astronomical tides are amplified: the European continental shelf, the Patagonian shelf, the Yellow Sea ,... Attempts to extract the characteristics of such tidal waves (M4, MS4, and M6) have been presented by Andersen (1999) for the European shelf. Although the long altimetric records allow now to extract the amplitude and the phases of these constituents 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 need to fully map these non linear high frequency tidal waves. The required

accuracy and precision are the same as above (centimetric, 5 km resolution, no major constraint on the time sampling, except the well known limitations due to aliasing). Large swath altimeter satellite missions, like WSOA on T/P-Jason track, with 13 km resolution and 150 km swath will allow to get a full coverage of areas such as the North Sea. Although the space resolution will be at the higher bound, such measurements will help a lot to map these non linear waves. The usefulness of these data is however dependant on the level of accuracy and on the insurance that the elementary pixels over the ocean will not be contaminated by the presence of the coasts in the swath. The limitations over the year in the operation of the instrument could be another important limitation in the de-saliasing of the tidal signal.

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 :

1. Minimum requirement

- Continue the Jason series for long-term, precise altimeter system
- Fly a post-ENVISAT mission to continue the Jason-1+ENVISAT configuration after 2006. Alti-Ka is a good candidate and could be a demonstrator for a future microsatellite constellation system (GANDER).

2. “More ambitious” requirement

- Fly a three satellite constellation (interleaved Jason tracks or ENVISAT/ERS tracks with a 35/3 repeat period) (in addition to the Jason series) that will provide a very significant improvement for SSH operational applications and will “pave the way” for a more complete GANDER constellation.

3. A demonstration of WSOA on board Jason-2 should be flown and results of the WSOA/Jason-2 demonstration should be used for the definition of future operational systems (post 2010 systems).

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