

Special Issue on “Satellite Altimetry: New Sensors and New Application” Edited by Ge Chen and Graham D. Quartly

Full Research Paper

AltiKa: a Ka-band Altimetry Payload and System for Operational Altimetry during the GMES Period

Patrick Vincent^{1,*}, **Nathalie Steunou**², **Eric Caubet**³, **Laurent Phalippou**³, **Laurent Rey**³, **Eric Thouvenot**² and **Jacques Verron**⁴

¹IFREMER, 155 rue Jean-Jacques Rousseau, 92138 Issy-Les-Moulineaux, France

²Centre National d'Etudes Spatiales, 18 Avenue E. Belin, 31401 Toulouse Cédex 9, France

³Alcatel Alenia Space, 26 Avenue J.F. Champollion, BP 1187, 31037 Toulouse Cédex 1, France

⁴LEGI, UMR 5519, BP 53, 38041 Grenoble Cédex 9, France

E-mail addresses: Patrick.Vincent@ifremer.fr, Nathalie.Steunou@cnes.fr,

Eric.Caubet@alcatelaleniaspace.com, Laurent.Phalippou@alcatelaleniaspace.com,

Laurent.Rey@alcatelaleniaspace.com, Eric.Thouvenot@cnes.fr, jacques.verron@hmg.inpg.fr

* Author to whom correspondence should be addressed

Received: 6 August 2006 / Accepted: 10 March 2006 / Published: 17 March 2006

Abstract: This paper describes the Ka-band altimetry payload and system that has been studied for several years by CNES, ALCATEL SPACE and some science laboratories. Altimetry is one of the major elements of the ocean observing system to be made sustainable through the GEOSS (Global Earth Observation System of Systems) and GMES (Global Monitoring of the Environment and Security) programs. A short review of some mission objectives to be fulfilled in terms of mesoscale oceanography in the frame of the GEOSS and GMES programs is performed. To answer the corresponding requirements, the approach consisting in a constellation of nadir altimeter is discussed. A coupled Ka-band altimeter-radiometer payload is then described; technical items are detailed to explain how this payload shall meet the science and operational requirements, and expected performances are displayed. The current status of the payload development and flight perspectives are given.

Keywords: altimeter, radiometer, ocean mesoscale circulation, Ka-band.

1. Introduction

In partnership with scientific laboratories and industry, and for several years, CNES has studied the feasibility of a high-resolution ocean topography mission based upon a new class of wide-band Ka-band altimeter in preparation of the post-ENVISAT mission and in order to complement the OSTM/Jason-2 mission. A preliminary definition study of a coupled altimeter-radiometer instrument has been performed in 2001-2003 with the support of Alcatel Space.

Altimetry is a key technique to provide ocean users with the dynamic data to contribute to the development of operational ocean applications. To answer the user needs in terms of time-space sampling of the ocean for operational purposes, the AltiKa payload could be embarked on a constellation of three identical satellites flying in the same orbit plane with a 120 degrees lag in terms of position on the orbit, as a complement to Jason-like reference missions [1]. The central objective is the retrieval of the ocean mesoscale circulation and data assimilation in global or regional ocean models. Moreover, other applications of the mission have been identified: coastal altimetry, continental water studies, ice sheet monitoring, low-rain systems characterization are the main 'secondary' objectives identified so far.

The proposed architecture for the Ka-band altimeter is based on the classical deramp technique for pulse compression and takes benefits of Alcatel Space and CNES experience in the development of Poseidon-1, -2 and -3 and SIRAL (European Space Agency Cryosat mission). A bi-frequency radiometer is part of the compact Ka-band payload. Both altimeter and radiometer share the same antenna.

Apart from the combined altimeter and radiometer, this payload also consists of a DORIS plus LRA (Laser Retroreflector Array) orbitography system that will ensure a high level of accuracy in terms of orbitography.

Sections 2 to 4 are devoted to an extensive overview of the context in which mission requirements were defined. The altimeter / radiometer instrument is described in sections 5 and 6. Specific items are detailed in section 7 to explain how this payload shall meet the science and operational requirements. Expected performances are displayed in section 8. Last, section 9 gives the current status of the payload development and flight perspectives.

2. Altimetry in the GEOSS and GMES perspectives

The Global Earth Observation System of Systems (GEOSS) is designed to be the world-wide system of atmospheric, oceanic, and terrestrial observing systems integrated so as to monitor continuously the state of the Earth, to increase understanding of dynamic Earth processes, to enhance prediction of the Earth system, and to further implement environmental treaty obligations (see [2], for instance).

The GMES program (Global Monitoring for Environment and Security) launched in 1998 by the European Commission represents a concerted effort to bring data and information providers together

with users, so they can better understand each other and agree on how to make environmental and security-related information available to the people who need it. GMES will be the European contribution in the worldwide GEOSS. A challenge for GMES is to gather relevant data and provide innovative, cost-effective, sustainable and user-friendly services, which will enable decision-makers to better anticipate or integrate crisis situations issues relating to the management of the environment and security.

In this overall framework, GMES Marine Services are proposed to support, reinforce and improve the European capacities linked to:

- verification and enforcement of international treaties, and assessment of European policies;
- enabling of sustainable exploitation and management of ocean resources (offshore oil and gas industry, fisheries...)
- improvement of safety and efficiency of maritime transport, shipping, and naval operations, as well as of national security and reduction of public health risks;
- anticipation and mitigation of the effects of environmental hazards and pollution crisis (oil spills, harmful algal blooms);
- advanced marine research for better understanding of the ocean ecosystems and their variability;
- contribution to ocean climate variability studies;
- contribution to seasonal climate prediction and its effects on coastal populations;
- support to specific services for coastal management and planning.

The sustainability of GMES Marine Core Services is dependent on the long-term availability of satellite and *in situ* observing systems, on the European integration and organisation of the Core Service segment, as well as on close links with research and development activities. The observing systems required for Marine Core Services are integrated into a much wider context of coordinated observing systems and data providers at international level, such as the World Weather Watch (WWW), the Global Ocean Observing System (GOOS), Earth Observing Satellites, numerical weather forecasting centers, national ocean forecasting centers, etc. While some components, such as the WWW, the EUMETSAT satellites, or the Data Buoy Cooperation Panel (DBCP) are firmly established, other ocean components, endorsed by GOOS, rest on uncertain foundations, without guarantee of continuity so far. Thus an absolute prerequisite for GMES Marine Core Services is to ensure the sustainability of observing systems, including telecommunication facilities, and the centers for data management.

Several demonstration satellites, e.g. ENVISAT, should reach their end of mission around 2008, at the time when the GMES Marine Services are expected to be phased in. This is of course a matter of serious concern, and it is necessary to plan for the continuity of key missions to provide global coverage of essential variables such as sea surface height, temperature, wind and waves, fluxes, ocean colour and salinity.

The value of space-based measurements of SSH has been clearly demonstrated to contribute in answering a variety of ocean science questions such as in seasonal forecasting by providing realistic model initializations. The precision altimetry data from TOPEX/Poseidon (T/P) and Jason 1, when

calibrated precisely with tide gauge measurements, have provided the ability to monitor the rate of sea level change with a projected accuracy of less than one millimetre per year [3]. Continuation of the precision altimeter missions in the T/P - Jason orbit is necessary for sustaining this level of accuracy in monitoring long-term sea level change. Although adequate for many other applications, altimetry from the planned National Polar-orbiting Operational Environmental Satellite System (NPOESS) will not achieve this level of accuracy.

Four altimeter missions are flying at this time: T/P, Jason-1, Envisat, and Geosat Follow-on. By 2008, it is possible that the only altimeter flying will be Jason-2. Two different solutions can help achieving the space and time requirements of observations to provide adequate resolution: a constellation of several nadir altimetry satellites (see [1] for instance) or the use of wide swath altimetry (onboard one platform) with at least a ten km resolution and 200 km swath (Rodriguez and Pollard [4], Enjolras et al. [5]). Throughout this paper, only the first solution will be considered.

3. The need for high resolution ocean topography measurements to observing ocean mesoscale dynamics

Following Chelton and Schlax [6], the most problematic features of ocean circulation from the perspective of altimeter sampling are the mesoscale eddies and fronts that are of interest in the sea-surface height (SSH) and ocean velocity fields. These features are essential to understanding the dynamics of ocean circulation on all space and time scales. Theoretical studies of the cascade of energy over scales from 100-1000 km have always suffered from the lack of high-resolution observations. Numerical model simulations indicate that, in many regions of the world ocean, this mesoscale variability plays a key role in the large-scale ocean circulation and climate variability in the form of eddy transport of momentum in eddy-mean flow interaction and in the form of meridional eddy transport of heat. Global synoptic observations of the eddy field have never been available to test the accuracy of the model simulations.

Despite all the progress made through the last decade, there is still much to learn from altimeter data for mesoscale variability studies. Following Le Traon [7], investigations that could be carried out include:

- More detailed comparisons of altimetry with eddy resolving models (including comparison of higher order statistics such as frequency/wavenumber spectra and Reynolds stresses);
- Regional characterization of the three dimensional frequency/wavenumber of sea level (and velocity) and relationship with forcing fields and dynamics; Relationship with turbulence theories;
- Better characterization of seasonal/interannual variations in eddy energy and relationship with forcing fields (mean current instabilities, winds);
- Phenomenological (global) characterization of eddies (eddy census): size, rotation, diameter, life time, propagation, etc. and relationship with theories and models.
- Detailed dynamical structure of eddies. Estimation of the vorticity field (in and out of the eddy), divergence and deformation fields. Use in synergy with high resolution sea-surface

temperature (SST) and ocean color images. Estimation of vertical circulation and biogeochemical coupling.

- Relation and interaction between eddies and Rossby waves.
- Eddy heat fluxes (in combination with SST remote sensing data). Contribution to the total heat fluxes.
- Eddy mean flow interaction. Role of eddies on the general circulation and climate.

All above studies would benefit from higher space and time resolution.

One should note that the best use of high resolution altimetry data will be when they are assimilated with in-situ and other remote sensing data into global eddy resolving models (and nested shelf/coastal models). This will indeed open a large range of scientific (see above) and operational applications. In particular, the capability of providing precise velocity estimations will be of great importance for operational applications (offshore, fisheries, marine safety, etc.)

Empirical analysis and data assimilation approaches will be used in the next section to derive and justify mission requirements in terms of ocean mesoscale observations.

4. Deriving mission requirements for ocean meso-scale applications

4.1 Merging multiple altimeter missions to map ocean mesoscale signals

Mapping the ocean mesoscale variability can be performed through optimal interpolation methods which use an a priori knowledge of the space and time scales of the ocean signal. When data are mapped onto a regular space/time grid using such interpolation methods, the along-track long wavelength errors (or high-frequency ocean signals) can induce artificial cross-track gradient at smaller scales and thus spurious eddy signals [8]. The effect is particularly important in low eddy energy regions and when several altimeter data sets are merged. Along-track long wavelength errors can also lead to other serious problems. A well-known example comes from GEOSAT for which errors in the tide correction were aliased to produce spurious Rossby wave like signals in the mapped data [9]. To minimize these problems, the mapping method should either take into account an along-track long wavelength error (i.e. a correlated noise due to orbit, tidal or inverse barometer residual errors) or the long wavelength errors should be removed before mapping [8]. Merging multi-satellite altimeter data sets is generally necessary to map the mesoscale variability. To merge multi-satellite altimetric missions, it is first necessary to have homogeneous and cross-calibrated data sets. Homogeneous means that the same geopotential model and reference systems for the orbit and the same (as far as possible) instrumental and geophysical corrections should be used (e.g. same tidal models, same meteorological models, etc). Cross-calibrated means that relative biases and drifts must be corrected and also that the orbit error must be reduced. An effective methodology is to use the most precise mission such as T/P and Jason-1 as a reference for the other satellites [10-11]. This allows a reduction of orbit error for the other satellites to few cm rms even if the initial orbit errors are as large as 1 m rms [10].

When altimetric data have been homogenized and cross-calibrated, the next step is to extract the sea-level anomaly (SLA) for the different missions. It is preferable that the SLAs from different missions be calculated with respect to the same ocean mean using a common reference surface (e.g. either a

very precise mean sea surface or mean profiles consistent between the different missions). The final step is to merge the SLAs from the different missions via a mapping technique. Ducet et al. [12] provide a detailed analysis of T/P and ERS-1/2 merging over a five year period, in particular to quantify the contribution of merging in the description of the ocean mesoscale circulation.

4.2. Ocean mesoscale mapping capabilities

Le Traon and Dibarboure [13] have quantified the mesoscale mapping capability when combining various existing or future altimeter missions in terms of SLA and zonal (U) and meridional (V) velocity. Their main results are as follows:

- There is a large improvement in sea level mapping when two satellites are included. For example, compared to T/P alone, the combination of T/P and ERS has a mean mapping error reduced by a factor of 4 and a standard deviation reduced by a factor of 5.
- The velocity field mapping is more demanding in terms of sampling. The U and V mean mapping errors are two to four times larger than the SLA mapping error. Only a combination of three satellites can provide a velocity field mapping error below 10% of the signal variance.

Le Traon et al. [14] have shown that sea level mapping errors were larger than the ones derived from Le Traon and Dibarboure [13] formal error analysis by a factor of 1.5 to 2. This is mainly due to high frequency signals (periods below 20 days). In areas with large mesoscale variability, these signals represent 5 to 10% of the total sea level variance [15] and are associated with high wavenumbers. They account for 15 to 20 % of the total velocity variance. In shallow and high latitude regions, these high frequency signals account for up to 30-40% of the total sea level and velocity variance; there, part of these signals correspond to large scale barotropic motions.

To better analyze the impact of the high frequency signals on the sea level and velocity mapping, Le Traon and Dibarboure [16] systematically computed the mapping errors on the instantaneous fields and on 10-day averaged fields for various satellite configurations. Their main finding is the role of high frequency signals in the error budget. Since these signals cannot be resolved with any of the configurations they assumed (up to 4 Jason-1- like satellites in an interleaved orbit pattern), they strongly limit the mapping accuracy. As a result, the velocity mapping errors always remain larger than about 15-20% of the signal variance even for a four satellite configuration.

4.3. Analysis from a data assimilation perspective

Data assimilation is a powerful means for a dynamical interpolation of data and may be used to assess the spatial and temporal requirements of a satellite system (e.g. using a model forecast as an a priori knowledge instead of climatology). Demonstrating the value of data assimilation is the central objective of GODAE, the Global Ocean Data Assimilation Experiment [17]. Providing general requirements from a data assimilation perspective is, however, a difficult issue. Since the first steps in these directions [18-20], much progress has been made, and much more consistent results are today displayed regardless of the data assimilation techniques or/and the numerical models used.

In the following, we refer to data assimilation experiments based on the SEEK (Singular Evolutive Extended Kalman) filters, a family of reduced order Kalman filters in which the estimation error is expressed in terms of a sub-space that evolves with time according to the ocean dynamics [21-23]. These experiments were performed in the frame of the GAMBLE (Global Altimeter Measurements By Leading Europeans) project [24]. The model configuration is that of a simplified double-gyre system driven by surface wind, which includes a western boundary current zonally propagating across the ocean basin and generating mesoscale eddies. This mimics with a very good statistical similarity the eddy-active general circulation of the ocean in the mid-latitudes, such as the Gulf-Stream system. The general strategy of the numerical experiments is that of the Observing System Simulation Experiments (OSSE). Twin assimilation experiments are realized using several observing systems based on one, two and three altimeters flying simultaneously. The assumed satellite mission parameters are those of T/P, Jason and ERS. Data collected along tracks are pooled together at regular interval (typically a few days) to perform the analyses synoptically. Observation errors consistent with those of real data are added as a random signal to the pseudo-observations.

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

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

Overall, the results using three satellites confirm other studies indicating that a third satellite is necessary to control the mesoscale features satisfactorily. However, the selection of the optimal configuration is not trivial.

4.4 Resulting requirements for mesoscale measurements

From these and other (e.g. [25-26]) studies, the following refined requirements for mesoscale applications can be derived in terms of constellations of nadir altimetry satellites:

1. The minimum requirement is to continue flying a two satellite configuration (after Jason-1 and ENVISAT) with one long-term reference mission (Jason series). A two-satellite configuration provides already a good representation of the mesoscale variability (sea level mapping errors of the order of 10% of the signal variance). However, it cannot provide a sufficiently accurate estimation of the velocity field (e.g. below 10% of the signal variance) and will not allow to track small eddies (e.g. diameter below 100/150km).

2. This can be very significantly improved with an optimised three satellite configuration. Compared with the Jason-1 and ENVISAT tandem (or T/P+ERS), such configurations would allow a reduction of sea level and velocity mapping errors by a factor of about 2 to 3. It is also likely to partly resolve the large scale high frequency barotropic motions (see for instance [27]). Possible orbit configurations could be based on the Jason pattern with interleaved ground-tracks (which would yield a track separation of about 100 km at the equator and a repeat period of 10 days), or an ENVISAT orbit with all three satellites overflying the same ENVISAT ground tracks (which would yield a track separation of about 80 km at the equator and a repeat period of 35/3 days). The Jason orbit based scenario is slightly better for mapping the meridional velocity field but the ENVISAT orbit based scenario has the advantage of providing measurements at high latitudes.

3. To further improve the mapping quality (which is needed for some of the envisioned scientific and operational applications), it is required to resolve the high frequency and high wavenumber signals, i.e. sample the ocean with a time sampling below 10 days and 100 km. This is likely to require a constellation of more than six satellites and/or use different concepts for satellite altimetry such as wide swath techniques as described in [4-5].

Given the previous results, the coming sections will then describe the technical details of an original Ka band altimetric payload that could be embarked on micro-platforms so that getting constellations of such payloads in orbit could be cost-effective.

5. The AltiKa payload

The AltiKa payload includes :

- a Ka-band altimeter (35.5-36 GHz)
- a dual-frequency radiometer (23.8/36.8 GHz),
- a DORIS receiver,
- a Laser Retro-reflector Array (LRA).

The main instrument of the payload is the Ka-band radar altimeter. This altimeter is derived from the Poseidon altimeter and operates at 35.75 GHz. A dual frequency microwave radiometer (23.8 and

36.8 GHz) is embedded in the altimeter. A detailed description of the altimeter / radiometer instrument is given in section 6.

To achieve adequate orbitography performances, it is proposed to embark a DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) receiver [28]. The receiver that is envisaged for an AltiKa mission is the most modern and compact one which is developed for the Jason-2 mission. DORIS is a dual-frequency system (400 MHz and 2 GHz) based on network of emitting ground beacons spread all over the world. The DORIS on-board package is composed of:

- a dual-frequency antenna (omnidirectional antenna located on the nadir face of the satellite),
- a BDR which is composed of two DORIS chains in cold redundancy accommodated inside the same electronic box. Each DORIS chain includes a MVR (Mesure de Vitesse radiale) unit achieving beacon' signals acquisition and processing, navigation, Doppler measurements storage and formatting, electrical satellite interfaces management functions, and a USO (Ultra-Stable Oscillator) delivering a very stable 10 MHz reference which is also used by the altimeter.

A laser retroreflector array (LRA) will also be implemented on the payload, in order to calibrate the precise orbit determination system and the altimeter system several times throughout the mission. The LRA is a passive system used to locate the satellite with laser shots from ground stations with an accuracy of a few centimetres.

Mass and power budgets (see below) are such that the payload can be accommodated either on a micro-satellite, either as a passenger on opportunity missions.

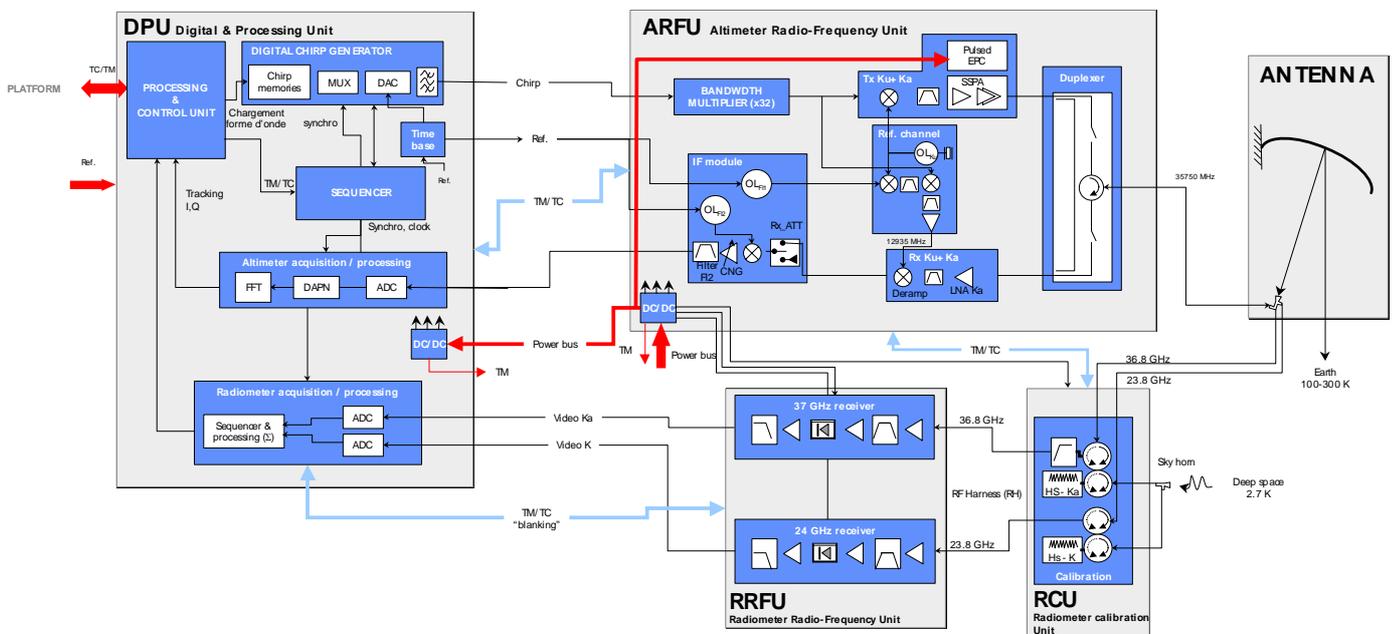


Figure 1. Instrument block diagram.

6. Instrument description

A preliminary definition study of a coupled altimeter-radiometer instrument was performed in 2001-2003 with the support of Alcatel Space [29-30]. The following description is based on the results of this study.

The proposed architecture for the Ka-band altimeter is based on the classical deramp technique for pulse compression. The AltiKa altimeter is based on proven concepts and already developed sub-systems, as it inherits a lot from Siral (European Space Agency CRYOSAT mission) and Poseidon-3 to fly on the JASON-2 mission.

The radiometer is of the total power type and is based on the direct detection principle. The altimeter and the radiometer share the same antenna.

Description of the different units

As shown on the block diagram (see Figure 1), the instrument is made of 5 units.

- The Digital and Processing Unit (DPU)

The Digital unit is composed of 5 boards and the mother board.

- The chirp board (see Figure 2) contains the digital chirp generator, the sequencer (ASIC), and the time base which converts the 10 MHz reference from Doris to a 160 MHz reference. There is a high recurrence from the ESA CRYOSAT/SIRAL interferometric altimeter instrument for this board.

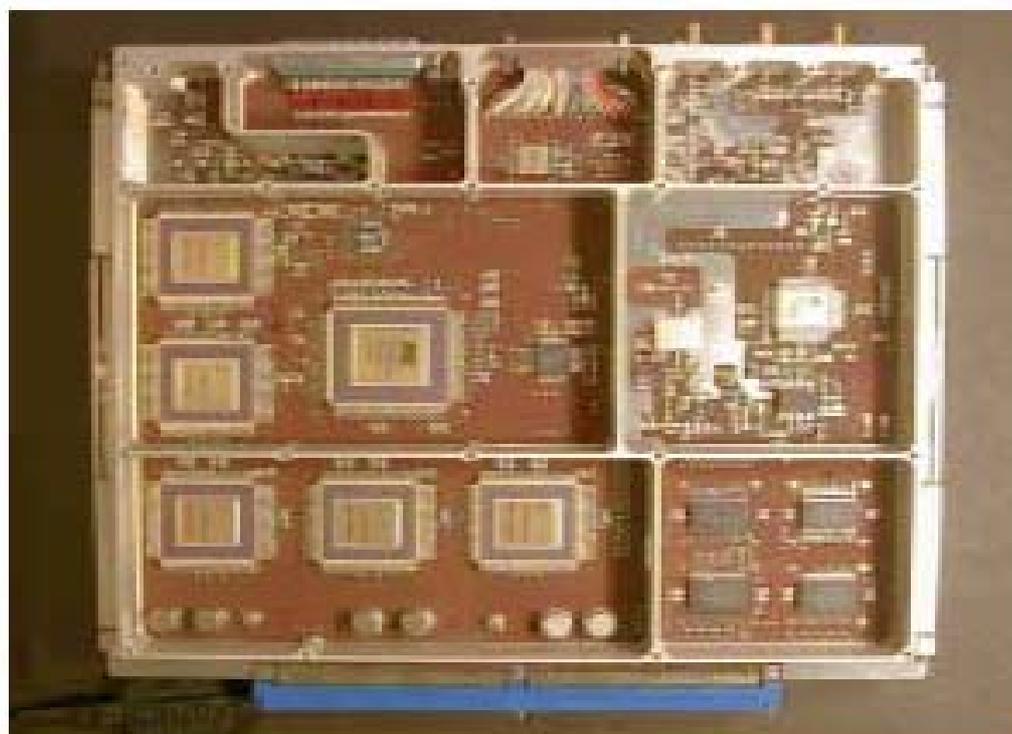


Figure 2. Chirp / sequencer / time base board.

- The altimeter processing board is very similar to the POSEIDON-3 one to be flown on Jason-2. The main elements are an ADC (Analog to Digital Converter), a DAPD (Digital Amplitude Phase

Demodulator), the FFT 128 points ASIC, the RAM to be used for high data rate mode, the time averaging function (accumulation of elementary waveforms in order to reduce the speckle noise)

- The DSP board which contains the DSP21020 board (SIRAL recurrence)
- The DC/DC board (based on SIRAL)
- The Radiometer processing board is a new development

- The Altimeter Radiofrequency Unit (ARFU)

The Altimeter Radiofrequency Unit is based on POSEIDON-2/3 modules (with no C-band).

- The bandwidth multiplier module is adapted to 500 MHz bandwidth from POSEIDON-3.

The transmission (Tx) module structure (Tx Ku + Tx Ka + SSPA module and EPC + Ka LO (Local Oscillator) is recurrent from POSEIDON-3 with some internal adaptations. The SSPA (Solid State Power Amplifier) is a new development: indeed, a 2 Watt High Power Amplifier (HPA) is needed for the link budget, which represents a state of the art device.

- The reception (Rx) module (Rx Ku + Rx Ka + reference chain + LO Ku + deramp function) is recurrent from POSEIDON-3 with some internal adaptations.

- The Intermediate Frequency (IF) module (Digital gain application + anti-aliasing filter + LO) is fully recurrent POSEIDON.

- DC/DC module is based on POSEIDON-3 module

- The duplexer (see Figure 3) is the interface between the antenna, the transmission module (Tx) and the reception module (Rx). It is similar to POSEIDON-3 Ku duplexer.

-



Figure 3. Altimeter Ka-band duplexer.

- Antenna

The antenna is composed of a fixed offset reflector with a 1 m aperture, a 0.7 m focal length and a 0.1 m offset, a three-band feed (35.5-36 GHz; 23.6-24 GHz; 36.6-37 GHz) and a sky horn pointing to deep space, thus providing a cold temperature reference to the radiometer.

Separation of the radiometer polarization from the altimeter polarization, and separation of Ka altimeter and radiometer channels through discrimination of polarization have been achieved by designing dedicated polarisers.

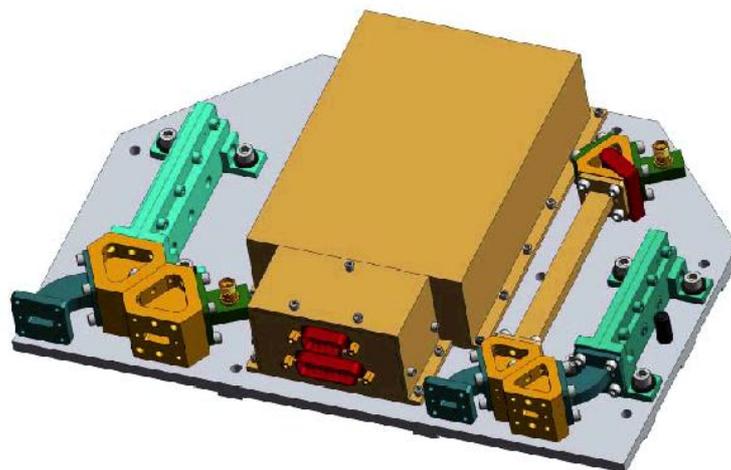
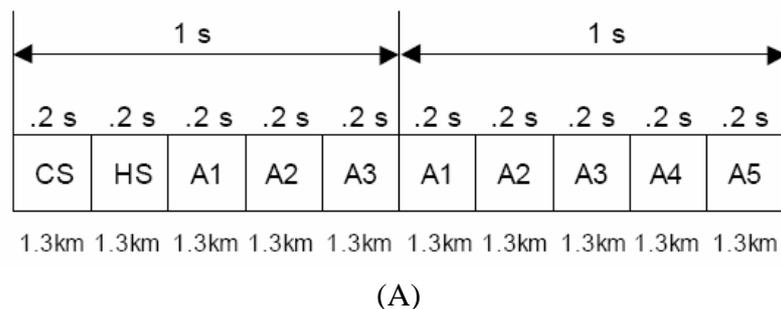


Figure 4. Radiometer measurement cycle (A) and Radiometer calibration unit (B).

The main antenna performances can be summarized as follows:

- Altimeter: gain >49.3 dB and 3-dB aperture <0.6°
- Radiometer 3-dB aperture : 0.8° at 23.8 GHz and 0.6° at 36.8 GHz
SLL <-25 dB leading to a beam efficiency of 96 to 98 %

- Radiometer Radiofrequency unit

The radiometer is a total power radiometer with direct detection. The radiometer radiofrequency unit consists of two RF receivers. These receivers will be the same as the ones used in the framework of the MEGHA-TROPIQUES mission on the MADRAS radiometer. They are developed by ASTRIUM-F.

- Radiometer calibration unit

The radiometer must be switched-off during radar altimeter emission. The radiometer measurement cycle is shown on the left panel of Figure 4. In the nominal mode, radiometer receivers measure antenna temperatures (A1 to A5). In the internal calibration mode, receivers are either connected to a sky horn pointing to deep space (cold reference) (CS) or to a load at ambient temperature (hot reference) (HS). This internal calibration can be performed every few seconds. Measured temperatures are averaged over 200 ms. The radiometer calibration unit (right panel of Figure 4) performs altimeter bandwidth filtering and commutation to calibration sources.

Instrument characteristics

Table 1 displays a summary of the main parameters and budgets of the coupled altimeter/radiometer instrument.

Table 1. Altimeter / radiometer parameters and budgets.

Parameter	Value
Altimeter band	35.75 GHz \pm 250 MHz
Pulse bandwidth	500 MHz
Pulse duration	110 μ s
Altimeter Pulse repetition frequency	4 kHz
Echo averaging (altimeter)	25 ms
Spectrum analyser (altimeter)	128 points
Altimeter Link budget	11 dB (sigma naught = 6.5 dB)
Antenna diameter	1000 mm
Focal length	700 mm
Offset	100 mm
Radiometer band	23.8 GHz \pm 200 MHz 36.8 GHz \pm 200 MHz
Radiometric resolution	<0.5 K
Radiometric accuracy	<3 K
Radiometer averaging	200 ms
Mass (altimeter+radiometer)	<33 kg
Power consumption (altimeter+radiometer)	<76 W

Instrument main modes

- Calibration modes

Two calibration modes are available on the instrument. First, the Calibration 1 mode provides the altimeter point target response (complex spectrum). The transmission channel is looped back to the

corresponding receiver input through the calibration attenuator. In order to obtain a high resolution for this response, the central frequency of the spectrum analyzer can be scanned by a step thinner than the frequency resolution. The second calibration mode, the calibration 2 mode, is designed to measure the receiver transfer function after deramp (in the frequency domain) by averaging the natural thermal noise in the reception channel over a long period. Altimeter analysis window has to be positioned to a range that guarantees the absence of returned echoes.

These calibrations are available by ground telecommands. The results will be used in the ground processing in order to take into account the signature of the instrument.

- The nominal acquisition and tracking modes

Several options are available to run these modes, as a new experimental processing feature will be implemented AltiKa (as well as on the Jason-1 POSEIDON-3 altimeter): the coupling of the altimeter with the so-called DORIS/DIODE navigator (see [31] for instance, for a description and performances of the DIODE navigator onboard Jason-1). Indeed satellite position and velocity bulletins from this DORIS/DIODE navigator are available on board every 10 seconds. The idea is to use this information in the altimeter processing, either in acquisition or in tracking mode. The aim of this new mode is to improve the behavior of the instrument in coastal regions and above in-land waters. It shall be noted that the GLAS (Geoscience Laser Altimeter System) instrument onboard the ICESat platform already uses GPS (Global Positioning System) measurements and an onboard Digital Elevation Model (DEM) to control capture of the digitized laser echo return waveform on every pulse [32].

In terms of the acquisition mode:

The acquisition mode aims to detect the useful signal and initialize the position of the analysis window whenever the instrument is powered up or loses track. The first phase consists of exploring all the possible altitudes and locking the tracking loops. Two options may be used for the Ka band altimeter. In the classical acquisition mode, a ± 25 km range window is run through until a waveform is detected. In an experimental acquisition mode, a very narrow range window could be used around the altitude provided by DIODE.

In terms of the tracking mode:

Because the satellite altitude can change rapidly (1 meter in 50 ms) as well as the backscatter coefficient (due to varying sea state, wind conditions, ...), which leads to a change in the return power, echoes have to be “power tracked” and “range tracked”. The tracking algorithm computes estimates based on 25 ms accumulated waveforms. Indeed, in order to reduce the speckle noise, waveforms are accumulated before their processing and transmitting to the ground. About 100 elementary return pulses are accumulated, which corresponds to a cycle of 25 ms.

In order to maintain the echo power level at a constant level after accumulation and FFT, an AGC (Automatic Gain Control) loop (1st order loop) is first used.

Then, in order to remain correctly positioned within the frequency analysis window and to make a correct summation for each range gate from one pulse to the next, a 2nd order range tracking loop is

used to maintain the waveform front slope at a determined range gate. In addition to a classical POSEIDON type algorithm, an experimental tracking mode using the DIODE information can be used. In the latter case, the range instruction is processed by using the DIODE altitude and an additional on-board data set containing the elevation of the surface. This means that to perform this “open” tracking process, a DEM providing the height above the geoid at the nadir point along the whole orbit has to be stored on board the altimeter.

Last characteristic to mention is that a high data rate mode will be available on AltiKa. It will provide complex in phase and in quadrature waveforms at the PRF rhythm and will be used to analyze speckle and echo characteristics in transition regions.

Accommodation

The instrument can be accommodated on a micro-satellite or as a passenger on an opportunity mission.

The feasibility of the accommodation of AltiKa on a SSTL (Surrey, UK) platform has been studied. An artist view of the accommodation results is provided in Figure 5. The platform was based on a known TopSat platform.

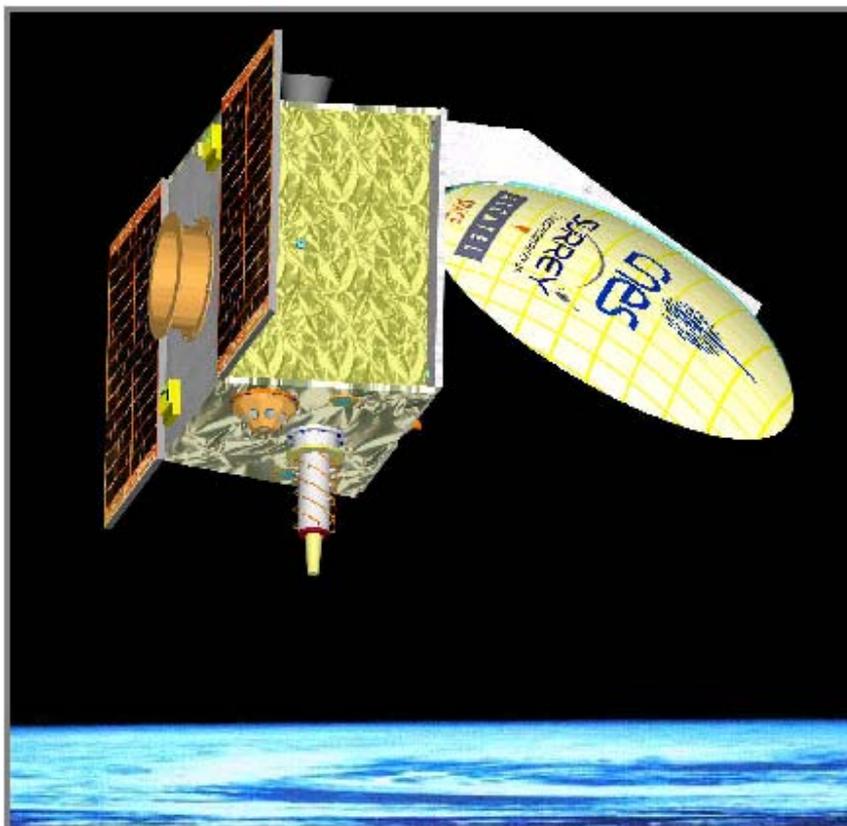


Figure 5. Artist view of the SSTL platform accommodation.

7. Rationale for ka-band selection

Following is a list of items that help understanding why the Ka band has been selected for the altimeter instrument of the AltiKa payload.

Technical aspects

Selecting the Ka-band allows a larger bandwidth (500 MHz), which provides a vertical resolution of 0.3 m instead of 0.5 m in Ku-band. With such a resolution, the altimeter is close to a beam limited one: there is no ‘plateau’ in the echo, since it strongly attenuates shortly after the leading edge, due to the small antenna aperture. This will greatly reduce the pollution of ‘land gates’ into ‘ocean gates’, when considering land-sea transition areas.

The shorter decorrelation time of sea echoes at Ka-band also enables to double the number of independent echoes per second compared with Ku-band altimeters. The instrument is thus designed for a high Pulse Repetition Frequency (PRF) around 4000 Hz, adjustable along the orbit.

Moreover, due to the smaller antenna beamwidth, the Brown echo has a sharper shape in Ka-band than what is obtained with conventional Ku-band altimeters. This point is illustrated on Figure 6. The antenna footprint is thus reduced: at 800 km altitude, the 3-dB footprint radius is about 4 km versus 15 km for Poseidon 2 (Jason-1). This also contributes to improve spatial resolution versus classical Ku-band altimetry and to discriminate types of surface in transition zones (coastal areas, sea ice boundaries, and so on).

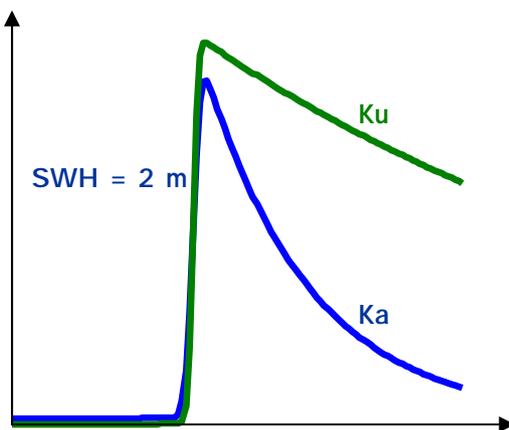


Figure 6. Waveform shapes in Ka- and Ku-bands for a 2 m significant waveheight (SWH).
(Horizontal axis: Time; Vertical axis: Return Power)

All these above aspects, associated with a high performance on-board algorithm, entails a higher expected performance using altimetry in Ka-band.

Ionospheric aspects

In addition, in the Ka-band, ionospheric effects are most often negligible. Indeed, the ionospheric error is inversely proportional to the square of the frequency and the typical expected effect on the range is a delay of about 0.02 ns (corresponds to 3 mm). In any case, when required, DORIS may provide a dual frequency correction in extreme and non frequent ionospheric conditions.

Rain issues

Propagation of Ka-band electromagnetic waves is known to be sensitive to atmospheric conditions which may lead to significant atmospheric attenuation. This attenuation includes contributions from gazes (with values varying from 0.4 to 2.1 dB when humidity varies from 7.5 to 50 g/m³), clouds (cumulus and cumulonimbus being generally the main contributors (0.2 to 0.7 dB) to the total loss; stratocumulus may also lead to an 0.05 to 0.2 dB attenuation) and rain.

Attenuation by rain, and possibly snow, is computed from rain rate and rainfall thickness (see Table 2). Let us consider climatic zones as defined by UIT-R (Union Internationale des Télécommunications – Radiocommunications), and let us restrict our analysis to ocean and polar areas. Then, it comes that precipitation rates are less than 1.5 mm/hr during 95% of an year or even less than 1 mm/hr during 90% of the time, except in the Philippines area where figures should be doubled. (For information, if we assume a 99% figure to be the nominal specification in terms of altimeter measurement capability, then the maximum precipitation rate to be taken into account has to be increased to 12 mm/hr, or even 65 mm/hr for a 99.9% figure. This would be dramatic in terms of technical specifications of the instrument in the Ka-band).

Assuming that the data return rate is respectively 90% and 95% level, the total attenuation (2 ways) is less than 2.4 dB and 3.6 dB respectively. Reaching the 90% or even 95% data return rates is thus fully achievable without any technical difficulty.

Table 2. Rain rates (mm/hour) and thickness (km), as provided by UIT-R.

rate (mm/h)	0.1	0.5	1	2	5
Attenuation due to rain (dB/km)	0.02	0.1	0.2	0.4	1
Attenuation due to snow (dB/km)	0.002	0.015	0.06	0.2	1.5

Latitude	0°	30°	45°	60°	75°
Maximum thickness 99% of time (km)	4.5	3.5	2	0.5	0.2

Complementary studies can be performed in order to better analyze seasonal effects and optimize local time of ascending/descending nodes of the orbit if a sun-synchronous orbit is selected: indeed, besides improving the link budget –which should be a difficult task- local time of sun-synchronous orbits provides a degree of freedom to possibly enlarge the 90% and 95% figures that are reported above and then reach near full availability of measurements. (As a side comment, it may be considered that flying a sun-synchronous orbit opens the issue of tidal aliasing in terms of mission definition. The ocean tide topic has been widely addressed by oceanographers dealing with T/P or ERS data. As discussed in section 4, complementing T/P-like missions with sun-synchronous missions is now widely accepted as providing the needed altimeter data set to retrieve large scale and mesoscale ocean signals with the appropriate level of quality –if other parts of the systems are of course of the required quality-. Then, consideration of a sun-synchronous orbit for AltiKa missions complementing a T/P-follow on missions is fully acceptable on a mission point of view)

In addition to the attenuation effect, rain cells also impact the shape of the waveforms: specific algorithms have to be used in order to retrieve geophysical parameters correctly in the presence of rain. Such algorithms are presently under development: for instance, simulations are being run to analyze the variation of the shape of the echoes in the presence of rain cells that are characterized by a given rain rate and a characteristic diameter.

In the past, several studies investigating the effect of rain on dual frequency T/P altimeter data have proposed a rain flagging procedure based on the departure of measured Ku and C band data from theoretical Ku/C band backscatter coefficients relationships. More recently, methods of determination of oceanic rain cell characteristics from the analysis of altimeter waveforms have been proposed and tested. These studies have mainly investigated Ku and C band altimeter measurements for which the signal attenuation by rain is one or two orders of magnitude smaller than that at Ka band. Because the method developed in the past to compute the altimeter waveforms in presence of rain are based on some approximations that are no longer valid for the Ka band, Tournadre [33] developed a new approach that has been shown to perform better for strong attenuation. Rain distortion/detection algorithms as well as flagging algorithms in the presence of rain are presently under development based on Tournadre [33] preliminary studies.

Note that, symmetrically, the sensitivity of Ka band measurements to rain may also lead to a way of estimating very light rainfall over the oceans, for which we dramatically lack of information and which could lead to a great improvement of our knowledge of the oceanic rain climatology [33].

Minimizing penetration issues over some types of continental surfaces

Flying AltiKa on an ENVISAT like orbit would allow the acquisition of data over ice sheets, and accurate surface topographies could then be generated: this could indeed be a secondary objective of an AltiKa mission as recalled in the paper introduction. In the Ka band, electromagnetic wave penetration effects are minimized, which is particularly important over continental ice surfaces. Also, the scattering coefficient can be assumed to be inversely proportional to the radar wavelength at a power 4. From Ku to Ka bands, the scattering coefficient will increase by a factor 55 : volume scattering will then be clearly dominant over surface scattering. Inversely, the radar wave extinction will also increase, leading to a penetration depth over the snow surface between 0.1 and 0.3 m (versus

2 to 10 m in Ku-band). The altimetric observation and height restitution will thus correspond to a thin subsurface layer. The accuracy will then be considerably improved. Such a topic is discussed in [34].

In terms of radiometer instrument

As far as the radiometer is concerned, the aim is to perform the measurements necessary to get the wet troposphere correction with a sufficient accuracy. Moreover, the instrument has to be compact in order to be possibly embarked on a micro-satellite. This led to the selection of a dual frequency radiometer of the total power type and based on the direct detection principle. The 23.8 and 36.8 GHz frequencies allow sharing of the antenna with the altimeter.

8. Expected altimeter performances

Measurements objectives and principle

The main parameters to retrieve from return waveforms are (see Figure 7):

- the range, standing for the distance measurement between the satellite and the sea surface,
- the significant wave height (SWH),
- the backscatter coefficient σ_0 which is directly related to the surface wind,
- thermal noise and antenna mispointing can also be derived from the measurement.

To estimate these parameters on sea surfaces, the Hayne's model [35] is commonly used as it is an analytical formulation of the return power depending on these different parameters.

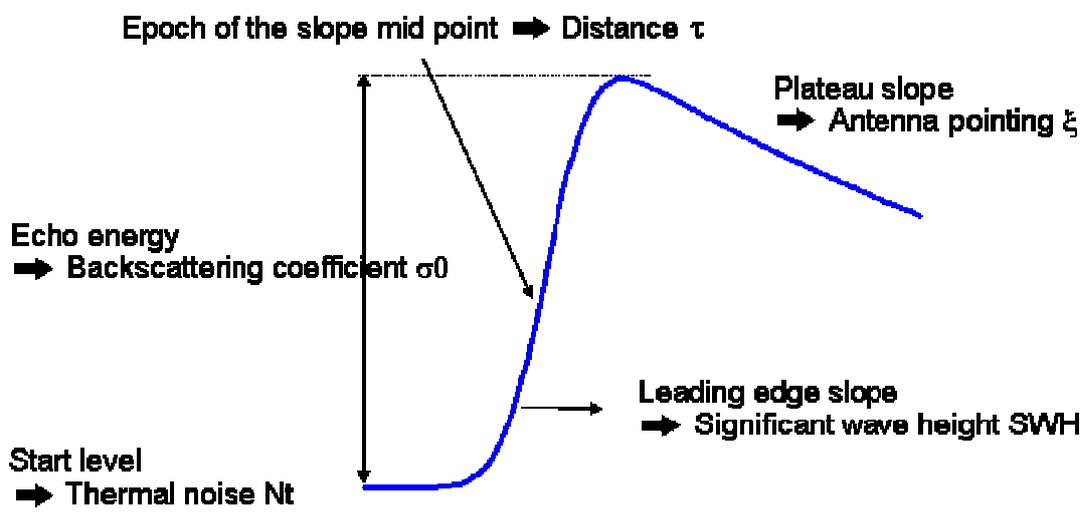


Figure 7. Hayne's model with associated parameters.

Something to point out is the large sensitivity of Ka-band echoes to satellite mispointing, due to the small antenna aperture, which entails a high attenuation and deformation of the return waveform. This is shown on Figure 8. The platform pointing accuracy is thus required to be better than $\pm 0.2^\circ$ at 3σ , which is something that has been proved to be fully achievable in flight on microsatellite platforms such as the CNES MYRIADE series.

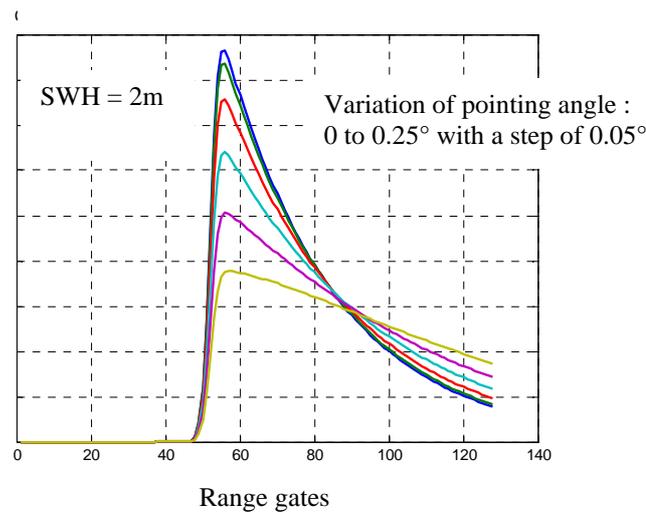


Figure 8. Pointing errors effect on Ka-band waveforms.
(Horizontal axis: Range gate number; Vertical axis: Return Power)

The next sections will deal with a variety of aspects of the performance budget.

Ka-band waveform generation from a simulator run over ocean and non ocean surfaces

Analyzing the behavior of the instrument in ocean and non ocean conditions and in particular over land and water transitions (coastal areas, inland water) is of course of major interest. The first aspect to check is the acquisition duration: the shorter this duration, the faster the instrument can track a useful signal and even get a return signal above very small water areas. The second aspect is of course the range tracking design. On AltiKa, both a classical tracking loop and an open tracking loop based on a coupling with DORIS/DIODE and a DEM are implemented and optimized in order to improve as much as possible the instrument behavior over non ocean areas compared with POSEIDON-2/ Jason-1 whose tracking algorithm was optimized over sea surfaces. In order to characterize this behavior, a simulation tool has been developed: it consists of building altimeter waveforms along a portion of orbit over all types of surfaces by using a DEM (as illustrated on Figure 9) and then running all tracking algorithms on these waveforms. The performance can then be derived from the analysis of the losses of track, the time spent in the acquisition mode, the comparison of useful samples that would be transmitted in telemetry and so on.

Performance of the instrument acquisition phase

Let us first characterize the acquisition duration. In the nominal acquisition mode, with a search range of ± 25 km, the acquisition duration can last up to 2.8 s. This can be very critical because about 18 km in the along-track ground direction is covered during this time. Coupling the search phase with DORIS/DIODE outputs, this acquisition duration will decrease down to 400 ms only. Such a large improvement can prove very useful in particular to detect small continental water areas.

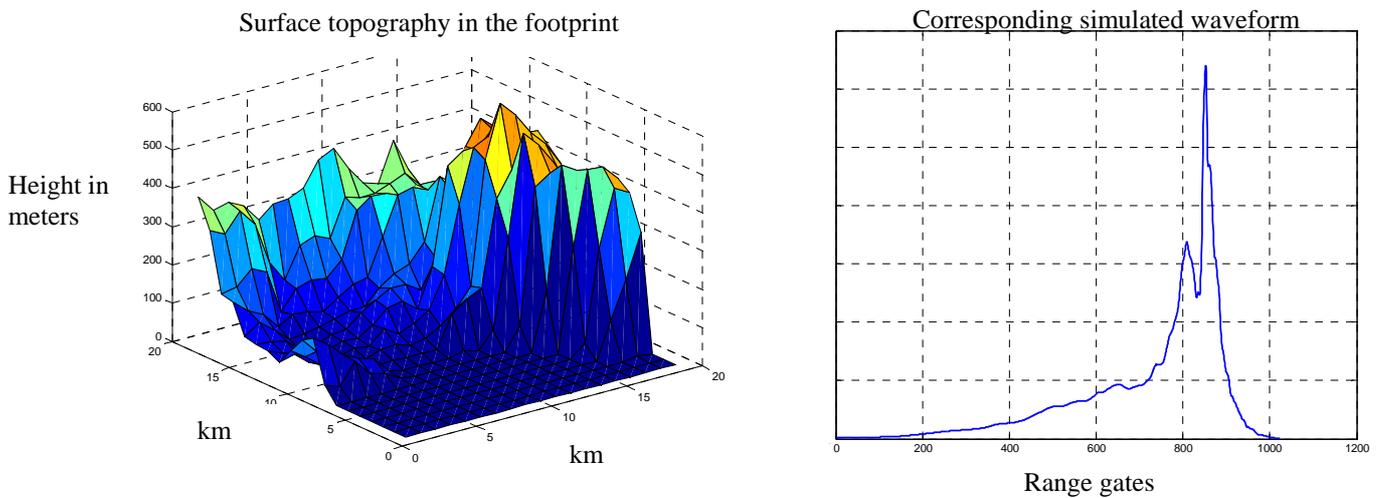


Figure 9. Simulated sea to land transition echo over a topography known from a DEM.

Performance of the instrument tracking phase

Let us now go to the tracking performances, that is evaluating the capability to remain tracked even with land perturbation, and also to detect a useful signal as soon as possible. In this respect, coastal and continental water areas have been addressed with a particular emphasis, based on the coupling with DORIS/DIODE and the embarked along-track DEM. The DEM has been designed a priori in order to be optimized in areas of interest (coasts, lakes, rivers, deserts, ...): to do so, even if the nadir point is above a land surface, the distance found in the DEM corresponds to the distance from the surface of interest. An example of such an optimization is illustrated on Figure 10. The validation and optimization of such an along track DEM is a critical issue as it has to be very accurate, with regards to the range analysis window of 30 meters. (The basic concept is very different from the GLAS instrument that works with much larger windows and may then use less critically accurate DEMs).

In the classical tracking mode, the input of the loop is a range error calculated from a median discriminator. The principle is to estimate the range gate that corresponds to half of the total power of the echo and then derive the error, the theoretical gate being known. Range instructions are then computed by the loop from the error. Signal to Noise Ratio (SNR) is also calculated and is the basis of the criterion that is used to advertise loss of track (when SNR is too low).

Transitions from water to land are generally well processed with a median discriminator. Over such transitions, using the algorithm benefiting from DORIS/DIODE and a DEM rather than a classical tracking loop does not improve tracking very much. However, coupling the altimeter with the DORIS/DIODE navigator greatly improves the performance in transitions from land to water areas.

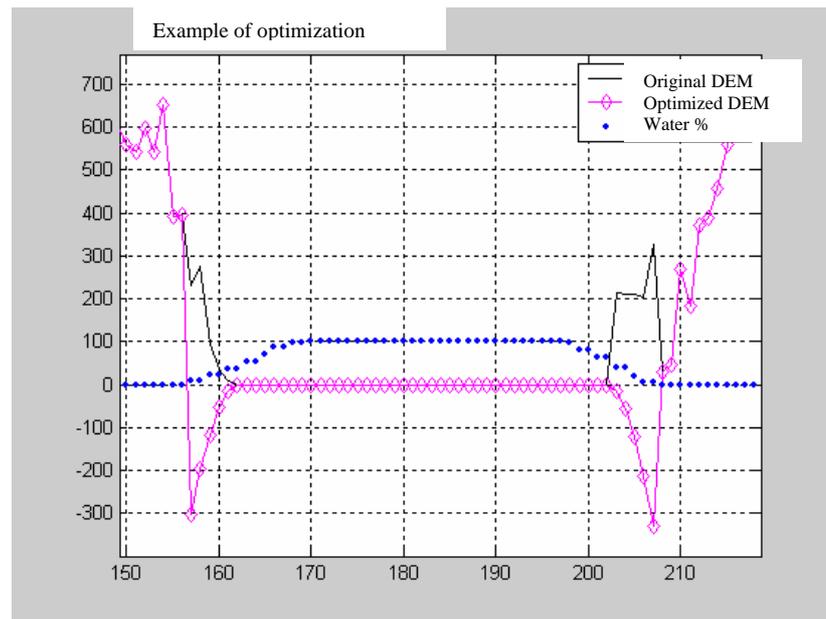


Figure 10. Distance optimization in the on board DEM.

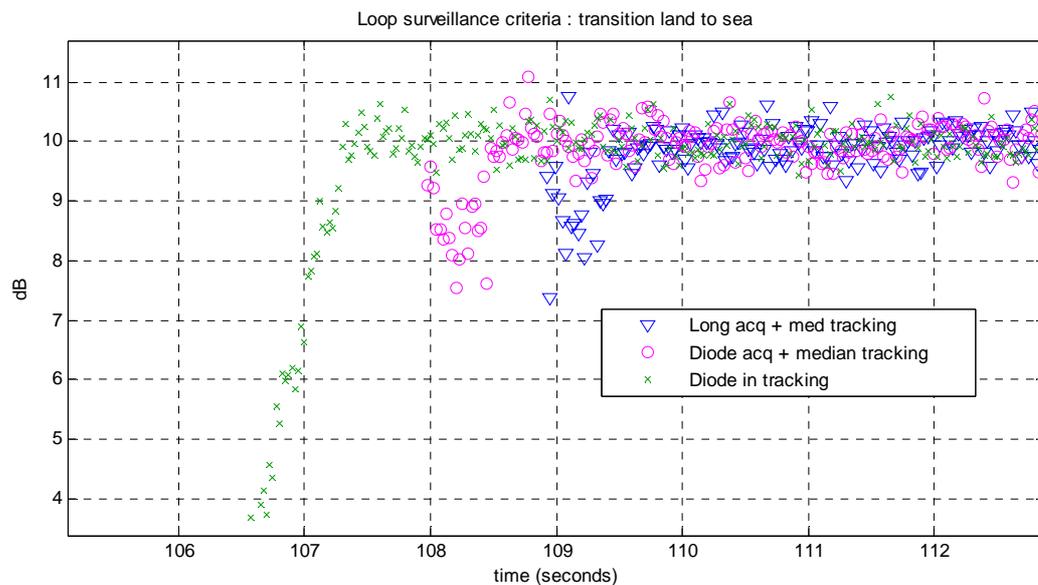


Figure 11. Comparison of tracker behavior in a land to sea transition with several options (Vertical axis: SNR in dB, Horizontal axis: time).

The performances of the various tracking algorithms over land to sea transitions can be compared on Figure 11. The loop surveillance criterion is based on the value of the signal to noise ratio. This plot illustrates the improvement reached by using the coupling process with DORIS/DIODE. Indeed, in this case, using DORIS/DIODE in the search phase results in keeping track 1 second more than when using the classical tracking loop algorithm. The result is even better when using DORIS/DIODE and a DEM, as the altimeter then keeps track 2 seconds more. This example is obtained in good environment conditions as the relief along the considered coast is not very sharp: This is illustrated on Figure 12

where the topography is displayed together with the footprint of an echo having 45% of water in it. The corresponding echo is displayed on the left panel of Figure 12, after tracking using Diode and a DEM.

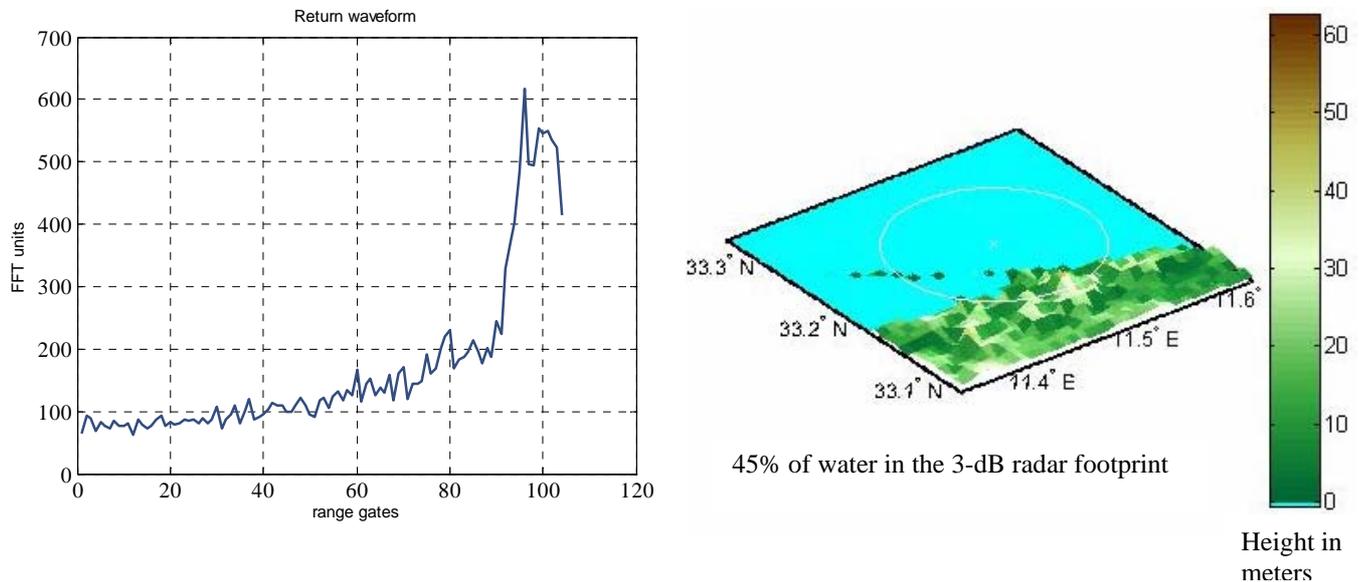


Figure 12. Land to sea transition conditions associated with simulation results plotted on Figure 11.

Most often water must be in at least 30% of water of the radar footprint to detect an echo. However, this depends a lot on the relief in the vicinity of the transitions. It should also be underlined that echoes are often affected by some deformations in transitions areas, such as : a low signal to noise ratio, a mispointing effect, etc.

Range bias and noise over ocean-like surfaces

Estimating performances of the instrument over sea surfaces is performed using simulation tools based on the Hayne's model [35]. The following results are based on 200 second simulations of tracking loops, and a ground retracking process based on a four parameter MLE (Maximum Likelihood Estimator) algorithm estimating range, SWH, σ_0 and pointing. Performance is evaluated by comparing the estimated parameters with simulation entries, and issuing biases and noise measurements. A 12 dB SNR is assumed, and the carrier satellite is assumed to fly at an 800 km altitude.

Figure 13 shows the expected 1 second range noise. For a 2 meter SWH, the range noise is less than 1 cm. Compared with the Ku-band range noise (in the same conditions of altitude and SNR as for the Ka band), there is an improvement of about 40%, mainly related to the increase of the PRF, leading to 40 elementary measurements in one second instead of 20.

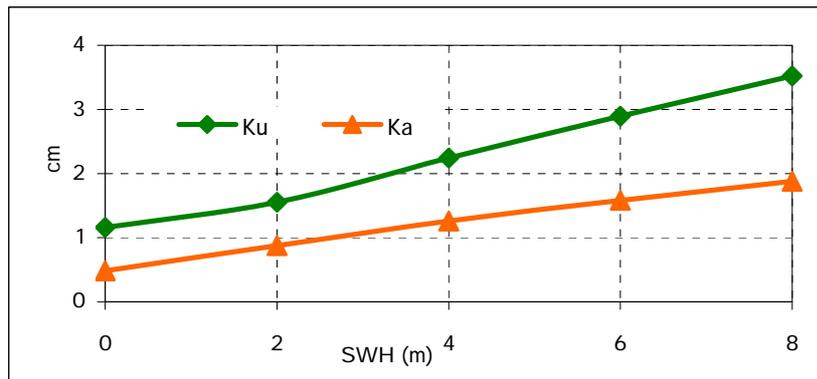


Figure 13. 1 second range noise (cm) versus SWH: Ku (green diamonds), Ka (red triangles).

In terms of significant waveheight, noise at 2 m is less than 5 cm for a 2 m SWH, and remains less than 8 cm for a 8 m SWH.

Biases on the measurements are very low: they are about 5 mm on the range and 1.5 cm on the SWH, and they are stable with SWH.

At the beginning of the section, we pointed out the sensitivity of Ka-band echoes to satellite mispointing. This topic has been addressed in terms of ground retracking performances. In that respect, it has been proved [36] that a four parameter MLE algorithm is very well suited to simultaneously estimate the mispointing angle together with the classical geophysical parameters from the waveform: noise and bias figures are fully stable as a function of mispointing, as far as mispointing is lower than 0.25 degree.

9. Perspectives for an AltiKa mission and conclusion

The technical feasibility of a coupled altimeter / radiometer AltiKa payload has been demonstrated. The altimeter shall provide sea-surface measurements with a very high accuracy; improved performances over other types of surface shall also be reached, first thanks to the reduced size of the radar footprint compared to a Ku-band instrument, and second thanks to the implementation of new tracking algorithms. Complementary data will thus be acquired and made available above coastal areas, lakes, rivers: as a consequence, efforts should now be put on ground processing algorithms to better retrieve geophysical parameters in these zones (both for altimeter and radiometer data).

As mentioned before, a preliminary definition phase of the instrument has been conducted with the support of ALCATEL SPACE from November 2001 to June 2003. Because an opportunity to embark the AltiKa payload on the OCEANSAT-3 platform has appeared in the frame of a cooperation between CNES and ISRO (Indian Space Research Organization), a delta phase B has started at the beginning of July 2005, with an expected start of the phase C/D during the first half of 2006. The launch of OCEANSAT-3 is presently planned in 2009-2010. This mission would thus be a demonstration of Ka-

band altimetry as a complement to the Jason-2 mission. The AltiKa payload on OCEANSAT-3 may then be considered as the post-ENVISAT altimetry gap filler.

On a longer time scale, the AltiKa payload could be the core of a permanent, operational, high-resolution altimetry system composed of a constellation of microsattellites embarking a recurrent payload, or as a combination of microsattellites and minisattellites. The AltiKa payload may then be a very good candidate to help constituting the altimetric component of the to be sustained GMES satellite ocean observation system.

Acknowledgments

The work presented in this paper involved a large number of scientists who have been contributing through the AltiKa Mission Group: The authors would like to thank all these scientists for their continuous contribution to the AltiKa mission definition. The main author performed most part of his AltiKa work when he was a member of the CNES Space Agency. Last, the authors would like to thank David Hancock and an anonymous reviewer for their fruitful comments which helped improving the paper.

References and Notes

1. Vincent, P.; Thouvenot, E.; Steunou, N.; Verron, J.; Baharel, P.; Le Provost, C.; Le Traon, P.Y.; Caubet, E.; Phalippou, L. AltiKa3 : A high resolution ocean topography mission ; *Proceedings of IGARSS'02 Symposium, Toronto, Canada* **2002**.
2. Group on Earth Observations, Global Earth Observation System of Systems: 10 year Implementation Plan Reference Document, *GEO 1000R/ESA-1284, ESA Publications Division Ed., The Netherlands*, **2005**.
3. Leuliette, E.W.; Nerem, R.S.; Mitchum, G.T. Calibration of TOPEX/Poseidon and Jason Altimeter Data to Construct a Continuous Record of Mean Sea Level Change. *Marine Geodesy* **2004**, *27*, 79-94.
4. Rodriguez, E.; Pollard, B. The measurement capabilities of wide swath ocean altimeters, *Report of the High –Resolution Ocean Topography Science Working Group Meeting, D.B. Chelton Ed.; Oregon State University, USA* **2001**.
5. Enjolras, V.; Vincent, P.; Souyris, J.C; Rodriguez, E.; Phalippou, L.; Cazenave, A. Performances study of interferometric radar altimeters : from the instrument to the global mission definition. *Sensors* **2005**, This issue.
6. Chelton, D.B.; Schlax, M.G. The resolution capability of seas-surface height fields constructed from a tandem TOPEX/POSEIDON and Jason-1 altimeter mission, *Report of the High – Resolution Ocean Topography Science Working Group Meeting; D.B. Chelton Ed., Oregon State University, USA* **2001**.
7. Le Traon, P.Y. Mesoscale variability: what can we learn from high resolution altimetry? *Report of the High –Resolution Ocean Topography Science Working Group Meeting D.B. Chelton Ed.; Oregon State University, USA* **2001**.

8. Le Traon, P.Y.; Nadal, F.; Ducet N. An improved mapping method of multisatellite altimeter data; *J. Atmos. Oceanic Technol.*, **1998**, *15*, 522-534.
9. Schlax, M.G.; Chelton, D.B. Detecting tidal aliased errors in altimeter height measurements. *J. Geophys. Res.* **1994**, *99*, 12603 – 12612.
10. Le Traon, P.Y.; Gaspar, P.; Bouysse, F.; Makhmara, H. Using TOPEX/POSEIDON data to enhance ERS-1 orbit. *J. Atmos. Ocean. Tech.* **1995**, *12*, 161-170.
11. Le Traon, P.Y.; Ogor, F. ERS-1/2 orbit improvement using TOPEX/POSEIDON: the 2 cm challenge. *J. Geophys. Res.* **1998**, *103*, 8045-8057.
12. Ducet, N.; Le Traon, P.Y.; Reverdin, G. Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1/2. *J. Geophys. Res.* **2000**, *105*, 19477-19498.
13. Le Traon, P.Y.; Dibarboure, G. Mesoscale mapping capabilities of multiple satellite altimeter missions. *J. Atmos. Oceanic Technol.* **1999**, *16*, 1208-1223.
14. Le Traon, P.Y., Dibarboure, G.; N. Ducet, N. Use of a High-Resolution Model to Analyze the Mapping Capabilities of Multiple-Altitude Missions. *J. Atmos. Oceanic Technol.* **2001**, *18*, 1277-1288.
15. Minster, J.F.; Gennero, M.C. High frequency variability of western boundary currents using ERS-1 three day repeat altimetry data, *J. Geophys. Res.* **1995**, *100*, 22 603 – 22 612.
16. Le Traon, P.-Y.; Dibarboure, G. Velocity mapping capabilities of present and future altimeter missions : the role of high-frequency signals. *J. Atmos. Oceanic Technol.* **2002**, *19* (12), 2077-2087.
17. International GODAE Steering Team, Strategic Plan, *GODAE Report 6, Published by GODAE International Project Office, Melbourne, Australia, 2001*.
18. Kindle, J. C. Sampling strategies and model assimilation of altimetric data for ocean monitoring and prediction. *J. Geophys. Res.* **1986**, *91*, 2418-2432.
19. Verron, J. Altimeter data assimilation into an ocean circulation model: sensitivity studies to orbital parameters. *J. Geophys. Res.*, **1990**, *95* (C7), 11443-11459.
20. Verron, J.; Cloutier, L.; Gaspar, P. Assessing dual altimetric missions for observing the midlatitudes ocean. *J. Atmos. Ocean Tech.* **1996**, *13* (5), 1073-1089.
21. Pham, D. T.; Verron, J.; Roubaud, M.C. Singular evolutive extended Kalman filter with EOF initialization for data assimilation in oceanography. *J. Marine Systems* **1999**, *16* (3-4), 323-340.
22. Brasseur, P.; Ballabrera, J.; Verron, J. Assimilation of altimetric data in the midlatitude oceans using the SEEK filter with an eddy-resolving primitive equation model. *J. Marine Systems* **1999**, *22* (4), 269-294.
23. Verron, J.; Gourdeau, L.; Pham, D.T., Murtugudde, R.; Busalacchi, A.J. An Extended Kalman Filter to Assimilate Satellite Altimeter Data into a Non-linear Numerical Model of the Tropical Pacific: Method and validation. *J. Geophys. Res.* **2000**, *104* (C3), 5441-5458.
24. Cotton, D.; Allan, D.; Ménard, Y.; Le Traon, P.Y.; Cavaleri, L.; Doornbos, E.; Challenor, P. GAMBLE : Requirements for future satellite altimetry: Recommendations for Missions and Research Programmes, *Contact report Framework 5 – EVR1-CT-2001-20009, 2004*.
25. Jacobs, G. A.; Barron, C.N.; Carnes, M.R.; Fox, D.N.; Hurlburt, H.E.; Pistek, P.; Rhodes, R.C.; Blaha, J.P.; Crout, R.; Whitmer, K.R. Navy altimeter requirements. *NRL/FR/7320--99-9696, Ed. By Naval Research Laboratory, Stennis Space Center, MS, USA 1999*.

26. Jacobs, G. A.; Barron, C.N.; Rhodes R.C. Mesoscale characteristics. *J. Geophys. Res.* **2001**, *106*, 19581-19595.
27. Tierney, C.; Wahr, J.; Bryan, F.O.; Zlotnicki, V. Short-period oceanic circulation: implications for satellite altimetry. *Geophys. Res. Lett.* **2000**, *27*, 1255-1258.
28. Nouel, F.; Bardina, J.; Jayles, C.; Labrune, Y.; Trong, B. DORIS : a precise satellite positioning Doppler system, In *Astronautics, Adv. Astron. Sci., ed. by J.K. Solder, Springfield, Virginia, USA, 1987*, vol. 65, 311–320.
29. Caubet, E.; Phalippou, L.; Thouvenot, E. Design status of a combined Ka-band altimeter/radiometer. *Proceedings of the OPTRO 2002 Symposium, Paris, France, 2002*.
30. Caubet, E.; Steunou, N.; Meerman, M. Phase B and breadboard results of the Ka-band altimeter for future micro-satellite altimetry missions, *Proceedings of IGARSS'03 Symposium, Toulouse, France, 2003*.
31. Jayles, C.; Vincent, P.; Rozo, F.; Balandreaud, F. DORIS-DIODE: Jason-1 has a navigator onboard. *Marine Geodesy* **2004**, *27*, 753-771.
32. McGarry, J.F.; Saba, J.L.; Sun, X.; Abshire, J.B.; Yi, D.; Brenner, A. Performance of the GLAS Onboard Surface Detection Algorithm, *AGU Fall Meeting, San Francisco, USA, December 2003*.
33. Tournadre, J. Estimation of rain fall from Ka-band altimeter data, *Proceedings of IGARSS'99 Symposium, Hamburg, Germany, 1999*.
34. Rémy, F.; Legresy, B.; Vincent, P. New scientific opportunities from Ka-band altimetry, *Proceedings of IGARSS'99 Symposium, Hamburg, Germany, 1999*.
35. Haynes, G.S. Radar altimeter mean return waveform from near-normal-incidence ocean surface, *IEEE Trans. On Antenna and Propagation* **1980**, *AP.28(2)*, 687-692.
36. Steunou, N. Bilan de performances altimètre AltiKa, *Note DTS/AE/INS/IR-NT-2003-09, CNES, Toulouse, France, 2003*.