THE FUTURE ROLE OF SATELLITE ALTIMETRY – EARLY RECOMMENDATIONS FROM THE GAMBLE PROJECT.

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ABSTRACT

The launch of Jason and Envisat brings to 5 the number of radar altimeters simultaneously orbiting the Earth. Already national and international space agencies are making plans for the next generation of altimeters and altimeter-carrying spacecraft. For the near future (2005-2010), an OSTM/Jason-2 mission is being planned jointly by CNES, NASA, EUMETSAT, and NOAA, including a core mission based on a Jason-2 follow on instrumentation, and a demonstration mission involving the new concept of an Interferometric Wide Swath Altimeter. The official approval of the OSTM/Jason-2 mission will ensure the continuation of high precision altimetry after TOPEX/POSEIDON and Jason-1.

With respect to this background, this paper addresses the issue of establishing anticipated user requirements (from research and commercial organisations) for 2005-2010 and beyond, and hence deriving recommendations for possible complementary missions which could fly in this time frame. This issue has been the basis of an EC funded programme called GAMBLE (Global Altimeter Measurements By Leading Europeans). Within GAMBLE, SOS and CNES are convening meetings of some 24 European laboratories involved in different aspects of satellite altimetry. During the first phase of the GAMBLE programme anticipated user requirements over the next decade were discussed, and priorities identified. One key requirement clearly established was a need for improved sampling in time and space. During the next phase the project partners will review the technologies and mission opportunities that may be available over the next 10 years and discuss how this technology may be best used to satisfy user requirements. Possible solutions could involve the supplementation of precise long-term JASON-class missions with a number of relatively inexpensive micro-satellites, together with the development of technological advancements such as swath altimetry.

We first review the user needs identified within GAMBLE along the two application themes of sea surface height (SSH) and sea state data. We then discuss some of the implied requirements (and possible solutions) in terms of orbit determination and satellite tracking before finally assessing the capabilities of some possible mission specifications.

We view GAMBLE as a good example of the perceived need in future to merge the requirements of the marine operators for improved forecasts and models, with those of longer-term climate research on regional and global scales.

1. FUTURE PROSPECTS FOR OCEAN ALTIMETRY MISSIONS

Satellite altimeter measurements have now been continuously available since 1991, through the ERS1, TOPEX/Poseidon, ERS2, Geosat Follow-On, Jason, and ENVISAT missions. Measurements from these instruments have revolutionised our knowledge of the ocean, through studies in sea level, ocean circulation and climate variability.

The next planned mission is Jason-2 in 2007, which is expected to fly a "conventional" nadir altimeter and an experimental wide swath altimeter which will provide SSH measurements across a 100 km swath on either side of the nadir ground track. However, no missions are planned as "follow-ons" to GFO or ENVISAT, until the first US "NPOESS" altimeter, due in 2011 (see Fig. 1). Thus we have a potential situation in 2007-2011 when there would only be one operational satellite altimeter. This would interrupt the 2 satellite coverage required to carry out global scale ocean climate monitoring (e.g. Koblinsky et al, 1992, Lindstrom et al, 2001).

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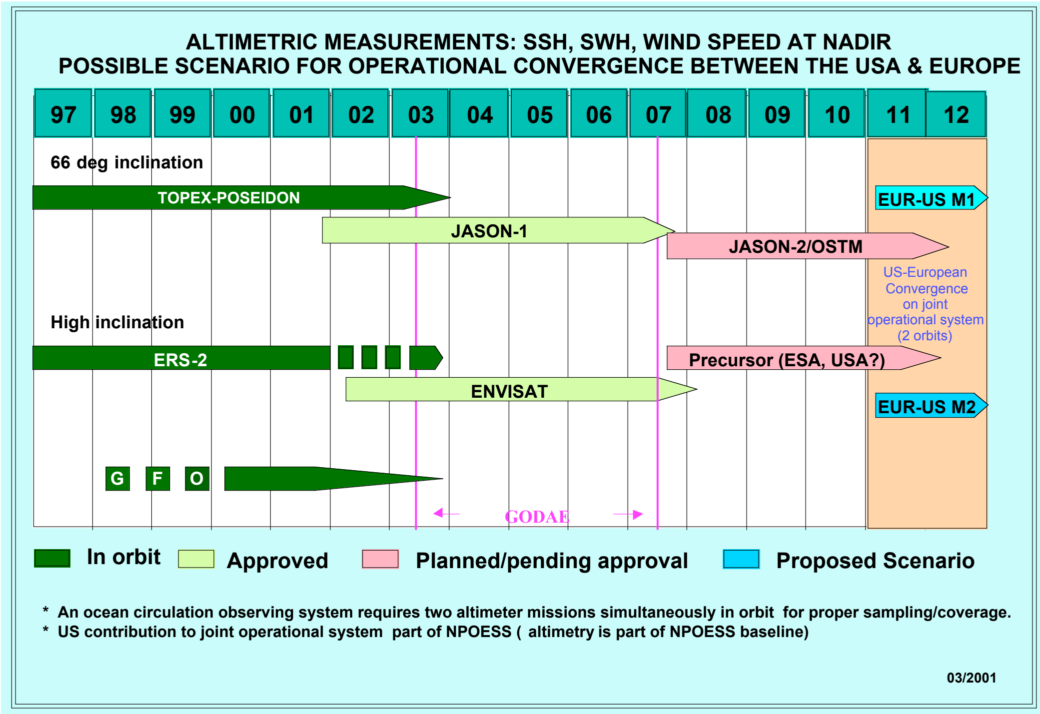

Figure 1. Satellite altimeter missions – operational, planned and proposed 1997-2012

A number of proposals for additional missions are at varying stages of preparation. They include, from Europe:

- SWIMSAT – A wave measuring satellite radar which would provide direction and wavelength information (Hauser, 2001).
- AltiKa – Ka band altimeter on a micro-satellite platform (Verron et al. 2001).
- GANDER – A constellation of wave-measuring altimeters on micro-satellite platforms (Jolly and Allan, 2000)

2. APPLICATIONS OF ALTIMETER DATA

This section summarises two reports compiled by the GAMBLE partners (le Traon et al, 2003, and Cavaleri et al, 2003) which identified the major issues of interest in the two main areas of applications of altimeter measurements (SSH and sea state), and established what developments may be required over the next 5-10 years to satisfy users requirements. These requirements were established through discussions and workshops, building on existing studies. Sources of information are too numerous to list in full here but included the HOT SWG report (Chelton, 2001) reports from EC programmes (e.g. COMKISS, Cotton et al, 2000), the EUROGOOS user requirements (Fischer and Flemming, 1999), and reports by offshore operators (e.g. Grant and Shaw, 2001). Contributors represented a wide range of scientific and commercial users, including representatives of the GODAE, EuroGOOS, GLOSS programmes, and members of the offshore exploration, shipping, and value adding metocean communities.

2.1 SEA SURFACE HEIGHT

Climate and mesoscale applications

For global and large scale climate monitoring, 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 (Koblinsky et al., 1992). 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. It is now known that the kinetic energy of ocean circulation in the open ocean is dominated by eddies of the scale of the Rossby radius (15-230km). Thus existing altimeter missions cannot resolve the structures of the most energetic component of the ocean circulation (Fu, 2003). Other missions are therefore required to measure this mesoscale signal (estimated to have an SSH signature of 4-8 cm, and a scale of variability represented by the Rossby radius), which cannot be well observed with a single mission.
Le Traon and Dibarboure (2002) quantified the mesoscale mapping capability of combined altimeter missions. The main results were:

- Compared to T/P alone, the combination of T/P and ERS reduces mean mapping error of Sea Level Anomaly (SLA) by a factor of 4 and the standard deviation by a factor of 5.
- The velocity field mapping errors are 2 to 4 times larger than the SLA error. Only a combination of three satellites can provide a velocity field mapping error below 10% of the signal variance.

Data assimilation studies (Le Traon et al., 2003) indicate 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 important scientific and operational applications), it is necessary 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 (e.g. wide swath techniques). Fu (2003) discusses wide swath altimetry issues in detail.

Assuming the Jason series continue to provide a long term reference, additional measurement systems do not have to provide such 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.

Coastal Applications

The coastal domain poses very strenuous space/time resolution and accuracy requirements, with a need to resolve SSH signals of 2-5 cm, at a spatial resolution of ~10km, and a revisit interval of 1-2 days. However, in these regions it is more difficult to satisfy these requirements, due to the land contamination of the altimeter/radiometer footprints. Altimetry should therefore be combined with other technologies that provide detailed fields over shelves (SST and ocean colour observation from space, coastal radars, and other in situ sources), and through assimilation into coastal circulation models.

Tidal Studies

The S1 and S2 tidal solutions need to be improved over coastal and shelf regions, where their present accuracy is only ~20 cm. Complementary studies are required for coastal areas, including satellite altimetry observations with higher space resolution on a non sun-synchronous orbit.

The resolution of some of the key remaining uncertainties in tidal modelling requires high resolution sampling, these include the resolution of short wavelength tidal characteristics due to mid ocean ridges, over shelves and approaching the coast, where non-linear dynamical processes are significant. Wide 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.

Requirements from Offshore Operators

Discussions with offshore operators identified that ocean currents were presently the major source of uncertainty in their knowledge of marine conditions. Users were aware of the potential of satellite altimeter data, indeed some were actively engaged in trials involving altimeter derived data products (e.g. the EC OPERALT and ESA EMOFOR projects). Such trials, and initiatives such as the MERCATOR project, highlight the value, and importance, of availability of Near Real Time (NRT) altimeter SSH data. However users still felt there was a deficiency in the quality and amount of ocean current information. Daily to weekly surface current charts were regarded as providing sufficient temporal resolution – spatial resolution was seen as a bigger problem. (for more details of offshore user requirements see Cotton, 2003b)

2.2 SEA STATE

Satellite altimeter data have made significant contributions to studies of ocean sea state, in terms of developing an understanding of the nature of large scale inter-annual variability, and developing physical models for interactions at the air-sea boundary – thus supporting the improvement of coupled circulation models, and particularly wave forecast models. The operational assimilation of NRT altimeter wave height data into wave models has been shown to result in an improvement in model performance. The major areas where further improvement in provision of altimeter sea state data are requested by users are discussed below:

Sampling

In terms of the scales of variability in the ocean wave field, altimeter data are scarce on a global scale, with large gaps in space and time. An orbit with a return period of ten days implies less than forty revisits to any location per year, and this with a gap of 2.5° between adjacent tracks. Whilst large scale climate studies have been possible with such sampling, studies have identified sparse sampling as a major source of error in the sample mean (Woolf and Challenor, 2002). It is clear that most operational applications of altimeter sea state data, in particular those in which NRT data are employed in wave forecasting and monitoring, would benefit significantly from a higher resolution in space and time than is presently available. Indeed some users have indicated an order of magnitude increase in sampling is desirable. This is particularly so for services which warn of severe conditions, when NRT availability of data (ideally < 1 hr) is also a priority. To provide a monitoring service to suit these requirements would require a sampling scheme that revisited each ocean region at least twice (preferably four times) a day.

Assimilation into Models
Altimeter significant wave height data are now operationally assimilated into many wave forecast models. However, the impact of altimeter data is limited to a relatively narrow band either side of the ground track, at least in the range of wind-waves. The main drawback has been the inability to correct the individual wave systems that compose the two-dimensional spectrum. SAR data have been useful in this respect, as they provide information on the long wavelength spectrum. The accurate prediction of swell in models remains problematic.

Other Wave Parameters
An accurate wave period parameter would be of significant benefit to many users. Users also need wave direction (important for design as well as for operational use), and separate estimates of height, period and direction for wind-seas and swells. Also a better understanding of wave processes is required for further improvements to models. Both issues lead to a requirement for 2D wave spectra.

Coastal Studies
Coastal areas present a particular challenge. As for SSH, the time and space variability scales are much smaller in these regions. To date the altimeter has not been able to provide information very close to the coasts, due to land contamination of the altimeter footprint. Within this region (5-7km of the coast), wave height gradients are especially high.

Air-Sea Flux Climatologies
Climatologies of air-sea fluxes (momentum, heat, gas, freshwater) are of vital importance 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 (Glover et al, 2001).

Event and Process Studies
There is significant interest at present in extreme conditions. Of course it is in these conditions when human and environmental safety are most at risk, but when in-situ instrumentation are most vulnerable. Satellite instrumentation is not vulnerable in the same way and so is able to continue to provide measurements.
Areas of specific interest include.

- The study of wind and wave fields associated with events such as tropical storms or cyclones. This issue is of particular interest to JCOMM/WMO, because of the significant human impact.
- The study of “Rogue” waves is presently of high interest to the offshore community. The physics is not fully understood, and there is a need for more data to support the development of theory.
- A particular problem at high latitudes is the sudden development of polar lows. These can generate severe wave conditions which models are unable to predict accurately. More satellite measurements at latitudes poleward of 60° could help to make a significant improvement.

3. FUTURE MISSION OPTIONS

New altimeter concepts exist that address the issues of improving sampling and improving data provision through a wider range of parameters, or improved reliability/accuracy in those presently available.
Briefly, these new concepts are:

Constellation of micro-satellite altimeters – Altika and GANDER
AltiKa has been designed as a range measuring altimeter with built in dual frequency radiometer (Verron et al, 2001), GANDER was designed as a low power, inexpensive Ku band wave measuring radar (no radiometer) – (Jolly and Allan, 2000). Altika could offer a SSH measurement accuracy of ~5.5 cm, a constellation of 3 satellites would provide across track spatial resolution of 350 km in daily coverage, 6 satellites would provide this across track resolution once every 12 hours.

Wide Swath altimetry
Swath altimetry would provide SSH in a ~100km swath on either side of the satellite, but no sea-state information off-nadir. The accuracy of SSH measurement would vary across the swath, presently available estimates (Rodriguez and Pollard, 2001) suggest between 4-10 cm. See also Fu, 2003. A Wide Swath altimeter is due to be flown on Jason-2/OSTM.

Use of GPS reflections.
Potential to provide a major improvement in sampling (~75 km day^{-1}), but technology is not mature and further studies are required. Significant averaging may be required to bring down random errors (estimates suggest 6cm accuracy could be achieved with averaging over 10 days. (Zuffada, 2001)

"Wittex"
A constellation of micro-satellites employing delay Doppler altimeters (similar to the SIRAL altimeter on Cryosat). Possible bi-static operation increases the number of ground tracks. Height accuracy estimated at 4cm, Doppler processing allows a higher along track resolution (1km). (Raney and Porter, 2001)

SWIMSAT
A wave-measuring real aperture radar, with a possible height measuring capability at nadir. Measurement of wave spectra in 50 x 50km to 90 x 90 km cells, in a dual sided 100km swath. Would provide global coverage at 100 km resolution after 7 days. (Hauser, 2001)

4. TECHNICAL/SCIENTIFIC ISSUES AND POSSIBLE SOLUTIONS

In this section we identify issues raised in the user requirements which require some modification to proposed or existing altimeter systems, and propose some solutions to the problems raised. Cotton (2003a) provides more detail.

Wet troposphere and Ionosphere Corrections
The estimated the range error associated with (corrected) wet troposphere delay is 1.7 cm rms, and from the ionosphere 1.0 cm (Scharroo, 2002). Ideally these corrections should be directly measured by dedicated instrumentation (radiometer, dual frequency). All previous satellite altimeters have had a microwave radiometer to measure the wet troposphere correction, but not all have carried dual frequency altimeters (e.g. ERS1, ERS2, Geosat, Geosat Follow-On), and so have relied on modelled ionosphere corrections. There have been recent improvements to atmospheric models and it is anticipated that model estimates of wet tropospheric correction may have become more accurate. Studies are required to quantify the errors if a radiometer is not operated.

Orbits and Tracking
Future high-accuracy altimeter satellites should carry either a GPS/Galileo or DORIS receiver for high-accuracy, near continuous tracking. A laser retro-reflector would provide a fail-safe backup.
The TOPEX/Poseidon and Jason missions have proved that each of the three available tracking devices (SLR, DORIS and GPS) adds unique information to the orbits and the force and measurement models. This combination is therefore recommended for future missions.
For missions that have to rely only on SLR measurements for orbit determination, the dual cross-over technique could be used to save costs on other more expensive orbit tracking solutions (DORIS, GPS). Studies have 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 (see Doornbos et al, 2003). Thus the fitting of a laser retro-reflector should be a minimum, but perhaps sufficient, enhancement to a micro-satellite platform with limitations on space/weight and power.
If real-time orbits are required, the DORIS/DIODE navigator system is flight-proven. Similar accuracy in real time is not currently available from GPS, because of the need for auxiliary information.

Orbit Choice
In order to continue multi-decadal time-series of altimetry data over the same ground tracks, the orbit choices of both Jason and Envisat must be adopted for their follow-on missions. 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 the altimeter instrument. This may be an issue for microsatellite altimeters with limited power budgets.

Orbit Maintenance / repeatability
With present technology, all future missions should be able to satisfy orbit repeatability specifications of ± 2km of nominal ground track, without modifications. There is a trade off to be determined between frequency of orbit manoeuvres, and the need to have long stable orbits for orbit calculations.

Sea State
New wave period algorithms are being developed. They anticipate an accuracy of ~0.5 s, though further testing is required (Gommenginger et al., 2003).
Directional wave spectra (and separate wind sea and swell information) can only realistically be achieved through synthetic or real aperture radar missions (e.g. ENVISAT ASAR, or SWIMSAT).

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.

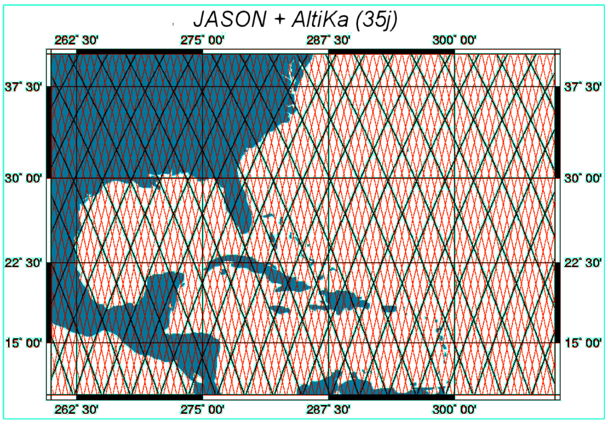

Figure 2 - ~10d sampling that would be offered by JASON + 3 Altika satellites

Sampling Regimes

Studies investigating the effectiveness of different sampling strategies for monitoring mesoscale sea surface height features (see Le Traon et al, 2003) 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° 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.

To best map fast-moving wave fields, frequent revisits are required to ocean regions (6-12 hours), but a wider inter-track separation (300-400km) may be satisfactory. Mesoscale SSH features (eddies) may only be 100km across, and so would require mapping with higher across-track resolution, but they change more slowly than wave fields and so could be sampled less frequently. Further simulations are required to identify preferred sampling regimes for different applications. As an illustration of the possible coverage from a small constellation, Figure 2 shows the tracks from the ENVISAT 35 day orbit and the JASON 10-day orbit. If 3 microsatellite altimeters were to be evenly spaced along the ENVISAT orbit, this figure then demonstrates the sampling that would be acquired in slightly over 10 days.

5. SUMMARY AND RECOMMENDATIONS

Two activities remain in the GAMBLE project, which comes to an end in November 2003.The first is to identify priorities for research, and the second is to provide recommendations for the configuration of future missions.

Priorities for Research

In the remaining phase of GAMBLE, one aim is to identify priorities for further research. In particular it is intended to identify important themes of research that would benefit from (or require) a co-operative international approach. A report will be produced in early November with recommended priorities and possible initiatives.

The themes that have arisen from the earlier discussions are:

From the climate/ocean research community:

- Can we measure mesoscale ocean variability?
- Can we measure barotropic ocean variability?
- Tidal issues, in particular tides at high latitudes and baroclinic tides.
- How are ocean parameters (sea level, wave height, …) going to change as the climate warms?
- Can altimetry contribute to the study of CO_2 (and other gas) transfer in and out of the ocean?

From the wave/offshore community:

- Accurate predictions of swell.
- Better predictions of quickly evolving severe events.
- Better understanding of how rogue waves occur.

Improved statistics of extreme events.
Are altimeter measurements of high winds and waves reliable?
Better reliability in nowcasts and forecasts of surface and subsurface currents.
Where are the major sources of error in wind/wave models?
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.
Can we measure wave steepness or breaking with altimeters? Are these related to structural damage?

Sampling Issues:
The main priority for operational missions is an improved resolution in time and space.
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.

On the more technical level:
What are the relative benefits (mapping errors, cost, reliability) of the options of a constellation of altimeters,GNSS reflectometry or wide-swath altimeters?
What are the prospects for cheap dual frequency or synthetic aperture Cryosat type altimeters?
What impact will the measurement of the geoid by GRACE/GOCE have on the use of altimeter constellations?
Range corrections – Further studies are required to investigate errors associated with using modelled wet troposphere corrections.
Maturity of technologies - On what time scale will GPS reflectometry provide a practical measuring capability?

Clearly the area where constellations of altimeters are going to have the most impact is in mapping the oceans. In general we are looking for research areas where progress can be made from improved spatial/temporal sampling. However there are other areas that will support the use of constellations. For example the identification of rogue waves in altimeter products or the development of cheap dual frequency altimeters. In addition, many climatologies (e.g., of monthly mean wind speed and wave height) will be improved simply by virtue of higher sampling.

Future Missions
The final major activity of GAMBLE will be to look at possible altimeter mission scenarios in the future, and provide recommendations for future missions to complement those already planned. These recommendations will be based on a careful assessment of user requirements and an objective view of how well past and present altimeter missions have addressed these needs.
There are three time frames to consider:

The present situation (2003-2007)
How are the data streams from the present missions TP, Jason, GFO and ENVISAT best used?
For research applications
For operational use
To identify optimum configurations for the future

The mid-term future (2007-2011)
To ensure continuity of dual altimeter sampling a second mission must be ready to complement JASON-2/OSTM. A second mission should have the necessary capability to maintain continuity from ENVISAT, but may also be used to test / prove a new mission concept.

The Long Term Situation (2011 and beyond)
In this time frame 2 altimeter missions are so far planned (labelled as EUR- US M1 and M2 on figure 1). Possible options for supplementary missions are wide swath altimeter or/and a constellation of microsatellite altimeters.

The final GAMBLE report, containing recommendations for research and future missions, will be available from the project coordinators (the authors of this paper) and through the GAMBLE web site (http://www.alltimetrie.net)

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