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RADAR STATE OF THE ART AND NEW CONCEPTS FOR GAMBLE

DRAFT

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1. INTRODUCTION

The purpose of this document is two fold:

- to give an overview of the state of the art in radar altimeters design and performances
- to provide a status on new altimeters and other radar concepts, under study or developments

2. STATE OF THE ART IN RADAR ALTIMETERS

Current radar ocean altimetry missions are based on a nadir looking altimeter as it can be shown that this geometrical configuration leads to better elevation budget error. Although the nadir altimetry principle is well known we recall first the basics for completeness. A summary of the most recent altimeter instrument and geophysical performances are also reported in this Chapter.

2.1 Nadir altimeters

Operating principle – radar waveform
Radar altimeters are microwave instruments, which transmit pulses at the pulse repetition frequencies (PRF). The pulses are subject to linear frequency modulation (chirp) with a large bandwidth, typically from 320 MHz to 500 MHz. The vertical resolution of the radar is inversely proportional to the radar bandwidth. However, the ultimate resolution is obtained after processing of the radar echo and is generally more than an order of magnitude smaller than the radar vertical resolution.

With such large transmitted bandwidth, the altimeter operates in the so-called pulse limited mode. It can be shown that the requirements on the instrument pointing control and knowledge are generally relatively easy to meet. This is not the case of beam limited configuration.

Each pulse is reflected by the surface and is returned to the altimeter a few milliseconds (e.g. 5 ms at 800 km) after its transmission.

At the assumed instant of reception, a second (reference) pulse is generated within the altimeter but is not transmitted. Instead, it is mixed with the returned pulse. This technique is known as Full Deramp technique, and it enables to reduce dramatically the processed (e.g. 1.2 MHz instead of 320 MHz for Poseidon 2). For large range window, e.g. in the case of swath altimeter, the deramp technique may not be appropriate.

The altimeter's operating principle is shown in Figure 1.

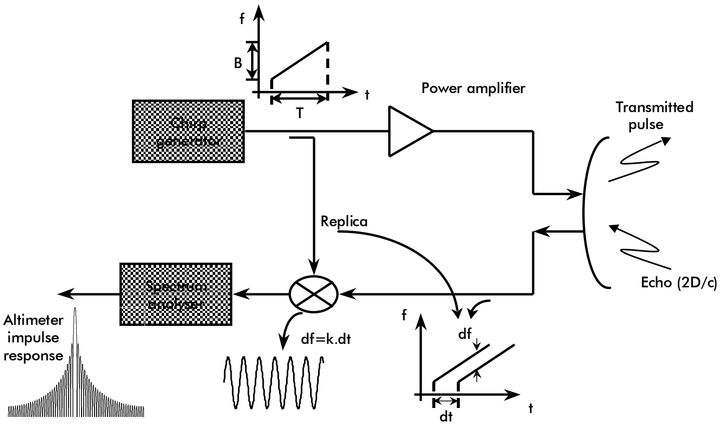

Figure 1: Altimeter operating principle

As the pulse phase is parabolic, after mixing, on the signal's return from a point target, we obtain a pure frequency signal proportional to the satellite/target range (d). This is called the range impulse response. The signal is then processed by spectral analysis using a Fast Fourier Transform (FFT).

Power waveforms

The power waveform is the change of the power of the echo as a function of time (after complete deramp). It can be shown that it is a composite signal corresponding to the convolution of the three following terms:

- the sea response to a Dirac radar pulse,
- the altimeter response to a point target (impulse response),
- the distribution of heights of zero-gradient surface points (or wave distribution).

The sea echo can be modelled by analytical formula, (using some approximation). The most used model has been formulated by Brown, and is known as the Brown's model. A description is given in .

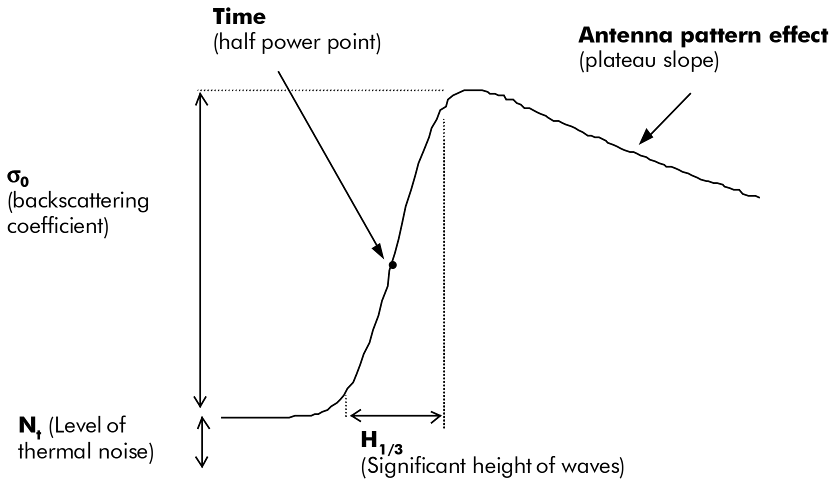

Figure 2: Brown Echo for a sea surface

After receiving the thermal noise from the instrument, the hit of the radar wave on the sea surface gives rise in power, with a rapid leading edge.
The measurement of the maximum amplitude of the power allows to derive the backscattering coefficient of the ocean surface, which in turns allows to measure the wind speed.
The time corresponding to half the power in the leading edge provides the distance between the radar and the sea surface.
The slope of the leading edge is related to the roughness of the sea i.e. to the height of the waves. The trailing edge of the echo depends mainly on the antenna gain pattern and the pointing of the radar antenna.

In fact, speckle must be added to the average Brown echo, with an exponential probability at each range gate and for each elementary pulse.

Over flat ice-surfaces like sea-ice the power waveforms deviate dramatically from the ocean echo due to the specular nature of reflection, and they become very peaky. The shape of the echo can become very complex over the ice sheet margins due to the combination of the topography and Sigma 0 variation.

Definition of the fine estimation processing

During the range measurement phase, the fine estimation of the backscattering coefficient σ_o, significant wave height (SWH or $H_{1/3}$), range, pointing error (ξ), and thermal noise (Nt) is performed by a Maximum Likelihood Estimator (MLE) algorithm. This processing is known as re-tracking which allows an estimation of the range with an accuracy (random noise) much smaller than the resolution of the compressed pulse (typically few cm for a compressed pulse length of 50 cm).

Operation principle

The altimeter operation is based on 3 main functions:

- Acquisition
- Tracking in measurement mode
- Calibration 1 and 2.

These functions are described herefater:

Before reaching the tracking phase (used to keep the radar echo at a set position in the FFT analysis window), it is necessary to bring the signal into this window. The acquisition phase positions the radar echo inside this window and initializes tracking loops.

The tracking algorithm is used during the range measurement phase and is a closed loop system.
The tracking is designed to:

- keep the rising front of the returned signal at a determined position in the FFT analysis window (range processing),
- keep the signal at a given amplitude using an Automatic Gain Control loop (AGC). The instruction generates a digital gain control (CNG) value, which drives a variable-gain amplifier.

The tracking processing requires the computation of the mean of several echo signals. Computation of the mean takes into account any range rate variation using a step by step shift (fine altitude correction).

The measurements are delivered to ground while the instrument is tracking.

Definition of calibration processing

In order to know the instrument contribution to the measurement, internal calibration is necessary. The internal calibration is of primary importance to monitor and correct of the instrument transfer function and of its drift if any. There are two types of calibration:

- Calibration 1: Measuring the impulse response. This processing mode gives the altimeter impulse response. The transmission channel is looped back to the corresponding receiver input via calibration couplers. The spectrum obtained is the radar impulse response.

- Calibration 2: measuring the reception channel profile. The calibration 2 processing mode is designed to measure the altimeter transfer function. It measures within the useful echo band the thermal noise spectrum filtered by the radar's baseband / intermediate frequency cross-section. It is also designed to check that there is no interference in the spectrum by analyzing the thermal noise of the reception channel over a long period while the altimeter reception windows are positioned at a programmed range value guaranteeing the absence of return echoes.

Dual-frequency operation

As any radar the altimeter measures range through a time measurement. The time delay due to the ionosphere (varying as $1/f^2$) and to the troposphere needs to be corrected for in order to have accurate measurement of true range. The ionospheric contribution is corrected by making range measurement at two different frequencies typically chosen between S or C and Ku band.
For instance the Poseidon 2 dual-frequency (C+Ku) altimeter is based on the principle described above for each frequency band. C and Ku-band pulses are not transmitted simultaneously but interlaced. This simplifies the hardware, some sub-assemblies thus being common to both bands.
Other frequency combination are possible such as for instance a Ku and Ka, for correcting the ionospheric path delay.

2.2 Nadir altimeter performances

The following Table gives an overview of the most recent flying altimeters characteristics. Note that, the Alti-Ka altimeter is being studied in a phase B by Alcatel for CNES.

	Poseidon 2	**RA-2**	**GeoSat-FO**	**Alti-Ka**
Mission	Jason-1	Envisat	GFO	Alti-Ka[3]
Altitude (km)	1330	800	800	Up to 800 km
Frequency (GHz)	13.6 (Ku) / 5.3 (C)	13.6 (Ku) / 3.2 (S)	13.5 (Ku)	35.5 (Ka)
Tx Bandwidth (MHz)	320 / 100-320	320-80/160	320	480
Pulse width	105.6 μs	20 μs	102.4 μs	105.6 μs
PRF (kHz)	1.8/0.3-0.45	1.8/0.45	1 (Geosat)	4
Best Vertical Resol. (cm)	46	46	46	30
Pulse Limited	yes	yes	Yes	yes
Tx power (W)	7 / 19 (SSPA)	60 (TWT) / 63 (SSPA)	7 (SSPA)	2 (SSPA)

Range noise over ocean	2.2 cm (C+Ku) SWH=2m Rate=1Hz	<4.5 cm	≤3.5 cm SWH=2m Rate=1Hz	0.8 cm SWH=2m Rate=1 Hz
Significant Wave Height	10 cm @ SWH=2 m	??	??	??
Wind speed/ sigma0 noise	1.5 $m.s^{-1}$ / 0.7 dB	??	??	??
Power consumption (W)	69	161	71	56 (including radiometer)
Total Mass (kg)	58 with redundancy	110 with redundancy	28 partial redundancy	26 (including radiometer)
Data rate	20 kb/s	100 kb/s	?	21 kb/s

Table 1: System characteristics of present and future conventional altimeters

3. NEW ALTIMETER CONCEPTS

Several new altimeter concepts, with respect to nadir altimetry, have been proposed in the last ten years. They mainly pursue some of the following objectives:

- to improve the spatial/temporal sampling: this can be achieved either by off-nadir altimetry (swath) or by a constellation of nadir altimeters,
- to access to the bi-dimensional height distribution of the ocean surface: again off-nadir altimeters combined with SAR and interferometry techniques is a possible solution and has been proposed by the JPL for the WSOA instrument. A constellation of nadir altimeters such as Wittex has also been proposed,
- to improve the vertical resolution, by increasing the transmitted bandwidth as for the Alti-Ka altimeter,
- to improve the spatial resolution, by a combination of the altimetry technique with SAR and interferometry such as for the SIRAL instrument of the Cryosat mission, or by having a smaller antenna footprint (Alti-Ka),
- to measure ocean and ice surfaces with a single instrument,

This Chapter deals with the fairly new concepts of SAR interferometric altimetry. It is divided in two sections, the first one dealing with Interferometric SAR altimeter at nadir and the second one with swath radar altimeter.

The Alti-Ka instrument concept and the radar of the SWIMSAT mission for the observation of the ocean surface wave spectra are briefly described in

3.1 NADIR ALTIMETRY WITH SAR AND INTERFEROMETRY

3.1.1 CONCEPT

The concept, is based on a nadir-looking radar which can be operated in the pulse-limited conventional mode over relatively flat surface such as ocean and Antarctica interior, and in the high spatial resolution mode over topographic areas such as coastal zones (ice margins) and sea-ice.
The high spatial resolution mode (SAR) is based on Doppler processing and therefore it allows for an improvement of the resolution in the along-track direction only.
The across-track interferometric mode (SARIn) combines SAR and interferometry, and it is used for determining the angle of arrival of each resolution cells in the across-track direction.

This concept is used for the SIRAL (SAR Interferometric Altimeter) instrument of the CryoSat mission (see chapter 4.1.3.

The principle of interferometric SAR in a mono-pass configuration (i.e. two antenna mounted on the spacecraft) is given in Figure 3.

Some modifications with respect to conventional interfreometric SAR are inherent to this system:

Doppler filtering is used for the enhancement of the along-track resolution. This requires to transmit coherent pulses at a PRF larger than the Doppler bandwidth. However because the required resolution is generally much smaller than the antenna size (ultimate resolution achievable with a SAR is half of the antenna size) the coherent integration time is smaller than the antenna dwell time. The processing for focusing the Doppler beam can therefore be achieved by using a simple Fourier transform. This is done for SIRAL where the along track resolution is typically 200 m. For the same reason the number of looks for each resolution cells can be very large (typically from 60 for 180 for SIRAL) while keeping the along track resolution constant. In addition, if a larger number of looks were needed an averaging in the along and across track direction could be done but to the detriment of the spatial resolution.

A second antenna provides a second take of the scene, which is used for surface height retrieval (as for SAR interferometry) and quality control of ambiguities due to layover. The interferometric baseline is orthogonal to the satellite velocity and to the nadir direction.

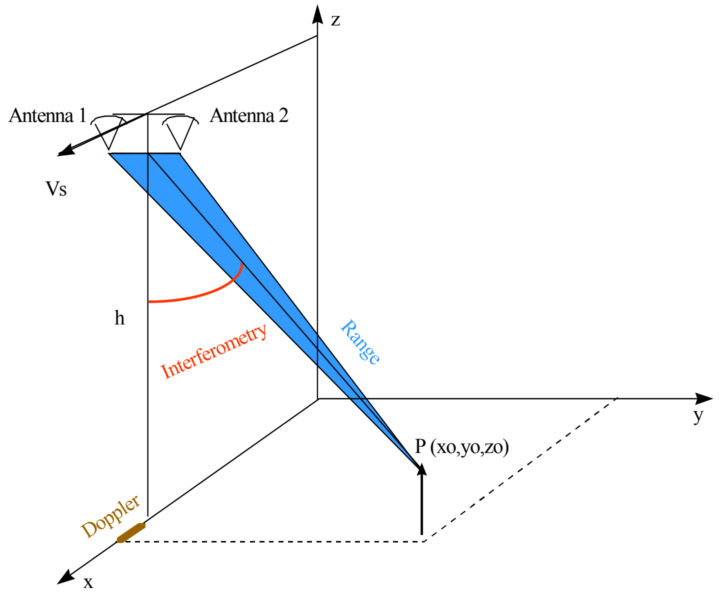

Figure 3 : Principle of interferometric SAR

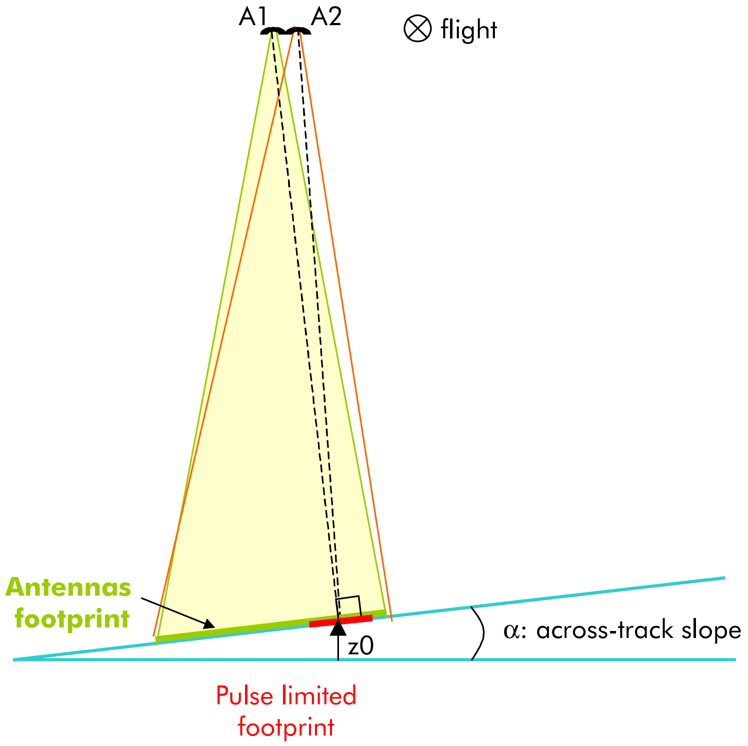

Figure 4 : Principle of measurement of a SAR interferometric altimeter at Nadir

After range and Doppler processing, the resolution cells mapped on a flat earth surface are shown in Figure 5 for a 220 m along-track resolution (64 pulses). Each ring represents an iso-range cell and each 'horizontal' band represents a Doppler bin (i.e. along track position).

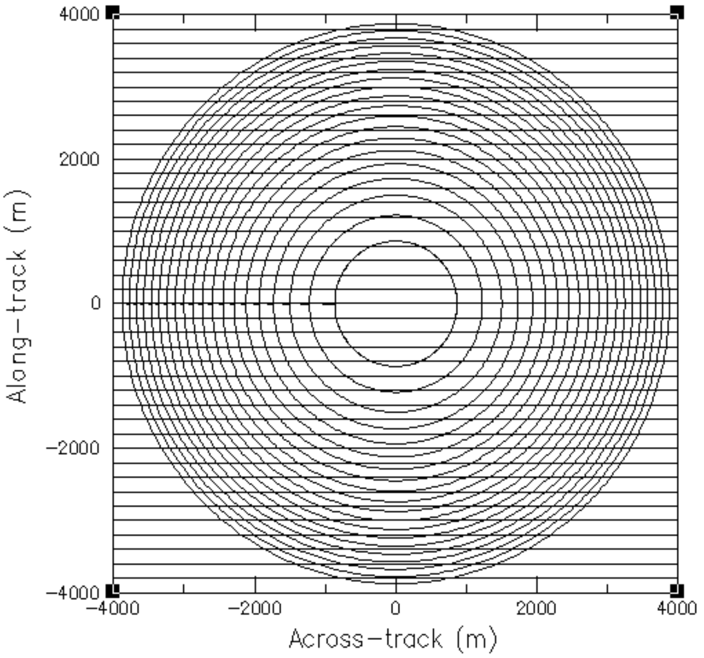

Figure 5 : Resolution cells on a flat surface for a nadir looking altimeter with Doppler focusing

The advantages of a nadir looking radar with respect to off-nadir are twofold:

- Compatibility with conventional pulse limited altimetry (ocean or relatively flat surface)
- This configuration allows to minimise the vertical accuracy (σ_z) of the retrieved surface height.

As shown from Figure 5, a limitation of the nadir configuration is that, as for conventional altimetry, the 'point of first return' corresponding to the pulse limited footprint plays a fundamental role in the interpretation of the data. Indeed, we see that all other cells are ambiguous for a non-tilted surface. In other words this configuration does not provide a swath over surfaces which are not strongly tilted (i.e. slope larger than the antenna beam, say more than 2 degree).

3.1.2 PROCESSING SCHEME

The processing flow chart is more complex than for conventional altimeters as it requires the Doppler focusing and the interferometric processing, prior to echo-retracking. A schematic is given in shown in Figure 6. This chart does not presume whether the processing is done on ground or on board. For instance, for SIRAL, raw data (i.e. after the ADC) in the SAR and SAR interferometric modes are downlinked to ground for processing. However it is to be noted that the data rate of SIRAL is about three order of magnitude larger Poseidon 2 data rate (20 kb).

The radar echoes are first deramped, digitized and stored in a memory. At this stage the range compression is not completed, and range (or delay) has simply be transformed into frequency.

As mentioned earlier focusing techniques are not needed as the required along-track resolution for the altimeter only requires short integration time, i.e. the azimuth phase law is almost constant. The azimuth FFT is then performed on a set of N_p pulses referred to as a burst. The azimuth impulse response characteristics (PSLR, ISLR) are close to those of an ideal sinc function.

Prior to the azimuth FFT a linear phase ramp is used to colocate the looks.

The range curvature during the integration time depends on the relative satellite-target along-track position and on the azimuth resolution. The range curvature is null for a target located at nadir and maximum at the edge of the antenna beam. For SIRAL for instance, the maximum range curvature within a burst is about 0.35 m for a 220 m azimuth resolution, i.e. less than the range resolution. In that case range cell migration can be left non-corrected without too big a loss on the performances of the impulse response. However, burst to burst range-migration must be corrected in order to perform multilooking.

The range compression is completed by taking the inverse Fourier transform (IFFT). The same processing is applied to the echoes received by the second antenna, which provides the second take for the interferogram computation. The power waveform and the interferogram obtained for successive bursts are multilooked for reducing the speckle.

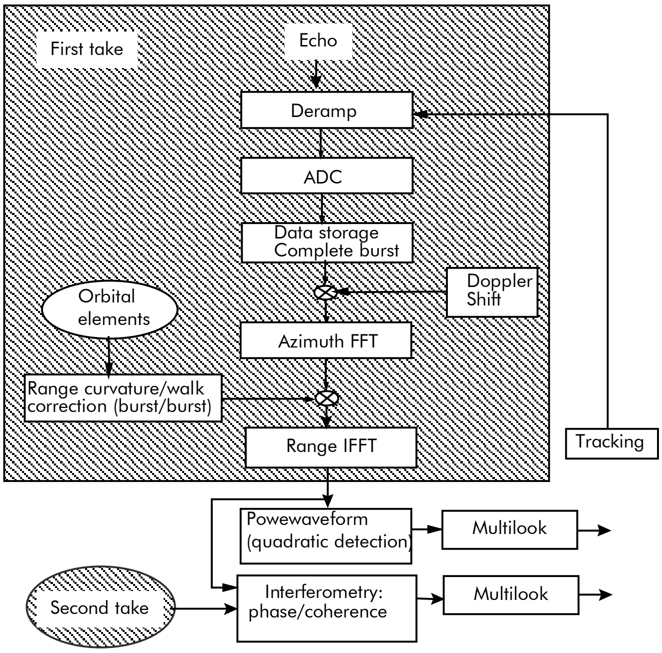

Figure 6 : Typical processing flow chart for a SAR Interferometric altimeter

3.1.3 Off nadir altimetry: swath altimeter

Off nadir altimetry using the SAR interferometric technique is similar to the SIRAL concept with the difference that the antennas illuminate a swath off-nadir as show in Figure 7. The motivation is obviously to acquire a non-ambiguous swath and therefore to have access to the bi-dimensionnal distribution of heights and to the ocean currents. The size of the swath is typically determined by considerations on the spatial coverage, temporal repeatitivity and by the scale of the ocean eddies to be observed. Typically swath around 50 to 100 km could be achievable.

A double swath concept, symmetrical with respect to nadir can also be envisaged in order to improve the spatial and temporal sampling.

The inclination of the baseline would depend on the single or double swath selection. It can be shown that the baseline should ideally be orthogonal to the boresight at the middle of the swath if one wants to minimise the height error due the interferometric phase error [Rodriguez, 92]. For a double swath configuration symmetrical with respect to nadir, the interferometric baseline should be oriented orthogonal wrt to nadir if equal performances are desired for each side.

The major technical challenge for such an instrument remains the antenna subsystem and the required accuracy in the interferometric phase measurement. The mast length is around 5-10 m, and must be deployable to allows the accommodation under the launcher fairing. The dimension of the antenna themselves (say around 3 m* 0.3 m) should also be deployable. The stringent accuracy in antenna phase centre stability and knowledge of the attitude baseline (typically tenth of arcsec) combined with deployment constraints makes such a system particularly critical for Europe. The US claims extremely good performance of the antenna subsystem thanks to the heritage acquired in the SRTM (Shuttle Radar Topographic Mission) which used a 60 meter boom.

Other critical points to be assessed are the internal and external calibration of this instrument, again regarding the interferometric phase and the antenna baseline attitude.

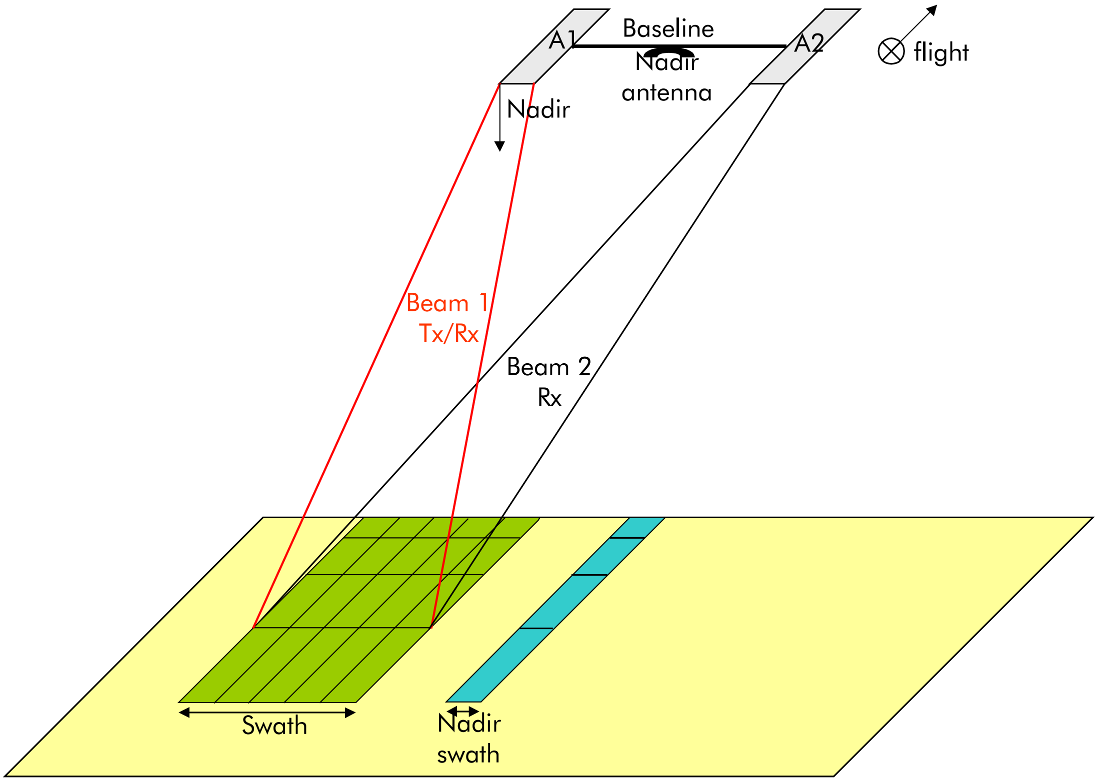

Figure 7 : Off-nadir SAR Interferometric Altimeter (single swath)

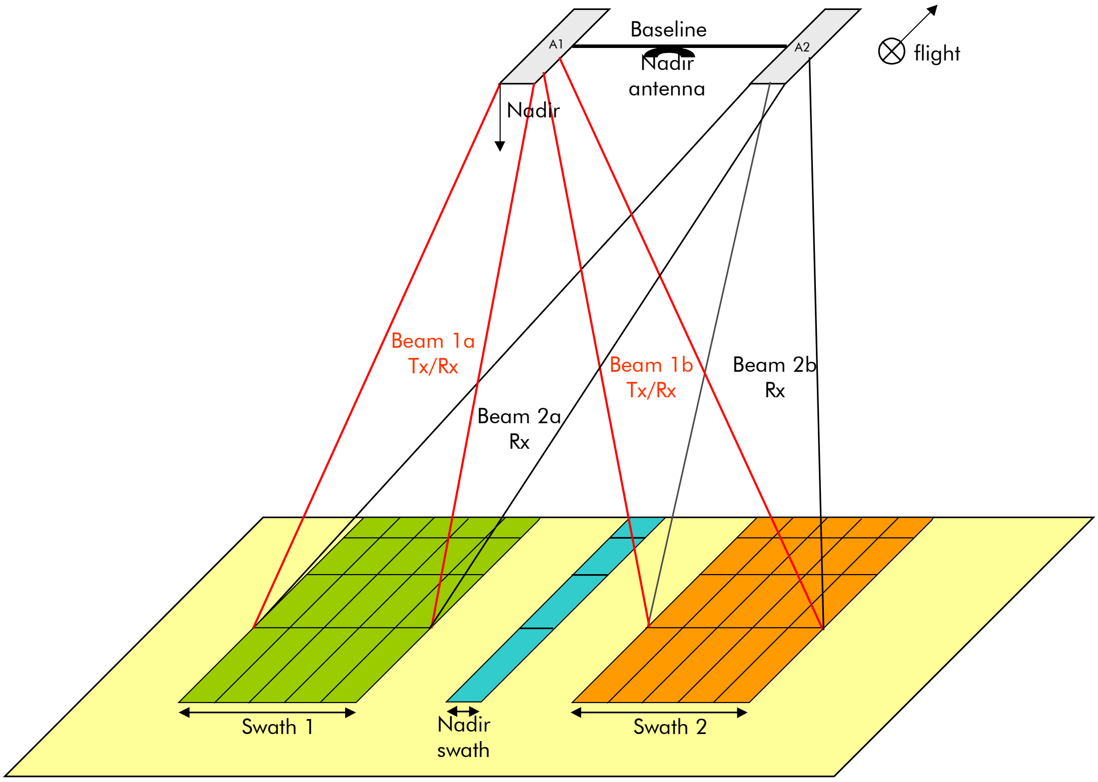

Figure 8 : Off-nadir SAR Interferometric Altimeter (Double swath)

4. MISSION REVIEWS

4.1 PAST AND PRESENT MISSIONS

4.1.1 ENVISAT

The European Space Agency's earth observing satellite ENVISAT is due for launch beginning of 2002. Among other instruments, this satellite will carry an advanced dual frequency radar altimeter, the RA-2, which will build upon the success of the altimeters on the ERS-1 and ERS-2 satellites, and the Doris positioning system. As for ERS missions, ENVISAT will generate highly accurate ocean topography measurements, and also will provide near real time sea state data to the Global Meteorological Transmission network. ENVISAT measurements, jointly with Jason-1 data (and ERS and T/P data), will be invaluable in describing, understanding and forecasting the ocean dynamics at short to long scale. Because of their early launch in 2001, these two data sets will be extensively used in preparing and assessing the potential synergy between future altimetric missions, as advocated in this GAMBLE thematic network proposal.

4.1.2 JASON-1

JASON-1, a joint US/France mission designed as a follow-on to the phenomenally successful TOPEX/POSEIDON (T/P) mission, will be launched end of 2001. During most of this decade T/P has delivered very precise measurements of the variations in the level of the ocean surface to the ocean and marine research community. This data set has permitted tremendous progress in research on ocean circulation, specially for the low frequency part, and in studying its impact on climate. The contribution of T/P data has been essential in many other domains (tides, mean sea level, seasonal and intra-seasonal signal, planetary wave propagation etc.). The early recommendation from the scientific community arguing the necessity for continuing such dedicated altimetric missions proved strong enough to convince of the need for a follow-on to T/P.

The Jason-1 satellite payload is as for T/P except for the mass, volume and power consumption, which have been reduced by a factor of 3 to 4, due to miniaturisation of the instruments. Mounted on-board will be the Poseidon 2 dual frequency altimeter (Ku and C bands for ensuring accurate ionospheric corrected range measurements), the Doris system, a GPS receiver and a laser retro-reflector (for precise orbit determination) and a radiometer (to accurately measure the troposphere water vapour content). Despite a reduced total mass of about 500 kg, the Jason-1 satellite will deliver sea surface height measurements with the same accuracy as T/P along the same ground tracks (identical 10 days repeat orbit).

Jason-1 will continue the T/P research mission but will also support the development of emerging operational oceanography by providing usual Interim Geophysical Data Records (within 3 days) and near-real time products (within 3 hours). These new real time products will include not only on-board computed range measurement and Doris orbit, but also wind speed and wave-height, as derived from altimeter signal, to be used in particular in forecast sea-state models. It is already planned that Jason-1 will be succeeded by Jason-2 in 2005, at a time when global ocean forecasting systems are planned to start running in an operational way.

4.1.3 CRYOSAT

To be completed with possible ocean application

The purpose of the CryoSat mission is to determine trends in the ice masses of the Earth. Of principal importance is to (a) test the prediction of thinning perennial Arctic sea ice due to global warming, and (b) reduce uncertainty in the contribution to sea level of the Antarctic and Greenland Ice Sheets. These questions provide the primary mission goals. CryoSat will provide observations for:

- The determination of regional and basin-scale trends in perennial Arctic sea ice thickness and mass.
- The determination of regional and total contributions to global sea level of the Antarctic and Greenland Ice Sheets.

Trends determined by CryoSat within its lifetime will be limited by the natural variability of ice thickness. The importance of its measurements will be increased by a future flight of an equivalent mission two decades or so later. Nonetheless, the actual performance will allow CryoSat in its own lifetime to determine whether the observed changes in sea ice signal important trends in Arctic climate or merely the ephemera of inter-annual variability at short spatial scales, and to reduce the uncertainty in the ice sheet contribution to sea level to a magnitude similar to that associated with other sources of sea level rise.

The secondary mission goals of CryoSat are to make observations of:

- The seasonal cycle and inter-annual variability of Arctic and Antarctic sea ice mass and thickness;
- The variation in thickness of the world's ice caps and glaciers.

To address the above objectives, the CryoSat payload comprises an enhanced altimeter system for the ice sheet interiors, for sea ice and for ice sheet margins and other topography. Three operative modes are foreseen:

- Conventional pulse limited operation for the ice sheet interiors (and ocean if desired).

- Synthetic aperture operation for sea ice.
- Dual-channel synthetic aperture/interferometric operation for ice sheet margins.

A full description of the detailed objectives, mission and system requirements may be found in Wingham et al. (1999).

4.2 REVIEW OF PROPOSED MISSION CONCEPTS

4.2.1 A large constellation concept based on low-cost instruments: GANDER

The GANDER concept is to launch a number of microsats where the primary payload is probably limited to a single frequency radar altimeter and a precision navigation system in order to fill the gaps created by Envisat and JASON. The number depends on the requirements. For the resolution of eddies requested in the 1987 report to NASA it was thought that 4 would be enough to provide a 50km spatial resolution over a 15-day sampling period. As one moves more towards the requirements of day-to-day marine operations, timeliness of delivery - or the need for near real-time information on fast changing events such as storms at sea - assumes an ever increasing importance. Somewhere in between the research needs for increased knowledge on ocean heat transfer and the operational requirement to locate and track the passage of storms at sea, lies an area where an increased number of altimeters would generate information on currents (updated say at weekly intervals) which would benefit transocean shipping and offshore operations as well as climate research.

The frequency of the altimeters to be carried - C, Ku or Ka band or a suitable mix - has yet to be determined as has the navigational systems (DORIS, GPS, Galileo, laser ranging etc.). Each carries advantages and disadvantages according to the requirements of a particular client community. Several of these application areas were identified in the ESA Call for Proposals including improved predictability of ocean weather in both the short and long-term.

4.2.2 A delay Doppler altimetry system for high resolution: WITTEX

The Applied Physics Laboratory of Johns Hopkins University has proposed a method of increasing the efficiency of a radar altimeter by making use of the Doppler spectra of the returned signal. The technique effectively combines the sampling of small cells within the altimeter footprint from a number of different pulses.

The WITTEX Proposal, also from Johns Hopkins University, builds on the miniaturisation allowed by the Delayed Doppler Altimeter (DDA). It suggests that 3 mini satellites equipped with DDA's are launched together in the same orbit (separated by 200 - 900km) so that they sample the ocean on closely parallel ground tracks (12 - 50km).

4.2.3 A to be demonstrated wide swath concept for ocean circulation: the Wide Swath Ocean Altimeter (WSOA)

In order to map ocean mesoscale phenomena adequately, it is necessary to be able to resolve phenomena which are on the order of the Rossby radius of deformation (a conservative value would be on the order of 30km) and have a typical lifetime on the order of a month. It is not possible to reconcile both of these requirements with a single nadir looking altimeter: the TOPEX altimeter has a repeat cycle of 10 days, but an equatorial separation of 310 km. Given a sufficient number of satellites, it is possible to meet these requirements, but at the cost of coordinating and launching multiple platforms, as well as cross-calibrating different systematic errors due to orbit and instrument biases.

The Wide Swath Ocean Altimeter (WSOA) concept is an attempt to meet the requirements using a single platform. The WSOA consists of a suite of instruments: a conventional nadir altimeter (Ku and C-band nadir altimeters, 3-frequency radiometer, and GPS receiver) supplemented by a Ku-band radar interferometer [Rodriguez and Martin, 1992] [Rodriguez et al., 2001]. The nadir altimeter is used for high precision basin scale measurements, for the estimation of ionospheric and tropospheric delays, and for the calibration of the interferometer.

The radar interferometer illuminates 100 km swaths on either side of the nadir track using right and left-looking beams. The intrinsic cross-track resolution varies from approximately 670 m in the near range to about 100 m in the far range. The along-track resolution is given by the azimuth beamwidth, and is approximately 13.5 km. In order to have spatially uniform resolution cells, and to reduce random measurement error, the final measurements are averaged to 15 km resolution cells.

The 200 km swath enables the WSOA to achieve near global coverage with a single instrument.
Another advantage of the 200 km swath is that, in contrast with a nadir looking altimeter, a typical point on the ocean surface will be imaged at least twice within a 10-day repeat period, and often more frequently. The multiple looks at the same point can be used to improve temporal sampling, but, perhaps more importantly, to reduce random measurement errors by averaging, optimal interpolation, or assimilation. The high accuracy of requirements for ocean topography measurements implies that the measurement error budget must be thoroughly understood. The errors for interferometric measurements and for the WSOA in particular are described in detail in [Rodriguez and Martin, 1992] [Rodriguez et al., 2001]. The WSOA errors can be derived into three components: random errors, media errors, and platform roll errors. The random error contribution depends on the system signal to noise ratio (SNR), on the length of the interferometric baseline, and on the processing used. The WSOA interferometer does not directly measure tropospheric, ionospheric, and EM bias corrections, but uses the corrections from the nadir altimeter. Spatial variability of the ionosphere, troposphere, wave and wind fields over the scales of the swath will induce residual height errors.

Finally, the lack of knowledge in the spacecraft roll angle induces height errors. In order to remove these errors a calibration scheme has been designed which uses ascending and descending WSOA data at crossover regions to estimate and remove the roll error.

One of the principal advantages of the WSOA measurements is that one can obtain the two-dimensional sea surface, rather than just the traditional along-track profiles measured by nadir altimeters. The availability of a two-dimensional height field allows the calculation of surface topography derivatives in the zonal and meridional directions. This means that it is possible to estimate the full vector geostrophic velocity everywhere WSOA measurements are available, rather than the single component of the velocity measured by a nadir altimeter.

Similarly, the Laplacian of the height field can be used to estimate the geostrophic relative vorticity.

4.2.4 A low-cost ocean/ice multi-objective concept: The Ka-band integrated altimeter/radiometer.

The objectives of Ka-band altimetry as reported in an above dedicated section were translated into some main features of the Ka-band payload:

- get an altimeter instrument whose range noise performance may be so that the recovery of the ocean short wavelength features is improved,
- get an altimeter instrument with an improved space resolution along-track and a better performance when approaching or leaving coastal boundaries,
- get an altimeter instrument that will minimise the penetration effects over media such as continental ice,
- embark an orbitography system that will ensure a high level of accuracy in terms of orbitography and that will ease the connection of historical altimetry series within a common well surveyed geodetic reference frame,
- embark a microwave radiometer that will help correcting altimeter measurements for wet troposphere effects.

To answer the previous requirements, it has been proposed to compose an AltiKa payload with:

- A single frequency Ka-band (35 GHz) altimeter instrument
- A two-frequency radiometer,
- A DORIS receiver,
- A passive laser retroreflector array.

To comment on some aspects of the Ka-band system, we can add the following:

- At Ka-band, the ionosphere effects are much lower than at Ku-band and maybe considered as negligible, except for some exceptional ionospheric situations (in the latter cases, the embarkment of DORIS may provide a backup solution to retrieve the ionospheric correction). This is one reason for the choice of such a frequency band for a single frequency altimeter.
- The decorrelation time of sea echoes at Ka-band is shorter than at Ku-band. This gives the possibility to significantly increase the number of independent echoes per second compared with Ku-band altimeters. The instrument is designed for a high Pulse Repetition Frequency (PRF) around 4000 Hz.
- The antenna beamwidth is smaller for the Ka-band altimeter than for Ku-band POSEIDON 2. This gives a Brown echo, which is sharper than the echo obtained with altimeters such as POSEIDON 2; the echo power is also lower due to larger gain variation in the pulse limited footprint.
- The 480 MHz bandwidth that may be used at Ka-band will provide a high vertical resolution (0.3 m) which is improved with respect of all flying altimeters (including Jason and ENVISAT)
- It is known that Ka-band EM waves are sensitive to rain. In addition to attenuation effects, perturbation of echoes by rain has to be analysed in terms of the retrieval of the 3 geophysical parameters to be estimated from waveforms.

The selection of the radiometer type has been driven by:

- The basic science requirement, that is to perform the measurements necessary to get the wet troposphere correction with a sufficient accuracy;
- The willingness to embark the AltiKa payload on a microsatellite, which requires a compact and simple instrument.

Frequencies have been selected to be optimal for the case of a dual frequency radiometer, that is 23.8/36.5 GHz. A three-frequency radiometer would be more difficult to embark because the lowest frequency (19 GHz) would impact the system on the microwave and antenna point of views. In addition, it is possible to overcome this drawback by adapting a wet troposphere retrieval algorithm incorporating the relationship between the wind and the altimeter backscatter coefficient (for instance, such a solution is used for the ENVISAT altimetry).

The 23.8 GHz frequency will use the full width of the allocated bandwidth, that is 400 MHz. Concerning the 36.5 GHz frequency, the fact that it is near from the altimeter frequency does not allow the use of the whole allocated bandwidth which is 1 GHz. In addition, the accuracy of the wet tropospheric correction does not much depend on this bandwidth. Then, it is envisaged to use a 400 to 700 MHz bandwidth with a high probability to select a 400 MHz band (so that the high frequency of the radiometer is centred at 36.8 GHz).

After comparing the known radiometer concepts, a so-called "Total Power" radiometer was selected because it has the simplest architecture and also provides the best radiometric sensitivity. The counterpart is the necessary frequent radiometric calibrations because of the high sensitivity to the gain variations.

One of the initial requirements to design the AltiKa payload was that it should be possible to embark it on a microsatellite and that it could also be provided as a whole to become a passenger on an opportunity platform.

This has lead to define an integrated instrument that allows for interface optimisation and reduction of the number of units (boxes). Indeed, the integrated instrument is composed of:
- One microwave unit that gathers all microwave functions of the altimeter and the radiometer, including the calibration functions of the radiometer and the sources of the antenna.
- One processing unit that gathers all functions dedicated to the altimeter and radiometer processing, as well to a global management unit.

The payload is identical for each microsatellite of the constellation, when considering 3 AltiKa satellites to answer high resolution ocean topography requirements.

4.2.5 A concept focused on waveheight and wave spectra: SWIMSAT

Presently, assimilation of satellite altimeter data in wave prediction models is based upon observations of the total energy (or significant wave-height) of the wave spectrum, ignoring spectral properties. Assimilation of spectral properties of the waves is important since the assimilation of only significant wave height requires assumptions on the characteristics of the wave field, in particular on the separation between wind-sea and swell, which causes errors or weak impact of the assimilation. Attempts to include spectral information in the assimilation process have been mainly limited to regional areas, e.g. the Atlantic Ocean, but they have shown encouraging results, and have demonstrated the value of spectral wave data for sea-state prediction models. The same added value will also contribute to wave climate and coastal applications. Also, the estimate of sea-state bias affecting range altimeter measurements should be considerably improved when the spectral properties of the wave field are taken into account. This has lead German/French groups to propose the SWIMSAT concept, which will use real-aperture rather than the synthetic aperture radar techniques. The measurement principle is to use a dual-beam radar at Ku-band (13.6 GHz). One of the beams is pointed towards nadir, the other is pointed at a 10 degree incidence angle and scans around the vertical axis over 360 degrees in azimuth. Such a technique has already been developed and validated using airborne radar systems in France and USA. Feasibility studies of the spaceborne concept have proved very positive, so that instrument and mission characteristics are now well defined. In terms of orbit, an inclination between 65 and 115 degrees is acceptable to cover the whole ocean, whereas sun-synchronism will allow minimising constraints on the electric power supply by the satellite, even if not mandatory. The altitude of the orbit is partly constrained by geometrical considerations. The requirement is that the swath of the radar beam (swept during one rotation of the 10 degree incidence beam) be comparable to grid mesh sizes of wave prediction models and be compatible with reasonable assumptions concerning the homogeneity of the surface within the swath. An altitude ranging between 450 and 600 km is acceptable. However, optimising orbit parameters for one or several SWIMSAT satellites within a GAMBLE constellation (including GANDER satellites, Jason-2, AltiKa and SWIMSAT) is of course different from optimising them for a sole SWIMSAT mission. SWIMSAT is proposed in 2001 to ESA in the context of "Opportunity Missions" of the Earth Explorer Program, for an expected launch in 2006.

For sake of completeness, we should also notice that there is Russian proposal from IAP/RAS (Russia) to fly a rotating 'knife-beam' altimeter, primarily for measuring ocean wave spectra.

4.2.6 An altimetry concept for the far-future: GPS altimetry

There is also some interest in an alternative system to radar altimeters, which depends on the analysis of the return of GPS transmission received by satellites in LEO in terms of the dynamics of the reflecting sea surface. Satellite altimeters and scatterometers transmit radar pulses and record the return - specular reflection from the nadir path of the altimeter, and back-scatter from oblique incidence angles for the scatterometer. The concept of bistatic radar is to use different satellites to transmit and to receive the radar pulse - in particular to make 'parasitic' use of transmissions from the 24 GPS satellites - to obtain estimates of the parameters provided by the altimeters and scatterometers; surface elevation, wave height and near-surface wind velocity.

The concept has been discussed for about 15 years, eg Hall & Cordey (1988), Garrison et al. (1997). The USA has an on-going programme investigating the detection and interpretation of reflected GPS by airborne receivers. ESA's 'PARIS' project has been studying the possibilities - and problems - of satellite receivers since 1993 (Martîn-Neira, 1993).

The first report of a spaceborne observation of GPS reflections was from the space shuttle, reported by LaBrecque et al. (1988). To our knowledge, no reflections have yet been obtained by an unmanned satellite. A secondary mission of the satellite 'CHAMP' launched in July 2000 (a small satellite project led by GeoForschungsZentrum Potsdam) is to test its nadir GPS antenna but this experiment is still pending.

From the studies that have analysed preliminary GPS data for such altimetric measurements, it shall already be stated that the GPS altimetry technique is the less mature of techniques reported here and that it should not be envisaged for a 2006 mission. Moreover, the GPS technique is not based on radar instrument and will not be addressed in the study.

The historical and present missions were recalled because a large inheritage from them comes into the definition of near-future missions.

A fairly new concept for altimetry, which will be further studied, is the swath altimeter. This instrument is similar to an inclined SIRAL, but more work will be necessary to assess the performances of the concept, the sizing and the criticality of the instrument and its accommodation on the satellite. It is to be noted that Alcatel has already performed for CNES some accommodation analysis of a swath instrument studied by the US.

Other concept(s) of interest for the mission may be identified during the course of the study, either by our team or on recommendation from ESA at Kick-Off. They will of course be analysed in the study. For instance the SWIMSAT mission (formerly known as VAGSAT) will embark a conical scanning radar for the measurement of the bi-dimensional ocean wave spectrum. This mission has been proposed in answer to the *call for ideas* of the ESA EEOM. Alcatel has performed a pre-phase A study of VAGSAT in 1996, and is currently involved in the SWIMSAT mission (Hauser et al., 2001)

5. INSTRUMENT COMPLEXITY

It is already anticipated that the main driver for the instrument complexity, and for the satellite will be:

- The selection of the orbit as it affects many of the radar system parameters (SNR, resolution, etc…) and the design of the altimeter
- The selection of a single satellite configuration, or a constellation. This will be driven by the user requirements in particular the need for space/time repeatability of the measurement and instrument coverage capability.
- The stability and the calibration of the interferometric baseline if a swath instrument with a large baseline is used (typically from 5 to 10 m),.
- The accommodation of a swath altimeter instrument.

Table 1 gives an overview of the ranking of the complexity/criticality of the different instrument alternatives, based on Alcatel expertise. The conventional nadir altimeter and off-nadir SAR interferometric altimeter expertise are based on Poseidon 2 on board Jason 1, Alti-Ka (phase B), and SIRAL (C/D phase).

	Conventional nadir Alt.	SAR Interfero Nadir	SAR Interfero Swath
Demonstrated	Yes	Should be in 2004 with Cryosat	No with the required accuracy
RF Unit	Low	Medium	Medium
Digital Unit	Low	Medium	High (OB processing)
Antenna Subsystem	Low	Medium	High (mast)
External Calibration	Low	Medium	High
Size	Small	Medium	Large
Accomodation complexity	Small	Medium	High

Table 2 : Complexity / Criticality of altimeter concepts

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