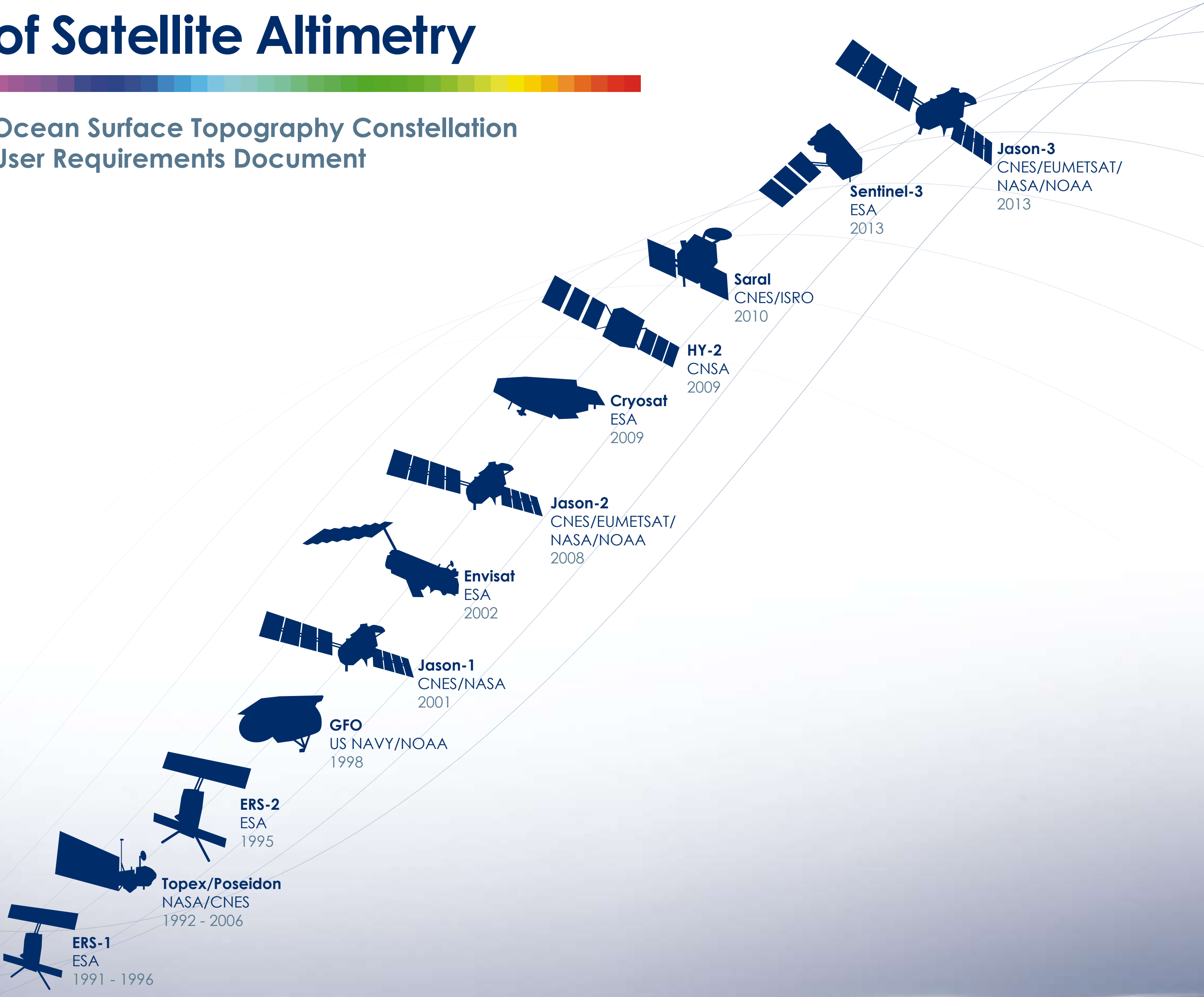
The Next 15 Years of Satellite Altimetry

Ocean Surface Topography Constellation User Requirements Document



Prepared by

P. Escudier (CLS) and
J.-L. Fellous (Orange Bleue Conseil)

Intentionally left blank

TABLE OF CONTENTS

Intentionally left blank

EXECUTIVE SUMMARY

After over fifteen years of satellite altimetry time has come to take stock of the progress made. From the early 1990s learning period to the late 2000s the community of ocean altimetry data users has grown from a narrow group of selected PIs to a broad family of well-trained practitioners, ranging from researchers to operational ocean forecasters. This evolution was made possible thanks to the many advances in satellite technology, data processing, transmission delays, algorithm development on the one hand, and on the other hand thanks to the effort of several centres worldwide, which have worked at developing integrated products and producing them in near-real-time for operational use.

The present document builds on the recommendations of the Venice conference in March 2006, which highlighted this progress and derived high-level requirements for the next 15 years of satellite altimetry, and on the outcome from the Assmannshausen meeting in January 2008, which followed up with recommendations for future mission planning. It aims to harmonize mission planning amongst the altimeter providers, to lay the basis for timely access to altimetry data, to share lessons learned, especially for the new partners in altimetry, and, to provide the next level of detail for planning the next 15 years. It is an element of the Ocean Surface Topography Constellation activity, initiated by CEOS in 2006 and led by EUMETSAT and NOAA, scoping to improve altimetry mission coordination amongst the many participating agencies and nations, including the USA, Europe, India, China, and the Russian Federation. In that purpose it has been assembled in a way that implied a wide consultation and outlines requirements and targets ensuring a broad community buy-in.

This document lists high-level requirements placed upon the altimetry satellite constellation for the next 15 years to meet the major operational and science objectives to monitor the ocean topography. This source document is intended to be the input which will guide the definition of requirements of future altimetry missions. The requirements are functional and do not imply a specific design of each element of the constellation.

The document recalls the history of satellite altimetry, with a collection of initially independent missions, eventually leading to the establishment of the concept of an Ocean Surface Topography Constellation. This involves a series of reference missions which overlap in time and provide the absolute accuracy of the global constellation, complemented by at least two and preferably three other core constellation missions extending the coverage to high latitude and ensuring denser geographical and time resolution, and by contributing missions which add to the ensemble and benefit from its overall accuracy and coverage.

The document contains a thorough analysis of the user requirements stemming from the numerous research fields, operational applications and services which benefit from altimetry data, including operational ocean forecast systems, seasonal forecast, mesoscale and coastal applications, climate, marine meteorology, extreme events, sea level rise, studies of global ocean circulation, variability, tides, inland waters and ice, etc.

Based on this analysis a series of high-level user requirements has been defined that supports the rationale for the minimum composition and general characteristics of the Ocean Surface Topography Constellation and can serve to quantitatively define its technical characteristics.

Specific requirements, targets and overall guidance are summarised at mission level regarding constellation mission definition, calibration/validation, data management, as well as at altimetry system level as regards sampling characteristics, performance and error budget.

This document is intended to be a living document, and will be subject to regular updates and improvements, based on progress made by the ocean community and space agencies in this extremely active domain of research and application.

Intentionally left blank

1. FOREWORD

After over fifteen years of satellite altimetry time has come to take stock of the progress made. From the early 1990s learning period to the late 2000s the community of ocean altimetry data users has grown from a narrow group of “happy-few” selected PIs to a broad family of well-trained practitioners, ranging from researchers to operational ocean forecasters. This evolution was made possible thanks to the many advances in satellite technology, data processing, transmission delays, algorithm development on the one hand, and on the other hand thanks to the effort of several centres worldwide, such as those now consorted in “MyOcean” in Europe and “BlueLink” in Australia among others, which have worked at developing integrated products and producing them in near-real-time for operational use.

The present document builds on the recommendations of the Venice conference in March 2006, which highlighted this progress and derived high-level requirements for the next 15 years of satellite altimetry. It also builds on the outcome from the Assmannshausen meeting in January 2008, which followed up with recommendations for future mission planning.

This document aims to harmonize mission planning amongst the altimeter providers, to lay the basis for timely access to altimetry data, to share lessons learned, especially for the new partners in altimetry, and, to provide the next level of detail for planning the next 15 years.

It should be seen as an element of the Ocean Surface Topography Constellation activity, initiated by CEOS in 2006 and led by EUMETSAT and NOAA, scoping to improve altimetry mission coordination amongst the many participating agencies and nations, including the US, Europe, India, China, and the Russian Federation. In that purpose it has been assembled in a way that implied a wide consultation and outlines requirements and targets ensuring a broad community buy-in.

Intentionally left blank

2. INTRODUCTION

2.1 PURPOSE AND SCOPE

This document lists high-level requirements placed upon the altimetry satellite constellation for the next 15 years to meet the major operational and science objectives to monitor the ocean topography. This source document is intended to be the input which will guide the definition of requirements of future altimetry missions. Recognizing that science and operational objectives of altimetry cannot be handled by a unique mission, this should allow maximizing the synergy between those missions and improving the efficiency of the global altimetry constellation or system of systems. The requirements are functional and do not imply a specific design of each element of the constellation (e.g. a mission of the constellation can meet more than one requirement simultaneously.

These mission objectives are built on the strong heritage from the use of previous altimetry missions developed by space agencies in Europe (ESA, CNES, EUMETSAT) and in the U.S. (NASA, NOAA, US Navy).

This document follows up the “Purple book” [1] initiative, which defined in 1992 the requirements for altimetry missions in the period 1990-2010 and has served as the basis for mission implementation during this period. It is splinted in three parts:

- Section 2: Introduction
- Section 3: Scope of altimetry mission applications. This was built based on published references completed by specific interviews of key experts.
- Section 4 provides an explanatory introduction to Sections 5 and 6, which include the set of requirements that shall be met to fulfil the user requirement listed in Section 3. Justification of these requirements is in the referenced papers which synthesize science findings and more than 20 years of studies managed by space agencies.

2.2 BACKGROUND

2.2.1 THE RECENT HISTORY OF SATELLITE ALTIMETRY

With the introduction of satellite remote sensing in the 1970s, traditional oceanographers were provided a new tool to collect synoptic observations of conditions at or near the surface of the global ocean. Since that time, there has been dramatic progress. Satellites are revolutionizing oceanography. Subsurface observations (e.g., the Argo network) and satellite-derived observations of the sea surface—collected as an integrated set of observations and combined with state-of-the-art models—have proven their ability to yield highly accurate estimates of the three-dimensional, time-varying distribution of properties for the global ocean. Neither satellites nor *in situ* observing systems can do this on their own. And if such observations can be collected on a sustained and timely basis, they can provide oceanographers with an observational capability conceptually similar to that which meteorologists use on a daily basis to forecast weather.

Our ability to understand and forecast oceanic variability, how the oceans and atmosphere interact, critically depends on an ability to observe the three-dimensional global oceans on a long-term basis. Indeed, the increasing recognition of the role of the ocean in weather and climate compels us to implement an *integrated*, *sustained* satellite and *in situ* observing system for the oceans. Such a system may complement the observing system which already exists for the atmosphere, thereby extending our capability to address the coupling between the oceans and atmosphere.

During the decade of the 1980s, considerable efforts were devoted in the U.S. and Europe to convincing traditional oceanographers that satellites were an important observational tool ready to be exploited for ocean science. A broadly based Satellite Planning Committee (1984) established in the U.S. published a report entitled *Oceanography from Space: A Research Strategy for the Decade, 1985-1995*, linking altimetry, scatterometry and ocean colour with the major global ocean research programs being planned at that time, the World Ocean Circulation Experiment (WOCE), Tropical Ocean Global Atmosphere program (TOGA), and Joint Global Ocean Flux Study (JGOFS). By examining the potential synergy between oceanic variables which could be measured from space, this led to the idea of understanding the ocean as a system. This strategy, still being followed today, served as a catalyst to engage the greater community, to identify the most important missions and to develop an approach for their prioritization.

The European ERS-1 was launched in 1991 and ERS-2 followed in 1995; included in the payload for each was an altimeter package. The U.S.-French Topex/Poseidon was launched from Kourou in August 1992. Its accuracy represented the culmination of more than a quarter of a century of steady incremental progress in the succession of altimetry satellites. The first, GEOS-3 (1975), detected the sea surface height changes from gravitational effects over major trenches. Then Seasat (1978) showed that ocean eddy signatures could be measured by altimetry. Next, Geosat (1985) was useful as well for measuring eddy variability, with ERS-1 and -2 being improvements over Geosat, because they included radiometers for the water vapour correction and had better orbit determination. The high-density data set acquired by ERS-1 during its geodetic mission, together with the dense Geosat data (once declassified), provided a detailed view of the marine gravity field with a spatial resolution better than 5 km.

Topex/Poseidon featured even better orbit determination and showed the importance of dual-frequency altimetry for reducing errors due to ionospheric effects. Topex/Poseidon data were also useful for improving the orbits of ERS-1 and -2 [2] through analyses of Topex/Poseidon and ERS crossovers as demonstrated (Figure 1) by the DUACS project [3]. The long data record—since 1992—has enabled an analysis of interannual variability, such as the spatial extent of the El Niño; has started to resolve decadal variability in the global oceans associated with phenomena such as the North Atlantic Oscillation, Pacific Decadal Oscillation, and Indian Ocean Dipole; and has contributed to the knowledge of the spatial variability of global sea level rise.

Anticipating this success a new strategic planning document was released in 1992, describing *"The future of space-borne altimetry: Oceans and Climate Change"*, edited by C. Koblinsky, P. Gaspar, and G. Lagerloef [1]. This so-called "Purple Book" established firmly the concept of a space-based ocean circulation observing system including a high-altitude, low-inclination mission carrying a high-precision altimeter package (the reference mission) on a non-sun-synchronous, repeat orbit, for the determination of large-scale ocean currents, complemented polar-orbiting missions carrying altimeters providing an extended temporal and spatial sampling providing information on the mesoscale eddies.

This strategy came to fruition in the early 2000s. Jason-1 was conceived by NASA and CNES as an altimetry mission to follow Topex/Poseidon mission—maintaining its accuracy, but at a lower cost. It was launched in December 2001. ESA's Envisat was launched in March 2002; its payload included a radar altimeter the Doris tracking system, a microwave radiometer (MWR), an advanced SAR (the ASAR), an advanced ATSR (the AATSR), and the Medium Resolution Imaging Spectrometer (MERIS) The combination of ENVISAT, Jason-1, Topex/Poseidon (which had been moved to an interleaved orbit with Jason-1), ERS-2 and GFO allowed high-resolution mapping of sea surface height variability and demonstrated the capability of multi-satellites altimetry to monitor mesoscale variability and to feed ocean models, paving the way for operational oceanography [4].

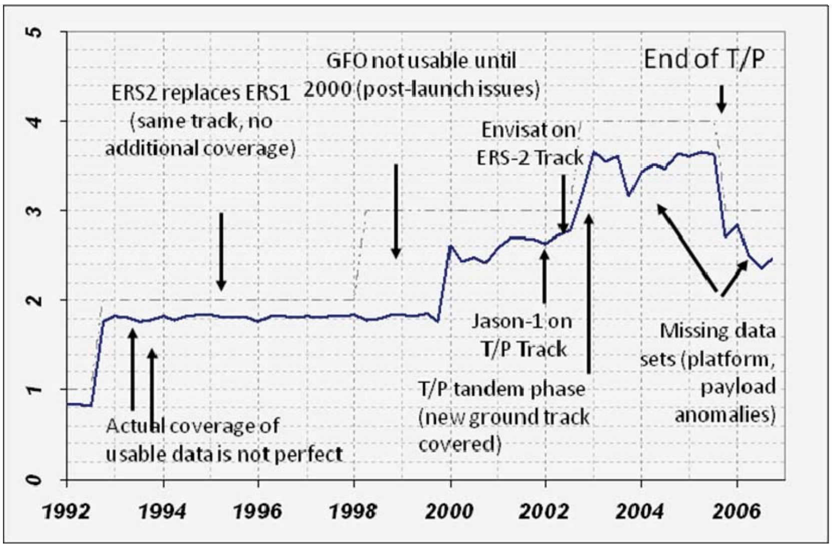


***Figure 1** – Number of altimeters in operations used by SSALTO/DUACS (solid line) taking into account monthly unavailability and number of altimeters that DUACS would have used with an ideal coverage and data editing (dashed line).*

By that time operational centres became more and more acquainted with this type of data and expressed interest in the continuation of these series and this led to the involvement of operational agencies. The European Space Agency recently initiated the Sentinel Series, including ocean-dedicated missions [5, 6, 7, 8, 9, 10]. New initiatives from India (SARAL) and China (HY-2) complement the US/Europe efforts to develop an altimetry satellite constellation.

2.2.2 A NEW USER REQUIREMENTS DOCUMENT

Altimetry data have proven extremely useful (and in fact irreplaceable) for data assimilation into ocean forecasting models, and a coalition of centres in Europe, assembled through the European Large Integrated Project MERSEA, have developed a European strategy in the context of GMES to provide *Marine Core Services*, based on ocean modelling and data assimilation. The European GMES Bureau is establishing a Marine Core Service Implementation Team, which has clearly formulated its requirements in terms of observation from satellite data [11, 12]. In addition operational coupled ocean-atmosphere (and wave) models are being developed and used by meteorological agencies, such as ECMWF in Europe or NOAA/NCEP in the US for hurricane, seasonal longer range and forecasts (HWRF/HYCOM/WAVEWATCH). In order to provide adequate sampling of the ocean, an appropriate combination of multiple satellite data is necessary.

Furthermore space agencies participating in CEOS, the Committee on Earth Observation Satellites, have engaged in a process to improve their coordination, particularly as regards the response to the requirements of the Global Climate Observing System (GCOS), many of which pertains to ocean observation and specifically altimetry and sea surface topography. Moreover CEOS agencies have established the so-called "Virtual Constellations for GEO", with a view to respond to long-term requirements for Earth Observation in the framework of a Global Earth Observation System of Systems. Amongst the first four prototype constellations is the "Ocean Surface Topography Constellation", involving CNES, DLR, ESA, EUMETSAT, NASA, NOAA, ISRO, SOA, and currently led by NOAA and EUMETSAT. The Venice Symposium on "15 years of Progress in Altimetry", held in March 2006, had produced a consensus set of recommendations concerning the transition of satellite altimetry into a sustained global system supporting operational oceanography and climate monitoring [13]. The Ocean Surface Topography Constellation Workshop [14] held in Assmannshausen, Germany, in early 2008 took up those recommendations and outlined a roadmap (Figure 2) for their implementation over the next 15 years.

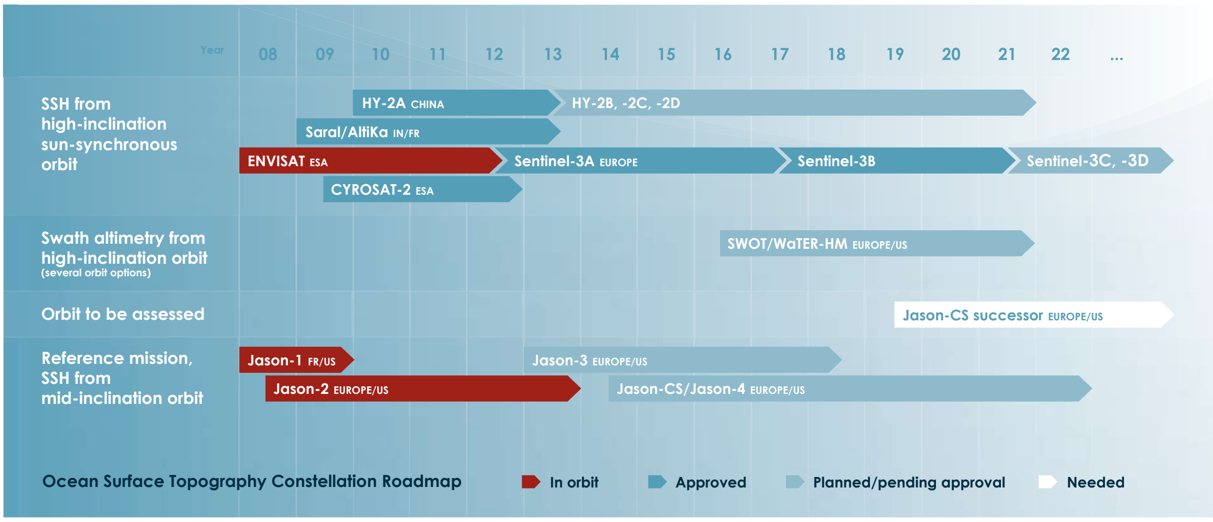


Figure 2 *– Altimetry roadmap (from the OST Constellation Workshop, Assmannshaussen, Germany, January 2008)*

Time is now ripe for the establishment of a new high level user requirements document in pace with the long-term strategy for ocean altimetry, that will respond to these various endeavours and provide a firm basis for worldwide contributions to this essential observation. The OST virtual constellation will rely on the following contributions:

- A series of reference missions which overlap in time,
- Core constellation missions, and,
- Contributing constellation missions.

The reference missions provide the absolute accuracy of the global constellation.

The core constellation missions extend the coverage to high latitude and ensure denser geographical and time resolution to monitor the global ocean with the appropriate sampling.

The contributing constellation missions will provide additional time or space coverage and in return will benefit from the absolute accuracy improvement provided by the reference mission and from the complementary coverage provided by other contributing agencies.

2.2.3 THE NEED FOR ALTIMETER MEASUREMENTS

Altimeter measurements have become an essential component in many earth observation sciences, and particularly in ocean studies. Since the launch of Topex/Poseidon and ERS-1/2 in the early 90s, followed by Jason-1 and Envisat and complemented by GFO, this continuous sampling of the ocean by altimetry measurements has permitted the development of operational oceanography Ocean modelling and forecasting systems have been built up based on this continuous and accurate ocean state observation, associated with an increasing number of *in situ* measurements. Operational oceanography then moved from experimental to sustainable and allowed development of end user applications, environmental monitoring and downstream services.

Several skills are now required from altimeter missions:

- Precise ocean sampling by multi-mission measurements in order to allow analysis and forecast of the ocean state through model assimilation.
- Continuous and accurate observation for mean sea level monitoring and climate change estimation and forecasting
- Additionally, sufficient wind/wave determination for assimilation into atmospheric meteorological models, taking advantage of these parameters derived from altimeter measurements).

This multiplication of altimetry applications has made the expression of mission requirements a more complex endeavour

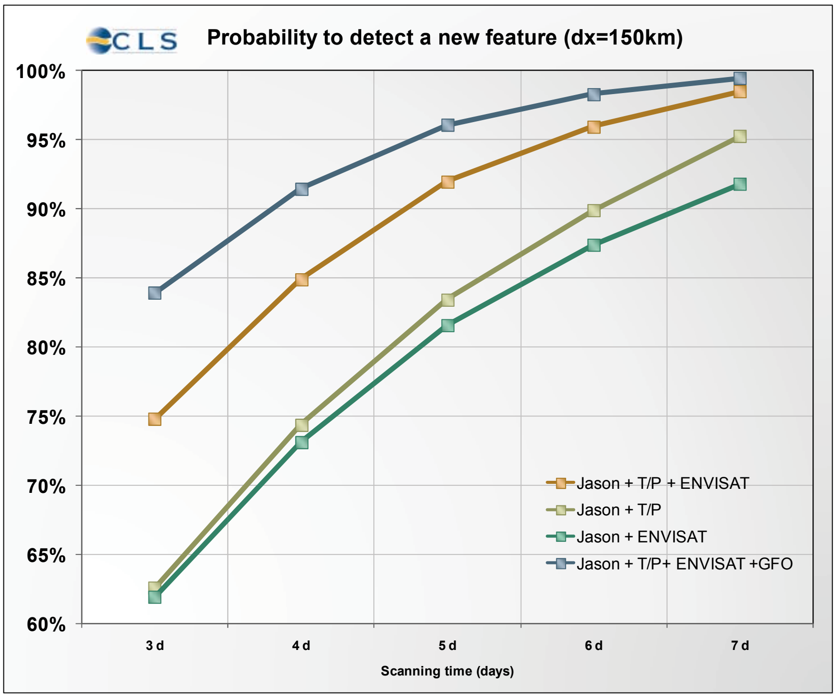


***Figure 3** – Probability to detect a new (or changing/moving) structure as a function of the scanning time for signals with a de-correlation scale of about 150 km (e.g., mesoscale feature). Geometrical simulation is limited to the Atlantic and performed with Near-Real-Time data (after [3]).*

According to the report from the Jason-3 Application Working Group [15], several altimetry missions flying together are necessary to ensure the required ocean observation capacity, together with *in situ* data measurements:

- Continuity of high accuracy altimeter missions, following Topex/Poseidon, Jason-1 and Jason-2/OSTM missions,
- Complementary higher inclination altimeter missions, at least two and preferably three other missions (Figures 3 and 4), to ensure the required space/time sampling for non-degraded operational service of sea surface height, dynamic topography and sea state determination.

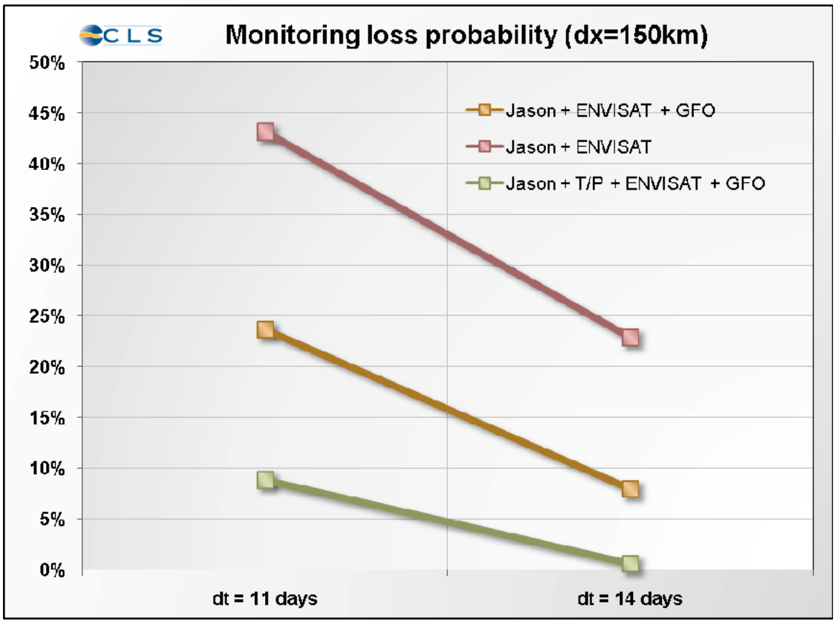


Figure 4 *– Probability to lose continuous tracking of a 150 km structure for de-correlation times of 11 and 14 days and for constellations of 2 to 4 satellites* (after *[3]).*

2.2.4 OPERATIONAL OCEANOGRAPHY UNDER DEVELOPMENT IN EUROPE

Operational oceanography and sustainable services to environmental stakeholders and downstream applications will be the main goals of the GMES Marine Core Service (MCS) which is currently building up within Europe. The MyOcean project, selected for implementing the GMES MCS, gathers a large number of European contributors [16]. It aims at developing this operational capacity, based on continuous high accuracy observations. In particular, the Sea Level Thematic Assembly Centre (SL-TAC) will be the operational service providing sea level observations for Monitoring and Forecasting Centres and downstream services. One major component of the global set of ocean observations is provided by altimeter missions.

2.3 KEY TERMS AND DEFINITIONS

Requirement
A “requirement” as used in this document specifies a condition, parameter, or capability with which the system design must be compliant, verifiable, and have a demonstrated achievement during the mission. In other words *a requirement is critical to the mission success.* All requirement statements are preceded by the word “**REQ**” and use the verb “shall”.

Target
A “target” as used in this document specifies a condition, parameter, or capability with which the system design will strive to be compliant but it is not mandatory that such compliance be verifiable or have a demonstrated achievement during the mission. Mandatory compliance or demonstrated achievement is not required because the capabilities in the systems limit the performance, because the inherent technical difficulty with the achievement is too great, or because cost of achievement is too large, or even because it cannot be verified. Nevertheless, a target is tracked like a requirement so if resources or capabilities permit compliance, better system performance will result. All target statements are preceded by the word “**TARG**” and use the verb “will”.

Guidance

A "guidance" as used in this document specifies a design condition, parameter, or capability which is critical for the achievement of mission performances. It represents the state-of-the-art, based upon the heritage of the last 15 years of altimetry. Different design concept may be proposed, pending appropriate justification that it will allow to fulfil mission requirements. A guidance is considered critical to the mission success. All guidance statements are preceded by the word "**GUID**".

3. SCOPE OF ALTIMETRY MISSION APPLICATIONS

Altimetry missions started initially as research satellites, though one of their goals was to "pave the way to future altimetry satellites" providing supporting operational ocean forecasting. At present and in the future the operational altimetry satellite component can be seen as "a service to the research community".

While this document focuses on the requirements for satellite altimetry, one should keep in mind that observing the ocean requires an integrated system, including space-based and *in situ* elements. Synergies exist between satellites and complementary observing systems; for example: altimetry, Argo, and Grace for global sea level rise; altimetry and scatterometry complemented by ocean surface sensors for wind-wave generation and wind-driven currents; etc. An ocean observing system missing the adequate balance of complementary space-borne, surface and sub-surface systems would not provide the proper monitoring of the key ocean parameters of societal importance, such as sea level rise, hazardous wind and waves, storm surges, etc. and would not deliver the benefits that are expected from its deployment.

3.1 OPERATIONAL SERVICES

Among the objectives of altimetry was the development of operational data production and distribution: this objective has been achieved beyond initial expectations. Today, several operational ocean or meteorological services rely heavily on data products provided by altimetry satellites. For those services, the continuity in altimetric measurements as well as in the data access systems and tools is essential. As explained in the introduction of this document, two fairly distinct classes of operational applications exists, each leading to specific requirements.

Short-term products: Operational applications related to ocean and climate monitoring (and/or forecasting) are mostly concerned with time scales of several days to months. A latency of a few days is acceptable, in particular as it allows a better orbit determination and hence a more accurate altimetric precision. Requirements for Slow Time critical (STC) products will be derived from those short-term application needs.

Near-Real-Time products: Applications related to marine meteorology involve much shorter time scales, both in terms of phenomena observed and in terms of data flow needs. Near-real-time availability of the products is absolutely necessary; therefore corresponding operational services will use Near-Real-time (NRT) products (typically data within three hours of collection).

Beyond purely operational applications it should be noted that Cal/Val activities also require a relatively short data delivery delay, because they may have a direct impact on the on-time GDR production. Cal/Val participants mainly use short-term products (STC) but some specific activities (e.g., support for an *in situ* ocean campaign) might require the use of near-real-time products.

Finally, as already mentioned above, an important aspect of all applications, whether research or operational, described in this document is that they all require the combination of altimetry measurements with other data, either from *in situ* networks or from other satellite missions. Therefore the operational requirements for altimetry missions have to take into account this necessary integrated approach.

3.1.1 SHORT- AND MID-TERM APPLICATIONS (OCEAN CLIMATE)

3.1.1.1 OPERATIONAL OCEAN FORECAST SYSTEMS AND SEASONAL FORECAST

The Global Ocean Data Assimilation Experiment (GODAE) was initiated in 1997. The objective of this international initiative was to set up a *"global system of observations, communications, modelling and assimilation that will deliver regular, comprehensive information on the state of the oceans"*. In this framework, operational and research institutions from Australia, Japan, United States, United Kingdom, France, Norway, Italy, etc. have been developing global ocean data assimilation and ocean forecast systems [17]. Such systems are already running operationally and depend heavily on satellite ocean observation systems.

3.1.1.2 MESOSCALE AND COASTAL APPLICATIONS

The monitoring and forecasting of mesoscale ocean signals (30-300 km and 20-90 days of typical scales) has specific applications in domains like fisheries, marine safety, monitoring of oil spills, marine fauna surveys, oil drilling, commercial navigation and military defence. One of the first quasi-operational applications of altimetry, conducted by NOAA with Geosat data in association with *in situ* and satellite imagery data, was the survey of the meandering of Gulf-Stream and associated eddies.

This part of the ocean signal is particularly important because of its high variability and rapid time-space evolution associated with strong energy transfer between the ocean surface and sub-surface and atmosphere. Monitoring and predicting the three-dimensional structure of mesoscale activity is a sensitive issue for specific submarine applications It also has civilian applications in fishery and fauna survey because of the preference of certain species to follow eddies, current meanders or oceanic fronts.

Mesoscale as well as coastal activities have a rapid time-space evolution (less than 5 days) which requires a dense and homogeneous temporal and spatial sampling (making necessary the combination of coordinated, simultaneous altimeter satellites) and data available with a very short delay. A specific effort must be conducted in the near-coast areas (less than 20 km from the coast) where dedicated processing and adequate corrections (as for tides and troposphere) will be needed.

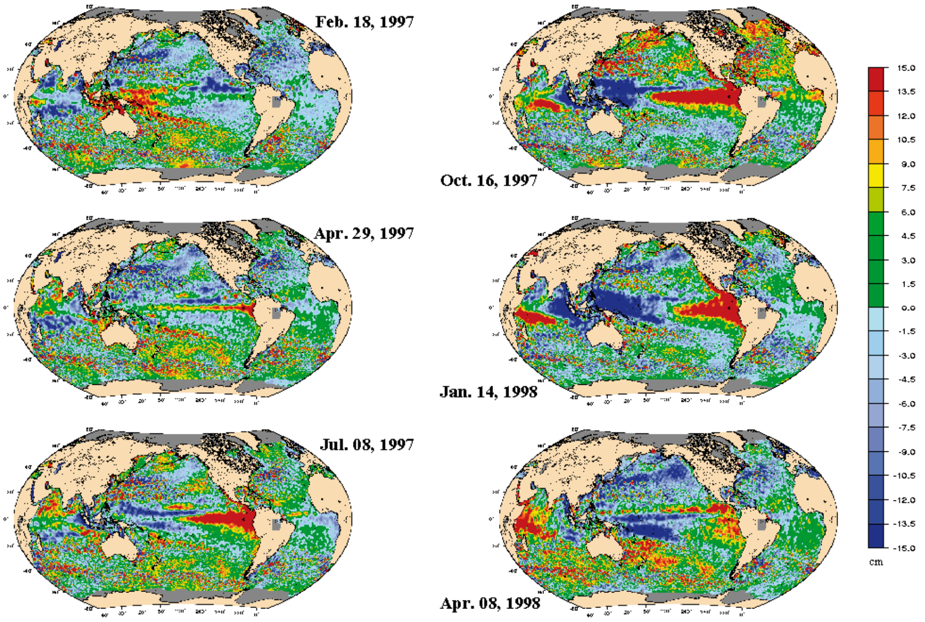


Figure 5 *– Maps of sea level anomalies in 1997-1998 showing the evolution of the El Niño phenomenon.*

3.1.1.3 CLIMATE APPLICATIONS

Prediction of El Niño type events is a particularly important issue because of the impact of such interannual anomalies on climate and consequently on economic and social activities of countries affected by these events. They have an impact not only over the tropical Pacific region, where they are generated and most apparent, but also on the entire Earth's climate. Recent attempts to improve forecasts of ENSO events have been implemented using coupled ocean-atmosphere models fed by *in situ* and satellite data including altimetry. These first altimeter data assimilation runs have improved the long term forecasting skill (6 months to 1 year in advance) in ECMWF and other centres [18, 19]. In addition to ENSO there are many ocean variations from intra-seasonal to interannual scales, such as the Indian monsoon, which have a great impact on climate involving typical scales from 300 to 3,000 km and from 100 to 1,000 days (even decadal signals have been detected). High quality altimetry is able to detect with an unprecedented accuracy the corresponding changes in sea level (Figures 5 and 6). For example the birth and death of Kelvin and Rossby waves which are generated by wind fluctuations can be captured very precisely by altimetry. Incorporation of such information into models is of primary interest to improving forecasts.

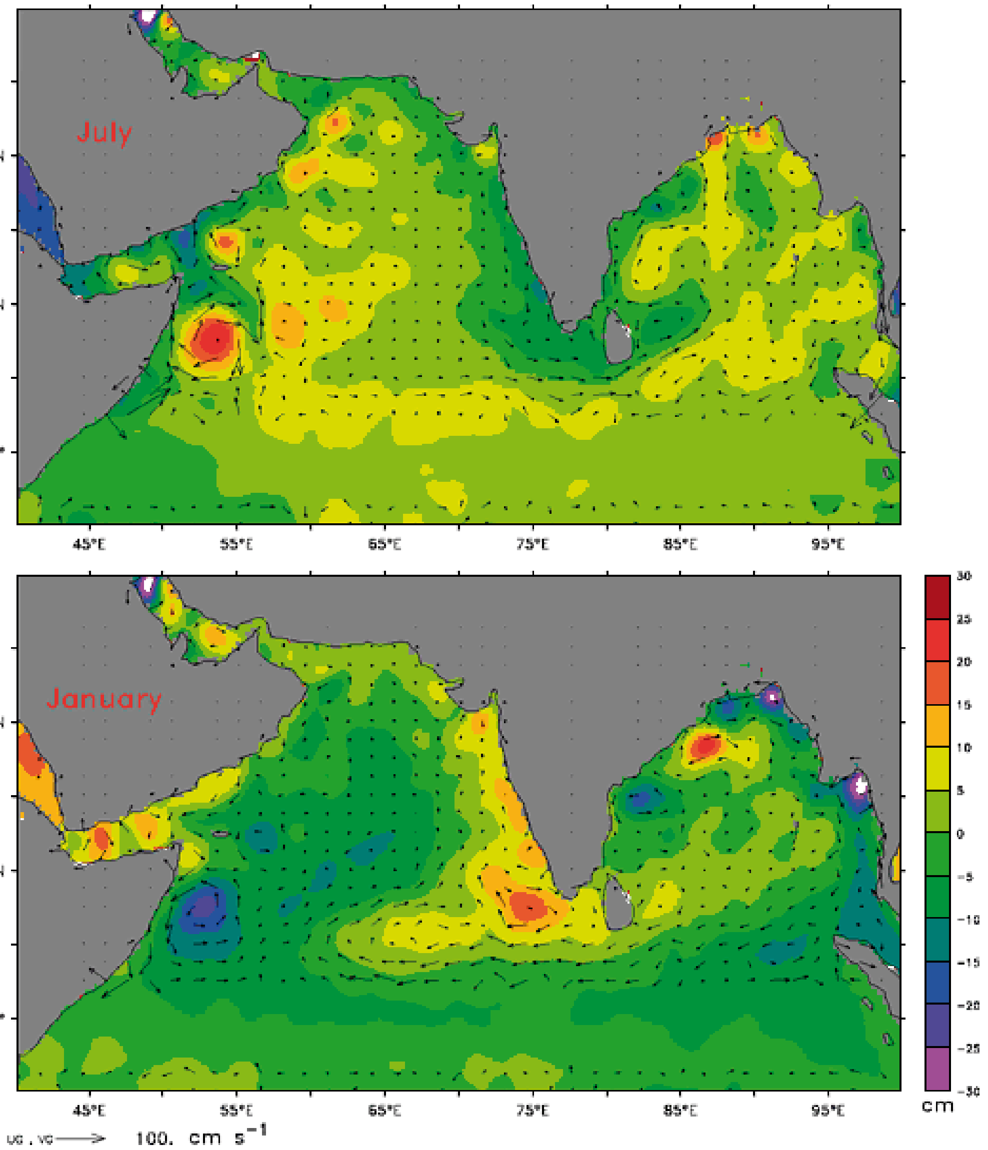


Figure 6 *– Mean over several years of sea level anomalies (cm) and geostrophic currents (cm/s) from Topex/Poseidon in January (winter monsoon) and July (summer monsoon)*
(Credits: National Institute of Oceanography, Goa, India).

The GCOS Implementation Plan Satellite Supplement [20] clearly states the need to "ensure continuous coverage from one high-precision altimeter and two lower-precision but higher-resolution altimeters" and presents challenging target requirements (accuracy: 1 cm; spatial and temporal resolution: 25 km horizontal resolution, daily observing cycle; and stability: 0.5 mm/decade). Altimetry missions in the past have fulfilled or exceeded initial objectives placed on the error budget, pushing back the limit of observability of large scale ocean signals. Significant signals with centimetre amplitudes are now detected without applying any data filtering, confirming the benefit of similar accuracy and sampling requirements for follow-on missions.

3.1.2 NEAR REAL-TIME APPLICATIONS (OCEAN WEATHER)

3.1.2.1 MARINE METEOROLOGY APPLICATIONS

The two parameters measured by altimetry that have meteorological applications are wind speed and significant wave height (SWH). Sea-state forecasts are crucial for many activities related to maritime industries (e.g., fishing, oil drilling, and navigation). New generation models have been implemented to provide better sea-state analysis and prediction. However, sea-state is a parameter which changes rapidly within a few hours, requiring dense

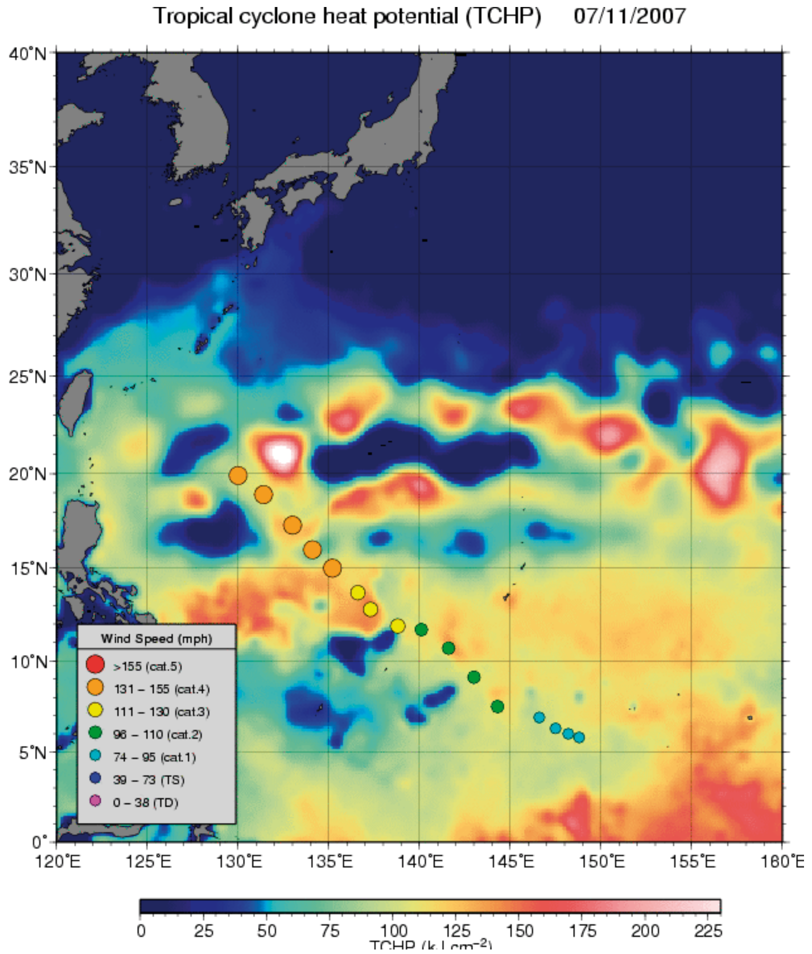


***Figure 7** – Tropical heat potential and typhoon ManYi induced wind speed, 11 July 2007*
(Credits: G. Goni, NOAA)

and frequent measurements and availability within a few hours. Conventional *in situ* networks are not dense enough to constrain the models efficiently, especially in the southern hemisphere where *in situ* data coverage is very sparse. Interest in satellite data is then obvious; multiple satellite inputs allow significant improvements in time and space resolution. Wind speed and SWH measured by altimetry have shown their potential through preliminary experiments of altimetric data assimilation into models using ERS, Topex/Poseidon, Envisat and Jason-1 data. Operational systems are already running in several meteorological centres providing reliable 12-24 hours forecasts. However it must be recognised that many National Meteorological Services, particularly in developing countries and emerging countries have never routinely used SWH in their operational forecasting, though these products are simple, integrated and readily available on the GTS. Significant efforts have to be devoted to increasing awareness, developing capacities and promoting the use of these products.

3.1.2.2 OTHER NEAR-REAL-TIME APPLICATIONS: EXTREME EVENTS

Tropical cyclones and hurricanes are among the most frequent catastrophic events in warm seas. Their birth is now well understood, but forecasts of their pathways and changes in intensity are of major importance for people living in coastal areas affected by tropical cyclones. Several parameters derived from altimetry can contribute to this forecast. First, as described in the previous section, wave height and wind speed data are used for marine meteorology and therefore benefit traditional hurricane forecasting. Second, the knowledge of mesoscale circulation is a valuable tool to be used for intensity forecasting. Indeed, advances in the mapping of mesoscale circulation have helped map deep, warm features, such as those associated with the Loop Current in the Gulf of Mexico. Since the heat content of the underlying ocean plays a major role in hurricane birth and intensification, cold and warm eddies can modify the intensity of hurricanes.

The Tropical Cyclone Heat Potential (TCHP) is an altimeter-derived parameter proportional to the integrated vertical temperature from the sea surface to the depth of the 26°C isotherm. In addition to maps of SST and ocean model output, maps of TCHP have proven to be very useful to monitor sudden intensification of tropical cyclones (Figure 7).

3.2 SCIENCE OBJECTIVES

The altimetry satellite constellation should be designed to provide accurate sea surface topography to determine the general circulation of the ocean and understand its role in the Earth's climate, hydrological and biogeochemical cycles. Very accurate, i.e. within 1 cm at a basin scale, global, homogeneous and adequately sampled in time and space sea surface topography measurements are required to precisely monitor the ocean and fulfil the requirements of the various applications described hereafter.

3.2.1 MEAN SEA LEVEL TREND

Mean sea level is a pertinent indicator of global climatic changes related to global warming. Because of thermal expansion from temperature increases, the ocean occupies a larger volume. One degree of temperature rise over one hundred meters of depth is enough to increase sea level by a few centimetres. Sea level also rises due to mass transfer between earth or atmosphere and ocean such as inputs from melting glaciers. Sea level rise, if it continues for hundreds of years, would have dramatic socio-economic and environmental consequences. This is why it is so important to monitor the current sea level trend. Until recently, the only instruments capable of monitoring the sea level trend were tide gauges, which have shown about 15 cm of elevation over the twentieth century.

Altimetry data have confirmed the sea level rise observed by tide gauges over the last 16 years. However, this signal represents only about 3 millimetres per year (Figure 8) on average with a large regional variability, which demands extreme caution when interpreting the results (Figures 9a and 9b). The detection of such a small signal is very difficult. Indeed it requires a millimetre-level control on the potential drifts of the altimetric system components (altimeter, geophysical corrections, orbit, system reference...) The error in sea level trend estimation will decrease as the time series becomes longer. This reinforces the need for multi-decadal (and continuous) altimetric observations. It also implies a precise inter-calibration between successive satellite time series to fully resolve the measurement bias between missions. In parallel further combination with satellite gravimetric measurements (e.g., the Grace mission) is being conducted, which helps separate the thermal expansion component from the global mass change component Justification for altimetry mission error requirements associated with this application is documented in [21 .

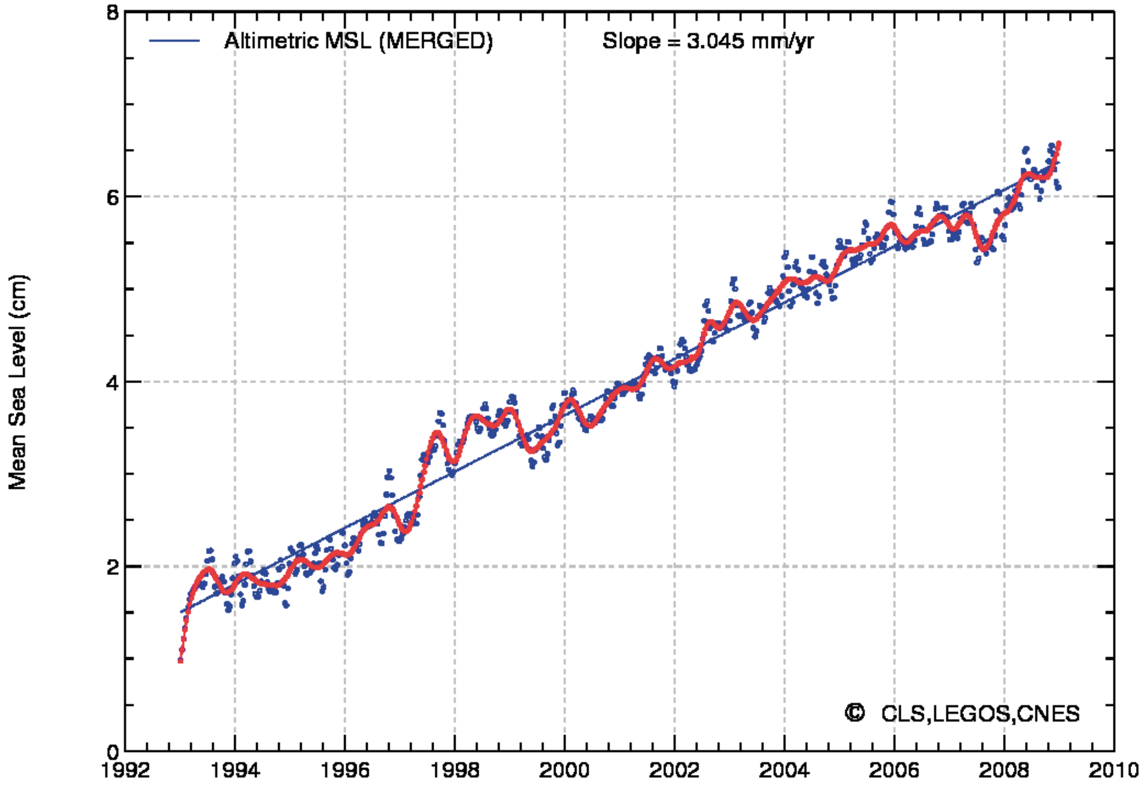


Figure 8 – Global mean sea level since October 1992 as seen by the altimetry satellites. Seasonal variations have been removed. Data are corrected from inverse barometer effects, but not from post-glacial rebound (Credits: CLS/Legos/Cnes).

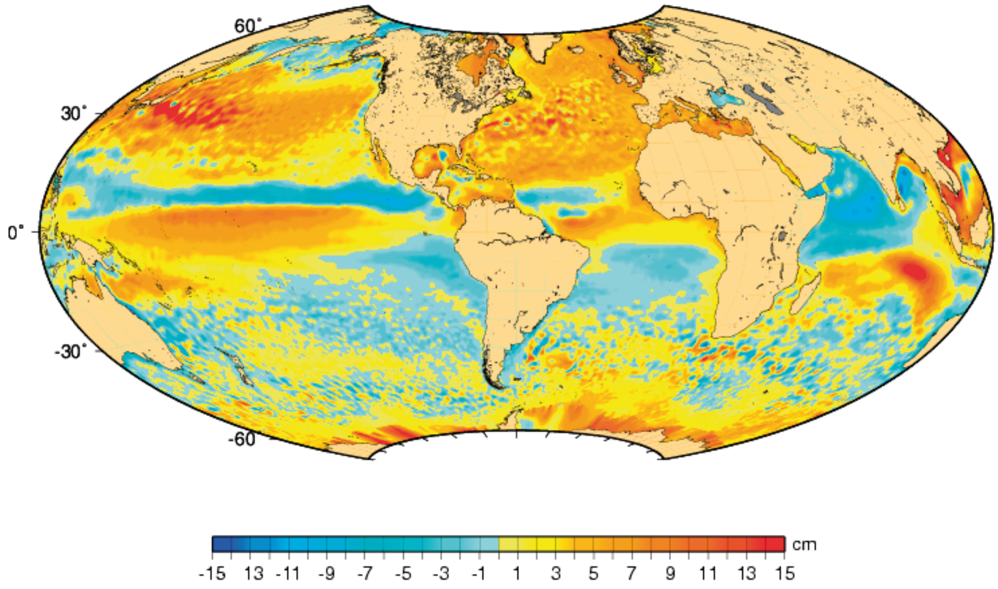


***Figure 9a** – Sea level variations averaged over 15 years over Northern Hemisphere (autumn)*

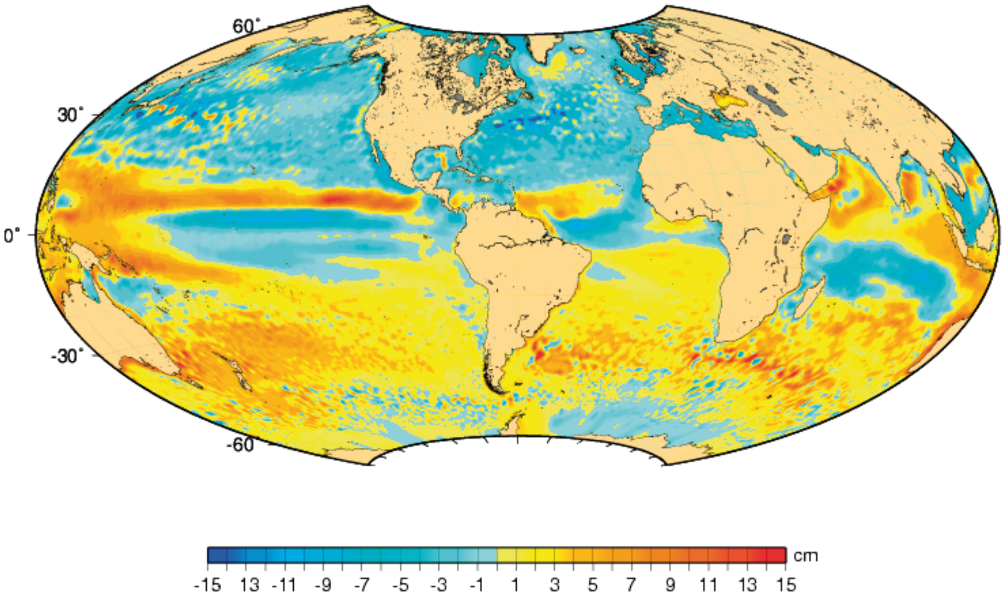


***Figure 9b** – Sea level variations averaged over 15 years over Northern Hemisphere (spring)*
The water warms in summer and cools in winter, hence a difference of about ±10 cm in sea level between Northern and Southern Hemisphere seasons (Credits: CLS/Aviso)

3.2.2 MEAN GLOBAL CIRCULATION

Satellite altimetry is a unique tool to retrieve the mean global ocean circulation, provided that one has access to an independent measure of an accurate geoid. Such a determination is particularly important to describe and characterize the main features of the ocean circulation, i.e. the location, intensity, transport of the main currents, and their interaction with temporal variability (i.e. mesoscale, seasonal, annual signals). The global ocean circulation, as determined from altimetry, is also useful to validate and initialize global ocean models and to adjust data assimilation techniques.

The largest uncertainty in determining the mean global ocean circulation from altimetry resides in the geoid, the needed reference surface, especially at the smaller scales (below 200 km). This geoid uncertainty has been greatly reduced by combining altimetry observations with models and by using gravimetric data from dedicated gravity satellite missions. The Champ mission launched in 2000 and the Grace mission launched in 2002 are providing new gravimetric data sets able to resolve scales below 400 km with accuracy better than 5 cm. The successful launch on 17 March 2009 of the Goce mission will improve this geoid knowledge at shorter scales, below 200 km.

To depict the large scales of the mean ocean circulation, the orbits of altimetry satellites must be known very accurately, i.e. at least with the same quality as that provided by Topex/Poseidon, Jason-1 and Jason-2/OSTM. Because of the low-frequency variability of some ocean phenomena (decadal and inter-decadal scales), future **reference missions** having the same quality are necessary to produce a climate-quality data record. They will improve the estimate of the mean dynamic topography.

3.2.3 INTRA-SEASONAL TO INTERANNUAL VARIABILITY

The temporal changes in sea level are usually determined along the repeat tracks of altimetric satellites. This orbit configuration allows one to compute a mean sea level along the track which is then subtracted from individual profiles to retrieve the temporal signal, thereby eliminating the time-independent geoid effect. Ground track repeatability has to be as accurate as possible in order to avoid any contamination by cross-track geoid slopes. This is why an orbit repeating within 1 km of the mean track should be maintained for future altimetry missions. However additional satellites flying non-repetitive tracks should be considered for geodetic applications or for ocean applications depending on improvements in future geoid models.

The ocean is changing on all temporal and spatial scales, from hours to years and from kilometres to basin scales. Apart from short timescale events (storm surge, tsunamis, tides), the dominant energy lies in mesoscale eddies which typically have temporal scales of 0.5-3 months and spatial scales of 50-300 km. Other features include intra-seasonal to interannual oceanic variations whose large spatial scales have an impact on climate change.

At the intra-seasonal scales (10-100 days), the large scale variability is mainly driven by oscillations coherent over thousands of kilometres and which directly respond to the high-frequency wind forcing. The mean amplitude of this variability is quite weak and does not exceed a few centimetres, with a 1 cm level significance. Other oscillations at periods longer than 100 days are due to the propagation of Rossby waves which transport energy across ocean basins. Intra-seasonal variations have also been detected in the western boundary currents (Kuroshio, Gulf-Stream) with altimetry data. It is certain that this intra-seasonal variability has an important role in ocean dynamics as well as in the ocean-atmosphere coupling, but further observations over longer periods are still necessary before the mechanisms involved in this process are fully understood.

The annual cycle of the ocean was observed for the first time on a global scale with the required accuracy using Topex/Poseidon data. This cycle is the result of close but complicated interactions between the ocean and atmosphere (i.e. solar radiation change, heat fluxes, wind forcing etc.). An accurate knowledge of the seasonal cycle is especially important to evaluate and to adjust at first order both ocean and climate models. However, as long as the altimetric time series is not long enough to completely resolve the interannual variability, uncertainties in the seasonal cycle will remain. As the peak to peak amplitudes of the seasonal signal can reach 15 cm in some areas, it is desirable to have a 1 cm level of confidence in the observation of this signal. Such an objective can only be fulfilled by gathering several decades of high-quality altimetry data.

Seasonal cycles differ from one year to the next because of interannual changes which have a direct impact on climate. El Niño episodes in the tropical Pacific are famous and dramatic examples of such interannual anomalies corresponding to strong interactions between ocean and atmosphere. Several warm ENSO (El Niño Southern oscillation) episodes were observed by altimeters, especially the strong 1997-98 event. This altimetry-based monitoring has led to better understand the mechanisms involved, such as the propagation of Kelvin waves and reflected Rossby waves. Prediction of these phenomena is a major issue in improving climate forecasting. Assimilation of altimetric and other types of data in coupled ocean-atmosphere models will play a key role in this domain. Other interannual events with a period of a few years have also been observed (e.g., the North Atlantic and Pacific Decadal Oscillations). This again highlights the need for longer altimetric time series (several decades) with appropriate sampling and accuracy. The amplitude of these interannual sea level changes can reach 10-15 cm over several thousands of kilometres in the zonal direction but an accuracy of 1 cm at basin scales is required to discriminate them from other effects and also detect weak precursor effects which can have amplitude of the order of only 1 cm.

At this point in time, the question of the impact of using altimeter data on seasonal forecasts is not resolved. The more general question of the impact of assimilating data into ocean models for their initialization for seasonal forecasts has been extensively discussed in [22]. Ocean observations can have a significant impact in reducing errors in initial conditions due to a bad knowledge of the external forcings or to large errors of the ocean model. However effects linked to the quality of the coupled model and to the shock associated with the coupling of ocean and atmosphere models initialized to unbalanced conditions can mask the signal brought by the observation. ECMWF has shown that altimeter data can bring some improvement in the skill of the forecasts in the tropics, though the magnitude of this improvement is barely significant given the size of the sample. Over the time scale needed for the assessment of a seasonal forecast system (of about 2 decades), and provided that Jason-class high precision missions are continued, altimetry has the advantage of being a steady component of the ocean observing system

3.2.4 MESOSCALE AND COASTAL OCEANOGRAPHY

The mesoscale signal has typical spatial scales of 50-300 km and time scales of 0.5-3 months. It is mainly associated with the formation and propagation of eddies which are very energetic and have a key role in the horizontal and vertical transport of heat, carbon and other nutrients in the ocean. These eddies are mainly the consequence of mean flow instabilities and/or interaction of the mean flow with topography. They are present everywhere but they are especially concentrated in regions of strong currents such as the Gulf Stream, Kuroshio, and Antarctic Circumpolar Current. They may persist over several years, while moving across the ocean basins (Figure 10) and this has implications on the temporal and spatial sampling, which needs to be as homogeneous as possible in order to ensure their recognition and track their displacement. This cannot be achieved unless the orbit selection of the various components of the satellite constellation is carefully coordinated.

This mesoscale energy concentration was revealed in the global variability maps which were among the first results obtained by altimetry They show that the maximum of the variability can reach more than 40 cm (near strong currents), while a minimum of less than 3 cm is still significant in regions of low variability. The space-time distribution of mesoscale energy can also be studied from altimetric along-track spectra These statistical global results are useful for revealing the spatial and temporal distribution of mesoscale energy and to assess the capability of models to reproduce mesoscale signals.

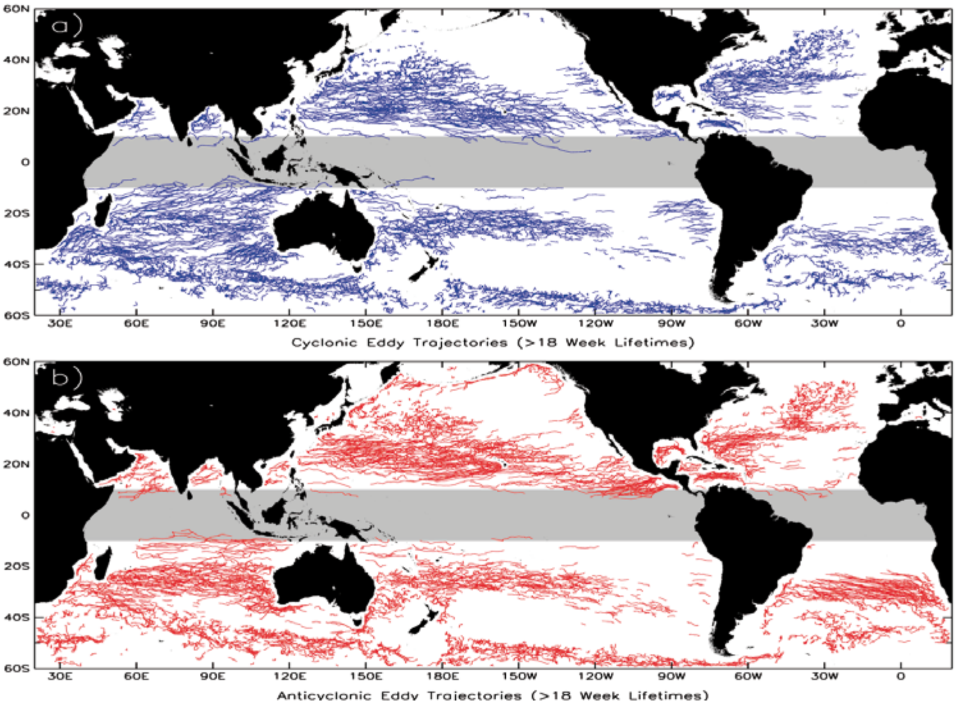


Figure 10 *– Anticyclonic (top) and cyclonic (bottom) eddies with lifetimes longer than 18 weeks tracked from altimetry data. Both kinds are moving westwards, with respectively a slight (less than 10°) equatorward and a slight poleward tendency. Some regions see more anticyclonic eddies (e.g., West of Central America, the Tehuantepec and Papagayo eddy area), others more cyclonic eddies (e.g., Humboldt Current along the Pacific coasts of South America). In the most active regions, like the Gulf Stream, eddies lifespan is often quite short, and thus relatively few of them appear on the figures* (Credits: D. Chelton, Oregon State University).

Many human and commercial activities are concentrated in the coastal domain, requiring continuous monitoring and forecasting. It is a complex and fragile domain involving many processes such as the accumulation of organic matter and fresh water transported by rivers, strong winds, sea ice at high latitudes, dense water formation, coastal tides, and the interaction between coastal currents and open ocean circulation. Understanding such complex, short space and time scale, processes is not easy and requires the development of very specific models and the use of multiple data sources. Altimetry is among the most helpful data for such studies but, as for mesoscale studies, multi-mission data merging and dedicated processing are needed to improve the resolution and utility of the data (Figure 11).

To cover the whole mesoscale and coastal domain it is necessary to increase the spatial sampling by merging (in an optimal way with cross-calibration) different altimetric data sets. As demonstrated during the period 2002-2005 this multi-satellite combination (Figure 1) is essential to fully resolve the mesoscale signal and to better understand its time-space evolution and its interaction with the mean flow as well as seasonal and interannual ocean dynamics.

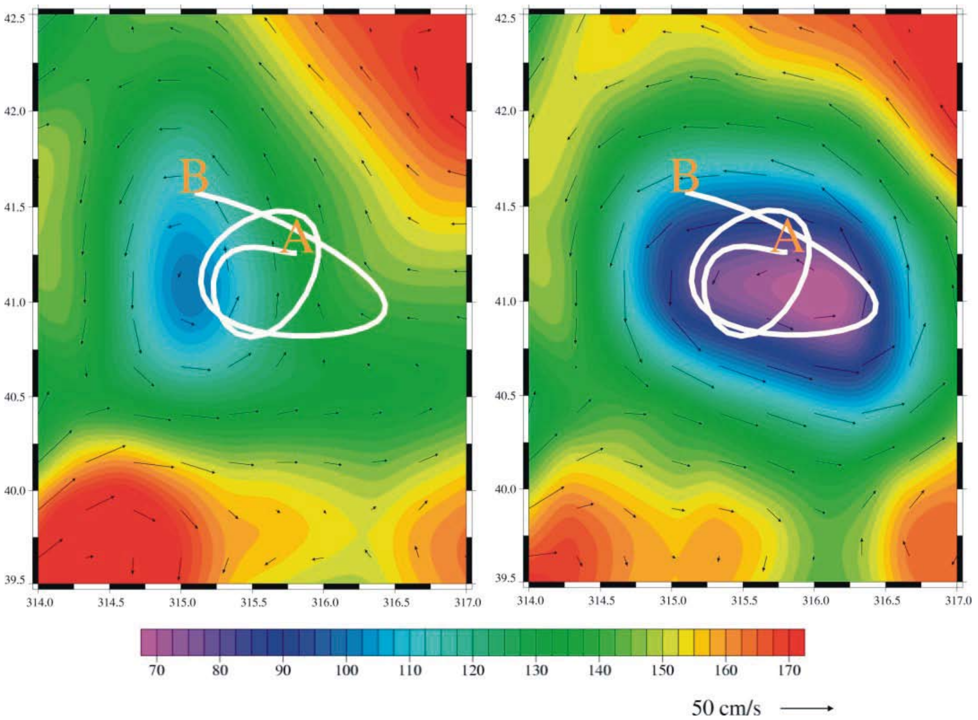


Figure 11 *– Buoy trajectory (white line, from May 14 to 28, 2003, from A to B) and merged absolute dynamic topography in the Gulf Stream on May 21, 2003, with "only" two satellites (left), and with four satellites (right) The right map better matches the eddy materialized by the buoy path* (Credits: A. Pascual CLS).

In coastal areas the difficulty is even larger because the size of the signals is even smaller requiring a denser sampling. In addition specific care in the data processing, as described in section 3.2 4 is necessary to provide valuable information.Moreover in areas close to the coasts (less than 20 km) the proximity of land contaminates the altimetric and radiometric signals Thus, adaptive tracker and/or specific re-tracking of altimeter waveforms and near-shore geophysical corrections (such as coastal tide models and marine boundary layer tropospheric corrections) are needed.

3.2.5 TIDES

Thanks to altimetry data, several ocean tide models of unprecedented accuracy (2-3 cm rms) have been produced for the main diurnal and semi-diurnal components (M2, S2, N2, K2, O1, P1 and Q1). These results have made a significant improvement in applying the altimetric data to ocean circulation studies (Figure 12), as tides are considered a major correction in the data. Tide knowledge improvement (by direct analysis of altimetry data or by assimilation of the data into hydrodynamic models) is the result of the high quality data sets. It is also the consequence of an adequate space-time sampling. To monitor tides, specific sampling characteristics are required to avoid aliasing and discriminate the various tide components. For that purpose the orbit inclination and phasing selected for the Topex/Poseidon and Jason series was specifically optimized.

Considering the complexity of the tides it will be required to continuously monitor the tidal signals through altimetry measurements. Preliminary solutions exist for the long period tides but they need to be updated using longer altimetric time series. Thanks to the extreme accuracy of altimetry data it has been possible to observe the weak signal of internal tides and to understand better the tidal energy dissipation and its interaction with ocean circulation and ocean bottom topography In coastal regions denser spacing is necessary to resolve the short scales of the ocean tides

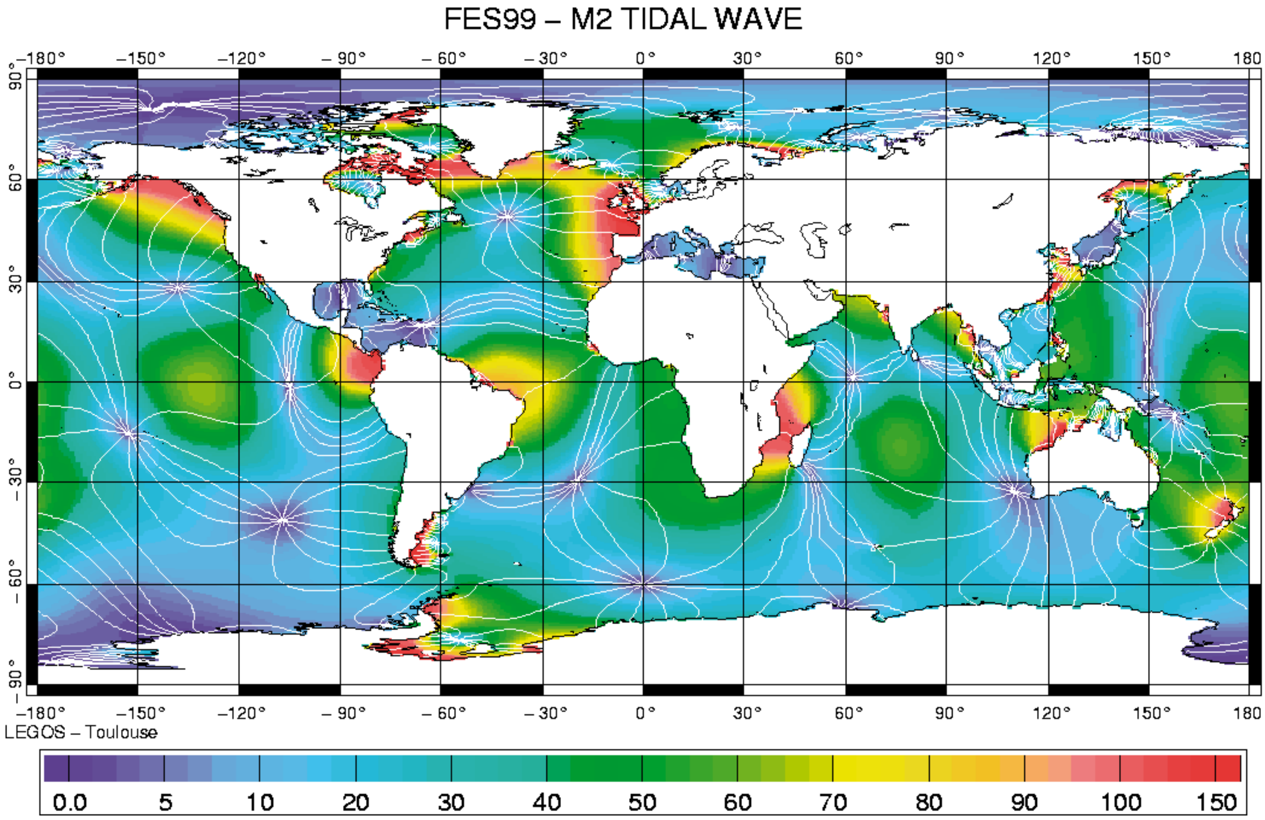


Figure 12 – *Amplitude in centimetres of the main tidal component (semi-diurnal wave M2) from the FES99 model* (Credits: CLS/Legos).

3.2.6 MARINE METEOROLOGY

In addition to sea surface height, satellite altimeters provide estimates (derived from radar backscatter signal characteristics) of significant wave heights and wind speed, both of which are of operational and scientific interest in marine meteorology. From a climate point of view, it is very valuable to take advantage of the altimetric coverage of sea-state and wind speed observations in regions where conventional observations are especially sparse (like in the southern hemisphere). This allows comprehensive studies of the climatology of these parameters, their time-space characteristics, and their variations at intra-seasonal to interannual scales. Additional studies include propagation of swell, interactions between sea-state and currents, etc. These studies are especially useful to validate and initialize meteorological models, a preliminary step before running routine assimilation of altimetric data into meteorological models (see above section 3.1.2 on real-time applications). Merging multi-satellite data sets is necessary when studying sea-state parameters because this provides an improved time-space sampling for resolving their temporal and spatial variability.

Altimetry-derived sea state and sea level data are also used to adjust, validate and improve models simulating dramatic and sudden events such as hurricanes or tsunamis. As an example, altimetry has been advantageously used to investigate the interactions between upper ocean thermal structure and the intensification of hurricanes. Results of such studies were used to improve forecasts based on the combination of altimetry, sea surface temperature and ocean models.

The water vapour content measured by radiometers on-board altimetric satellites are dedicated to the correction of altimetric data, but can also be used to monitor atmospheric characteristics in the troposphere and to constrain operational weather models. In the same way, studies of the ionosphere and upper atmosphere can take advantage of the ionospheric electron content measured by the dual-frequency altimeters and the atmospheric drag estimated during precise orbit determination. These global data give interesting information on the solar and geomagnetic characteristics of the atmosphere. Rain and ocean/atmosphere gas fluxes at the sea surface are other parameters that can be derived from the analysis of dual-frequency radar altimeter measurements.

3.2.7 INLAND WATERS AND ICE STUDIES

Because of the importance of understanding the hydrological cycle and of managing the Earth's water resources, inland water level and ice observations are becoming more and more crucial, especially to monitor the space-time variations of rivers, lakes, reservoirs and flooded regions. In this regard altimetry is a very useful tool capable of measuring the water level, volume and discharge of these inland waters. Despite inappropriate technical design and orbit geometry for such applications significant results have been obtained with past altimeters data over sea ice, enclosed seas, lakes, large rivers and flat continental topography. These specific applications may use the GDR processing or special altimetric waveform re-tracking if needed (because of reflection characteristics which are different from the open ocean). New information is expected from dedicated missions such as the ESA's CryoSat.

The main requirement then is to have an altimeter able to track over these surfaces and to have access to the level 1 altimetric data. Combining various altimeters will allow getting the spatial resolution which is essential for such applications.

3.2.8 GEODESY AND GEOPHYSICS

The ocean geoid has been much better known since altimetric data became available (the first altimetric ocean geoids were computed with GEOS 3 and Seasat data). Sea level height measured by altimetry represents to first order the ocean geoid signal because of its much larger amplitude (10 to 100 times more) than the ocean dynamic topography. A very accurate altimetric mean sea surface, comprised of the geoid and mean dynamic topography, has been obtained using the high density Geosat, ERS and GFO altimeter data. Topex/Poseidon and Jason-1 data, despite their larger spatial sampling, have usually been used as the reference data set, in terms of accuracy, to improve the other satellite data sets.

Geodesists and geophysicists are extracting a great deal of information from the short scales (10-100 km) of these altimetric mean sea surfaces. Short wavelength tectonic features (e.g., seamounts) never observed before are visible in the data (Figure 13).

An ultimate goal for oceanography is to discriminate the mean dynamic topography from the mean sea surface. This requires a "true" geoid accurate at short spatial scales. The combination of mean sea surfaces with ocean circulation models is an indirect way of retrieving the geoid. But satellite gravity missions such as Champ and Grace have greatly improved the resolution and accuracy of marine geoids up to 400 km. The ESA Goce mission, launched in March 2009, should help resolve even shorter scales.

An accurate and monitored terrestrial reference frame is needed to make proper use of altimetric measurements. Altitude measurements should use the International Terrestrial Reference Frame System. The three currently available precise orbit determination systems (Doris, GPS and laser) allow computing satellite orbits as well as the position of ground tracking stations which then are incorporated in the ITRF. Such additional observations have an immediate impact on reference system quality and related parameters like Earth rotation parameters, measurements of vertical displacements of stations due to tectonic movements, large scale post-glacial rebound, and atmospheric or oceanic load effects. Determining these movements with the required millimetre accuracy is essential to de-correlate them from sea level rise determined from altimetry and/or tides gauges. The accumulation of very precise Doris, GPS and laser data simultaneously with highly accurate altimetric data, through missions like Topex/Poseidon, Jason-1 and Jason-2/OSTM is certainly the best way to accomplish such an objective.

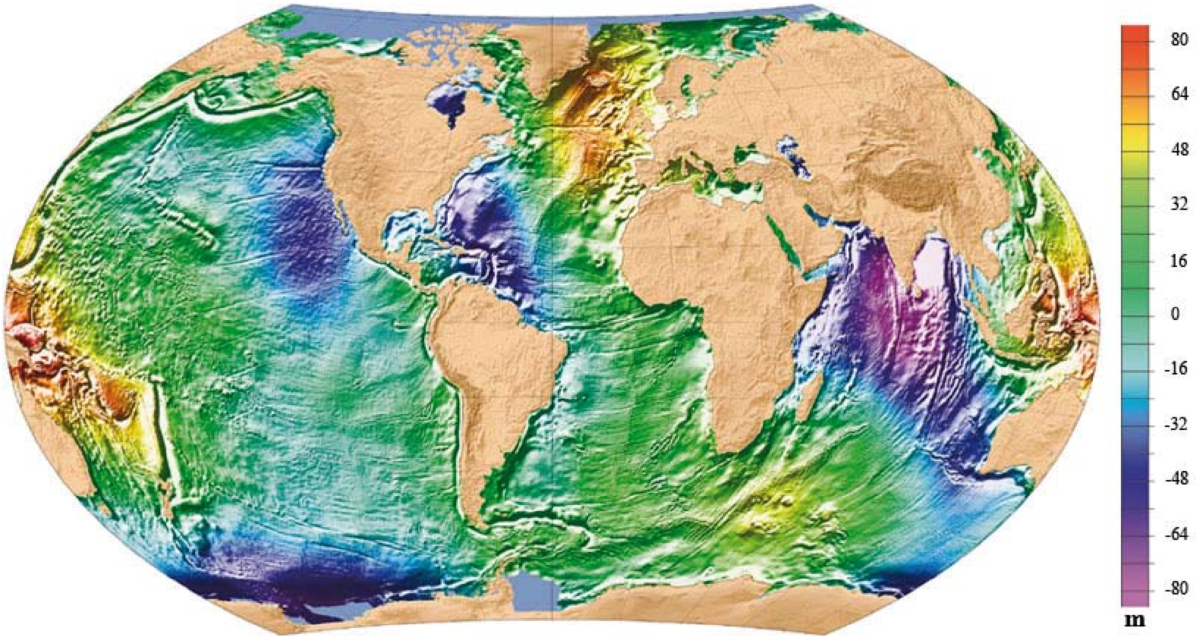


Figure 13 *– Mean sea surface, computed from 12 years of altimetric data. Main height variations are due to the geoid; small features are due to the seafloor topography, e.g., ridges and trenches.*

3.3 SUMMARY OF HIGH-LEVEL USER REQUIREMENTS FOR THE ALTIMETRY CONSTELLATION

The above sections can be summarised in two ways. Firstly one can derive a series of qualitative key findings that usefully support the rationale for the minimum composition and general characteristics of the Ocean Surface Topography Constellation. These key findings are listed in the table hereunder:

Climate applications	Continuous coverage from one high-precision altimeter and two lower-precision but higher resolution altimeters is needed to detect and monitor ocean climate signals.
Marine meteorology applications	Continuity of surface wind speed and significant wave height measured by altimetry as well as ocean heat content derived from combined altimetry and sea surface temperature observations are required for routine use in operational weather and extreme event forecasting.
Mean sea level trend	Monitoring sea level rise has the most demanding requirements in terms of accuracy continuity and overlap between consecutive missions
Mean global circulation	A reference mission with Topex/Jason-type accuracy is needed to retrieve the mean dynamic ocean topography and global ocean circulation. This retrieval also requires the availability of an independent and accurate geoid.
Intra-seasonal to interannual variability	Ocean topography measurements with 1-cm accuracy at basin scale over several years are required to determine ocean variability features with periods from months to years.
Mesoscale and coastal oceanography	Increased spatial sampling, using high-precision wide-swath altimeters or a constellation of small altimetric satellites, is needed to monitor mesoscale eddies and ocean currents in coastal areas.
Tides	Tidal corrections to altimetric measurements continue to impose specific constraints on the reference mission orbit characteristics: altitude, inclination, phasing.
Marine meteorology	Altimetry applications to marine meteorology impose requirements on the time-space sampling and on data transmission and processing delays.

Inland and ice studies	Inland and ice studies impose specific constraints on altimeter signal tracking capabilities, orbit accuracy and spatial resolution, better achieved through dedicated missions.
Geodesy and geophysics	To contribute to, and benefit from, geodetic and geophysical studies, altimetry missions require precise orbit determination systems, and an appropriate combination of altimeter data from the reference mission and complementary missions providing denser sampling.

Secondly one can derive high-level user requirements that can serve to quantitatively define the technical characteristics of the constellation. The Table below summarises these high-level user requirements:

General	A balanced ocean observing system including altimetry plus other space and *in situ* techniques shall be developed and maintained.
Operational services	Near-real-time and short term products are necessary to support operational oceanography.
Mesoscale and coastal applications	The altimetry constellation shall allow monitoring of ocean mesoscale features having typical scales of 30-300 km and 20-90 days.
Climate applications	The altimetry constellation shall provide continuous coverage of the ocean to support climate monitoring and operational services. Continuity of a reference mission with Topex/Jason-type accuracy is needed to detect and monitor ocean climate signals.
Marine meteorology applications	In complement to altimetry products the altimetry constellation shall provide near real-time sea state measurements (wind speed and significant wave height) to support marine meteorology.
Other near-real-time applications and extreme events	The altimetry constellation shall provide mesoscale information of the ocean to support monitoring and forecast of hurricane and weather extreme events.
Mean sea level trend	The altimetry constellation shall provide continuous monitoring of the mean sea level rise with an overall error budget better that 1mm/year.
Mean global circulation	A reference mission with Jason type accuracy is needed to retrieve the mean dynamic ocean topography and global ocean circulation. This retrieval also requires the availability of an independent and accurate geoid.
Intra-seasonal to interannual variability	Ground track repeatability of ±1 km has to be maintained for the altimetry missions (reference and core missions) as long as geoid uncertainties will require the use of reference mean tracks to process the data. The altimetry constellation shall provide continuous coverage of the ocean seasonal cycle with an accuracy of 1 cm on every basin to support climate modelling and seasonal forecast. The altimetry constellation shall provide continuous coverage of the ocean interannual variability with an accuracy of 1 cm on every basin to support climate modelling and seasonal forecast of events such as El Niño.
Mesoscale and coastal oceanography	The altimetry constellation shall provide continuous coverage of the mesoscale variability (50-300 km, 0.5-3 months) with accuracy consistent with the 3-40 cm amplitude of such phenomenon. This implies the processing and distribution of multi-mission products.
Tides	The altimetry constellation shall provide monitoring of tides, which imply specific selection of the orbit of the reference mission to avoid aliasing of the major constituents at periods larger than 180 days.

Intentionally left blank

4. OCEAN SURFACE TOPOGRAPHY CONSTELLATION USER REQUIREMENTS

The two following sections present the set of user requirements that can be derived from the analysis of ocean surface topography measurement use and perspective.

This set of requirement can be fulfilled by a virtual constellation as defined by CEOS. This constellation shall combine the following elements:

- A series of reference missions which overlap in time,
- Core constellation missions,
- Contributing constellation missions.

The reference missions play a specific role in the system as they provide the absolute accuracy of the complete system, other missions being tuned to the reference. Then the fulfilment by those reference missions of the set of requirements defined in the following sections is essential.

Core constellation missions also play a key role in the system by providing, combined with the reference mission, the minimal time and space coverage necessary to monitor the ocean. Their absolute performances may be less optimized than those of the reference mission, however good performance are important to complement the reference mission for climate applications (e.g., monitoring mean sea level) and to overcome potential outages in the series of reference missions products.

For the contributing missions these requirements shall be considered as guidance. They will play an important role to complement the constellation coverage and thanks to the tuning capacity of the combined reference and core missions, potential errors will be compensated so that they will have a significant impact to the constellation.

Fulfilling the complete set of requirements requires coordination between various agencies:

- Space agencies providing the space component and taking care of mono-mission products processing and distribution down to level 2,
- In situ agencies providing in situ information necessary to perform calibration and validation of the altimetry measurements,
- Operational centres taking care of mono-missions products inter-calibration and level 3 or 4 products processing and distribution.

Coordination between those agencies and operational centres shall include exchange of parameters describing the various components of the system and results of validation and calibration activities.

Intentionally left blank

5. SCIENTIFIC AND OPERATIONAL REQUIREMENTS

5.1 MISSION REQUIREMENTS

Altimetry satellites are intended to lay the foundation for a continuing program of long-term observations of the oceanic circulation and its variability.

Future altimetry missions shall be designed to allow an optimum continuation of the previous mission and to satisfy the long term observation requirements as defined in the following sections.

TARG-5.1.a A maximum of altimeter echoes will be acquired and analyzed over inland waters and sea ice, and over oceans as close as possible to the coast.

REQ-5.1.b The constellation shall be designed to provide 15 years minimum of continuous monitoring, in order to ensure the long term observation monitoring objective until new technology may become available.

REQ-5.1.c For each altimetry mission the relevant agency (or agencies) shall issue the following set of documents:

- Mission requirements coordinated by Agencies and validated by user representatives. They shall include observation performance requirements and Cal/Val requirements.
- System requirements established by agencies and reviewed by user representatives. They shall include a further breakdown of observation errors (performance allocation) and specifics on the Cal/Val required. This shall include in particular Mission performance budget and Cal/Val plan.

REQ-5.1.d For each altimetry mission the relevant agency(ies) shall set up an international scientific group that will interact with the project team for Mission requirements and design, performance budgets and Cal/Val activities.

REQ-5.1.e Each altimetry mission (satellite and ground system) shall be specified in a way which allows timely acquisition and distribution to data users of Near-Real-Time (NRT) and Slow Time Critical (STC) Geophysical Data Records to support operational applications.

REQ-5.1.f The altimetry constellation shall at least include two subsets: a series of overlapping reference mission delivering high-quality altimetry measurements, and a complementary set of at least two and preferably three satellites providing an improved geographic coverage for mesoscale circulation.

TARG-5.1.g The altimetry constellation will include additional missions allowing sub-mesoscale ocean motions to be observed and providing geodetic measurements:

- **REQ-5.1.h** The altimetry “reference component” shall meet the accuracy, continuity and coverage of the Topex/Poseidon, Jason-1 and Jason-2/OSTM missions for describing and understanding the ocean circulation, and its influence on climate. This mission shall also support tide modelling effort.
- **REQ-5.1.i** The “mesoscale component” shall continue the Geosat, GFO, ERS-1, ERS-2, Envisat missions for describing, understanding and forecasting the mesoscale variability of the ocean. It shall allow also the monitoring of sea state, wind and wave, at global scale.
- **TARG-5.1.j** A “sub-mesoscale component” will open new science and operational applications in the open ocean, coastal areas, inland waters and ice monitoring.
- **TARG-5.1.k** A “geodesy component” will allow the description of the short scale features of the geoid to be improved.

Specific requirements in term of sampling and performances for both components are defined in following sections.

5.2 CAL/VAL REQUIREMENTS

REQ-5.2.a Each mission shall include a NRT verification phase intended to qualify the system with respect to operational objectives.

REQ-5.2.b A first verification workshop gathering the project team and the scientific group shall be held at the end of this phase in order to allow the start of Near-Real-Time and Slow Time Critical product delivery.

REQ-5.2.c Each mission shall include a science verification phase, with a minimum duration of 6 months after launch for recurring missions, 9 months when new technology is used or when there is no overlap with a previous mission, intended to qualify the system with respect to the science requirements. This phase shall be concluded by a final verification workshop followed by the observational phase and shall focus on consistency with previous missions in order to guaranty the continuity of the data set.

REQ-5.2.d During the verification phase of the mission, all ground-processing algorithms and all critical output quantities and associated errors shall be verified and calibrated. It shall be done through statistical analysis and by comparison with external measurements. The calibration/verification accuracy shall be compatible with error budget specifications.

The parameters to be verified include altimetry range and associated corrections, orbit, wind speed and SWH. In addition to the biases, the calibration process shall provide an estimation of the individual drifts of the system components.

REQ-5.2.e The system shall allow performing external independent calibration of the measurement.

REQ-5.2.f To support external calibration requirement laser retro-reflectors on board each altimetry mission shall be designed to provide altitude verification with overhead range measurements to an accuracy of ± 1 cm (1 sigma) using available laser stations. This shall be complemented by appropriate in situ instrumentation.

REQ-5.2.g During the verification phase, the Near-Real-Time Data Records (NRT) and Slow Time Critical Data Records (STC) shall be provided with a delay of 1 week to the main science investigators so that they can participate in a timely manner in the Cal/Val effort.

REQ-5.2.h At the end of the verification phase, a complete report on Cal/Val activities shall be presented to users, including a revised error budget and derived calibration and drift quantities and updated ground-processing algorithms. The verification effort shall be pursued beyond the initial verification phase.

REQ-5.2.i GDR production shall start at the end of the science verification phase with the last updated algorithms. Calibrations (internal and external) shall be introduced into processing so that GDR quantities provide correct geophysical measurements.

REQ-5.2.j Instrument calibrations and product quality shall be monitored at least weekly throughout the life of the mission. The calibrations, including internal instrument calibrations, shall be documented.

REQ-5.2.k Specific care shall be taken to guarantee the continuity and homogeneity of climate time series of mean sea level. This shall allow meeting an overall stability of 0.1 mm/year for the mean sea level trend. It implies inter-calibration between various altimetry mission and inter-calibration with *in situ* tide gauge network. Proper allocation of this global error budget to altimetric measurement, radiometric measurement and Precise Orbit Determination shall be made.

REQ-5.2.l Mission planning shall take into account the necessity to ensure an overlap of at least 6 months between a satellite follow up and its predecessor. In case new technology is used for the new satellite this overlap shall be extended to 9 months. During this period both satellites should fly in tandem, providing overflight of the same ground track with a time difference of 10 minutes maximum. It is necessary to ensure precise cross calibration/ validation of the two missions. This shall allow meeting the requirement about absolute and relative biases defined hereafter in the error budget section.

TARG-5.2.m In case a tandem phase between two successive satellites cannot be set up, adequate in situ instrumentation will be used to ensure the best possible calibration/validation of the new mission.

REQ-5.2.n As a result of the calibration process, adequate calibration parameters shall be provided to users to connect previous mission time series with the new one.

5.3 DATA REQUIREMENTS

Standard levels of data processing are adapted to the specificity of the altimetry along track measurements according to the following definitions:

- Level 1: This includes earth positioning, instrumental corrections from what can be deduced from pre and post launch internal calibration.
- Level 2: This includes geophysical corrections necessary to get a geophysical measurement of the dynamic topography. This level includes in particular the modelling of sea state effects, atmospheric propagation, tide modelling and high frequency atmospheric forcing. It includes the combination of products from the various sensors (altimeter, radiometer, precise orbit determination) and reference surfaces (e.g., geoid, mean sea level).
- Level 3: This is a multi-satellites product which includes re-sampling on a standard ground track, correction of biases and errors which can be computed by comparison with the reference missions. This product is the basic input for ocean model assimilation.

REQ-5.3.a Each mission shall produce, validate, archive and distribute three types of products:

- The level 2 Geophysical Data Records (GDR) shall be distributed in a timely, complete and well-documented manner to data users and shall contain all the parameters required to compute the derived ocean and geophysical parameters.
- The level 2 Slow Time Critical Geophysical Data Records (STC) shall be designed to satisfy the short and mid-term application requirements including oceanographic requirements, as well as Cal/Val requirements, oceanographic experiment support and applications in coastal areas.
- Level 2 NRT operational data products should be provided to users within 3 hours of collection.
- For specific applications (re-tracking over ocean, coastal areas, lake, land or ice) and calibration purposes level-1 products of the various sensors, the Sensor Geophysical Data Records (SGDR), shall be made available on request, to interested data users. This includes Altimeter SGDR containing altimeter waveforms, radiometer level1B and pre-processed orbitography data (Doris and GPS).

TARG-5.3.b NRT operational products will be delivered within 30 min of data measurements

REQ-5.3.c These products shall be structured in a similar way (pole to pole half) and shall use the same reference standards, derived from those of the reference mission in order to allow inter-calibration.

REQ-5.3.d A complete documentation of the various products shall be distributed including the format of the files, definition of all the parameters and flags, the way to use the data and the algorithms used to generate the data. Any change in the data generation and/or processing shall be communicated to data users in a timely manner, and documentation shall be updated.

REQ-5.3.e The GDR shall be made available to users, on a cycle basis, within 40 days of data acquisition by the satellite. They shall contain at least 95% of the ocean data during any 12 month period with no systematic geographical gaps, plus all the land and ice data for which the altimeter is tracking. The GDR shall constitute the final and fully validated products. They shall be archived and systematically delivered to data users.

REQ-5.3.f The GDR shall contain, at a rate of 1 record per second, the best estimates of altimetric range measurement, the time tag and earth location, plus the best associated instrumental and environmental corrections and the most accurate orbit altitude. They shall contain additional geophysical parameters, i.e. wave-height, sigma-naught and derived wind speed, atmospheric surface pressure, tides, mean sea surface and geoid. They shall also contain altimeter at a rate equivalent or larger than 10 measurements per second (see Table A in annex for reference).

REQ-5.3.g OGDR and STC products shall be made available to data users through secure electronic links, offering a maximum of reliability, in order to reduce the transmission time delay.

REQ-5.3.h The STC shall contain the same parameters as the GDR and have the same structure as the GDR, the difference between both products being the level of validation.

REQ-5.3.i The STC shall be distributed within 1 to 1.5 calendar days of data acquisition by the satellite (goal: 1 day latency) and shall contain 95% of the ocean data during any 12 months period with no systematic geographic gap.

REQ-5.3.j The NRT shall contain, at a rate of 1 record per second, all parameters needed for meteorological and specific Cal/Val applications (time-tag, location, wind speed, wave-height, sigma-naught and range for the two frequencies, radiometer measurements, orbit, and geophysical corrections to range).

REQ-5.3.k The NRT shall have the same structure as the GDR and STC. However their content is not fully validated and the precision is limited by the 3-hour latency constraint. It shall contain, at delivery time, at least 75% of the ocean data no older than 3 hours, and 95% of the ocean data no older than 5 hours. NRT parameters that depend on external geophysical data (e.g., atmospheric pressure fields) shall be calculated using up-to-date external input. In order to maintain the 3-hour timeline however, most recent external data shall be used to calculate the NRT parameters. If some external data are not available at the time of NRT production, the most relevant replacement value shall be provided, which can be the most recent available data or a predicted value.

TARG-5.3.l For all products a specific effort will be conducted to provide valid data as close as possible to the coast, as well as over ice and inland waters.

REQ-5.3.m All information needed to connect time series between satellites shall be provided to data users. This includes the altimeter and radiometer radar instrument bias and drift and the relative biases.

TARG-5.3.n In order for users to validate the data access links and operational data processing systems for these data, simulated operational NRT and STC data sets will be made available as test files before the launch.

TARG-5.3.o For the same access and operational processing validation objectives, NRT and STC data files will be produced soon after the launch of the satellite, i.e. after the assessment phase. Routine NRT and STC production will start at the end of their respective verification phases with the last updated algorithms.

REQ-5.3.p It shall be possible to re-process and distribute all GDRs products when improved algorithms are available. This requirement shall in particular support the long term climate analysis.

REQ-5.3.q Multi-mission, inter-calibrated level 3 products shall be produced, validated, archived and distributed. These products shall be designed to deliver homogeneous data sets to user. Relative biases, long wavelength and medium wavelength, that can be retrieved by intercomparison of the different missions shall be identified and removed in these products. This process shall allow taking benefit of the reference missions to enhance the accuracy of the other missions.

REQ-5.3.r Multi-mission products shall include:

- Multi-mission offline products based on the combination of every missions GDRs and produced within 2 months of data acquisition,
- Multi-mission Slow Time Critical products based on the combination of every mission STC products produced within 3 days of data acquisition.

REQ-5.3.s Data Policy shall be based on CEOS standards, WMO Resolution 40 and existing agreements between agencies. This shall include in particular free and unrestricted access (no restriction, either geographical or temporal) to all level 2 products.

6. ALTIMETRY MEASUREMENT SYSTEM REQUIREMENTS

The altimetry measurement system analyzed in this document is composed of a series of satellites (i.e., a constellation) equipped with an altimetry payload. This constellation shall be coordinated in term of orbit selection, relative phasing of satellites within the constellation, launch date and design lifetime according to the requirements documented hereafter. This should allow an optimal time and space sampling of the ocean by the global constellation.

REQ-6.a The altimetry payload embarked on each satellite shall be designed to provide an absolute precise measurement of the under-satellite ocean surface altitude with respect to a documented and monitored earth reference system.

TARG-6.b The altimetry payload embarked on each satellite will be designed to provide an absolute precise measurement of the under-satellite non ocean surface (rivers, lakes, ice...) altitude with respect to a documented and monitored earth reference system.

REQ-6.c This payload shall also provide measurements of the wind speed module and of significant wave heights over ocean.

GUID-6.d The payload shall be a system combining the following sensors:

- A Precise Orbit Determination payload providing the absolute altitude of the satellite with respect to the earth reference system,
- A radar altimeter providing the relative distance between the satellite and the earth surface associated with the wind speed and the significant wave height. This radar altimeter should provide an auxiliary measurement to correct the basic radar information from ionosphere effects if necessary to meet the measurement accuracy requirement (dual frequency radar),
- A microwave radiometer providing the wet path delay along the radar altimeter path due to troposphere. This auxiliary payload shall be considered as mandatory as long as external atmospheric models and/or observation do not meet accuracy requirements documented hereafter.

The elementary altimetric measurement is produced by the combination of the altitude measurement produced by the POD with the radar altimeter distance corrected by the radiometric wet troposphere correction and if necessary by the dual frequency ionosphere correction.

To produce this composite measurements several requirements shall be taken into account at each satellite system level:

- **GUID-6.e** Precise positioning with respect to satellite centre of gravity of POD and altimeter antenna phase centre to meet the error budget (before launch, and after launch following ergol consumption) shall be performed;
- **GUID-6.f** Precise co-location of altimeter and radiometer beams and precise altimeter beam pointing with respect to local nadir to meet the error budget shall be performed;
- **GUID-6.g** Use of a unique time reference system for POD, altimeter and radiometer or precise calibration of relative time tagging errors to meet error budget shall be performed;
- **GUID-6.h** Use of a calibrated frequency reference to drive the altimeter in order to meet the error budget shall be performed.

GUID-6.i Surface forces affecting the motion of satellite shall be compatible with the POD performance requirement; this may drives the design of the satellite in terms of consequences on air drag, solar radiation pressure, and thrusters' effects during and after manoeuvres.

REQ-6.j The satellite ground track will be controlled to take into account the uncertainty of the geoid in order to meet the required error budget. In case of use of a non repeat orbit or repetitive orbit with long repeat cycle the lack of precise surface reference for the ocean surface measurement degrades the usefulness of such measurements for ocean monitoring. However such missions are valuable and shall be taken into account in the altimetry constellation as complementary missions.

REQ 6.k The overall altimetry constellation shall allow to properly monitor the oceanic variability from short scales of 100 km up to basin scale of 10 000 km. In order to do that the accuracy of the merged altimetry product combining every available satellite shall be a decade below the dynamic of the observed signal as illustrated in Figure 14.

TARG-6.1 The overall altimetry constellation will allow proper monitoring of the oceanic variability from short scales of 10 km up to 100 km. In order to do that the accuracy of the merged altimetry product combining every available satellite shall be below the dynamic of the observed signal as illustrated in Figure 14

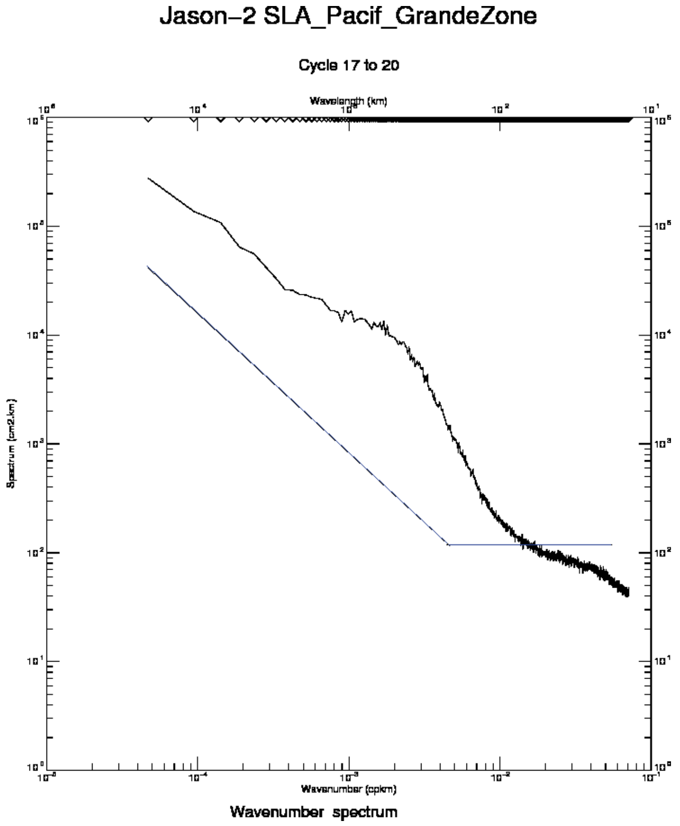


Figure 14 – *Along-track altimeter wave number spectrum for the Gulf Stream area from Jason-1 (in black) and associated requirement for the altimetry constellation (in blue).*

6.1 REFERENCE MISSION SAMPLING AND PERFORMANCE REQUIREMENTS

The reference altimetry mission satellites shall meet two sets of specific requirements:

- Specific orbit selection to allow proper monitoring of diurnal effects such as tides, and,
- Specific error budget to monitor large scale oceanic signals.

Aliasing of diurnal signals is a function of altitude and inclination of the orbit used by the satellite. Flying on sun-synchronous orbits is the worst case, which prevents from monitoring such signals. Flying in high inclination orbits induce long aliased periods of this diurnal signal, which prevents from adequate sampling. Other signals with precise repeat characteristics such as the various tidal components may be aliased into long term signals, which prevents precise monitoring. A large number of papers have documented these effects and analysed the adequate orbital parameters to be used to minimize those effects. The EUMETSAT study on optimisation of future altimeter orbits provides a state of the art synthesis of the adequate range. In particular those constraints lead to the selection of non sun-synchronous orbits having inclination comprised between 66° and 78°.

REQ-6.1.a Orbit selection for the reference missions shall be optimized to allow adequate sampling of tides signal.

6.1.1 SAMPLING AND ERROR BUDGET

REQ-6.1.1.a The reference mission sampling characteristics shall be:

Application	**Parameter**	**Spatial Resolution**	**Time Resolution**	**Latency**	**Accuracy**
Global mean sea level change	Sea surface topography	500 km	10 days	10 days	0.5 mm yr-1
Seasonal to interannual prediction	Sea surface topography	300 km	5 days	5 days	4 cm
Large scale variability	Sea surface topography	300 km	10 days	3 days	2 cm
Tides (Sun-synchronous)	Tidal constants—sea surface height	100 km	non-sun-synchronous Orbit >100 visits to each location	N/A	2 cm

Table 1 *– Reference mission sampling characteristics*

It is fair to say that the solid experience acquired worldwide with the Topex/Poseidon and Jason series confirms the perfect adequacy and robustness of these requirements

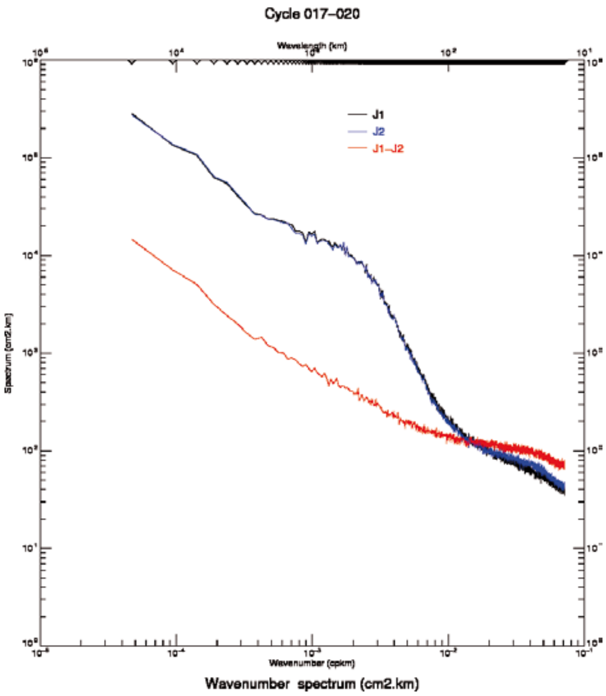


Figure 15 *– Wave number spectrum from Jason-1, Jason-2 and their difference*

REQ-6.1.1.b The reference mission accuracy shall be equivalent or better than the Jason-2/OSTM performance.

REQ-6.1.1.c To verify this accuracy the spectrum of the difference in measurements made by the two successive satellites during the tandem phase shall be computed and shall be equivalent or better that those computed between Jason-1 and Jason-2/OSTM at the end of the verification phase (Figure 15).

REQ-6.1.1.d The reference mission error budget shall be (for 1 sec average, 2 meters SWH, 11 dB sigma naught):

	REQ- GDR 40 days	**TARGET**
Altimeter range RMS	3 cm	2.25 cm
RMS Orbit (Radial component)	1.5 cm	1 cm
Total RSS sea surface height	3.4 cm	2.5 cm
System bias and drift (on global mean sea level after calibration)	5 mm and 1 mm/year	3mm and 0.1 mm/year

***Table 2** – Reference mission error budget*

The previous requirements are reproduced without any change from those of the Jason-1 and Jason-2/OSTM missions.

REQ-6.1.1.e The performance of the reference mission shall be at least as good as that of the Jason-2/OSTM system. Consequently, the requirements, in terms of error budget are summarized in Table 2 and are similar for the GDR to the post-launch Jason-2/OSTM error budget.

The performance in Table 2 may be summarized as follows:

- **REQ-6.1.1.f** The sea surface height shall be provided with a global and ultimate rms accuracy of 3.4 cm (1 sigma) over 1 second averages along satellite ground-tracks for typical sea-state conditions of 2 m SWH and 11 dB sigma-naught.
- **TARG-6.1.1.g** The reference system and ground-processing algorithms will be designed to minimize the geographically and temporally correlated errors.
- **REQ-6.1.1.h** The instrumental corrections, environmental corrections, and precise orbit determination shall be provided with the appropriate accuracy to meet the 3.4 cm requirement on the sea level height. This corresponds to a corrected range RMS error of 3 cm and precise orbit RMS error of 1.5 cm on the radial component.
- **REQ-6.1.1.i** The drift of the system (after calibration) shall not exceed 1mm/year.
- **TARG-6.1.1.j** The drift of the system (after calibration) shall not exceed 0.5mm/year.

TARG-6.1.1.k In addition to these requirements, targets have been established. Such targets are based on expected off-line ground processing improvements and are likely to reduce the error to 2.5 cm rms on the sea level height over 1 second averages.

TARG-6.1.1.l STC altimeter range and accompanying geophysical corrections will have the same accuracy as the GDR but are not fully validated.

REQ-6.1.1.m The STC orbit shall be a 2.5 cm class orbit. The derived sea level measurement shall have 3.9 cm accuracy for typical sea-state conditions of 2m SWH and 11 dB sigma-naught.

REQ-6.1.1.n Requirements on the accuracy of significant wave height measurements shall be equivalent to the one defined for mesoscale constellation for all type of products.

REQ-6.1.1.o Requirements on the accuracy of three-hour NRT operational products measurements shall be equivalent to the one defined for mesoscale constellation.

6.2 MISSION REQUIREMENTS FOR MESOSCALE AND SUBMESOSCALE ALTIMETRY

The mesoscale altimetry mission constellation shall meet two sets of specific requirements:

- **REQ-6.2.a** Specific orbit selection shall be performed to allow proper sampling of all time and space oceanographic signals, complementary to the reference mission.

- **TARG-6.2.b** As a complementary goal this constellation will also allow proper sampling of non ocean signals: river, lakes, ice.
- **REQ-6.2.c** The orbits of the different satellites shall be optimized to the extent possible to allow tracking of mesoscale features over long periods (>3 months).
- **REQ-6.2.d** Specific error budget to monitor the corresponding signals shall be performed.

6.2.1 ORBIT SAMPLING AND ERROR BUDGET

REQ-6.2.1.a The constellation shall allow sampling the earth surface with the following time and space characteristics delivering measurement of the following accuracy:

Application	Parameter	Spatial Resolution	Time Resolution	Latency	Accuracy
Mesoscale variability	Sea surface topography	25-50 km	5 days	3 days	2-4 cm

***Table 3** – Sampling requirements*

TARG-6.2.1.b For high resolution altimetry applications the constellation will allow to sample the earth with the following time and space characteristics:

Application	Parameter	Spatial Resolution	Time Resolution	Latency	Accuracy
Sub- mesoscale variability and Coastal features	Sea surface topography	10 km	1-2 days	1 day	1-2 cm
Tides near coasts and Topography	Tidal constants—sea surface height	10 km	> 100 visits	N/A	1-2 cm
Barotropic tides	Tidal constants—sea surface height	5 km	> 100 visits	N/A	2 cm
Non-linear tides	Tidal constants—sea surface height	5 km	> 100 visits	N/A	1 cm

***Table 4** – Sampling requirements for high-accuracy applications*

6.2.2 ERROR BUDGET

The performance of the mesoscale constellation shall be considered after cross calibration internal to the constellation and cross calibration with the reference missions. Biases, drifts and large scale errors are then controlled by the reference mission error budget.

REQ-6.2.2.a The mesoscale mission error budget shall be for 1 sec average, 2 meters SWH, 11 dB sigma naught) after cross calibration internal to the constellation and with the reference mission:

	REQ- NRT 3 hours	**REQ- STC 1 to 1.5 day**	**REQ- GDR 40 days**	**TARGET**
Altimeter range RMS	5 cm	3 cm	3 cm	2.25 cm
RMS Orbit (Radial component)	10 cm	2.5 cm	1.5 cm	1 cm
Total RSS sea surface height	11.2 cm	3.9 cm	3.4 cm	2.5 cm
Significant wave height (whichever is greater)	10% or 0.5 m	10% or 0.4 m	10% or 0.4 m	5% or 0.25 m
Wind speed	1.6 m/s	1.5 m/s	1.5 m/s	1.5 m/s
Sigma naught	0.7 dB	0.7 dB	0.7 dB	0.5 dB
System bias and drift (on global mean sea level after calibration)	N/A	N/A	N/A	3mm and 0.1 mm/ year

***Table 5** – Error budget*

The performance in Table 5 may be summarized as follows:

- **REQ-6.2.2.b** The sea surface height shall be provided with a global and ultimate rms accuracy of 3.4 cm (1 sigma) over 1 second averages along satellite ground-tracks for typical sea-state conditions of 2 m SWH and 11 dB sigma-naught.
- **REQ-6.2.2.c** The reference system and ground-processing algorithms shall be designed to minimize the geographically and temporally correlated errors.
- **REQ-6.2.2.d** The instrumental corrections, environmental corrections, and precise orbit determination shall be provided with the appropriate accuracy to meet the 3.4 cm requirement on the sea level height. This corresponds to a corrected range RMS error of 3 cm and precise orbit RMS error of 1.5 cm on the radial component.
- **REQ-6.2.2.e** STC altimeter range and accompanying geophysical corrections shall have the same accuracy as the GDR but are not fully validated.
- **REQ-6.2.2.f** STC orbit shall be a 2.5 cm class orbit. The derived sea level measurement shall have 3.9 cm accuracy for typical sea-state conditions of 2 m SWH and 11 dB sigma-naught.

Requirements on the accuracy of three-hour NRT operational products measurements may have a lower accuracy (Table 1). This may be particularly apparent in altimetric range noise and tracker bias corrections.

REQ-6.2.2.g The orbit altitude in the NRT products shall be a 10 cm class orbit.

6.2.3 SWH, SIGMA NAUGHT AND WIND

Significant wave height, sigma naught and wind measurements have direct users. In addition these measurements are necessary to properly model the sea state interaction with the altimeter measurement in order to apply appropriate correction. The following requirements are sized to fulfil this sea state bias modelling with an accuracy consistent with the overall altimeter error budget.

GUID-6.2.3.a The accuracy of significant wave height measurements shall be 25 cm or 5% SWH (whichever is greater) for 1 s averages. The validity domain shall be 1 to 20 meters. A goal of 15 cm or 3 % is expected based on off-line ground re-tracking.

GUID-6.2.3.b The absolute accuracy of sigma naught shall be better than 0.7 dB (for a sigma naught varying between 7 dB and 16 dB) with a resolution in telemetry better than 0.1 dB. The sigma naught drift over 1 year shall be measured with an accuracy of 0.2 dB with 0.1 dB as a goal.

GUID-6.2.3.c The derived wind speed accuracy shall be better than 1.5 m/s for 1 s averages (for a range between 3 m/s and 20 m/s).

GUID-6.2.3.d The accuracy on SWH in OGDR products shall be respectively 10% or 0.5 m (whichever is greater).

GUID-6.2.3.e The accuracy on wind speed in IGDR products shall be 1.6 m/s.

6.3 MISSION REQUIREMENTS FOR GEODETIC ALTIMETRY

TARG-6.3.a A complement to the mesoscale constellation should be implemented to meet geodetic and geophysical mission objectives. It should have the following characteristics:

Application	Parameter	Spatial Resolution	Time Resolution	Latency	Accuracy
Geoid determination	Sea surface topography	1-2 km	N/A	N/A	1-2 cm

Table 6 *– Mission requirements for geodetic applications*

Intentionally left blank

REFERENCES

[1] Koblinsky, C.J., P. Gaspar and G. Lagerloef (Eds.): The Future of Spaceborne Altimetry – Oceans and Climate Change: A long term strategy (so-called “Purple Book”), Published by the Joint Oceanographic Institutions Inc., 85 pp, March 1992.

[2] Le Traon, P. Y., and F. Ogor: ERS-1/2 orbit improvement using Topex/Poseidon: The 2 cm challenge, *J. Geophys. Res.*, 103, 8045– 8057, 1998.

[3] Dorandeu, J., L. Carrère, G. Dibarboure: Study on optimisation of future altimeter orbits - WP 2200: Multi-mission context and impact on orbit candidates, Eumetsat Report, 2008.

[4] Wilson, W.S., J.-L. Fellous, H. Kawamura, L. Mitnik: History of Oceanography from Space, Manual of Remote Sensing, 2005.

[5] Drinkwater, M., H. Rebhan, P.Y. Le Traon, L. Phalippou, D. Cotton, J. Johannessen, G. Ruffini, P. Bahurel, M. Bell, B. Chapron, I. Robinson, L. Santoleri and D. Stammer: The roadmap for a GMES operational oceanography mission, ESA Bulletin, (124), 42-48, 2005.

[6] Aguirre, M., B. Berruti, J.-L. Bezy, M. Drinkwater, F. Heliere, U. Klein, C. Mavrocordatos, P. Silvestrin, B. Greco and J. Benveniste: Sentinel-3: the Ocean and Medium-Resolution Land Mission for GMES Operational Services, ESA Bulletin, (131), 25-29, 2008.

[7] Aguirre, M., Y. Baillion, B. Berruti and M. Drinkwater: Operational Oceanography and the Sentinel-3 System, (Ed.) Olla, P., Space Technologies for the Benefit of Human Society and Earth, Springer, pp. 75-98 (DOI 10.1007/978-1-4020-9573-3), 2009.

[8] Dorandeu, J., *et al.*: Sentinel-3 definition optimization of Sentinel-3 orbit and data sampling for meso-scale observation CLS-DOS-NT-06-085, CLS, 5 July 2006.

[9] Le Traon, P.-Y., *et al.*: Definition scenarios and roadmap for operational oceanography. Final report to ESA contract 18034/04/NL/CB, April 2005.

[10] Dumont, J.P., *et al.*: Sentinel-3 Surface Topography Mission – Basic Level 0/1/2 Products Specifications

[11] Le Traon, P.Y., J. Johannessen, I. Robinson, O. Trieschmann: Report from the Working Group on Space Infrastructure for the GMES Marine Core Service, September 12, 2006

[12] Ryder, P.: GMES Fast Track, Marine Core Service, Strategic Implementation Plan, Final draft, 2007.

[13] Proceedings of the Symposium on 15 Years of Progress in Radar Altimetry, 13-18 March 2006, Venice, Italy (ESA SP-614), July 2006.

[14] Conclusions, Strategic workshop on ocean surface topography constellation, January 2008.

[15] Bonekamp, H., *et al.*: Report of the Jason-3 Applications Working Group (EUM/MET/REP/07/0076), 2007.

[16] See http://www.myocean.eu.org/

[17] Dombrowsky, E., L. Bertino, G. Brassington, E. Chassignet, F. Davidson, H. Hurlburt, M. Kamachi, T. Lee, M. Martin, S. Mei and M. Tonani: GODAE Systems in operation, Proceedings of the Final GODAE Symposium, 47-74, 12-15 November 2008.

[18] Leeuwenburgh, O.: Assimilation of along-track altimeter data in the tropical Pacific region of a global OGCM ensemble, *Q. J. R. Meteorol. Soc.*, 131, pp. 2455–2472, 2005.

[19] Vidard, A., M. Balmaseda and D. Anderson: Assimilation of altimeter data in the ECMWF ocean analysis system, ECMWF technical memorandum 546, 2008.

[20] Systematic observation requirements for satellite-based products for climate – Supplemental details to the satellite-based component of the “Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC”, GCOS-107 – WMO-TD N° 1338, September 2006.

[21] Ablain, M., A. Cazenave, K.D. Minh, G. Valladeau and S. Guinehut: A new assessment of global mean sea level from altimeters highlights a reduction of global trend from 2005 to 2008, 2009 (under review).

[22] Balmaseda, M., O. Alves, A. Arribas, T. Awaji, D. Behringer, N. Ferry, Y. Fujii, T. Lee, M. Rienecker, T. Rosati and D. Stammer: Ocean Initialization for Seasonal Forecasting, Proceedings of the Final GODAE Symposium, 47-74, 12-15 November 2008.

Reference was also made, among others, to the following publications:

P.-Y. Le Traon and G. Dibarboure: Mesoscale mapping capabilities from multiple altimeter missions, Journal of Atmospheric and Oceanic Technology, 16, 1208 - 1223, 1999.

P.-Y. Le Traon, G. Dibarboure and N. Ducet: Use of a high resolution model to analyze the mapping capabilities of multiple altimeter missions, Journal of Atmospheric and Oceanic Technology, 18, 1277-1288, 2001.

P.-Y. Le Traon and G. Dibarboure: Velocity Mapping Capabilities or Present and Future Altimeter Missions: the Role of High-Frequency Signals, Journal of Atmospheric and Oceanic Technology, 19, 2077-2088, 2002.

A. Caballero, A. Pascual, G. Dibarboure and M. Espino: Sea Level and Eddy Kinetic Energy variability in the Bay of Biscay inferred from satellite altimeter data, Journal of Marine System (in press), 2006.

A. Pascual, Y. Faugère, G. Larnicol and P.-Y. Le Traon: Improved description of the ocean mesoscale variability by combining four satellite altimeters, *Geophys. Res. Letters*, Vol. 33, 2, 13-16, 2006.

P.-Y. Le Traon and G. Dibarboure: Illustration of the contribution of the tandem mission to mesoscale studies, *Marine Geodesy*, 27, 3-13, 2004.

D. Alsdorf, E. Rodriguez and L.L. Fu: Risk Reduction Studies for WATER HM Survey, Communication to the Water-HM Science Working Group (SWG).

L.L. Fu and E. Rodriguez, High-resolution Measurement of Ocean Surface Topography by Radar Interferometry for Oceanographic Applications, 10.1029 - AGU 2004.

S. Nerem *et al.*: Orbit Selection for the WATER HM Mission, Proceedings of the first Water-HM meeting, 12 October 2007.
http://bprc.osu.edu/water/Meetings_WATERHM/FirstMeetingSWG_Fall2007/.

G. Dibarboure *et al.*: Preparing for the additional errors on wide-swath altimetry: precise roll error reduction, Proceedings of the 2007 OSTST Meeting, 2007.
http://www.Jason.oceanobs.com/documents/swt/posters2007/dibarboure_WSARollError.pdf

D. Chelton *et al.*: Global observations of large oceanic eddies, *Geophys. Res. Letters*, 34:L15606, 2007.

D. Chelton *et al.*: Report of the High-Resolution Ocean Topography Science Working Group Meeting, 2001 http://www-po.coas.oregonstate.edu/research/po/research/hotswg/HOTSWG_report.pdf

Gamble team: Final Report from the GAMBLE EC project, Requirements for Future Satellite Altimetry: Recommendations for Missions and Research Programmes, 2004.
http://www.altimetrie.net/

G. Dibarboure *et al* : Blue Sentinel Definition, Study P5: Optimisation of Sentinel Orbit and data sampling for mesoscale observation, ESA Report, ref: CLS-DOS-NT-06-0085

R. Ray: WATER HM and Aliasing Issues
http://bprc.osu.edu/water/Meetings_WATERHM/FirstMeetingSWG_Fall2007/RAY_WideSwth.pdf

Y. Ménard, L.-L. Fu, J. Lambin, H. Bonekamp and J. Lillibridge: OSTM/Jason-2 Science and operational requirements.

ABBREVIATIONS

AVISO	Archiving, Validation and Interpretation of Satellites Oceanographic data (WBS element of the SALP Project)
CNES	Centre National d'Etudes Spatiales
DUACS	Developing Use of Altimetry for Climate Studies
ECMWF	European Centre for Medium-Range Weather Forecasts
ESA	European Space Agency
GDR	Geophysical Data Record
GFO	Geosat Follow On
GMES	Global Monitoring for Environment and Security
MCS	Marine Core Service
NRT	Near-Real-Time
NWP	Numerical Weather Prediction
SWH	Significant Wave Height
TAC	Thematic Assembly Centre
STC	Slow Time Critical Product

Intentionally left blank

ANNEX

Standard content of altimetry product (from ESA Sentinel-3 definition [17])

Table A *- Set of typical parameters to be stored in Level 2 products*

Type of parameter	Parameter and frequency (Hz)		**NRT/STC/NTC GDR Low Resolution Mode**
Time-tag	Time-tag	1	
		20	**(1)**
Location and surface type	Location (latitude and longitude)	1	
		20	
	Surface type (land/sea mask)	1	
		20	
	Radiometer surface type	1	
Orbit	Satellite altitude	1	
		20	
	Orbital altitude rate	1	
		20	
	Additional orbit information (satellite velocity vectors, TBC Real beam direction vectors…)	20	
Altimeter range	Tracker range	1	
		20	**Main/Aux**
	Tracker range rate	1	
		20	
	Coarse and fine trigger delays	20	
	Altimeter range or TBC surface elevation (SAR mode)	1	**Main/Aux - Ocean**
		20	**Main/Aux - Ocean, Ice and Sea Ice**
Altimeter range corrections	Net instrumental correction	1	**Main/Aux - Ocean**
		20	**Main/Aux - Ice & Sea-ice**
	USO frequency correction	1	
	Mispointing correction (model)	1	
	Internal path delay correction	1	
	Modeled instrumental correction	1	
	Doppler correction	1	**Main/Aux**
	Delta Doppler correction (ice sheet)	20	**Main/Aux**
	Centre of gravity correction	1	
	TBD Specific instrumental corrections in SAR mode	20	
	Model dry tropospheric correction	1	
	Model wet tropospheric correction	1	
	Radiometer wet tropospheric correction	1	
	Altimeter ionospheric correction (dual-freq.)	1	**Main/Aux**
	GPS-derived ionospheric correction (GIM)	1	**Main/Aux**
	Model ionospheric correction	1	**If any**
	Sea-state bias correction	1	**Main/Aux**
Significant wave height	Significant wave height	1	**Main/Aux - Ocean**
	Leading edge width (ice)	20	**Main/Aux - Ice**

Significant wave height corrections	Net instrumental correction	1	**Main/Aux**
		20	
	Mispointing correction (model)	1	
	Modeled instrumental correction	1	
	TBD Specific instrumental corrections in SAR mode	20	
Backscatter coefficient	Scaling factor	1	
		20	**Main/Aux**
	Backscatter coefficient	1	**Main/Aux - Ocean**
		20	**Main/Aux - Ice and Sea Ice**
	Automatic Gain Control	1	**Main/Aux**
		20	
	Noise Power Measurement	20	
Backscatter coefficient corrections	Net instrumental correction	1	**Main/Aux**
		20	
	Correction for instrumental errors on AGC	1	
	Mispointing correction (model)	1	
	Internal calibration correction	1	
	Modeled instrumental correction	1	
	TBD Specific instrumental corrections in SAR mode	20	
	Atmospheric attenuation	1	**Main/Aux**
	Rain attenuation	1	**If any - Main/Aux**
Off-nadir angle	Square of the off-nadir angle (waveform)	1	
	Square of the off-nadir angle (platform)	1	
	Slope of the trailing edge (ice)	20	**Main/Aux - Ice**
Brightness temp.	Brightness temperatures	1	
Geophysical parameters	Mean sea surface height	1	
	Local slope of the mean sea surface	1	**If any**
	Mean dynamic topography	1	
	Geoid height	1	
	Ocean depth/land elevation	1	
	Inverted barometer height correction	1	
	Surface atmospheric pressure	1	
	HF fluctuations of the sea surface topography (MOG2D)	1	
	Elastic ocean tide height	1	**2 solutions**
	Equilibrium long-period ocean tide height	1	
	Non-equilibrium long-period ocean tide height	1	
	Loading tide height	1	**2 solutions**
	Solid earth tide height	1	
	Pole tide height	1	
	Digital elevation model	20	
Environmental parameters	Model wind vector (U & V components)	1	
	Altimeter wind speed	1	
	Radiometer wind speed	1	
	Radiometer water vapor content	1	
	Radiometer liquid water	1	
	Total electron content	1	
Specific SAR mode parameters	Phase corrections, Beam behavior parameters …	20	
	Freeboard	20	
	Coherence at re-tracking point	20	
	Interpolated ocean height	20	
	Surface height anomaly	20	
	Ice concentration parameter	20	
	Snow depth	1	
Waveforms	Waveforms (averaged, elementary)	1	
		20	
Re-tracking outputs	"Ocean" (epoch, Sigma C, amplitude…)	20	
	"Ice" (epoch, leading edge width, amplitude…)	20	
	"Sea-Ice" (epoch, amplitude…)	20	

Quality information	RMS, number and map of valid points of 1-Hz compressed estimates, Measurement id., Mode id., Sensor status, Quality flags, Environmental flags, Peakiness, Statistics, Error bars…	1 and 20	
Additional Quality information	Re-tracking outputs (Mean Quadratic Error, number of iterations…)	20	

(1) 20-Hz values or offset and step (provided in a header) allowing the retrieval of 20-Hz values from the 1-Hz value

(2) In case of on-board re-tracking (e.g., Poseidon-2)

Produced and published by

EUMETSAT

Eumetsat-Allee 1
64295 Darmstadt
Germany

Tél: +49 6151 807 366/377
Fax: +49 6151 807 379
Web: www.eumetsat.int