25 YEARS OF ALTIMETER DEVELOPMENTS AT ALCATEL ALENIA SPACE

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Abstract

The first preliminary studies on the definition of radar altimeter for Sea Surface Height (SSH) measurements started in the 80's in Alcatel Alenia Space under CNES and ESA contracts. At that time CNES contemplated the possibility of flying an ocean topography mission on its own. It was eventually decided to fly a NASA/CNES joint mission, Topex/Poseidon (T/P), embarking a US radar altimeter and a French experimental altimeter Poseidon. In parallel ESA decided to fly an altimeter on the European Remote Sensing Satellite (ERS-1) and initiated the preliminary studies. Thus Alcatel Alenia Space is involved in altimeters design and manufacturing for more than 25 years. Alcatel Alenia Space develops state of the art altimeters for ocean, ice and land applications which are presented in this paper.

1 From user needs to radar altimeters product line

A radar altimeter is a relevant instrument to answer to the following scientific thematics :

- Ocean surface topography, significant wave height and wind speed measurements
- Sea ice thickness, land ice topography and ice mass balance
- Land surface topography
- Inland water level monitoring
- Bathymetry (submarine topography)

For each of the surface topography applications the required accuracy of the measurements falls in the centimetres range which can only be achieved, for an all weather system, by radar altimetry technique. Radar altimeters are therefore very accurate instruments. Moreover, the long term stability of the altimeter is a crucial requirement when the mission objectives are related to climate issue (e.g. mean sea level, ice mass balance).

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 frequency bandwidth, typically from 320 MHz to 500 MHz. The vertical resolution of the radar is inversely proportional to the radar bandwidth, e.g. 48 cm and 30 cm for the above mentioned bandwidths. However, the ultimate resolution is obtained after processing (known as re-tracking) of the radar echo power waveforms and it is generally more than an order of magnitude smaller than the radar vertical resolution, typically below 2 cm for conventional radar altimeters over sea surfaces.

Current radar altimetry missions (TOPEX/Poseidon, Jason, ERS, Envisat, Cryosat) are based on nadir looking radar altimeters, i.e. the boresight of the antenna is aligned with the local normal to the surface, as it can be shown that this geometrical configuration leads to a better measurement accuracy. The drawback is that measurements are only provided along the satellite track giving a sparse coverage.

Conventional pulse limited nadir altimeters have a poor spatial resolution typically few kilometres, which impeded accurate measurements close to coastal areas and rapidly changing surfaces such as fragmented sea-ice and surface transitions. Along the satellite track it is possible to improve the resolution by processing the altimeter signal - known as beam-sharpening or unfocused SAR - providing that the radar pulses are transmitted at a sufficient rate (PRF). This radar mode, known as the SAR mode, is applied on SIRAL of the CryoSat Mission, and it is also envisaged for future ocean altimetry mission.

To deal with large slope surfaces, it is also necessary to locate the point of first return of the radar echo on the surface. This can be achieved using the SAR technique in the along track direction combined with the interferometric technique in the across track direction. This SAR interferometric mode is used on SIRAL for the Antarctica and Greenland margins which experience large slopes.

To circumvent the coverage limitation of nadir altimetry, swath altimetry has recently been proposed as an answer to the requirements for mesoscale ocean circulation monitoring and forecast. The concept allows a global coverage of the ocean within 10 days whereas the inter-tracks of a nadir altimeter are above 200 km at the equator.

2 The Poseidon altimeter family

Two altimeters flew on Topex/Poseidon : the US dual-frequency (Ku + C bands) NASA Radar Altimeter (NRA), which was the operational instrument and the CNES Ku-band **Poseidon-1** altimeter. The experimental Poseidon-1 altimeter was 4 times as light and consumed 5 times less power than the NRA (Figure 1). Poseidon-1 delivered a series of measurements (for about 10 % of the time) which were found to be in an excellent agreement with the measurements delivered by the operational NRA.

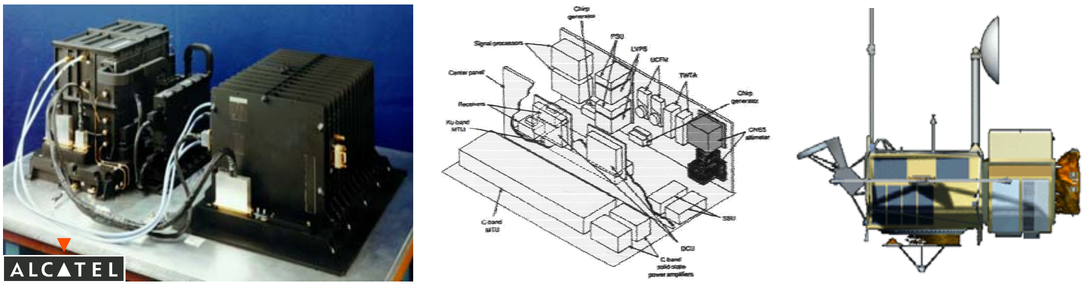

Figure 1. Left: Poseidon altimeter. Middle: The black boxes are the Poseidon-1 altimeter. The other components are the NASA radar altimeter in a redundant configuration. Right: NRA and Poseidon sharing the same antenna on the T/P satellite.

The TOPEX/Poseidon mission has been pursued by the Jason 1 mission launched in 2001, embarking a dual frequency (Ku and C band) altimeter **Poseidon 2** [1], as the single operational altimeter of the mission. The satellite and Poseidon 2 were manufactured by Alcatel Alenia Space under CNES contracts. Poseidon 2 is providing excellent measurements (see dedicated presentations in this conference). The range measurements are provided by the Ku band channel while the C band is used for correcting the excess path length due to the ionosphere.

Poseidon 2 inherited from Poseidon-1 state of the art technology in order to have excellent performances (Point Target Response and calibration) while minimising as much as possible the demand towards the satellite in terms of mass, volume and power. Solid State Power Amplifiers technology are used in Ku and C band for the Poseidon series.

Poseidon-2 carried on the Poseidon-1 heritage, while also incorporating new technological features that make it the world benchmark in its field, namely:

- Even more compact design for weight savings, plus low power consumption (Figure 2)
- Dual-frequency Ku + C bands operation.
- Improved measurement stability (Figure 3), thanks to compactness
- High reliability, for extended service life
- High in flight availability (>99.8 %)
- Compatibility with a large number of platforms

Jason-2 is a quadripartite program between CNES, NASA, Eumetsat and NOAA to ensure the continuity of data delivered by Jason-1. In May 2004, the CNES Board approved the order for the Jason-2 satellite, and chose Alcatel Alenia Space as prime contractor for building the satellite and the **Poseidon-3** altimeter. The Jason-2 launch is foreseen in mid-2008.

The Poseidon-3 bi-frequency altimeter is still the operational altimeter of the mission, with measurement precision identical to its predecessor Poseidon-2.

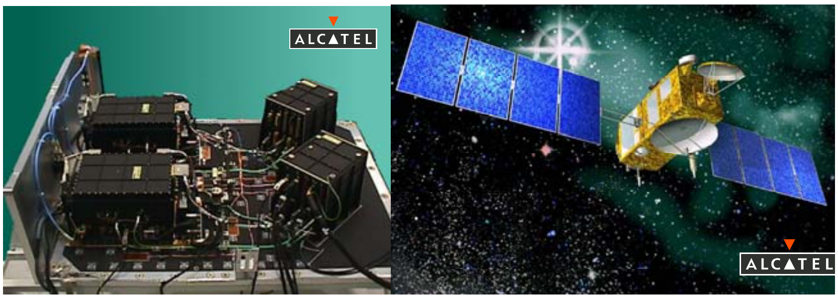

Figure 2: Poseidon-2 altimeter in redundant configuration (left) and its accommodation on the Jason satellite. Note the extreme compactness of the altimeter design with two boxes for each altimeter: the Radio Frequency Unit (RFU) and the Processing & Control Unit (PCU).

Moreover, Poseidon 3 also features an experimental mode that will support measurements closer to coastal zones, as well as on lakes and rivers. This will be achieved by an open loop tracker: the satellite to surface distance will be estimated by the altimeter using the real time orbit position predicted by DIODE (on board navigator based on DORIS receiver) and using the elevation of the surface with respect to the Earth GRIM5 geoid stored in a Digital Elevation Model within the altimeter.

The instrument's RF unit is recurrent from Poseidon-2, while the digital unit largely reuses electronics from the SIRAL radar altimeter on the CryoSat mission.

Thus Poseidon-3 will ensure the continuity of the product quality already provided by Poseidon-2 while improving the data coverage close to the coast, and it will also allows to keep an up to date design in particular with respect to the part obsolescence treatment.

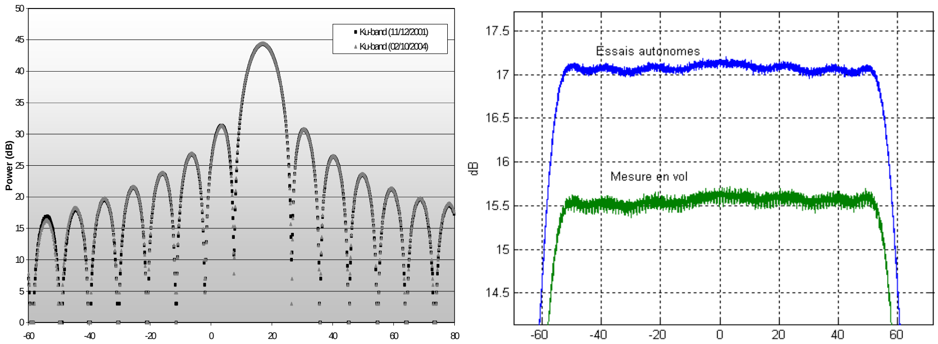

Figure 3: Poseidon-2 in flight performances. Left panel : Point Target Response (PTR) at the beginning of the mission and after 100 cycles of operation (1000-day). Note the extreme stability of the PTR during time, and its quality (close to the theoretical sinc^2 function). Right panel : In flight (green) and on ground (blue) Intermediate Frequency (IF) filter response during CAL2 calibration mode. Again note the extreme stability of the shapes of the IF filter with time.

3 ERS and Envisat Radar Altimeter family

ESA launched the ERS-1 (1991), ERS-2 (1995), and ENVISAT (2002) multi-applications satellites on sun-synchronous ~800 km orbits. The Radar Altimeter RA on board ERS satellites is a single Ku-band (13.575 GHz) altimeter with two bandwidth (330 MHz and 82 MHz) allowing operation over the ocean and over ice-surfaces. The repeat period of ERS 1-2 and Envisat orbits is 35-day allowing inter-track sampling of the T/P and Jason 10-day repeat period.

The Radar Altimeter of Envisat (RA2) is a dual frequency altimeter (Ku and S bands), with bandwidth agility (320 MHz, 80 MHz and 20MHz) for measuring the ocean and the ice surfaces [2]. The secondary channel (S band) has been added to RA-1, to correct ionospheric path delay. The S band was preferred to C band mainly for Radio Frequency compatibility with the C band Synthetic Aperture Radars of ERS and ENVISAT.

As required by the customer (ESA) the RA2 design is strongly based on the heritage of ERS 1&2 radar altimeter. The main evolution of the RA2 altimeter respect to RA ERS is the use of dual frequencies and the flexible tracking capability including the provision of individual echos to ground. The flexibility of the tracking algorithms allows the measurement in different scenario and minimise the transition between land and ocean. The use of individual echoes is a prototype to allow the analysis of inland water

A simplified RA-2 block diagram is sketched in Figure 4. The same hardware is used (on a time share basis) as much as possible for both the Ku and S band channels. All the subsystems - with the exception of the antenna - are redounded. RA-2 is composed of the following subsystems : Antenna, Ku-band front end electronics (KFEE), S-band front end electronics (SFEE), Ku band transmitter (KTx), S band Tansmitter (STx), Microwave Subsystem (MR), Frequency generation and conversion Unit (FGCU), Chirp Generator (CG), Signal Processor Subassembly (SPSA), Low voltage Power Supply (LVPS), Instrument Control Unit (ICU). The Ku band and S band High Power Amplifier (HPA) are respectively based on Travelling Wave Tube (TWT) and Solid State technologies and they both deliver 60 W RF power. The pulse width of RA and RA2 is 20 µs (against 100µs for Poseidon) which requires a larger RF transmitted power (delivered by a Travelling Wave Tube). The RA and RA2 demand (mass, power) towards the satellite is therefore larger than for the Poseidon family, but the level of end product performances falls in the same category, i.e. around 2 cm for the Sea Surface Height measurements.

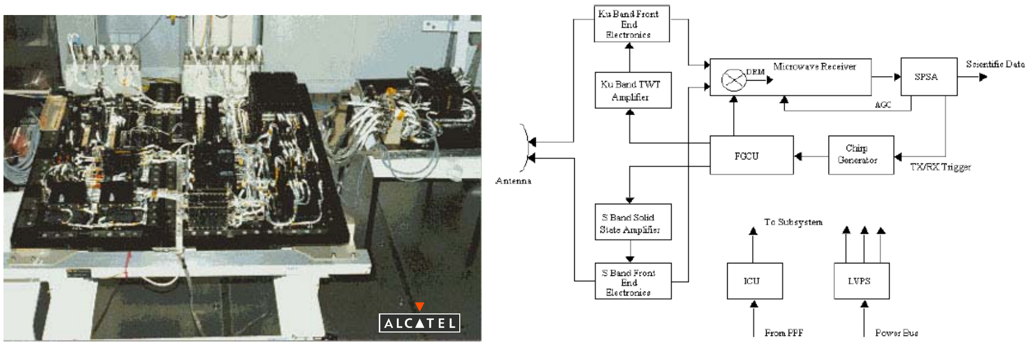

Figure 4: Envisat Radar Altimeter Flight Model (RA-2)

4 Alti-Ka a combined altimeter/radiometer

Ka band nadir altimetry has been proposed initially by CNES with a twofold objectives: to propose a compact instrument which can be accommodated on a constellation of micro-satellites as an answer to the need of improving the spatial coverage for mesoscale ocean applications, and to improve the altimeter range noise by using a larger bandwidth allocation and a higher PRF. Alti-Ka is a combined Ka-band altimeter (35.5-36 GHz) and radiometer instrument (23.8 & 37 GHz) with minimum cost, size, volume and power consumption which answer these requirements [3]. Note that at Ka band, the ionosphere path delay variations is about 9 times smaller than at Ku band and it can be corrected from ionospheric model with a sufficient accuracy. Obviously, thanks to its compactness, Alti-Ka can easily be accommodated as a passenger on larger platforms. The first implementation of Alti-Ka is planned to be on the Indian satellite Oceansat-3 for a launch in 2009. The Alti-Ka altimeter/radiometer is developed by Alcatel Alenia Space for CNES under a C/D phase contract. The Processing and Control Unit of Alti-Ka is inherited from the Poseidon-3 development.

Three key instrument parameters improve significantly the Alti-Ka altimeter performances compared to conventional Ku-band altimeters:

- The 500 MHz radar bandwidth provides 0.3 m vertical resolution instead of 0.5 m in Ku-band.
- Due to the smaller antenna beamwidth, the Brown echo has a sharper shape in Ka-band than that what is obtained with conventional altimeters in Ku-band. For example at 800 km, the 6-dB footprint is around 8 km versus 30 km for Poseidon-2 (Jason).

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

Comparison with Poseidon-2 altimeter shows that AltiKa will provide excellent range noise performances, i.e. around 0.8 cm against 1.7 cm for Poseidon-2. The expected improvement in SSH accuracy from Alti-Ka upon Ku band altimeters (after ionospheric correction) is close to a factor of 3. Alti-Ka will also be coupled with DIODE and a on board DEM stored in the PCU as for Poseidon-3. The main limitation of Ka-band is the atmospheric attenuation (rain rate, cloud and water vapour). The availability of the Alti-Ka measurements, in the worst case areas (e.g. tropics), has been estimated to 90-95 %.

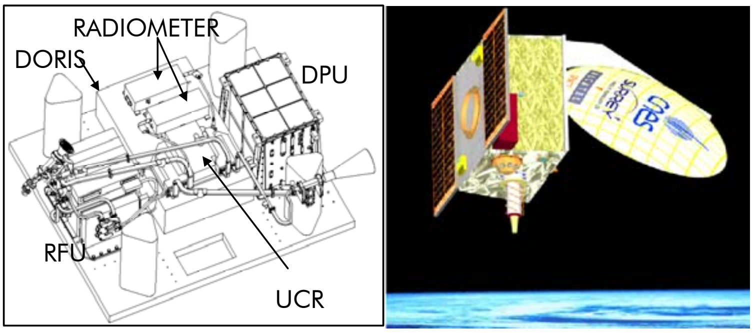

Figure 5: Alti-Ka Altimeter/radiometer and its accommodation on a micro-satellite (850 mm x 850 x 700 mm (without antenna and solar panel)

5 Summary of conventional radar altimeters features

A summary of the conventional radar altimeters features is given in **Table 1**.

Table 1: Summary of flying and on-going developments conventional radar altimeters

	Poseidon 2 & 3	**RA-2**	**Alti-Ka**
Mission	Jason-1 & Jason2	ENVISAT	Oceansat 3
Main target application	Ocean	Ocean + Ice caps	Ocean + Ice caps
Secondary application	Inland waters + coastal zone (Poseidon-3)	Inland waters	Inland waters + coastal zone
Altitude (km)	1336	800	Up to 800
Frequency (GHz)	13.6 (Ku) / 5.3 (C)	13.6 (Ku) / 3.2 (S)	35.5 (Alt.), 23.8 & 37 (Rad.)
Tx Bandwidth (MHz)	320 / 100-320	320-80-20/160	480
Pulse width	105.6 µs	20 µs	105.6 µs
PRF (kHz)	1.8/0.3-0.45	1.8/0.45	4
Best Range Resolution (cm)	46	46	30
Tx power (W)	7 / 30 (SSPA)	60 (TWT) / 60 (SSPA)	2 (SSPA)
Range noise over ocean @ SWH=2m &1Hz	1.7 cm	< 1.8 cm	0.8 cm
Power consumption (W)	69	114	< 80 (including radiometer)
Total Mass (kg)	58 with redundancy	110 with redundancy	33 (including radiometer) (without redundancy)
Data rate	20 kb/s	< 65 kb/s nominal operation < 100 kb/s individual echoes	38 kb/s

6 SIRAL for Ice monitoring

In 1996, ESA awarded a contract to Alactel Alenia Space to study the feasibility of a new altimeter concept with the objective of improving the spatial resolution and localization of the returned radar echoes over the polar ice surfaces. This study led to the SIRAL concept [4] which was proposed and retained for implementation on the Cryosat ESA first opportunity mission. The primary scientific objectives of the mission are twofold: to monitor the seasonal changes of the polar sea-ice thickness and to establish the ice mass balance budget of ice sheet in particular by making more accurate measurements of the margins of Antarctica and Greenland. These mission objectives requires to improve the spatial resolution upon conventional altimeters and to be able to locate the point of first return in the echo over topography to avoid the so called slope induced errors. Cryosat has been unsuccessfully launched in October 2005 (failure in the launcher stage separation). ESA has decided to pursue the mission and to build a replica, Cryosat-2 and SIRAL-2, for a launch early 2009.

SIRAL [5] is the main instrument of the Cryosat satellite. It is derived from conventional pulse-limited altimeter design, but in addition it features additional design characteristics which enable it to provide data which can be more elaborately processed on ground:

- The SAR mode is based on a high Pulse Repetition Frequency (PRF) coherent transmitted pulses to allow along- track processing. The achieved along-track resolution is 250 m - against 16 km for conventional altimeters. This mode, known as SAR mode is used over sea-ice to determine its thickness.
- The SARIn mode merges the SAR mode and the interferometry technique to resolve across-track slope over the ice margins –the steepest part of Antarctica and Greenland- with an accuracy of around 30 arcsec (i.e. 8 10-3 degree). The interferometer is based on two antennas and two receive chains operating simultaneously.
- The conventional pulse limited mode (Low Resolution Mode, LRM) is also activated over the Antarctica interior and over ocean.

These capabilities form the basis for the instrument name: SIRAL is an acronym for SAR/Interferometric Radar Altimeter and they make this instrument unique.

The instrument is split into three major subsystems (Figure 6). Two of these consist of discrete electronics boxes: the Digital Processing Unit (DPU), which provides all of the digital electronic functions of the altimeter, the Radio Frequency Unit (RFU), which contains all of the analogue electronics, mainly in the intermediate and radio frequency range.

The third subsystem is the Antenna Subsystem, consisting of two Cassegrain antennas mounted side-by-side, forming an interferometer across-track. Both antennas are identical but one is used both to transmit and receive whereas the other one is only used to receive echoes. The antenna structure is mechanically and thermally ultra-stable to achieve the stringent measurement accuracy of the surface slope.

An advanced tracking design – with bandwidth switching at 40 MHz- ensures robustness and accuracy over all types of ice topography, even in the rapidly changing high slope areas of the Antarctic margins.

The overall mass of SIRAL is 61 kg. The power consumption depends on the activate mode and it ranges from 95 W in LRM to 127 W in SAR mode.

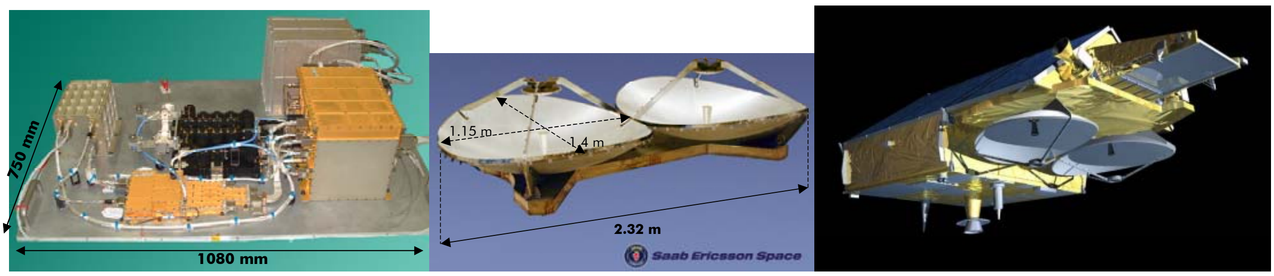

Figure 6: SIRAL (left and middle panels) and the CryoSat satellite. The two antennas are for the interferometric mode.

7 SRAL for the ESA Sentinel-3 mission

The SRAL concept has been initially proposed by Alcatel Alenia Space in the framework of the ESA Roadmap For Operational Oceanography Mission [6] study with the following operational oceanography mission objectives:

- Provides continuity of SSH, SWH and wind speed measurements with the quality of the Poseidon-3 for the continuity of data for an operational oceanography mission,
- To allows the measurement of sea ice-thickness with the same quality as for SIRAL for operational oceanography and climate change,
- To improve the along-track spatial resolution for ocean coastal applications,
- To guarantee the maturity of the concepts for all aspects of the mission, and maintenance.

These objectives can be achieved with low risk and maximum thanks to the SIRAL heritage.

This concept is currently under phase A/B study within the ESA Sentinel-3 Oceanography mission (also known as Blue Sentinel). SRAL stands for SAR Radar Altimeter, and benefits from the SIRAL and Poseidon-3 altimeter. SRAL is a dual band (Ku + C) altimeter operating in the conventional radar altimeter mode as Poseidon-2 and 3, giving the ocean performance in that mode. This mode will be the core of the operational mission ensuring a perfect continuity with previous altimetry missions such as Jason-1, Jason-2 and Envisat.

The SAR mode is identical to the SIRAL-SAR mode. SRAL would therefore provides an along track resolution of 290 m at ~800 km satellite altitude. This is acceptable for the sea-ice / ocean separation for measuring the free-board. This resolution also improves the coastal product. In SAR mode, the altimeter will be activated only in Ku band as for SIRAL.

There is no interferometric mode for SRAL, as only the ocean and sea-ice is addressed in that mission option.

The tracking will be derived from SIRAL. Moreover, tracking close to the coast can be slaved on the DIODE (DORIS based) on board navigator, or a GNSS navigator.

The SRAL design is derived from the SIRAL architecture with a Radio Frequency Unit (RFU), a Digital Processing Unit (DPU), a single antenna, as SRAL does not provide interferometry measurements. SRAL also benefits from Poseidon-3, in particular regarding the C band heritage (Tx SSPA, duplexer, antenna), the acquired expertise for open loop-tracking with a range window slaved on the on-board-navigator and a Digital Elevation Models stored in the DPU.

8 Swath altimeters

The ocean swath altimetry technique is based on near-nadir radar interferometric altimetry. The concept has been proposed by the US Jet Propulsion Laboratory as the Wide Swath Ocean Altimeter (WSOA) for flying on the Jason-2 mission.

The originality of the Alcatel Alenia Space concept [7] proposed within the framework of an ESA contract for studying new altimeter concepts, has been to revisit the WSOA concept, in particular regarding the functioning point. The main differences between WSOA and our concept come from the selection of a lower orbit 780 km against 1336 km for Jason-2/WSOA, and the selection of a non-deployable interferometric antenna subsystem with a short baseline 2.5 m (Figure **7**) against ~ 6 m for WSOA.

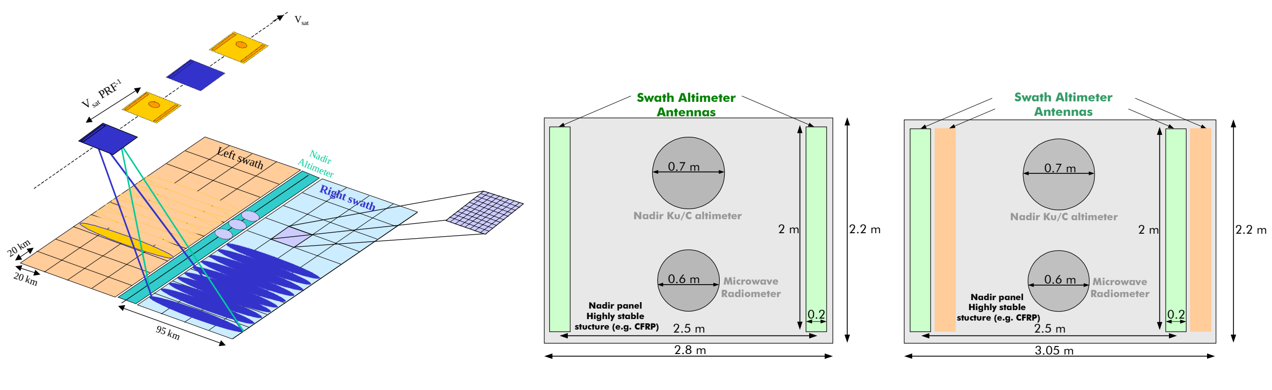

Figure 7 Left: The swath altimeter alternatively look at left and right swath. The SSH measurements are averaged to form a 20*20 km2 SSH measurement cell by averaging several thousands of elementary radar pixels (multi-looking).

The strip formed by the nadir altimeter footprint is also shown. Right: Antenna subsystem concepts for a 2.5 m non-deployable interferometric baseline. Left-right swath switching is performed by BFN on the left panel. Two antenna pairs are used for swath switching on the right. Nadir altimeter antenna and radiometer antennas are also shown.

The system parameters have been optimised with respect to performance while attempting to keep the radar complexity and its demand toward the satellite as small as possible. Reuse of existing technology and expertise from previous interferometric altimeters programs (e.g. TWT from WSOA, SIRAL) has also been taken into account to anchor the proposed functioning point. The ocean coverage of the swath altimeter is nearly complete for a 10 day repeat orbit. The antenna is based on a CFRP baseplate holding slotted waveguides Direct Radiating Aperture (DRA).

The concept can fit in small launchers (such as Rockot) and it offers tremendous simplifications for the instrument (fixed radiating antenna panels, shorter RF signal distribution, internal calibration access, etc…) and also for the platform and launch (accommodation, inertia) compared to WSOA. Because the requirements on interferometric baseline stability and baseline attitude knowledge are extremely stringent ~ 0.02 arcsec, it is obvious that a non-deployable antenna subsystem is an attractive solution.

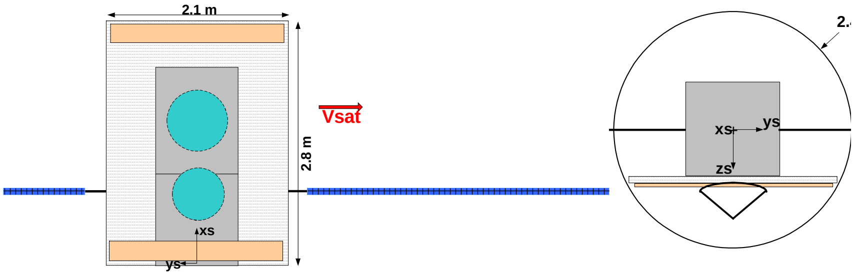

Figure 8: Accommodation of the swath altimeter on a small platform. A 2.4 m launcher fairing is illustrated (e.g. Rockot launcher). During operation, z_s is nadir pointed. The satellite velocity is along ys

The sea surface height accuracy budget including all sources of errors is presented in Table 2.

Table 2: SSH accuracy for a swath altimeter as a function of distance from nadir

7 m/s Wind Speed				
Distance from nadir (km)	25	45	65	85
Precise Orbit Determination (800 km)	2,5	2,5	2,5	2,5
Dry Troposphere Correction	0,7	0,7	0,7	0,7
Wet Troposheric Correction (1)	1,3	1,4	1,6	2,1
Ionosphere (2)	0,5	0,5	0,5	0,5
EM bias	2	2	2	2
Baseline Roll Calibration	1,4	2,5	3,6	4,7
Baseline Lengh Calibration	0,2	0,6	1,3	2,3
Baseline Length Expansion	0,1	0,3	0,5	0,9
Swath Altimeter Random Noise	2,1	2,2	2,6	3,8
SSH accuracy (RMS sum)	4,4	4,9	5,9	7,6

The outcome of the study are the followings:

- The 5 cm SSH accuracy objective for a swath altimeter is met for 50% of the swath.
- The interferometric baseline roll accuracy is the dominant factor of the error budget.
- The swath altimeter provides 8 measurements across-track. The concept is therefore ‘equivalent’ to 8 nadir altimeters flying in constellation.
- The error from the radar concept for the proposed functioning point is balanced with the other sources of errors. Improving the performance of the radar gives marginal improvement of the overall budget if the other terms of the budget are not improved as well. It is not worth having a much more larger baseline, as the error budget is dominated by the accuracy of the calibration of the interferometric baseline.

9 Conclusion

Alcatel Alenia Space (AAS) is continuously involved in the design and development of state of the art altimeters since the very beginning of the altimetry missions (Figure 9). This continuity has allowed AAS to propose performing altimeters with a minimum development risk and in a cost effective manner. The range of AAS altimeters answers all types of scientific needs, from operational ocean monitoring with conventional altimeters to the most challenging ice monitoring missions with high accuracy SAR interferometric altimeters. New concepts (Alti-Ka, SRAL, swath altimetry) are currently studied and developed in AAS to maintain this European pole of excellence and to meet the future expectations of the scientists and operational users in the near future.

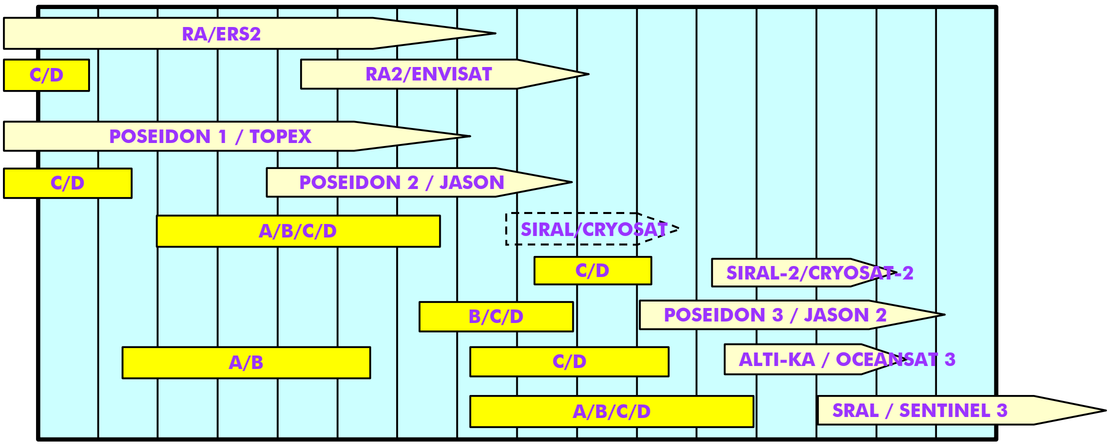

Figure 9: Alcatel Alenia Space altimeter product line.

Square boxes indicates the altimeter development phases. Arrows symbolise the mission lifetimes.

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