GAMBLE

Global Altimeter Measurements By Leading Europeans

Requirements for Future Satellite Altimetry:
Recommendations for Missions and Research Programmes

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Why GAMBLE?

Measurements from satellite radar altimeters have revolutionised our knowledge of the ocean, through studies in sea level, ocean circulation and climate variability. Satellite altimetry is recognised as an essential component of global ocean observing systems under programmes such as GODAE, CLIVAR and GOOS, and through its ability to provide stable and accurate long term monitoring of sea-level change.

Altimetry also lies at the centre of recent European developments in operational oceanography, such as MERCATOR, MERSEA, FOAM, TOPAZ, and MFSTEP. In addition altimeter wave data are routinely assimilated into wave forecast models, providing support to offshore operations around the world.

The GAMBLE thematic network has brought together European experts in ocean altimetry to consider future developments in satellite altimetry - with the aim of providing recommendations for research activities, and future altimeter missions, that are necessary to support and build on recent developments in operational oceanography and to maintain ocean monitoring programmes.

Over a period of 21 months GAMBLE held a series of workshops to identify and prioritise requirements of users, establish the state of the art in altimetric methods and technology, and so arrive at well-founded recommendations for future developments.

Requirements for Altimeter Data

Sea Surface Height

Operational oceanography systems being developed within the European GMES programme (MERSEA, MFSTEP), will require accurate measurements of ocean eddies and associated currents - the ocean “mesoscale”. The TOPEX/Poseidon+ERS (Jason-1+ENVISAT) configuration is a minimum configuration for observing this mesoscale. For the post Jason-1 period (2007 >), dual satellite coverage is a minimum requirement. For full resolution of eddies, measurements must resolve variability on the scale of the “Rossby” radius (~25 km). Three/four interleaved Jason-1 (or three ERS/ENVISAT) will allow a very good mapping of sea level and velocity. Compared to the T/P+ERS combination, improvement by a factor of 3 (more than 10 compared to T/P) would be achieved. Velocity mapping errors will remain, however, at the level of ~20% of the signal variance because of variability on small temporal and spatial scales. Much higher sampling rates in time (<5 days) and space (~50km) are required to map high frequency signals such as these. This would require constellations of six or more microsats and/or the application of wide swath techniques.

Sea State

Both research and operational applications require higher sampling to allow measurements of severe events. Because of the lack of observations, models are not able to provide accurate forecasts, or represent the true variability of wave fields generated by rapidly developing systems such as polar lows.

Studies have demonstrated that an improvement in forecasts can be expected if data from more than one satellite are assimilated into the wave models.

Accurate wave information continues to be the major requirement for offshore operators. Wave height and period information are particularly important in new and challenging operating conditions. Global measurements of the wave spectrum would also be of significant value to both researchers and offshore operators.

A better understanding is required of conditions in which "Rogue" waves are generated.

Current designs for wide swath altimeters are able to measure sea surface height but not wave height or wind speed across the swath. The SWIMSAT concept offers a capability to provide wave spectrum measurements.

What are the Stakes?

The launch of an altimeter-carrying ERS-1 in 1991, followed in 1992 by the dedicated altimeter mission TOPEX/Poseidon, confirmed the remarkable precision demonstrated by the pioneering but short-lived NASA spacecraft, Seasat, launched in 1978. The radar altimeter record may lack the glamour of the imagery provided by the synthetic aperture radar, or the vivid contrasts displayed in the imagery of ocean colour scanners, but its relative simplicity of operation coupled with an uninterrupted flow of all-weather, global data, make it one of the most revealing and versatile of all sensors for monitoring the oceans. Its pulses reflected from the sea surface can be analysed to provide accurate information on the Earth's gravity field, surface currents and eddies, wave height and wind speed, and, as we shall see, its performance over river estuaries and lakes is also proving useful in studies of the global hydrology budget.

What led to the series of GAMBLE Workshops sponsored by the Commission was the realisation by the user communities in Europe – research climatologists, oceanographers, forecasters, service companies and marine operators – that the future of altimetry was not entirely secure. To some extent it became a victim of its own success. TOPEX/Poseidon was launched in 1992 and was still working well when its successor JASON was launched in 2001. Likewise, the altimeter carried on ERS-2, launched in 1995, was still generating useful data when it was replaced by ENVISAT in 2002. It almost seemed that altimeters could go on working forever. That, of course, is not the case.

It was becoming increasingly obvious that although the precision of the altimeter's signal along its nadir track proved sufficient for most practical purposes, its sampling of ocean features was quite inadequate where consecutive passes could be over 3,000km apart. At the same time came the realisation that not only were there no firm plans to increase the number of platforms, but there was a chance that that number could soon reduce to one (JASON-2) with all the consequential risks, both to global research programmes and operational opportunities, should it fail.

The user communities became seriously alarmed and suggested a series of Workshops to discuss cost-effective options. This GAMBLE was funded by the research directorate of the European Commission through a Framework V Thematic Network, and this is a report of their findings and main recommendations.

Dissemination of results

The GAMBLE recommendations for research will be taken forward in a number of projects, under the auspices of EC Framework projects, and the EC/ESA GMES programme. The mission recommendations will be presented to a wide range of organizations and key players in the European ocean and space communities. The authors would welcome comments and suggestions. Please refer to the project web site – http://www.altimetrie.net for further information, and for access to the full reports.

Keywords: Satellite altimetry, currents, sea state, climate monitoring.

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The GAMBLE coordinators also wish to express their thanks to the European Commission for supporting this initiative and, in particular, to the officer assigned to the project (Alan Edwards) without whose patient, helpful, and sensible guidance the GAMBLE project would not have been the success it has proved to be.

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It is with deep regret that we record the passing away of Christian Le Provost, a key member of the GAMBLE team, which happened just as this report was being finalized. Christian has been a major actor in ocean altimetry for the past 25 years, and made unique contributions to TOPEX/Poseidon and Jason-1 projects. Christian's warm and friendly personality will be sorely missed.

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Glossary

AltiKa	Ka band altimeter, proposed by CNES
ASAR	Advanced Synthetic Aperture Radar (carried on ENVISAT)
CETP	Centre d'Etude des Environnements Terrestre et Planétaires, France
CHAMP	Challenging Mini-Satellite Payload, Research satellite
CICESE	Centro de Iinvestigacion Cientifica y de Educacion Superior de Ensenada (Mexico)
CLIVAR	International Programme on Climate Variability and Predictability
CLS	Collecte Localisation Satellites, France
CNES	Centre National D' Etudes Spatiales, France
CNRS	Centre National de la Recherche Scientifique, France
CRYOSAT	A satellite altimeter mission to monitor ice sheet thickness
DGFI	Deutsches Geodätisches Forschungsinstitut, Munich, Germany
DIODE	"Détermination Immédiate d'Orbite par Doris Embarqué" immediate onboard orbit determination by DORIS
DLR	Deutsches Zentrum für Luft und Raumfart (German Space Agency)
DORIS	Precise Orbit Determination system, on TOPEX and Jason
DUACS	"Developing Use of Altimetry for Climate Studies" – A Near Real time altimeter data processing system based at CLS, France
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
ENEA	Italian National Agency for New Technologies, Energy and the Environment
ENVISAT	European Environment Monitoring Satellite, launched 2002
ERA	ECMWF Re-Analysis. 15 year atmospheric hind-cast
ERS-1	1st European Remote Sensing Satellite (launched 1991)
ERS-2	2nd European Remote Sensing Satellite (launched 1995)
ESA	European Space Agency

ESF	European Science Foundation
ESRIN	ESA Space Research Institute. (Frascati, Italy)
ESSC	Environmental Systems Science Centre, Reading, UK
EUMETSAT	European Agency for operational meteorological satellites
EuroGOOS	European Contribution to the Global Ocean Observing System
FOAM	Forecasting Ocean Assimilation Model. Ocean circulation model at the UK Met. Office
GANDER	Proposal for a constellation of wave measuring Micro-satellite altimeters
Geosat	US Navy Altimeter Satellite (1985-90)
GFO	Geosat Follow-On - Follow on to Geosat (1998-)
GIM	Global Ionosphere Map
GMES	Global Monitoring for Environment and Security – A major joint EC/ESA programme
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-State Ocean Circulation Mission, ESA mission planned launch 2006
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GRACE	Satellite mission to improve mapping of the Earth's gravity field, launched in 2002
H_{max}	Maximum Wave Height
H_s	Significant Wave Height
IACMST	(UK government) Inter-Agency Committee on Marine Science and Technology
IAS – (PG)	International Altimeter Service – (Planning Group)
ILRS	International Laser Ranging Service
IPCC	Intergovernmental Panel on Climate Change
IRI	International Reference Ionosphere
ISDGM	Istituto per lo Studio della Dinamica delle Grandi Masse
Jason-1	Ku/C band altimeter launched in 2001 by CNES/NASA

Jason-2	Successor to Jason-1, Planned launch 2007 (also OSTM)
JCOMM	Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology
JPL	Jet Propulsion Laboratory (NASA).
LEGI	Laboratoire des Ecoulements Geophysiques et Industriels, France
LEGOS	Laboratoires d'Etudes en Geophysique et Oceanographie Spatiale, France
MERCATOR	A French operational oceanography programme
MFS	Mediterranean Forecasting System.
MPI	Max-Planck-Institut für Meteorologie, Germany
NASA	(USA) National Aeronautics and Space Administration
NCEP	(USA) National Centers for Environmental Prediction
NERSC	Nansen Environmental and Remote Sensing Centre, Bergen, Norway
NOAA	(USA) National Oceanographic and Atmospheric Administration
NPOESS	National Polar-Orbiting Operational Environmental Satellite System (USA)
OGP	International Association of Oil and Gas Producers
OSDR	Operational Sensor Data Record (refers to Jason data)
OSTM	Ocean Surface Topography from Space Mission – see Jason-2
PDF	Probability distribution function
POL	Proudman Oceanographic Laboratory (UK)
POD	Precise Orbit Determination
Poseidon	A solid state Ku band altimeter carried as an experimental instrument on TOPEX.
Poseidon2	Upgrade of POSEIDON adopted as the main altimeter on Jason.
PRARE	Precise range and range rate equipment. Orbit determination instrument on ERS-1 and 2
PROTEUS	ALCATEL mini satellite platform
RMS	Root Mean Square (a measure of data scatter)
SAR	Synthetic Aperture Radar
Scatterometer	Satellite radar instrument to measure ocean surface wind
SHOM	Service Hydrographique et Oceanographique de la Marine
SIRAL	Advanced interferometric, synthetic aperture radar altimeter, developed for Cryosat
SLA	Sea Level Anomaly
SLR	Satellite Laser Ranging
SOC	Southampton Oceanography Centre
SOS	Satellite Observing Systems (UK)
σ_0	Surface Radar Backscatter
SSH	Sea Surface Height
SSTL	Surrey Satellite Technology Limited (UK)
SWH, Hs	Significant Wave Height.
SWIMSAT	A proposal for a satellite borne Wave Measuring Radar.
TMR	TOPEX Microwave Radiometer
Tz	Zero Up-crossing Wave Period
TOPAZ	"Towards an Operational Prediction system for the North Atlantic European coastal Zones" – operational ocean modelling system for the North Atlantic and Nordic Seas (Norway)
TOPEX	Ku/C band altimeter launched in 1992 by CNES/NASA
TU Delft	Delft University of Technology, The Netherlands
WSOA	Wide Swath Ocean Altimeter – a proposed swath measuring altimeter
UKMO	United Kingdom Meteorological Office
U10	Wind speed referenced to 10m above the ocean surface
WAM	A widely used computer model for wave generation, propagation and dissipation
WITTEX	"Water Inclination Topography and Technology Experiment" – (USA) proposal for microsatellite borne radar altimeter using delay Doppler technique

1 Introduction

1.1 GAMBLE Overview

Measurements from satellite altimeters over the past ten years have enabled significant advances in oceanographic research and forecasting, in particular:

- A dramatic and unprecedented improvement in our knowledge of the global ocean circulation.
- mm precision measurement of year on year global sea level change (recognised as one of the key techniques in the monitoring of climate change) .
- Significant improvements in the accuracy of short-term sea state forecasts.
- An understanding of the characteristics of global wave climate variability.

Satellite altimetry is now recognised as an essential component of global observing systems under programmes such as GODAE, CLIVAR and GOOS. Altimetry is also central to the recent developments in ocean modelling such as MERCATOR and TOPAZ, and so lies at the heart of all systems being developed to provide operational ocean forecasting.

Each of these highly important applications requires a reliable and continuous provision of data from satellite altimeters. An agreement between NASA, NOAA, and EUMETSAT has secured the future for a mission to follow Jason-1, for the 2007-2011 period. However, the long-term provision of altimetry data is still not assured, and the needs of operational oceanography systems now being developed will not be met by present mission plans.

The GAMBLE (Global Altimeter Measurements By Leading Europeans) thematic network was established to address this highly important issue. GAMBLE was supported by the European Commission's Framework 5 programme over a 21 months period.

1.2 The Past

Altimeters had flown on satellites before 1978 but it was the Seasat mission in that year which demonstrated that a radar altimeter could measure its own height above the sea surface to a precision of around 10cm from an orbiting height of 800km. This meant that if due account were taken of contributions to the signal from atmospheric effects and biases at the sea surface – especially from uncertainties in the orbit, and variations in the gravity field over the oceans – the measured sea surface slope could be converted to estimates of a component of surface geostrophic currents.

On a number of subsequent missions leading up to Envisat and Jason the precision of the altimeter was increased to reveal a complex pattern of sea level anomalies produced by the meso-scale eddies (responsible for much of the ocean's heat transport) as well as western boundary currents and large scale events such as El Niño.

These are all well documented and the combined effectiveness and reliability of a sensor that works day and night in all weathers has ensured a continuous series of altimeter measurements since 1991.

Satellite altimeters have also provided a continuous time-series of global measurements of sea state, through measurements of wave height and wind speed. These measurements have allowed for the first time, studies of inter-annual variability in global wave climate and led to a better understanding of the character of between year variability. These data are now widely made use of by the offshore industry (shipping and offshore exploration) through statistical climate analyses and assimilation into met-ocean forecast models.

1.3 Future Prospects

Already national and international space agencies are making plans for the next generation of altimeters and altimeter-carrying spacecraft. For the near future (2007-2011), CNES, NASA, EUMETSAT, and NOAA are planning a joint OSTM/Jason-2 mission, which includes a core mission based on Jason-1 follow on instrumentation, and a demonstration mission involving the new concept of an Interferometric Wide Swath Altimeter.

However, no missions are planned as "follow-ons" to GFO or ENVISAT, until the first US "NPOESS" altimeter, due in 2011 (labelled as M2 in Figure 1.1). Indeed there are no plans for the "Precursor" mission indicated in Figure 1.1 This situation has potentially serious consequences with regard to our ability to monitor long-term ocean signals, and for the viability of "Operational Oceanography" systems now being developed.

At the time of writing, plans for the NPOESS "M2" altimeter mission are not finalised. Two options are being considered: a "free-flyer" or one instrument among several on a large, multi-instrumented, polar orbiting platform.

With regard to other future missions, a number of proposals are at varying stages of preparation (see also section 2.5). They include, from Europe:

- Cryosat – An ESA altimeter mission to measure ice mass balance and variability. Due for launch in 2005.
- 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).

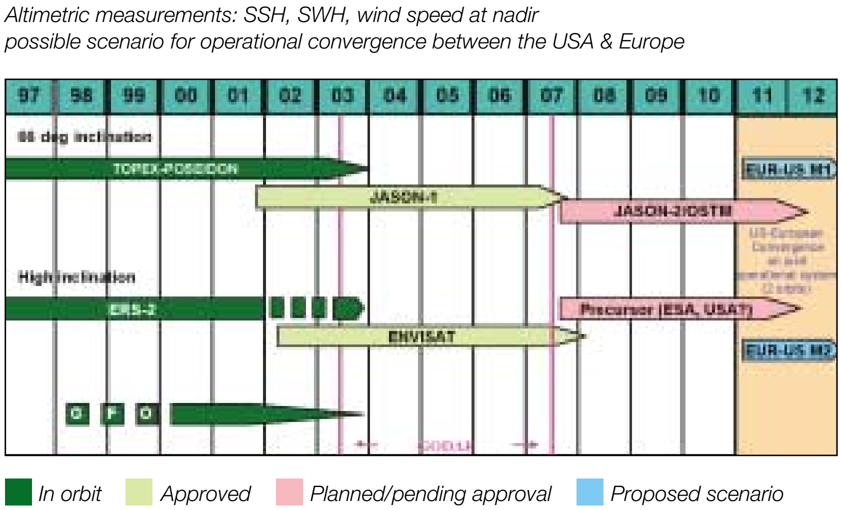


Figure 1.1 Satellite altimeter missions – operational, planned and proposed 1997-2012

1.4 European Social and Policy issues

European scientists, supported by advanced European technology are playing an increasingly important role in the search for evidence of a changing environment. Clearly, the protection of European coastlines is one of the most fundamental social objectives of the Community, but of equal importance in the shorter-term is the need to increase safety at sea while also making the European marine industry more competitive by reducing damage and delays inflicted on ships and offshore operations by adverse conditions (e.g. bad weather, unfavourable currents). Programmes to improve marine safety have been a recurring theme in EU policy for many years.

Monitoring key features of the environment in order to provide an 'early warning' of global climate change has always been a top priority for the EU. Many would rate this one of the most important services that European marine research workers can contribute to the world. Within 50 – 100 years changing sea levels and surface temperatures could have a profound effect on Europe's coastal defences, fisheries, aquaculture, tourism and weather patterns. A recent IPCC report (Gitay et al., 2002) highlights the serious implications of present climate trends.

Over 90% of the transport of goods in and out of Europe is by sea. Despite progress made in forecast models and communication systems, storms at sea still take their toll in lives, damage and delays.

- Some 150 ships of over 500 tonnes are lost every year; the marine insurance industry pays out $2.5 billion, and 24,000 lives are lost.
- A recent report by the Food and Agricultural Organisation (FAO) identifies fishing at sea as the most dangerous occupation in the world. The causes are two-fold - inadequate boats and ignorance of the conditions that await them.
- The environmental cost of cleaning-up oil spills following avoidable weather related incidents at sea can also be high. In recent years hundreds of million of Euros have been spent in the clean up operations following major oil spills in European waters.

Many European countries have highly developed meteorological forecasting centres and through the use of detailed models and high-speed computers, warnings of gales and their progression across the oceans are forecast in advance. Weather forecasts may be reliable for most of the time but the development of the strongest storms that do most of the damage is difficult to predict accurately by conventional means. Unfortunately, no matter how good the models or fast the computers their accuracy depends on the quality of the input data and this may be sparse, especially in bad weather where it has been shown that quality is diminished, particularly for data from *in situ* instrumentation.

There has been rapid development in operational ocean circulation models over the last 5 years to the point that a number of organisations now routinely produce weekly forecasts of ocean parameters throughout the water column. As well as providing important new insights into meso-scale ocean processes, products from these models have many practical applications – identification and location of ocean eddies, oceanic fronts and areas of up-welling, predictions of oil spill drift and, when coupled with ecosystem models, predictions of development of harmful algal blooms.

A number of questions may be asked. How can ocean satellites be made more relevant to the daily routine of marine operations? If they can be designed for a wider user community, is that community prepared to pay for information? If so, is there enough of a commercial market to encourage private investment into what was previously an exclusive public domain? Or should information on sea state and other features of operational value remain the province of national meteorological centres and be paid for from the public purse? GAMBLE did not directly address the economic issues (there may be a case for doing so), but brought together scientific and commercial user of altimeter derived products with the aim of identifying common requirements and so providing recommendations of realistic options for future altimeter missions that would serve the needs of both communities.

The need to make industry and academia work together is placed first on a list of socio-economic issues identified in a report by the European Science Foundation's Marine Board[1]. This need was recognised, and addressed, within GAMBLE by the presence of industry representatives in the Steering Group, and the inclusion of a workshop to identify the operational needs of industry.

Near real-time operation can only be achieved by a constellation of several observing platforms and the only way to afford the number required to (say) track the progress of storms at sea is to use small, special-purpose platforms. Recent studies carried out in European centres have confirmed that dedicated altimeters can achieve a good performance within the constraints of power, weight, size and pointing angle imposed by an 80kg micro-satellite. The means are at hand then to monitor ocean sea state and topography at the frequency required by marine operations. In themselves, these routine applications represent a considerable market which encompasses container ships, tankers, fishing boats, naval vessels, offshore platforms and leisure yachts as well as the routing and meteorological forecasting centres which serve them.

[1] *"Towards a European Marine Research Area", European Science Foundation, Marine Board, December 2000, http://www.esf.org/marineboard*

The issues addressed by GAMBLE - understanding processes governing global currents, improving short term predictions of sea state and currents, enhancing global observing systems – form the backbone of the first scientific challenge identified in the ESF Marine Board report. This report also calls for the development of infrastructure to support operational oceanography from satellites, and an improvement in co-ordination of space based activities to provide an enhancement of complementarity and competitiveness.

The GAMBLE programme reflects the new awareness in Europe that space policy must be shaped by the requirements of a wider user community. Science - especially that aspect aimed at improving our understanding of the changes taking place in our own environment - will retain a high priority. But satellite observations of the oceans have been almost exclusively directed in the past to climate/marine research. By investigating how science missions may now be combined with operational services that will provide bulletins on the sea conditions to support offshore operations, Europe will be making significant progress.

1.5 The “GAMBLE” Approach

Within GAMBLE, SOS and CNES convened meetings of some 17 European laboratories involved in different aspects of satellite altimetry. First, the team consulted with users of altimeter data through a series of workshops in Venice, Southampton, Delft and Stavanger, designed to identify and investigate the requirements that must be met to allow satellite-borne, polar-orbiting altimeters to resolve key features in the measurement of both sea surface height and sea state. Next, the project partners reviewed the technologies and mission opportunities expected to be available over the next 10 years and discussed how this technology may be best used to satisfy user requirements. A number of possible solutions were considered, including supplementing the 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 and wave spectrum measuring radar. Conclusions and recommendations were then presented and discussed during a 1-day session when European researchers were joined by American colleagues at the start of a meeting of the Jason Science Working Team held in November 2003 at Arles.

The approach was aligned upon six “themes”, given below with the name of the lead organisation:

Theme 1 - Sea Surface height *(**CLS**)*, *at TU Delft, The Netherlands*
Theme 2 - Sea State *(**ISDGM**)*, *at ISDGM, Venice, Italy*
Theme 3 - Orbit determination *(**TUD**)*, *at TU Delft, The Netherlands*
Theme 4 - Marine Operators Requirements *(**SOS**), at NPD, Stavanger, Norway*
Theme 5 - Research Programme *(**SOC**)*
Theme 6 - Constellation Optimisation *(**CNES**)*

In the next two sections of this document we summarise the findings from each of these six themes. Section 2 includes summary reports from Themes 1-5, addressing users requirements and provides recommendations for future research activities. Section 3 reviews the capabilities of available and planned technology and provides recommendations for future satellite altimeter missions.

Each Working Group prepared a report of its investigations. Readers who desire greater detail are referred to the original full reports, listed below:

[2] Section 3.1 of this report summarises the capabilities of planned and proposed future missions, but does not re-cap SSH and sea state error budgets

	Report Title	Section	Lead Author
Theme 1	Final Reports on Error Budgets / Feature Detectability in Sea Surface Height.	2.1	CLS
Theme 1	Subsidiary Report on TOPEX/Poseidon, Jason-1 Tandem Mission	2.1.4	CLS
Theme 2	Final Report on sea-state error budget/ Impact of GAMBLE in sea-state analysis and forecasting	2.2	ISDGM
Theme 3	Final Recommendations for Orbit Determination and Tracking	2.3	TUD
Theme 4	Report on Marine Operators’ Requirements	2.4	SOS
Theme 1-3	Report on Error Budgets and Potential Solutions	(3.1)[2]	SOS
Theme 5	Framework for Recommended Research Programme	2.5	SOC
Theme 6	Orbit Recommendations Satellite and payload specification recommendations	3.2	CNES

Table 1.1 Table of key scientific reports from GAMBLE

2 User Requirements for Satellite Altimeter Data

2.1 Sea Surface Height Features

(For full report refer to http://www.altimetrie.net/docs/GAMBLE_finalreport_theme1.pdf)

2.1.1 Objectives and Approach

The objectives of this work package were to summarize work that has been carried out to provide recommendations for future missions on:

- Sampling requirements for SSH (and surface current) measurements.
- SSH error budget (orbit, noise, corrections, repetitivity, geoid).
- Merging methodologies.

Main activities were the presentation and discussion of recent research involving the use of combined data from different altimeter missions with relation to applications (scientific and operational) of ocean sea surface height measurements. These discussions reviewed and built on the work presented at such meetings as Jason Science Working Team, and the High Resolution Ocean Topography meeting held at the University of Maryland in March 2001 (Chelton, 2001).

Aspects discussed included:

- Simulation of new altimeter missions/concepts.
- Theoretical analyses of sea level and velocity mapping capabilities of existing multiple altimeter missions.
- Analysis of the Wide Swath Ocean Altimeter system and constellations of 3/4 satellites (AltiKa, Wittex) – (Chelton, 2001).
- Analysis of the potential contribution of GPS reflected signals.
- Merging of data from existing missions (TOPEX/Poseidon, ERS, GFO, Jason and ENVISAT).

In addition contributions were taken from GAMBLE partners on data assimilation (LEGI, SHOM, NERSC and MPI), feature detection (SOC), and coastal regions (POL, LEGOS).

A joint workshop to consider sea surface height features and orbits and tracking requirements/capabilities was held at TU Delft. Presentations made at that meeting are available at the GAMBLE web site. Issues discussed at the workshop included:

- Overview of new altimeter concepts (Jason-2, Wide Swath Altimetry, Cryosat, AltiKa, GANDER) – CNES, ALCATEL, SOS, Ohio State University.
- Simulations of the contribution of present and future missions - LEGI, LEGOS, SOC.
- Refined requirements for sea level measurements, open ocean features, tidal features, and coastal features (particularly addressing sampling issues) – CLS, LEGOS.
- Requirements for Sea Surface Height Measurement Errors (general issues, orbits considerations, and issues related to measurements from micro-satellite platforms) - CLS, CNES, SOC, SOS, DUT.

In addition, CLS compiled a report on the TOPEX/Poseidon – Jason tandem mission to discuss the implications for multi-satellite sampling of features in sea surface height.

2.1.2 Measurement Issues

Mean Dynamic Topography

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

Mapping and merging of multiple altimeter missions

Merged multi-satellite altimeter data sets must be produced to map the meso-scale variability. An effective methodology is to use the more precise missions (e.g. T/P, Jason-1) as a reference. This reduces the orbit error for the other satellites to a few cm rms, even if the initial orbit errors are as large as 1 m.

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

2.1.3 Sea Level Measurement Requirements

Climate and meso-scale 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 meso-scale 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 significantly impact the meso-scale signal.

Studies have quantified the meso-scale 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. (see Figure 2.1)
- Mapping of the velocity field places higher demands on 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 well the meso-scale ocean circulation can be determined from multi-satellite configurations.

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

- The addition of a second altimeter improves the reconstruction of the meso-scale circulation by 18-28%, depending on the mission parameters. The addition of a third satellite makes an additional improvement of 10-16% depending again on the flight configuration.
- A 3-day interval between successive analyses appears to reveal meso-scale features better than other assimilation periods (intervals of 1, 3, 10 and 20 days were tested).
- With regard to meso-scale features, the scenarios which optimised spatial sampling (interleaved tracks, or space offset) performed very well when compared to those which optimised temporal sampling (time offset). In contrast, the case of two satellites flying in parallel (with an offset of 0.5° between tracks) seemed 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, higher altitude orbits support a less effective mapping capability.

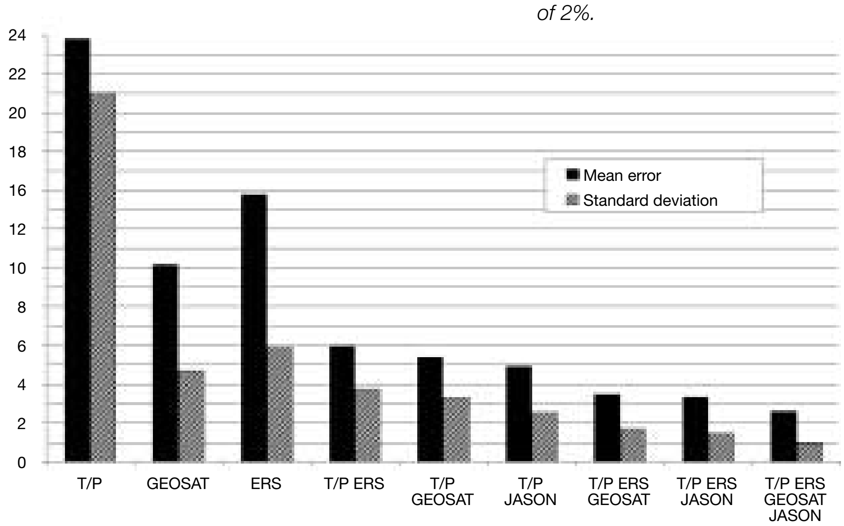


Figure 2.1 Mean and standard deviation of Sea Level Anomaly (SLA) mapping error for single and multiple altimeter missions (Le Traon and Dibarboure, 1999). Units are in % of signal variance. The calculation assumes a space scale of 150 km and a time scale of 15 days and a noise/signal ratio of 2%.

Overall, these results confirmed other studies which had indicated that a third satellite is required to capture the meso-scale features satisfactorily. The identification of the optimal configuration is not trivial. Assimilation experiments are being extended over longer periods to refine these conclusions.

To further improve mapping (required for some scientific and operational applications which have been proposed), it is necessary to resolve the high frequency and high wave-number 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).

Measurement Errors

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

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 metres 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 non-linear constituents can be of the order of 10 cm. Their patterns are also more complex as their frequency is higher.

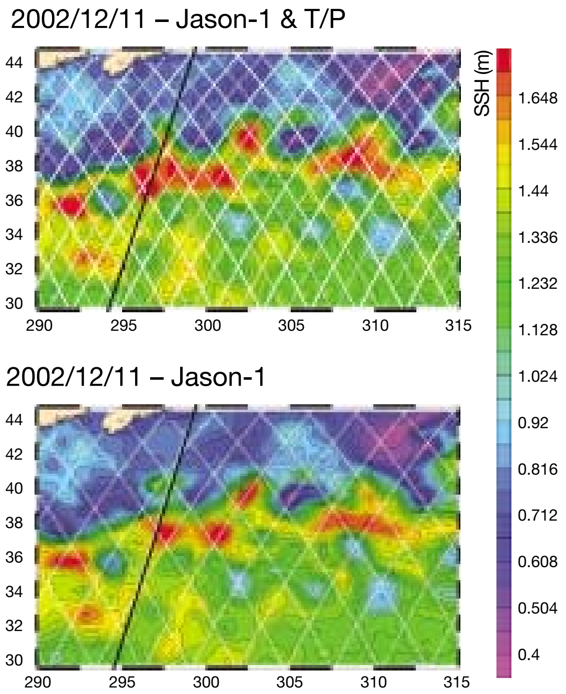
  Although long altimeter records now allow the amplitude and phase of these constituents to be extracted with an acceptable level of accuracy (2.5 cm), the short wavelength of these higher harmonic tidal waves is difficult to resolve by inter track interpolations. High-resolution altimetry is needed to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

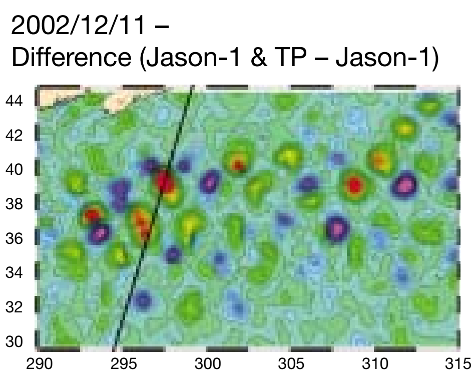
2.1.4 TOPEX/Poseidon / Jason-1 Tandem Mission

(For full report see http://www.altimetrie.net/docs/tandem_report_GAMBLE.pdf).

In September 2002 the TOPEX/Poseidon satellite was moved into an orbit so that the dual orbit configuration of Jason-1 and TOPEX/Poseidon was optimized to measure meso-scale oceanographic features.

In this configuration both TOPEX/Poseidon and Jason-1 are on a 10-day repeat orbit with interleaved ground tracks. This provides twice the spatial resolution achieved by TOPEX/Poseidon alone. The ability of this configuration to map meso-scale ocean features is an important consideration when discussing possible multi-satellite orbit configurations for future missions. To this end, CLS carried out a study for GAMBLE to analyze the ability of the tandem mission to provide improved mapping of sea level and ocean circulation variability.





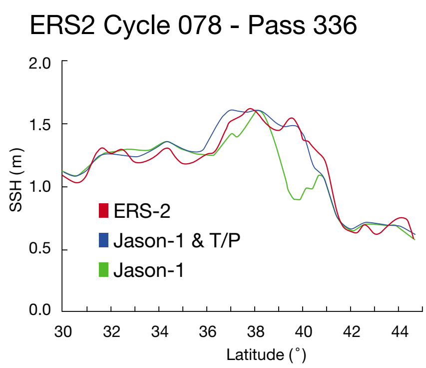


Figure 2.2: Absolute dynamic topography in the Gulf Stream region on December 11, 2002 derived from the combination of Jason-1 and TOPEX/Poseidon (T/P) (top figure). Jason-1 and T/P tracks are superimposed in white. The middle figure is from Jason-1 data only. The bottom figure is the difference between the Jason-1+T/P and Jason-1 map. Comparison with the sea level observed along an ERS track (red track) (below).

Several months of the TOPEX/Poseidon Jason-1 tandem mission were analyzed. The first requirement was to estimate a mean track for TOPEX/Poseidon consistent with a Jason-1 7-year mean. Results from the tandem mission were then compared with those derived from Jason-1 alone and an external verification was performed with ERS-2 data (Figure 2.2). These preliminary results are very encouraging and demonstrate the potential of an optimized two-satellite constellation for the meso-scale circulation monitoring. They also confirmed the results of earlier theoretical analyses by Le Traon and Morrow (2001) and Le Traon and Dibarboure (2002). Future studies should now be performed over a longer time series (at least one year) and should also analyze the contribution of the tandem mission together with ERS-2 / ENVISAT and GEOSAT Follow On data. Detailed analysis of velocity mapping error (through the comparison with surface drifters and current-meter moorings) and eddy/mean flow interaction estimations should be carried out. External comparison with very high resolution Sea Surface Temperature or Ocean Color images should also be performed to quantify the capability of multiple altimeter configurations to capture small space and time scales of the meso-scale variability.

2.1.5 Summary of SSH Requirements

Based on the discussions on requirements for Sea Surface Height measurements presented above it was recommended that a minimum requirement for an operational monitoring system would be 2 (preferably 3) altimeters, one of which would provide "Jason" class accuracy to provide the reference for others which could be less precise and could, for instance, be hosted on micro-satellites. A demonstration of wide swath altimetry would be required before such an instrument could be included in an operational configuration.

In considering a constellation of altimeters, priority issues are to:

- Identify preferred sampling regimes.
- Establish how to ensure satisfactory accuracy from micro-satellite swath range measurements (ionosphere, troposphere corrections, accurate orbit knowledge).
- Identify preferred orbits.

Table 2.1 provides indicative SSH measurement requirements, based on the identified characteristics of key features. "Latency" refers to the maximum desired time lag between the time of the measurement, and the availability of the data product to the user.

Application	Parameter	Indicative Measurement Requirements			
		Spatial Resolution	Time Resolution	Latency	Accuracy
Meso-scale variability	Sea surface topography	25-50 km	5 day	3 day	2-4 cm
Global mean sea level change	Sea surface topography	100 km	10 day	10 day	0.5 mm yr^{-1}
ENSO – seasonal to interann. prediction	Sea surface topography	200 km	5 day	5 day	4 cm
Large scale variability	Sea surface topography	200+ km	10 day	3 day	2 cm
Tides (Sun synchronous)	Tidal constants – sea surface height	100 km	non sun synch. Orbit >100 visits to each location	Not applicable	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	Not applicable	1-2 cm
Barotropic tides	Tidal constants – sea surface height	5 km	> 100 visits	Not applicable	2 cm
Non-linear tides	Tidal constants – sea surface height	5 km	> 100 visits	Not applicable	1 cm

Table 2.1 Indicative measurement requirements for applications of sea surface topography

2.2 Sea State Error Budgets and Feature Detectability

(For full report http://www.altimetrie.net/docs/GAMBLE_finalreport_theme2_030126.pdf)

2.2.1 Objectives and Approach

The objectives of this aspect of the GAMBLE project were to bring in expert opinion and hold discussions to provide recommendations for future missions on:

- Sampling requirements for sea state: wave parameters including significant wave height, wave period and direction; ocean surface wind speed; and other air sea flux parameters including rain rate, air sea gas transfer velocity and wind stress.
- Accuracy and reliability requirements for these parameters.
- Studies that may be necessary to ensure that best use is made of altimeter sea state data.

The general approach was to review and assess state of the art knowledge from most recent workshops and literature. Members of the GAMBLE team and external experts have offered written contributions and workshop presentations. A workshop was held at the premises of ISDGM, in Venice.

Contributions from GAMBLE partners included:

ALCATEL – Recent and proposed developments in altimeter instrumentation.

CETP – SWIMSAT mission proposal and results from a simulation of assimilation of wave spectra information into a global wave model.

CNES – Jason missions, and results from studies into Ka band altimetry.

ISDGM – Applications of sea state data near the coast and in the Mediterranean Sea.

SOC – Presentation of recent studies at SOC, including wave climate variability, investigations to develop new altimeter algorithms for wind speed and wave period.

SOS – Presentation of requirements for sea state data from the operational offshore user community (near real time and climatology).

Contributions from invited experts included:

CICESE (Mexico) – Requirements for satellite derived sea state data from countries without the resources to support large integrated monitoring systems.

ECMWF - Results from studies of assimilating significant wave height data into global wave models (estimates of error in altimeter, buoy and model measurements, the benefits to forecast accuracy of assimilating data from more than one altimeter mission), sea state bias theory.

Météo France – Studies in comparing performance of different wave models, and comparing the affect of assimilating altimeter significant wave height data, and wave spectra data (as would be available from SWIMSAT).

Meteorologisk Institutt, Norway – Emphasised the importance of improving the forecasting of extreme events that affect vulnerable coastal populations.

DLR –MAXWAVE, which investigated the physics and occurrence of very high “Rogue” waves.

UK Met. Office – Operational modelling and research at the UKMO. A key problem was identified as the accurate representation of the generation and propagation of swell.

2.2.2 Feature Characteristics

The distribution of wind and waves on the oceans is mainly characterised by the sharp distinction between the storm belt, at latitudes poleward of 40°-45°, and the tropical-equatorial zone. North/South of this zone a permanent west to east atmospheric flow brings with it a steady flow of storms. The border between the two areas depends on the season, with a shift to a more poleward position during the warmer months of the year.

The overall pattern reflects this distribution, with the strongest winds present at latitudes between 60°-70°. Local patterns exist close to the continents. Exceptions to the above pattern are the hurricanes, which are generated only in the sub-tropical belt. Their dimension is limited, at least with respect to the extra-tropical storms, but the extremely high winds still lead to extremely large waves.

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

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

The different time scales and spatial gradients present in different situations set different constraints on the desired altimeter sampling strategy. For climate purposes, there is no special constraint on the accuracy of the time and location of a pass, or on time interval between passes and the spacing between adjacent passes. The scale of the processes is fairly wide, with variations on the scale of hundreds of kilometres. The choice is a compromise between the number of data at each location and the spatial density of the information. For individual storms, particularly hurricanes, the time and space scales shrink dramatically. However, no particular optimum satellite orbit configuration can be chosen in advance because of the almost random (within the storm belt) distribution of the storms.

All this holds for the open oceans. Close to the coasts we find much larger spatial gradients. In these conditions a much higher density of information would be required, most likely beyond the practical possibilities of satellite altimetry alone. As for a detailed description of the open ocean climate, a step towards a solution lies in the parallel use of the information from the numerical models.

2.2.3 Priority issues

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

- *Accuracy*
  The accuracy of measurements is still an issue, more for wind speed than for wave height. It has not been possible to verify either of the parameters against in situ data for extreme conditions (wind speed > 20 ms^{-1}. H_s > 15m - see Cotton, 1998). It is for just such conditions that users have the most urgent need for accurate information, particularly for offshore operations.

- *Assimilation into Models*
  In application to forecast models, the altimeter has been the basic instrument for the supply of wave height information. However, the impact of altimeter data is limited to a relatively narrow band either side of the ground track (see Figure 2.3). The main drawback has been the inability to correct the individual wave systems that compose the two-dimensional spectrum at a given location. SAR data have been useful in this respect, boosting the development of techniques for the assimilation of the measured spectra. To date the assimilation of SAR data has required a priori knowledge of the spectrum, obtained from the model in which the data are to be assimilated.

  Recent studies at Météo France have demonstrated improved forecasting accuracy when data from more than one altimeter are assimilated.

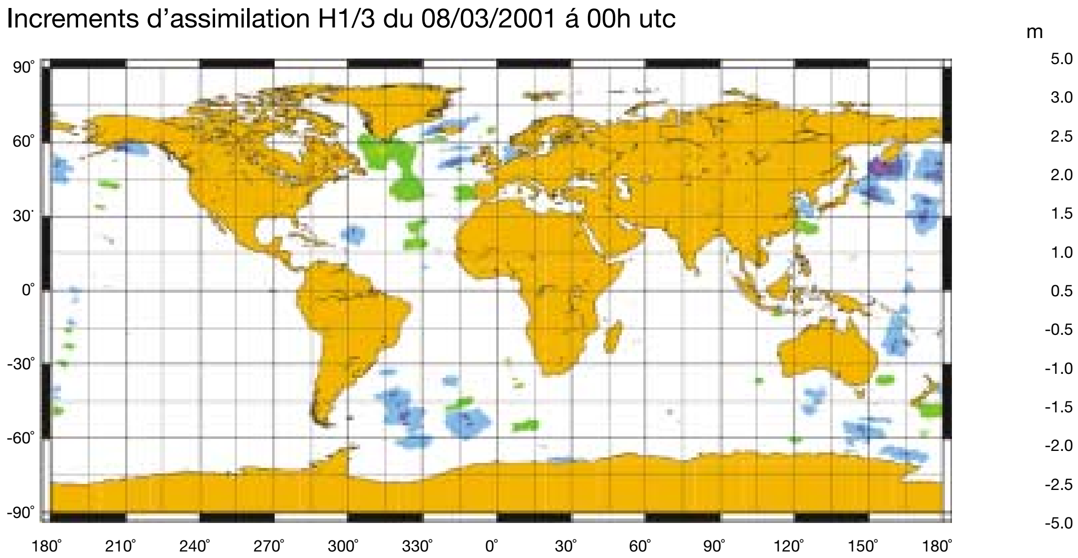


Figure 2.3. Analysis Increments (Analysis minus First Guess) from the assimilation of ERS2 altimeters wave height valid for 8 March 2001 at 00 UT: only increments larger than half a metre are represented.

Other Wave Parameters

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

- *Understanding of Wave Processes*
  One of the key issues for the improvement of numerical wave models is a better knowledge, hence formulation, of the physics of waves, and of their interaction with the atmosphere. Waves form the interface that controls fluxes between the ocean and atmosphere systems, that in turn control the earth climate. A better knowledge of the processes involved is highly desirable. However, the basic difficulty in studying the physics of waves, e.g. their generation by wind, is to characterise the processes taking place as a sequence of single, highly concentrated, events, but sparse in space and time. A satellite can only detect the integrated effect, and be used as the verification tool of a numerical model trying to represent the physical truth. In addition it is also clear that the application of altimeter data to this problem is limited because H_s is the only wave parameter that is routinely provided, therefore the availability of the two-dimensional wave spectrum is highly desirable.

- *Coastal Studies*
  Knowledge of the conditions in coastal areas present a particular challenge. To date the altimeter has not been able to provide information very close to the coasts, the minimum distance being in principle half the diameter of the area sampled by the radar. Besides, when flying offshore, a few seconds are required for the instrument to lock again on the sea surface. In this case data are available only from 20-30 km away from the coast. (N.B. Early results from ENVISAT promise improved performance in this respect.) In addition it is clear that a single altimeter cannot adequately sample the spatial variability that characterises the coastal environment.

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

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

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

- *Event and Process Studies*
  There is a growing interest in improving our understanding of the physics of extremely severe conditions. Of course it is in these conditions when human and environmental safety are most at risk, but it is exactly in such situations when in situ instrumentation are most vulnerable. Although the physical processes are different, satellite measurements are not vulnerable in the same way and so satellites offer an opportunity to measure extreme conditions.
  There are two areas of specific interest.
  - The study of wind and wave fields associated with events such as tropical storms or cyclones.
  - The study of occurrences and characteristics of so-called "Rogue" waves.

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

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

2.2.4 Summary of User Requirements

Table 2.2 provides a summary of user requirements, from the research and offshore operator communities, for "Sea State" information that can be derived from altimeter measurements. In this instance "Sea State" is defined to include wind and wave measurements, and air sea fluxes (including rain). As before, "latency" is the delay from the time the measurement is taken to the availability of this measurement to the user. Note that the resolution requirements for offshore and coastal near-real time data (30 km and 1 hour) are requirements for a final product which may be derived from a number of sources, not only altimeters. For the GANDER constellation, SOS proposed an altimeter sampling regime of 400 km every 6 hours (equivalent to 100km each day).

Thus, from the perspective of researchers and commercial users, priorities are:

- Improved sampling in space and time (uniformly distributed, so far as is possible).
- Availability of wave directional and wave period information – also separate wind sea and swell parameters (height, period and direction), wave steepness and joint distributions (e.g. of wave height / period, Hmax/Hs).
- Better combination of ocean / coastal monitoring resources (satellite, in situ, models) to provide improved warning of severe events with impacts on vulnerable populations.
- Implementation of a (new) wind speed algorithm valid for higher wind speeds.
- Validation of measurements at higher wave heights and wind speeds.
- Improved performance at coasts (higher along track resolution, quicker gain of ocean surface when the track comes from land to sea).
- Near real time availability of data (< 3 hours).
- Joint climatologies of altimeter and SAR data - e.g. groupiness, expected maximum wave heights, crest length.
- Climatologies of air-sea fluxes (momentum, heat, gas, freshwater) are important for climate studies. Dual frequency altimeters offer the possibility for direct measurements of surface wind stress, and air-sea gas transfer velocities.
- Improved estimation of sea state bias (information from the wave spectrum could help).

In terms of satellite missions, the interim recommendations were:

- Ensure continuity of coverage by at least 2 satellites, but ideally improve sampling frequency.
- To plan for a post-2011 capability to measure wave spectra, note that the anticipated 5 year lifetime of the ENVISAT (with reference to the ASAR), ends in 2007.
- Depending on the success of earlier missions, to consider a further wave spectra measuring radar and/or a significant (order of magnitude) increase in sampling.

This implied:

1. *Basic requirement for 2007-2011*
Jason-2 + 1-3 single frequency micro-satellite altimeters (e.g. Altika, GANDER).

2. *Further development for 2011 timescale*
Jason-2 + NPOESS + SWIMSAT + 1-3 (or more) single freq. micro-sat altimeters.

3. *Possible long term scenario for 2015+ timescale*
Jason series + NPOESS series + single frequency microsatellite constellation OR GPS reflectometry system + SWIMSAT successor.

[1]Separate wind sea and swell information desirable
[2]Dual frequency altimeter required.

N.B. Altimeter wave heights and wind speed measurements should ideally be accurate to the maximum of the expected range. Wind speeds are known to be inaccurate above 15 ms^{-1}.

Application	Altimeter Parameter	Indicative measurement requirements			
		Spatial resolution(km)	Time resolution	latency	accuracy
Climate Research	Sig. wave ht (Hs)[1]	100	1 mon	3 months	0.1 m
Offshore appls. (climate)	Hs[1]	1° x 1°	1 mon	Years	0.1 m
assimilation into models	Hs[1]	100	6 hr	3 hr	0.25 m
near real time - offshore	Hs[1]	30	1 hr	1-3 hr	0.25 m
near real time - coastal	Hs[1]	10	1 hr	1-3 hr	0.25 m
Joint U10/ Hs pdfs	U10/Hs	1° x 1°	1 mon	Years	0.1 m /2 ms^{-1}
Climate Research	wave period[1]	100	1 mon	3 months	0.5 s
Offshore appls. (climate)	wave period[1]	1° x 1°	1 mon	Years	0.2 s
near real time- offshore	wave period[1]	30	1 hr	1-3 hr	0.5 s
near real time- coastal	wave period[1]	10	1 hr	1-3 hr	0.1 s
Joint Hs / period pdfs	Hs/T	1° x 1°	1 mon	Years	0.1 m / 0.2 s
Offshore appls. (climate)	wave dir.[1]	1° x 1°	1 mon	Years	±10°
near real time- offshore	wave dir.[1]	30	1 hr	1-3 hr	±10°
near real time- coastal	wave dir.[1]	10	1 hr	1-3 hr	±10°
Offshore appls. (climate)	dir. wave spectrum	100 km	1 mon	Years	15° dirn, 10% wavelen.
Near real time	dir. wave spectrum	30	1 hr	1-3 hrs	10% max energy
Surface wind stress (U*)	$\Delta\sigma_0$[2]	100	1d	1d	0.1 m s^{-1}
Air sea gas transfer vel.	$\Delta\sigma_0$[2]	100	1d	1d	10 cm hr^{-1}
Rain rate	$\Delta\sigma_0$[2]	250	30d	90d	10 mm mon^{-1}
Event and feature studies	Hs	200	1d	3 hr	0.1m / 10%
	U10	200	1d	3 hr	2 ms^{-1} / 10%
	σ_0	200	1d	3 hr	0.1 dB
Global Mapping of "Extreme" Waves	Joint Alt/SAR data sets.	Requirements to be determined through research			
Extreme Event Warning Systems	Combined Hs/ sea level: alt/model/in-situ systems	kms	hours	hours	threshold to be determined
Sea State Bias	Hs, $(\Delta)\sigma_0$, wave spectrum	Various, according to sea surface height requirements			< 1 cm

Table 2.2. Indicative User requirements for altimeter derived sea state information.

2.3 Precise Orbit Determination and Range Corrections

(For full report see http://www.altimetrie.net/docs/GAMBLE_finalreport_theme3.pdf)

2.3.1 Objectives and Approach

The range observation made by the altimeter instrument must be related to the terrestrial reference frame through precise orbit determination; and account must be taken of the ionospheric and tropospheric effects on the travel time of the radar pulse. For these purposes, current altimetry systems such as Jason-1 and Envisat carry additional hardware: precise tracking capabilities for orbit determination, an altimeter with dual-frequencies for ionosphere corrections and a microwave radiometer to measure the wet troposphere correction. While these components are essential for the current and future reference class missions, the measurement requirements of several other possible future altimeter systems might lead to less strict hardware specifications. These alternatives may lead to a reduction in costs by allowing for an easier realization of the mission objectives using a micro-satellite platform or as a passenger payload on an existing platform. This section will discuss the various technical issues and available solutions.

The main objective is to provide recommendations for optimum orbits, orbit maintenance and satellite tracking and orbit error budgets that may be expected for various proposed satellite altimeter missions.

Contributions from GAMBLE partners included:
TU Delft – Orbit solutions, precise orbit determination, satellite laser ranging, and gravity field modelling.
CLS – Gravity field modelling.
CNES – The DORIS satellite orbit determination system.
SSTL – GNSS/GPS micro-satellite applications.
U Newcastle – Precise orbit determination, cross-over orbit reduction.
SOS – Sea state and GANDER micro-satellite issues.

Contributions from invited experts included:
Technical University of Munich – GPS Orbit Determination.
Ohio State University – Orbit Choices and Orbit Issues.

2.3.2 Precise Orbit Determination

Any error in the radial component of the computed orbit of an altimetry satellite directly affects the accuracy of the ocean topography science product. Precise Orbit Determination (POD) is traditionally based on a combination of force modelling and high-accuracy tracking data.

Tracking systems

There are currently three tracking systems available for cm-level orbit determination: Satellite Laser Ranging (SLR), DORIS, and geodetic GPS, each with its own specific characteristics.

SLR is the only system providing a direct and unambiguous highly accurate range measurement and is therefore essential for the calibration and verification of radiometric POD and altimeter instruments. In addition, the global network of around 30 laser stations is used to establish the position and motion of the Earth's centre of mass and rotation axis, which are of importance for altimetry-based research as well. The SLR community, organized under the International Laser Ranging Service (ILRS), puts a high priority on obtaining SLR measurements from altimetry satellites. These SLR measurements are usually used in combination with geodetic GPS or DORIS, ensuring an excellent stability of the reference frame.

The French DORIS system consists of a ground network of nearly 60 beacons, which are distributed evenly over the world for an excellent global coverage. The Doppler shift in the radio signals supplies range-rate data that can be used in dynamic or reduced-dynamic POD.

The GPS system was originally designed for ground-based positioning and navigation, but a number of special techniques have enabled the use of these signals for satellite positioning. Low cost GPS receivers are frequently flown on micro-satellite platforms, supplying an accuracy of several metres. A special receiver was first developed at JPL, enabling cm-level POD. Research on how to make optimal use of the various GPS signals for POD is ongoing.

In the absence of a radiometric tracking system, the SLR measurements alone might be too sparse for robust POD. After the failure of the PRARE tracking system on ERS-1 and the GPS receiver on GFO, the use of the altimetry data itself for orbit determination has been investigated. By using altimeter height differences over crossover locations, the orbit determination for these missions has been thoroughly improved. A careful parameterization scheme and weighting of the data ensures that the absorption of sea level variations into the orbit is limited.

POD schemes

The use of force models allows for the restitution of accurate orbits even when the tracking data contains gaps or outliers, while on the other hand, uncertainties in the force model can be solved for using the tracking data. This is the dynamic POD scheme. In reduced-dynamic POD, more and more force model parameters are estimated for higher accuracy. In the extreme case of kinematic POD, the force models themselves have become irrelevant, and the computed orbit completely follows the tracking data. Kinematic POD is only possible using GPS tracking, however the presence of systematic errors, outliers and data gaps currently make the dynamic and reduced-dynamic POD schemes more suitable for altimeter missions.

Force models, orbit choice and orbit maintenance

The two most important force model error sources, gravity and atmospheric drag, decrease drastically with the orbital altitude. However requirements on altimeter transmitter power and launcher restrictions generally favour lower orbits. Fortunately, gravity field models have dramatically improved in recent years, and the CHAMP and GRACE missions have brought down the gravity-induced orbit error for current altimetry satellites to below 1 cm. Atmospheric drag will quite likely remain a major error source at lower altitudes, especially during peaks in the 11-year solar activity cycle. The next high solar-activity period is expected to take place from 2009-2015.

The perturbation forces will also cause the orbit to drift so that corrective manoeuvres are required to maintain a repeating ground track. Again, the above arguments about the orbital altitude and solar activity cycle apply, so that the maximum number of manoeuvres is required for low satellites during high solar-activity.

Tracking system recommendations

Based on a mission's sea surface height measurement requirements, a POD requirement can be formulated, which will lead to specific hardware configurations, based on experience with previous missions. This is illustrated by the five cases identified below:

1. Primary SSH reference missions (the Jason-1 case): For the highest achievable level of POD accuracy (<2 cm radial RMS at 1336 km altitude) and additional redundancy, the combination of SLR, DORIS and Geodetic GPS is the recommended configuration.
2. Secondary SSH reference missions (the Envisat case): For <3-4 cm radial RMS accuracy at 800 km altitude, and orbits that are completely independent from altimetry, SLR plus either DORIS or Geodetic GPS are required.
3. Meso-scale SSH missions (wide swath, or small constellations): For <10 cm radial accuracy, an SLR retro-reflector is sufficient (but minimal) hardware. POD can then be performed using altimetry as additional tracking data. This approach has been proven using ERS-1, ERS-2 and GFO.
4. Meso-scale SSH/wind/wave large constellations (four or more satellites): A large constellation might burden the SLR tracking stations too much. There will be many more altimeter crossovers for radial orbit precision however. A non-geodetic GPS receiver instead of SLR will also provide stability in the along-/cross-track position components.
5. Wind/wave-only missions: There is no POD requirement for these missions.

When orbits are required in (near) real-time, the DORIS/DIODE navigator system is a flight-proven technology, delivering a radial accuracy of below 30 cm rms. Onboard orbit determination using geodetic GPS is more complicated due to the need for auxiliary data. However, accurate GPS orbits can be computed on the ground within a few hours of data acquisition.

2.3.3 Ionosphere and wet troposphere corrections

Altimetric systems such as Jason-1 and Envisat carry a dual-frequency altimeter and microwave radiometer, in order to give a direct and independent measure of the delay on the radar echo caused by free electrons in the ionosphere and water vapour and cloud liquid water droplets in the troposphere. Estimates of these properties can also be obtained by other means.

The ionosphere correction can also be obtained from models such as Bent and IRI or from analysis of dual-frequency GPS and DORIS data. The GPS-derived Global Ionosphere Map (GIM) correction is closest to the altimeter-derived values (see Figure 2.4), and is accurate enough for many applications. For the proposed Ka-band altimeter, the ionosphere delays will be much less than for the present Ku-band systems, and might be considered negligible under low solar activity conditions.

An alternative to the radiometer wet troposphere correction is available from atmospheric model fields supplied by ECMWF and NCEP. Since changes in the processing at these centres are known to cause jumps or drifts in the time series, these data are not suitable for applications such as sea level change. Moreover, these meteorological models are generally insufficiently accurate at the meso-scale (see Figure 2.4), so that model errors may be confused for actual meso-scale oceanic features. However, neither of these concerns plays a role in the application of the altimeter data for orbit determination, where the large-scale (>2000 km) behaviour dominates; smaller scale errors will be effectively filtered out in the POD process.

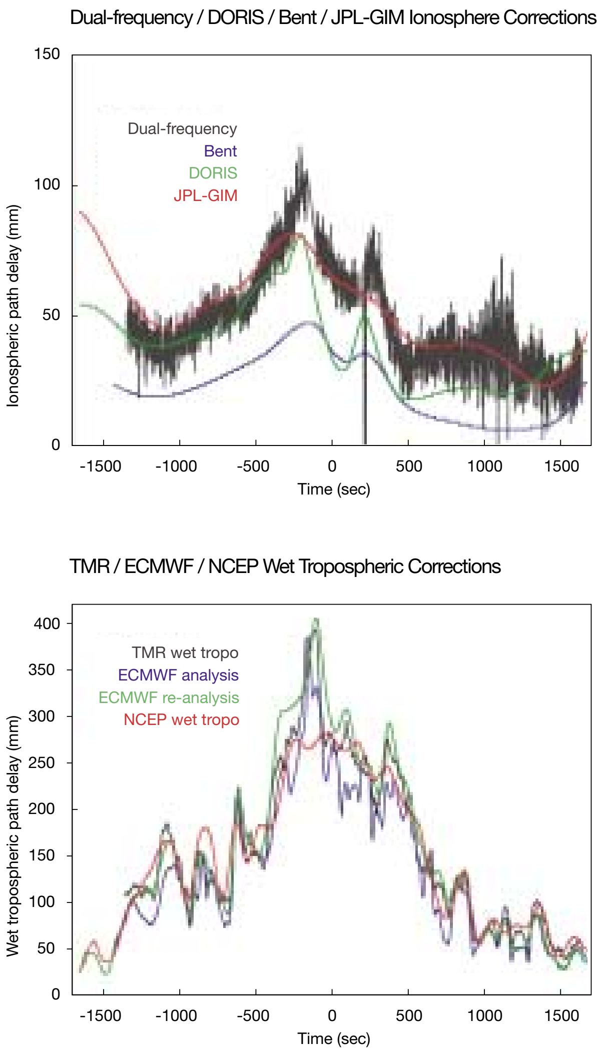


Figure 2.4 Along-track comparisons of ionospheric delay (top) and wet tropospheric delay (bottom) along a TOPEX/Poseidon track. The equator crossing is at 0 seconds on the x-axis. The values from the dedicated on-board instruments (dual-frequency, TMR) are compared with those derived from alternative measurements and based on models.

2.4 Offshore Operator Requirements for Altimeter Derived Data

(For full report see: http://www.altimetrie.net/docs/GAMBLE_OWS_Frep.pdf)

2.4.1 Objectives and Approach

Offshore operators are working to specifications that become more challenging year by year. These specifications can relate to operational activities, e.g. the need to operate within precise sea state limits, or for advance knowledge of "weather windows", or they can form part of the design procedure (planning for operations or vessel and structure design).

A priority of GAMBLE was to consider input from offshore operators, so that the requirements for future satellite altimeter missions are driven as much by the needs of offshore operators (taking into account commercial, safety or environmental considerations) as they are by the needs of the scientific community. Thus an operators' workshop was convened to allow operators to communicate their priorities, and to initiate a dialogue between GAMBLE partners and offshore operators to find the best way in which these requirements can be satisfied.

The workshop was planned with the support of the Met-Ocean Committee of the International Oil and Gas Producers Association (OGP), and hosted in Stavanger, Norway in the offices of the Norwegian Petroleum Directorate. Twelve representatives of the OGP community (from Shell, BP, Total, Chevron/Texaco, ConocoPhilips, and ExxonMobil) attended the workshop, in addition to members of the GAMBLE team and four invited speakers from the Met-Ocean information supply industry. We are grateful to the chair of the OGP Met-Ocean Committee, Chris Shaw, for his support in arranging this workshop.

2.4.2 Available Data Products – and Expected Developments

At the workshop, presentations from those developing new products derived from satellite altimetry helped to define the "state of the art". These included presentations on monitoring and forecasting ocean currents and ocean circulation by CLS and MERCATOR, operational wave modelling by the UK Meteorological Office, and a discussion of EO measurements of a recent severe storm to the North of Scotland by Satellite Observing Systems.

Key points were:

Sea Surface Topography / Ocean Currents

- Improved ocean current products are becoming available from operational programmes such as MERCATOR.
- Interpolated and gridded sea level anomalies and surface current fields. Available as 5-7 day averages, at resolutions of up to 1/3°.
- Forecasts and analyses of surface and subsurface currents are available from coupled ocean circulation models. Resolutions range from 1/3° (global) to 1/8° or better in regional models.

  (Figure 2.5 provides an example of output from the MERCATOR system.)

Ocean Waves

- Forecasts and analyses (hind-casts) are available from global and regional wave models which routinely assimilate satellite altimeter data (e.g. the UK Met. Office, Météo France. Resolutions range from 60km (global) to 12km (regional). Figure 2.6 show a UKMO forecast for a severe wave event to the North of Scotland in January 2003.
- Research is ongoing, aiming to provide improved representation of swell and identification of conditions favourable for "rogue waves".
- A case study shows that in situ and satellite altimeter data are consistent for significant wave heights to 12m.
- **Severe events have the greatest impact, but are often the most difficult to predict.**

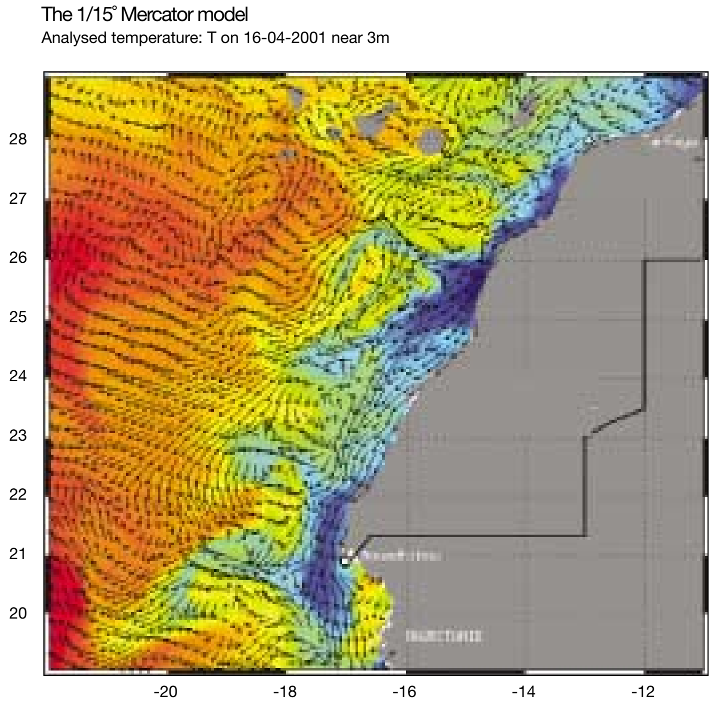
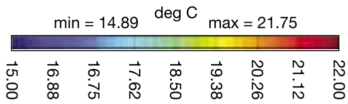


Figure 2.5 Example of Mercator 1/15° model output showing upwelling off the North-West African Coast, temperature at 3m depth and surface currents. For 18 April 2001



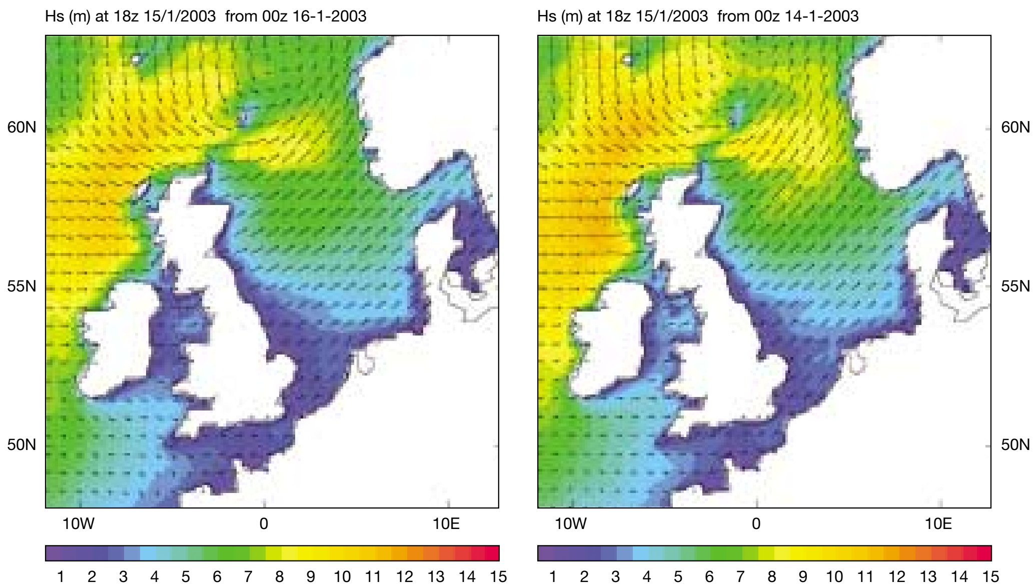


Figure 2.6 Hindcast (left panel) and forecast (right panel) of a severe wave event to the NW of Scotland on 15 Jan 2003). From the UK Met. Office.

2.4.3 User Priorities for ocean current and sea state data over the next decade.

A recent overview of user requirements from the perspective of the OGP community was given in a report for EuroGOOS (Grant and Shaw, 1999). They indicated that the most important parameter for offshore operations was wave height followed by wave period, wind speed and ocean currents. Other met-ocean parameters required are water elevation, air and sea temperature, visibility, cloud height and sea ice.

A presentation by Fugro GEOS discussed expected developments in the offshore renewables sector. The offshore renewables market is expected to grow significantly in the coming years (a predicted tenfold increase between 2010 and 2020). The largest potential wind power resource in Europe lies in the coastal waters around the UK.

Nowcasting International argued that whilst improvements in models and measurements in recent years have led to higher resolution forecasts with better accuracy, the presentation and delivery of data to users has been slower to evolve. Data should be formatted and systems established so that a specific set of required information is easily transmitted under the control of the customer.

Discussion

Discussions highlighted the following issues:

Ocean Currents

- Although wave heights continued to be the "most important" parameter for planning, design and operations, the biggest uncertainties lay in gaining accurate knowledge of ocean currents. Participants were aware of the potential of satellite altimeter data to improve our knowledge of ocean currents, and some US based users had made use of products on sites such as University of Colorado (http://www-ccar.colorado.edu/research/gom/html/gom_nrt.html) and the US Naval Research Laboratory (http://www.ocean.nrlssc.navy.mil/altimetry/). However, there was still felt to be a deficiency in the quality and amount of ocean current information.
- Currents derived from altimetry often seemed to be lower than those directly observed offshore.
- Daily to weekly surface current charts were regarded as providing sufficient temporal resolution – spatial resolution was seen as a bigger problem.
- One contribution suggested that a statistical approach may yield useful information on the amount and character of variability present in small scales for which there are limited direct measurements, and which are not well represented in models.

Ocean Waves

- Improved spatial and temporal resolution in waves is important.
- Wave period measurements are important even at low wave heights. Long, low swells can cause operational problems. Areas of particular interest in this respect are West Africa and North East Asia (specifically Sakhalin).
- Wave direction is important for design as well as for operational use.
- A particular problem at higher 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 pole-ward of 60° could contribute to a significant improvement.
- Swell - there is a problem in the advection of swell over long distances, which is connected to the resolution and to the dispersion intrinsic in the advection algorithms used in the wave models.
- Extremes – a large part of the difficulties experienced by wave models in forecasting extreme events is connected to similar problems in the input wind fields. The problem appears especially with storms which are characterized by large spatial gradients, in which cases peaks, of both wind and waves, are smoothed out and missed. The physics relevant in these extreme cases has a role. It is questionable whether the same physics apply to moderate and extreme conditions.
- Gustiness has a relevant role. The physical basis is properly understood, but the practicalities are difficult to handle for two reasons. ECMWF has implemented the role of wind gustiness in enhancing the maximum wave heights. However, gustiness is poorly understood from the meteorological point of view, and the present meteorological models do not successfully generate the high levels of gustiness found in nature. The second reason involves statistics. Gustiness introduces a strong element of randomness in the wind and wave fields, and there is no way, except by nowcast, to anticipate "when" and "where" an anomalous maximum will hit.
- Freak, or "rogue" waves - a theory for an estimate of their probability has been developed and recently implemented into the wave model at ECMWF. Obviously, as for gustiness, it is only possible to estimate the probability of freak waves of a given wave height.

2.5 Framework for Future Research

(For full report see http://www.altimetrie.net/docs/GAMBLE_WP7.pdf)

2.5.1 Objectives and approach

The purpose of this aspect of the GAMBLE project was to look at the scientific research questions that could be addressed by a constellation of altimeters and what further research is needed to fully utilise such a system. For the purposes of this report, scientific research was defined to include research into pre-operational oceanography, but not the real time supply of data to operational entities. Three groups of applications were considered: sea surface topography, sea state and non-ocean applications. Scientific research in general is driven by one of two motivations; requirements from some user or the scientist's curiosity. Satellite remote sensing, with its large capital requirements is generally driven by user requirements which will provide the main focus for this report. In some cases however we will introduce some ideas motivated purely by curiosity. Although GAMBLE has primarily focussed on oceanographic applications it was recognised that there are many interesting and important applications of altimeter data over land and ice.

Southampton Oceanography Centre drew up an original draft report. A half-day workshop was held in Toulouse in September 2003, and comments from the GAMBLE team incorporated in the final report. We present a summary of that report here.

2.5.2 User Requirements

The reports from the earlier parts of the GAMBLE project were used as the basis to set out the requirements for future research.

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 conditions likely to produce 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, since sparse sampling can often be identified as the principal source of uncertainty in the sample mean (e.g., Woolf and Challenor, 2002). In some cases (notably wind speed) present-day sampling is inadequate for a complete monthly climatology at a scale appropriate to the autocorrelation length scale of the measured variable.

Areas where altimeter constellations will have a significant impact include: -

- Ocean mesoscale
- Ocean barotropic signals
- Coastal studies
- Mapping the wave climate
- Better extreme waves for design
- Conditions likely to produce Freak waves
- Air-sea gas transfer (Kyoto monitoring)
- Land hydrology
- Land and sea ice monitoring

We also need to carry out research into altimeter constellations themselves. Areas that need investigation include: -

- Cost savings for batch production
- Constellation optimisation
- Should we mix wide swath and wave spectrum (SWIMSAT) altimeters in the constellation? How?
- How does losing one (or two) satellites degrade the constellation?
- How reliable will cheap altimeter micro-satellites be?

2.5.3 Sea Surface Topography

Many research topics involving mapping the ocean are presented in the High-Resolution Ocean Topography report by Chelton (2001). However that report only considers wide swath altimeters and small constellations of a few satellites. In GAMBLE we have been considering constellations from a few satellites to the 12 or so in the GANDER concept. One of the major issues for any large constellation of altimeters, where cost and mass considerations may not allow sophisticated tracking systems, is orbit determination. The orbits and tracking studies for GAMBLE (Section 2.3) have shown that satisfactory orbits can be provided through a combination of crossovers with well tracked altimeters and relatively cheap tracking systems such as laser retro-reflectors.

The main requirements for improved coverage in space and time are the need to look at coastal processes, mesoscale and barotropic fields.

Altimeter sea surface topography gains greatly in utility if it is assimilated into a numerical model of the ocean. There are a number of research questions related to assimilation. So far, studies have, understandably, concentrated on the effect an additional one or two satellites has on assimilation. There remain fundamental questions about the number of satellites and assimilation. What is the optimal number of altimeters to get the large-scale flow correct? In an eddy-resolving (permitting) model do we need to constrain every eddy with observations or is it possible to describe the eddy field statistically only constraining the occasional eddy, as at present? Coastal processes, in general, require a much higher space-time sampling than even 12 altimeters could provide. However the constraints from assimilating such data will be much stronger than for a small number of satellites.

The problems of identifying features and these assimilation problems are related. If we can identify a feature in the altimeter data then, crudely, the assimilation process will be able to constrain the model to 'fit' that feature. Assimilation schemes have been proposed that explicitly identify features and 'move' them to the correct place in the model. With the altimeter coverage from two satellites it is possible to identify features such as baroclinic Rossby waves, and the major current systems. When we come to the mesoscale however, it is almost impossible to track single eddies in time. Constellations will solve this problem and allow new research areas such as the tracking of Agulhas eddies across the South Atlantic and, in conjunction with sea surface temperature data, estimation of the heat transport from the Indian to the Atlantic Oceans.

Mesoscale features are generally hard to detect in altimeter data because of the poor spatial resolution of current configurations. This is perhaps most severe in coastal regions where both the spatial and the temporal variability are high. Barotropic signals can have large spatial signals but travel very rapidly and so are difficult to detect. They are clearly seen in altimeter data. In the past they were removed by an inverse barometer correction, recently the trend has been to use the output from barotropic models to make these corrections. These barotropic models are not only used as a correction for altimetry but also for time dependent gravity data from satellites such as GRACE. The input to these barotropic models is usually surface pressure and there is no assimilation of data. Because of the difficulty of observing barotropic signals in the ocean they have proved hard to verify. Frequent data from a constellation of altimeters would enable us first to verify how good these models are, and secondly to assimilate the data into the models themselves.

There are other phenomena, for example tsunamis and storm surges, where the sampling of one or two altimeters is not sufficient to detect the signal at the sea surface. Large constellations offer the promise of detecting such signals. Operationally this could be very important as both tsunamis and storm surges cause considerable amounts of damage and loss of life, particularly in the developing countries.

2.5.4 Sea State and Other Ocean Parameters

A constellation of altimeter satellites gives us much better spatial and temporal sampling to examine the wave climate. The research possibilities follow from this. We can divide the research opportunities into three areas: wave climate, extremes and new parameters.

Wave Climate

At present using two altimeters in the TOPEX/Poseidon and ERS orbits we can define monthly mean wave climate fairly accurately on a 2° x 2° square grid over the globe. If we are to conduct research into wave climatology and its changes over time and space in semi-enclosed areas we need a finer grid than is delivered by two satellites. In the open ocean 2° squares a finer grid would be useful for a number of research topics, for example wave height in storms (particularly associated with highly concentrated meteorological features such as Polar Lows) or looking at the interaction of waves with currents, in particular the Agulhas Retroflection. Having more passes per month per square will also make for superior climatologies, as the variability of the estimates will be reduced. As the number of satellites is increased it will become possible not only to define the monthly mean but also the within month variance, a parameter it is impossible to measure at present.

One of the current deficiencies in wave models is the way they deal with swell. Altimeters can in principle track swell as it propagates across the ocean, though at present this is difficult because of the poor sampling. With a constellation it would be possible to track the progress of a swell system simultaneously in both the wave model and in the satellite data. Such studies would increase our knowledge of the way swell propagates across the ocean and how it is represented in models. The prospect of measuring both wind speed and significant wave height (SWH) for these tracked swell systems also opens new avenues of research into atmosphere-ocean interactions, e.g. the role of sea state for the propagation of atmospheric systems and for air-sea momentum transfer, which would benefit weather forecasting models.

Such research is already under way for hurricanes using SAR images, from which both wind and sea state information can be extracted, although the present sampling by a single satellite (even if using SAR in wide scan mode) allows only for occasional and brief monitoring of the features of interest. Of course the presence of heavy rain in the centre of such storms causes significant difficulties for radar.

The calibration of wave measurements from satellites and the verification of wave models are closely connected. The number of coincidences between models and altimeters is so much higher than the coincidence of either with wave buoys that it makes sense to calibrate one against the other with the buoys being used as an additional constraint. We know that both wave models and altimeters work reasonably well for the majority of waves. In the extreme ranges there is more doubt. At very low wave heights (SWH ~ $<$ 0.5 m) and above ~20m SWH the altimeter is expected to have difficulty in providing reliable estimates. Little is known of the behaviour of wave models in high sea state regimes. Having a constellation of altimeters, all calibrated to each other and the global buoy network should provide enough coincidences to collect data in this important (but sparsely populated) regime of large significant wave height.

Extremes

One important potential application of altimeter data is the calculation of extreme wave heights for design conditions. The advantage of a satellite-based approach is that it should be possible to estimate the extreme conditions in a consistent way across the globe. However the application of altimeter data to these problems suffers from the drawback that the sampling is so infrequent that it is not possible to guarantee that we have observed the extreme conditions in a month. This contradicts some of the assumptions made in the methods used to estimate the return values. Increasing the number of observations by increasing the number of satellites will reduce this problem. Research is needed into this problem and into ways of solving it.

Another aspect of extreme value theory that needs research is the problem of estimating extremes of a field of data rather than at a single point. Although this could be looked at with existing data the improved identification of extremes from a constellation will make this a much more tractable problem.

There has been a lot of recent interest in so-called ‘rogue waves’. A rogue wave occurs when an individual wave is much higher than Gaussian statistics would predict for that sea state. An interesting research topic would be to see if any information on the non-linearity of the sea (Challenor and Srokosz, 1989 for skewness from altimeter) or on the highest waves could be extracted from the altimeter return signal. If it could, it would become much easier to map where and when in the world we could expect to see rogue waves. Assuming linear wave mapping under range propagating conditions (still controversial) investigation of individual waves in SAR imagery has shown that rogue waves may be much more prevalent that previously believed (Rosenthal et al., 2003).

Other Ocean Parameters

In recent years the estimation of new parameters from altimetry has been the subject of considerable interest. Of particular interest are wave period (Gommenginger et al, 2003), precipitation (Quartly, 1998), wind stress (Elfouhaily et al., 1998) and gas transfer velocity (Glover et al, 2002). Much of this work is still at the development stage and further research is needed into the properties of these parameters. Wave period can be estimated from a single frequency radar while precipitation and a proposed method of deriving gas transfer velocities need dual frequency altimeters. Wind stress requires one or two frequencies depending on the method used (Gommenginger et al., 2002). It may also be possible to make good estimates of wave breaking from satellites. Srokosz (1986) proposed a relationship between the fourth moment of the wave spectrum and the frequency of wave breaking. Since this moment is theoretically closely related to altimeter backscatter, altimetry provides a method of retrieving wave breaking frequency.

Precipitation and gas transfer involve the use of dual frequency altimeters. This additional capability would have to be factored into the cost of any constellation but would add significantly to the capability (as well as allowing the ionospheric correction to be easily calculated). Precipitation changes on very small scales and the very narrow swath of the altimeter has meant that it is difficult to produce reliable climatologies from a single altimeter (TOPEX). A large enough constellation would be able to produce climatologies with small enough uncertainty to allow the study of precipitation changes over the ocean from year to year and month to month.

Air-sea gas transfer is a very important topic but gas transfer velocities are very difficult to measure. In a ground-breaking paper Glover et al (2002) produce an algorithm to estimate the gas transfer coefficient from dual frequency altimeter data. Knowledge of the geographical distribution of gas transfer (and its integrals over various ocean basins) is vital if we are to understand the flux of carbon in and out of the ocean. Mapping such a parameter is very difficult, if not impossible, with only one or two satellites. A constellation would help us to produce credible maps and hence obtain integrated estimates of the fluxes of gases such as CO_2 over the oceans.

2.5.5 Non-Ocean Applications

Although GAMBLE is specifically concerned with the oceans, there are a number of research and operational aspects over both ice and land surfaces that should be considered. Altimetry over land has been carried out experimentally for a long time (e.g. Berry 1995 and 1999). In the past few years, research on interpreting individual land echoes has advanced to the point where most echo shapes can be interpreted. These advances have opened up a range of novel applications for satellite altimeter data, including mapping, surface hydrology and surface texture studies.

One of the key applications is the global land hydrology budget. As water resources in many parts of the world become increasingly scarce, the ability to provide independent global measurement and monitoring of water usage and distribution across national boundaries and from source to estuary of the strategic 'river corridors' becomes ever more important. Lake systems integrate precipitation: lake time series contain unique climate indicators and with a decadal time series already gathered and several further years from current missions, the continuation of this data stream is required to allow identification of climate shifts.

The current altimeter-based datasets can only identify seasonal and inter-annual variation. For most human-oriented applications, measurements are really required every 2-4 days. With such a system, returning data in near real time, drought prediction and mitigation, famine forecasting, flood prediction, hydropower applications and global monitoring of the earth's land water resources all become achievable.

The additional ability of such a constellation to return near-real-time data over the cryosphere should also not be neglected. Combination of the land surface hydrology, snow cover, and land ice mapping would allow the earth's freshwater resources to be effectively monitored globally.

2.5.6 Research into Constellations

So far we have considered research topics that can be tackled with a constellation of altimeters. Research is also required to provide an objective and scientific basis for recommendations on the specifications of any proposed altimeter constellation (i.e. number of satellites, orbits, instrumentation). First there is the question of the optimal number for a constellation.

A priori **we would expect the added utility of each satellite to fall as the number of satellites increases. However we need to accurately calculate this dependency, in particular we need to know what additional utility is gained from increasing the number in the constellation. This clearly depends upon the spatial and temporal scales of the parameter being studied. We would not expect to get the same answer for significant wave height as for sea surface height.**

A twist on this problem is the inclusion of new technology in the constellation: a wide-swath altimeter (WSOA) is due to fly on Jason-2; and SWIMSAT, which measures the wave spectrum, has been proposed to ESA. How would the inclusion of such systems in a constellation improve our understanding of the oceans? The proponents of such systems naturally concentrate on the use of a single system. However it is likely that these new technologies would be much more effective when used in combination with the improved sampling provided by a constellation. Once a constellation was established the risk involved in flying a new altimeter design would be reduced since the failure of a single component would have less effect than the loss of a stand-alone mission.

2.5.7 Conclusions

The last decade has seen radar altimetry moving from a research topic towards an operational system. **The next step is to go from a few satellites launched for research purposes to planned constellations optimised for operational applications.** In this review we have considered what research can be carried out with such a constellation and what research is needed to optimise a system of altimeters for operational purposes. If altimetry is going to complete the transition from a research tool to an operational system to be used in support of EU policy the issues addressed here will have to be tackled.

3 Future Strategy

3.1 Capabilities of Available and New Altimeter Technology

(For full report see: http://www.altimetrie.net/docs/GAMBLE_mtr_d8.pdf)

3.1.1 Mission Options

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

Briefly these new concepts are:

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

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

Operational Missions:

- Jason-1 – Accurate sea surface topography altimeter. Dual frequency (Ku/C band) Poseidon-2 solid-state altimeter with radiometer and accurate orbit positioning. 10-day repeat, 66° inclination orbit. Continues the 10+ year time series started with TOPEX/Poseidon. Launched December 2001. 5 year planned lifetime.
- ENVISAT RA2 – Accurate dual frequency (Ku/ S band) altimeter with radiometer and accurate orbit positioning. 35-day repeat, 98° inclination orbit. Continues the series started with ERS-1 (1991). Some enhanced tracking capabilities – better performance close to coasts. Launched March 2002, 5 year planned lifetime.
- Geosat Follow-On – Single frequency Ku band altimeter launched in 1998, 17 day repeat, 108° inclination orbit. Initial problems with satellite resets now overcome.
- TOPEX/Poseidon - Accurate, but 10 year old, sea surface topography altimeter. Dual frequency (Ku/C band) altimeter with radiometer and accurate orbit positioning. 10-day repeat orbit. Now in an orbit with interleaved tracks with Jason-1.
- ERS-2 - Single frequency Ku band altimeter (launched 1995). On 35 day repeat orbit. Has experienced some problems maintaining accurate attitude due to failed gyroscopes. However this problem is now largely overcome, through the application of an updated on board algorithm. Subsequently, in 2003, the on-board tape recorder has failed and ERS-2 measurements are now only available for locations when the satellite is in direct view of ESA ground stations.

Planned Missions:

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

3.1.2 Altimeter Capabilities

Table 3.1 reviews the capabilities of various existing and proposed altimeter missions. Two spatial resolutions that can be achieved are given, the first is the effective track separation over a period of 1 day, the second the best resolution for a climatology averaged over a period of 1 month. Sea surface height accuracy is for single pass 1 Hz data (including errors due to orbit, troposphere, ionosphere and EM bias corrections, and range noise).

3.1.3 Issues and Technical Solutions

Issues to be addressed include:

- *Range Accuracy*
  Corrections (ionosphere, troposphere, sea-state bias).
- *Orbits and Tracking*
  Accurate knowledge of orbits - particularly for micro-satellites. Selecting best orbits to meet mission goals.
- *Sea State*
  Can the requirements for new wave measurements (period, directional spectra) be satisfied by developments to “standard” altimeters, or do they require specific instrumentation?

  Improve accuracy and reliability of measurements under severe conditions.
- *Sampling Regimes*
  Which sampling regimes are preferred for different applications?

3.1.4 Sea State

Wave Period

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

Directional Wave Spectra / Separate wind sea /swell information

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

Severe Conditions

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

	Parameter	Accuracy	Range of valid data	Spatial Res 1 day / monthly climatol.	Comments
Jason GDR[1]	SSH H_s U_{10} T_z	4 cm 0.25 m 1.5 ms^{-1} 0.5s	 0-15m 0-15ms^{-1} 4-10 s	1350 km/ 2° x 2°	
	Dirn spectra, separate wind sea/swell	Not Available			
	$\Delta\sigma_0$[2] (various applications)	0.1 dB		1350 km/ 2° x 2°	
ENVISAT	SSH H_s, U_{10}, T_z, $\Delta\sigma_0$)	5.0 cm as Jason	as Jason	1350km / 2° x 2°	2nd frequency S band
Jason & TOPEX & ENVISAT / ERS-2 & GFO	SSH H_s, U_{10}, T_z (also $\Delta\sigma_0$ for JAS, TOP, & ENV)	4 – 6.5 cm as Jason	as Jason	~350km[4] / 1° x 1°	4[3] satellite sampling available *now* (from Sept. 2002 onwards)
SIRAL	SSH, H_s, U_{10}, T_z & $\Delta\sigma_0$	as Jason	as Jason	as Jason High resolution along track (< 1km)	Possibility to derive other sea state parameters
Swath altimetry	SSH H_s, U_{10}, T_z & $\Delta\sigma_0$ (only at nadir)	4-10 cm? (variable across swath) as Jason (only at nadir)	as Jason	20km in 10 days 1350 km/ 2° x 2°	100km dual sided swath Sea state measurements only given at nadir
GANDER - “Basic” Ku altimeter Constellation (no radiometer)	SSH H_s, U_{10}, T_z (not $\Delta\sigma_0$)	Alt requires modification for range measurements Original design specification 0.5 m, 2 ms^{-1}	as Jason	3 sats ~350 km / 1° x 1.3° 6 sats ~175 km / 0.75° x 1°	Single frequency, so no $\Delta\sigma_0$ parameters.
AltiKa Constellation	SSH H_s, U_{10}, T_z (not $\Delta\sigma_0$)	5.5 cm[4] Original design specification 0.5 m, 2 ms^{-1}	as Jason	3 sats: ~350 km / 1° x 1.3° 6 sats: ~175 km / 0.75° x 1° ~5 km footprint	Single frequency, so no Ds0 parameters. Ka less attenuated by ionosphere than Ku (but more attenuated by rain)
SWIMSAT	SSH H_s, U_{10}, T_z (not $\Delta\sigma_0$)	6 cm Nadir – as Jason	Nadir – as Jason	Nadir – as Jason. It may be possible to estimate H_s, U_{10}, T_z off-Nadir.	A single frequency Ku band nadir radar plus a rotating wave measuring real aperture radar. 100 km dual sided swath
	Directional spectra	15° direction 10% wavelength		50-90km cells, 100km res. after 7 days	
	Separate wind sea/swell, long wave steepness	Possible			
WITTEX[5]	SSH H_s, U_{10}, T_z (not $\Delta\sigma_0$)	4 cm as Jason	as Jason	Various high res. along track (< 1 km)	Tracks may not be evenly separated.
GPS reflectometry	SSH H_s, U_{10}, T_z	6cm after 10 days[6] To be determined		estimated average track separation of 75 km over 1 day.	Feasibility under study, not available until 2010+. No $\Delta\sigma_0$ parameters.

Table 3.1 Measurement capabilities of existing and proposed missions.

[1] *The near real time data set (OSDR) will have lower accuracies.*

[2] *Various parameters derived from $\Delta\sigma_0$, mostly experimental, and accuracy yet to be verified.*

[3] *ERS-2 and ENVISAT effectively sample the same ocean signal (on the same ground track 30 minutes apart).*

[4] *Assumes a 5 cm orbit accuracy and 0.8 cm range noise.*

[5] *The Wittex proposal includes a number of possible orbit configurations, including tracks separated by ~30km to provide across track slope and hence full 2D geostrophic velocities. Such a configuration would provide highly correlated sea state information however, and would be of limited interest in sea state applications.*

[6] *Averages of a number of measurements over a period of days may be required to bring down the errors.*

3.1.5 Sampling Regimes

Studies investigating the effectiveness of different sampling strategies for monitoring meso-scale sea surface height features 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.

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

3.1.6 Summary

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

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

3.2 Recommendations for Altimeter Missions

For full report see: http://www.altimetrie.net/docs/GAMBLE_WP8v1.pdf

3.2.1 Objectives and Approach

The aim of this final aspect of GAMBLE was in many ways the most important. Taking into account:

- Technical capabilities of available (and developing) technology,
- Characteristics of existing and anticipated altimeter missions,
- State of existing and emerging technologies (for platforms and instrumentation),
- Estimated time to develop and bring these new technologies into operation,
- The need to optimise costs,

- we wished to identify realistic options for satellite missions which would satisfy the key requirements from the operational, climate monitoring and research communities.

Based on the input of the GAMBLE reports from Themes 1-4 CNES compiled a draft set of recommendations. These were expressed for 3 time frames:

- Short-term (2004-2007)
- Mid-term (2008-2011)
- Long-term (> 2011)

These recommendations were reviewed by the whole GAMBLE team, and at a workshop held in Toulouse in September 2003. The final recommendations outlined below were also presented to the wider community (including representatives from the USA) at the final GAMBLE workshop held in Arles in December 2003.

3.2.2 Summary of Requirements

Sea Surface Height Applications

The minimum requirement will be to continue flying a two satellite configuration with one long-term precise mission (T/P/Jason series). This can be very significantly improved with an optimized three satellite configuration (reduction of sea level and velocity mapping errors by a factor of about 2 to 3). To resolve the high frequency and high wavenumber signals, a constellation of more than 6 satellites and/or use of wide swath techniques would be required.

Sea State Applications

Priorities are improved sampling in time and space (10-30 km/1h-6h) by satellite constellation and/or wide swath altimeters (e.g. SWIMSAT), availability of wave directional and wave period information by SAR and/or new concepts SWIMSAT), improved performances at coast. Near-real time availability of data (1-3 hours) is important for forecasting and monitoring of severe conditions.

Offshore Operations

For offshore operations, a priority is to gain accurate knowledge of ocean currents, with improved spatial resolution. Wave height remains the most important parameter for operations and design, but improved space-time resolution is required. Wave direction and period, swell and extreme waves are also important.

3.2.3 Mission Recommendations for the Short Term 2004-2007

Over this time period, Jason-1. ENVISAT (and GFO) are expected to operate. ERS-2[3] and TOPEX may continue, although they are now operating beyond their planned lifetime. The recommendations from GAMBLE for this period are given in Box 3.1.

[3] *N.B. ERS-2 is no longer providing global coverage.*

Recommendations for 2004-2007

- **Maintain Existing Missions**
  - As long as they are producing exploitable data,
  - Even in a degraded configuration (due for instance to deficiencies of one frequency of dual-frequency altimeters, radiometer, POD systems...),
    - Assuming the impact is not so severe so as to be incompatible with basic requirements.
    - Using dedicated tools and/or models to compensate (tropo/iono model, cross-over minimization, accurate mean sea surfaces...).
- **Continue T/P-Jason tandem mission**
  - as long as possible because of its proven usefulness.
- **Continue to provide near-real time capabilities**
  - with the shortest possible delay -
    - < 2 days for SSH,
    - < 5 hours for wind/wave
  - - into the operational systems on time, e.g.
    - DUACS for SSH into Mercator, FOAM, Topaz, MFS.
    - GTS for wind/wave into ECMWF and national Met Agencies.
- **Maintain and support satellite laser tracking,**
  - because of its significant contribution in Precise Orbit Determination.
  - to provide a fail-safe backup capability.
- **Prepare CRYOSAT altimeter data for Oceans applications by**:
  - Ensuring IGDR/GDR data production and access to the ocean users.
  - Developing appropriate techniques for processing the data.
    - Using the repeat sub-cycle (30 days), after constructing, from multiple altimetric time series, accurate reference mean sea level profiles along CRYOSAT tracks.
    - Developing GIM and Doris dual-frequency ionosphere models.
    - Improving wet troposphere models, based on other in-flight radiometers.
    - Studying the capability of near-real time products for ocean applications.

Box 3.1 Recommendations for altimeter missions for the short term – 2004-2007

3.2.4 Mission Recommendations for the Medium Term 2008-2011

The GAMBLE team has strong concerns regarding the situation that will exist during 2008-11. For this period only one satellite mission, Jason-2 OSTM, is presently scheduled. As indicated in earlier sections of this report, one single operational mission is not acceptable with regard to SSH, sea state, or operational requirements (e.g. DUACS error mapping higher than 20% with only one satellite, a limited 13% impact of altimetric SWH data assimilation into WAM sea-state model).

Moreover, because of the launch of Jason2/OSTM now scheduled end of 2007 at the earliest, there is a high probability of having a very damaging gap between the Jason-1 and Jason2/OSTM missions, and so a gap in the time series.

In case of an unexpected nightmare scenario, i.e. a failure of Jason-2/OSTM, and no other altimeters flying, there is no backup contingency.

Such a situation is incompatible with high priority issues related to global ocean monitoring, coastal area survey and water resources management, as indicated in the European GMES programme, nor is it sufficient to support operational ocean monitoring programmes like MERSEA and MFS in Europe, or Mercator and FOAM at the national level, which are part of the International GODAE initiative.

Bearing these strong concerns in mind, the GAMBLE Team recommendations for 2008-2011 are given in Box 3.2.

GAMBLE Recommendations for 2008-2011

- **Maintain current missions,** and their real-time capabilities, even in a degraded configuration, for as long as exploitable data are provided.
- Ensure that Jason2/OSTM is launched on schedule, without further delay beyond end of 2007, in order to avoid any potential gap in data coverage from the Jason-1 mission.
- Activate a Jason1/Jason2 tandem mission.
- Encourage the in-flight demonstration of new techniques,
  - wide swath radars (WSOA, SWIMSAT),
  - micro-satellite altimeters (Gander, AltiKa, Doppler, laser altimeters),
  - over-ocean GPS reflections.

The objective is to assess these systems with regard to requirements, for possible deployment in future missions (> 2011).

- Demonstrate and assess WSOA on-board Jason2/OSTM, involve PIs/CoIs.
- To consider and encourage public/private partnership to support future multi-satellite constellations adapted to sea-state operational requirements and consequently to SSH high resolution requirements.
- **Before mid-2004, to decide upon and initiate plans for at least one complementary mission in addition to Jason-2/OSTM to be operational in 2008.**
  - Such a two-satellite constellation is the minimum configuration, though not optimum, for dynamic topography needs, but does not meet the Sea-State operational requirements.
  - Two practical options available: the “proven” or “new” technology options.

Box 3.2 Recommendations for altimeter missions for medium term – 2008-2011

Options for a complementary altimeter mission, 2008-2011

Considering the absolute need and the high priority urgency for at least one conventional high inclination mission, complementary to Jason2/OSTM, the GAMBLE team recommends a strong endorsement by the EC, with support of space and operational agencies, to support a decision before mid-2004, between the two options which are realistically feasible with such a limited lead time, a “Proven Technology” option (taking the essential basic components from existing technology) – Box 3.3, and a “New Technology” (partly developed and not completely proven) option – Box 3.4.

On the next page we compare the relative merits of the “Proven” and “New” technology options for the recommended 2nd Altimeter Mission to be flown in the 2008-2011 time frame.

Proven Technology (Poseidon 3B)

Less expensive – Poseidon 3B approximately half the price of Poseidon 3A if built at same time

Satellite and payload development feasible in time-frame (< 4 years) *if decision is made before mid 2004.*

Jason 2B (Jason 2 replica) provides opportunity for proven low-cost complete altimetric system, with 1cm class POD and radiometer

Poseidon 3B on micro-satellite: no radiometer, no POD

Dual Frequency altimeter – ionospheric corrections, supports dual frequency applications

New Technology (AltiKa)

Cost higher because of need to develop new technology

Time-frame may be short for development required

New class of compact altimeter more suited to specific applications: coastal, ice, inland.

Opportunity to demonstrate new technology which could be applied in constellations. Possible research support from space agencies?

AltiKa on micro-satellite – built in Ka radiometer, DORIS and GPS an option

Single frequency applications only – but Ka band not sensitive to ionospheric delay

"Proven" Technology Option for 2007 Altimeter Mission

- **Altimeter:**
  Poseidon 3 B altimeter (replica of the Jason2/OSTM altimeter).
- **Platform Option 1**
  A micro-satellite platform equipped with
  - laser retro-reflector for orbit determination (10 cm class orbit capability)
  - appropriate attitude control/knowledge (0.1°)
  - near real time capability.

  Repeat orbit to take advantage of past reference mean passes

  35 days (ERS type) or 17.5 days (GFO type)

  Altitude: 800 km "class"
  - compatible with micro-satellite operation
  - better for assimilation
  - improved low altitude earth gravity field expected from GRACE and GOCE.
- **Platform Option 2**
  Passenger on-board an opportunity satellite (no orbit choice)
- **Platform Option 3**
  Jason 2B clone (same satellite and same payload as Jason 2/OSTM, including 1 cm class POD and radiometer)

Launch opportunity to be found

Box 3.3 Options using "Proven" Technology for a 2007 altimeter mission.

"New" Technology Option for 2007 Altimeter Mission

- **Altimeter:**
  AltiKa single-frequency altimeter and integrated radiometer (phase B completed).
- **Platform Option 1**
  A micro-satellite platform equipped with
  - laser retro-reflector for orbit determination (10 cm class orbit capability)
  - appropriate attitude control/knowledge (0.1°)
  - DORIS POD system and/or GPS receiver (< 4cm class orbit).
  - Near real time capability.

Repeat orbit to take advantage of past reference mean passes

35 days (ERS type) or 17.5 days (GFO type)

Altitude: 800 km "class"
- compatible with micro-satellite operation
- better for assimilation
- improved low altitude earth gravity field expected from GRACE and GOCE

- **Platform Option 2**
  Passenger on-board an opportunity satellite (no orbit choice).

Launch opportunity to be found

Box 3.4 Options using "New" Technology for a 2007 altimeter mission.

3.2.5 Mission Recommendations for the Long Term - Post 2011

The GAMBLE recommendations for the "long-term", i.e. beyond 2011 are given in Box 3.5 Recommendations for three possible missions, in addition to the planned NPOESS / Jason pair are given:

- A multi-satellite constellation based on new design altimeters which can be hosted on micro-satellites.
- Operational use of wide swath sea surface height measuring techniques.
- SWIMSAT wave measuring radar –the only option which addresses the user requirement for directional wave spectra.

A further recommendation suggests that research continues into the technique of using reflection of GNSS signals from the sea surface.

It is possible to conceive a combination of swath altimetry and micro-satellite constellations, the first to provide fine resolution (15km) of features in sea surface height, the second to provide frequent revisits of ocean regions and to improve sea state sampling.

Right we compare the capabilities of the two techniques.

Wide Swath Altimetry	**Constellation of Micro-satellites**
New technology, with challenging developments required. Unlikely to be ready for operational application until > 2011.	More conventional technology, less development required. Can be ready for operation in 2007, if decision is taken in early 2004.
No sea state measurements, except at nadir.	Sea surface height and sea state measurements.
Can satisfy operational oceanography requirements for sea surface height, but not sea state.	Can satisfy operational oceanography requirements for sea surface height and sea state.
Can provide global mapping of sea surface height at 15km resolution in 5 days. Allows "imaging" of sea surface height features.	Will provide lower spatial resolution in sea surface height than swath altimetry.
Single satellite – severe consequences of failure, if this were the only altimeter mission.	Multi-satellite constellation is robust to single satellite failure. May require > 1 launch, more complex ground segment?

GAMBLE Recommendations for Post 2011

Because, as recommended in European environmental monitoring programmes (e.g. GMES), there is a need to sustain an optimum altimetric service compatible with operational requirements and to support important new research in the ocean (meso-scale, coastal, tides, sea-state), over ice and inland waters, the GAMBLE team recommends that the EC, space and operational agencies:

- **Maintain the continuity of the T/P-Jason series over the long term**
  to keep alive this unique reference time series which started in 1992 and which is essential in many applications because of its high accuracy, consistency and robustness.
- **Develop and provide operational altimetric systems**
  Provide an operational altimetric system for systematic and continuous high-resolution sampling of the ocean by:
  1. **Building and supplying a series of multi-purpose Gander/AltiKa/Ku redundant altimeters** in order to produce low-cost (effect of mass production) altimeters with integrated radiometers, which can provide the required < 3 cm range accuracy and be accommodated on board a micro-satellite. They could be used for micro-satellite constellation, but also as nadir altimeters for other missions (e.g. WSOA missions, NPOESS, Ocean Watch...).
  2. **Launching (in 2011), a multi-satellite constellation** (a minimum of 3 satellites completed by the NPOESS altimetric mission), based on low-cost, mass-produced micro-satellites and simultaneous launches. Preferential orbits are 800 km class-orbit, high inclination, sun-synchronous ERS 35 days repeat orbit or non sun-synchronous GFO 17.5 days repeat orbit, but other orbits may be acceptable. < 10 cm class POD based on laser and low-class GPS and altimeter cross-over minimization. Laser, Doris and/or geodetic GPS tracking are optional for more accurate, independent and robust POD. Real-time capability. Radiometer on-board preferable but not absolutely needed. Altimeter measurement noise at a level of < 3 cm.
  3. **Launching an operational Wide Swath radar altimeter mission**, dependant on experience from in-flight demonstration (WSOA/Jason2), preferably on a high inclination sun-synchronous 10-20 days repeat orbit (non sun-synchronous orbit may be acceptable). Nadir altimeter needed. Very precise attitude knowledge is needed. POD preferable but not absolutely required. On board radiometer preferable.
- **Continue the development of new techniques** by conducting:
  1. **A demonstration in-flight SWIMSAT mission**. An instrument for measuring directional spectra, wind speed, significant wave height, dominant wavelengths, wave slope statistics, providing a unique contribution for constraining much better sea-state models and improving forecasts. A low altitude orbit (~ 500 km), high inclination (97-98°), is required with a repeat cycle between 8 and 35 days. Additional Sea Surface Topography measurements at the nadir, are exploitable assuming Orbit Determination accurate enough (10 cm class-orbit).
  2. **Investigate the potential of measurements, by low altitude satellites, of GPS reflections** over ocean to measure sea state and sea surface height.

Box 3.5 Recommendations for future altimeter missions in the post 2011 time-frame.

4 Conclusions

4.1 General

Through an extensive consultation exercise the GAMBLE team has carried out a detailed review of requirements for data products derived from altimeter measurements of sea state and sea surface, for operational and scientific use (including climate monitoring). The GAMBLE team makes the following general recommendations:

- Encourage space and operational agencies (CNES, ESA, Eumetsat, NASA, NOAA...) to define a common long-term strategy, based on the recommendations in section 3.2.
- Point out the vital link of these recommendations with the running of operational European environmental survey programs, like GMES and MERSEA, which rely on an uninterrupted, adapted data production service. The benefits encompass many aims central to GMES, including the monitoring of long term climate change (sea level), improved understanding and prediction of inter-annual and seasonal climate variability (El Niño, NAO), and enhancing security and safety of offshore operations (including shipping, offshore energy exploitation and defence).

4.2 Links to The European GMES programme

Over the last two years, the joint EC/ESA GMES programme has been taking shape and the initial period of the GMES action plan has been completed. GMES now encapsulates many of the EC priorities in the realm of environmental policy, and development of strategic EC capacity in monitoring the environment.

Ocean Monitoring is one of the priority themes under GMES. The stated goal of this theme is to expand the European capacity to produce global ocean information systems based on existing monitoring capabilities, in support of seasonal weather prediction, global change research, commercial oceanography and defence.

GAMBLE has directly addressed these targets and in many ways can be seen to have pre-empted these recommendations. It has consulted with users from meteorological agencies, those engaged in global change research, in commercial oceanography, defence, and in developing integrated “operational oceanography” systems. One of the key issues to recognise here is that, under present plans, “existing monitoring capabilities”, in regard to provision of satellite altimeter data, are expected to degrade significantly in the medium term. At present we are in the fortunate position to be receiving data from 5 satellite altimeters. After 2007, unless action is taken, we can expect to receive information from only one altimeter. This will have severe implications for the capability of operational systems being developed, such as MERCATOR, MERSEA, MFSTEP, FOAM, and TOPAZ – all of which require regular assimilation of reliable altimeter data to control the dynamics of their ocean circulation models. In addition, a failure of the one altimeter mission planned for the period 2008-2011 would break the continuous chain of precise altimeter global sea level measurements seen as an essential component of the international climate change monitoring programmes. *Early action is required to avoid this potentially disastrous situation.*

4.3 Research

Constellations of altimeters will play a vital role in future scientific research.

Areas where altimeter constellations will have a significant impact include: -

- Sea surface height: Ocean mesoscale, barotropic signals; coastal oceanography.
- Sea State: Mapping the wave climate, better extreme waves for design, freak wave detection.
- Other applications: Air-sea gas transfer (Kyoto monitoring), land hydrology, land and sea ice monitoring.

Areas that need investigation with regard to constellations of altimeters include: -

- Cost savings for batch production, constellation optimisation, redundancy and robustness.
- Should we mix wide swath and wave spectrum (SWIMSAT) altimeters in the constellation? How?

4.4 Future Missions to Increase Sampling

The solutions proposed by the GAMBLE team to reduce the problem of inadequate sampling fall into 2 distinct categories:

i) Develop and fly new sensors that increase the swath width.

ii) Employ constellations of small satellites designed to carry special-purpose altimeters developed from existing nadir-pointing models.

Such was the seriousness of the sampling problem that the GAMBLE team believed these two approaches should be seen as complementary, not alternatives.

Recommendations for new activities and missions included:

2004-2007

- Encourage operation of CRYOSAT to provide ocean data.
- Support continuation of laser tracking.

2007-2011

- To decide, within the next months, at least one complementary mission for flying in 2008
- To encourage demonstration of new techniques, including altimeters for micro-satellites, wide swath altimeters, and new wave radars.
- To demonstrate the "Wide Swath Ocean Altimeter" on-board Jason2/OSTM

2011 onwards

- Provide an operational altimetric system for systematic high-resolution sampling of the Ocean by:
  - Buildinga series of multi-purpose low cost redundant altimeters.
  - Launching a (minimum 3) multi-satellite constellation based on low-cost micro-satellites and altimeters and simultaneous launches (in 2011).
  - Launching an operational Wide Swath radar altimeter if supported by Jason2/OSTM.
- Continuing the development of new techniques by conducting
  - A demonstration in-flight SWIMSAT mission.
  - Investigating potential of measurements of GPS reflections over ocean to measure sea-state.

4.5 The Last Word

The GAMBLE recommendations were formulated from a thorough analysis of all aspects of satellite altimetry by a representative group of European specialists drawn from research, marine industries and service companies. They share a common concern. Monitoring of the ocean surface by more than one polar-orbiting, altimeter-carrying space platform is vital to achieving their objectives, and the objectives of the European Communities. There is little time left to implement an effective system.

The mission recommendations from GAMBLE offer a practical route to ensuring a back-up altimeter system is flying in 2008-2011. This represents the most fundamental tool for supporting the development of operational oceanography, together with improved monitoring of severe ocean weather conditions. We must also sound a warning note that, if the EC/ESA wish to encourage the introduction of commercial services on the back of these systems, businesses will be most reluctant to commit capital unless they can be assured of long term data supply. They will not risk investing in systems built on satellites designed primarily for research use, whose replacements cannot be guaranteed.

The opportunity now exists for Europe to take the lead in the deployment of monitoring systems based on constellations of robust, but technically advanced, micro-satellites. Such systems have the benefit of built-in redundancy, and can be produced very economically when compared to multi-instrumented research satellites.

47 46 45 44 43 42 41 40 39 38 37 36 35 34 33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2

5 References

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Appendix

Links to GAMBLE Documents

Documentation Web Page

http://www.altimetrie.net/documents.shtml

Reports on New Altimeter concepts

Alcatel report: Radar state of the art and new concepts for GAMBLE
http://www.altimetrie.net/docs/alcatel_altconcepts.pdf

ALTIKA: A micro-satellite Ka-band altimetry mission
http://www.altimetrie.net/docs/altika.pdf

WITTEX: A multi-satellite delay doppler radar altimeter proposal
http://www.altimetrie.net/docs/wittex.pdf

WSOA: The measurement capabilities of wide-swath ocean altimeters
http://www.altimetrie.net/docs/wsoa.pdf

High-resolution ocean topography from GPS reflections
http://www.altimetrie.net/docs/gps.pdf

SWIMSAT – A wave measuring satellite radar
http://www.altimetrie.net/docs/GAMBLE_kickoff_swimsat.pdf

GANDER – A proposal for a constellation of wave measuring micro-satellites
http://www.altimetrie.net/docs/GAMBLE_delft_cotton_gander.pdf

GAMBLE "Theme" Reports

Theme 1 Final Report: Sea height error budgets, feature detectability:
http://www.altimetrie.net/docs/GAMBLE_finalreport_theme1.pdf

Supplementary Theme 1 Report: The contribution of the TOPEX/Poseidon - Jason 1 tandem mission to meso-scale variability studies
http://www.altimetrie.net/docs/GAMBLE_tandemreport_theme1.pdf

Theme 2 Final Report: Sea state error budgets, feature detectability:
http://www.altimetrie.net/docs/GAMBLE_finalreport_theme2_030126.pdf

Theme 3 Final Report: Orbit determination and satellite tracking:
http://www.altimetrie.net/docs/GAMBLE_finalreport_theme3.pdf

Theme 4 Final Report: Future Priorities for Satellite Provision of Sea State and Ocean Current Data - 2005 and beyond: Marine Operator's Workshop
http://www.altimetrie.net/docs/GAMBLE_OWS_Frep.pdf

GAMBLE Mid-term Review: Technical Report on Error Budgets and Technical Solutions
http://www.altimetrie.net/docs/GAMBLE_mtr_d8.pdf

Theme 5 Report: Framework for Recommended Research Programme
http://www.altimetrie.net/docs/GAMBLE_WP7.pdf

Theme 6 Report: Recommendations for Future Altimeter Programmes (Satellites, payloads and Orbits).
http://www.altimetrie.net/docs/GAMBLE_WP8v1.pdf

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