ESA's NEW RANGE OF RADAR ALTIMETERS FOR THE EXTRACTION OF GEOPHYSICAL PARAMETERS FROM LAND, SEA ICE AND OCEAN SURFACES

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Abstract

Despite the loss of CryoSat, ESA's first Earth opportunity mission, during its launch sequence in Oct 2005 ESA have been fortunate enough to have acquired, processed to Level 1b and analysed a significant amount of campaign data from ESA's demonstration Airborne SAR/Interferometric Radar Altimeter System (ASIRAS) designed to have similar functionality to CryoSat's Synthetic Interferometric Radar Altimeter (SIRAL). This data acquisition took place for the original purpose of validating CryoSat retrievals.

Our initial analyses of the level 1b data have revealed some very interesting results both over land and sea ice test sites from respective campaigns conducted in the Arctic during the land-ice spring/autumn campaigns of 2004 and for sea-ice in the Bay of Bothnia during March 2005. Since a further ASIRAS campaign in the Arctic is guaranteed for April/May 2006 we look at how this data can be exploited in view of future ESA Earth observation radar altimeter missions. Verification of the ASIRAS data with coincident laser altimeter and *in-situ* data collected at test sites is also presented.

The paper also provides a review of key space and air borne radar altimeters dating from 1957 including those using the synthetic aperture radar (SAR) technique as applied to radar altimeters leading to the development of CryoSat.

1. Introduction

CryoSat was the first of the ESA Earth Explorer opportunity missions, a mission proposed by the scientific community in 1998 (*Wingham et al*, 1998). The proposal was underpinned by an urgency to reduce uncertainties in elevation measurements over land and sea ice fields not available using pulse-width limited radar altimetry. CryoSat was to be launched and placed in an orbital inclination of 92º on 8th October 2005; however, the Eurokot launcher underwent a most unfortunate failure a few minutes after launch resulting in the loss of the mission. Since the improvement in the understanding of key climate issues that instigated the original CryoSat proposal are now more urgent than ever (see §7.5, *IPCC*, 2001) it has been recognised internationally that there is an overriding concern to recover the mission. On Feb 24th 2006 the ESA Programme Board for Earth Observation approved a recovery mission and now ESA are in the very early days of planning CryoSat-2 for a launch in 2009.

It was recognised early on in the original CryoSat programme that one of the many major challenges with obtaining mission success was with the verification and validation of the CryoSat retrievals. Since CryoSat was primarily a mission to measure ice sheet elevation, sea-ice freeboard and thickness (*Wingham, et al*, 1999) it was necessary to design and test a validation infrastructure combining airborne and field campaigns, the CryoSat Validation Experiment (CryoVEx), at an early stage that could cope with both the logistical difficulties of operating in some of the most hostile environments of the Earth whilst being effective both in terms of cost and science return. These activities were undertaken by the CryoSat Validation and Retrieval Team (CVRT) and came under the responsibility of the lead investigator and validation manager with inputs from the CryoSat Science Advisory Group (CSAG) and CryoSat project.

At the time of the CryoSat launch all systems necessary to instigate a successful calibration and validation were in place. These included:

- End to end testing of CryoSat ground segment based in Kiruna, distribution of test data to Expert Support Laboratories (ESL), ability to re-process products off-line at the ESL using clones of operational processors housed at the ESL and ESTEC, ESA.
- Scientific testing of CryoSat level 1 and level 2 processors using numerous realistic land-ice, sea ice and ocean simulated test scenarios.
- Detailed testing of simulated transponder data at level 0, level 1a and level 1b with 3 non-operational dedicated transponder processors.
- ESA's ASIRAS level 1b processor operational in Alfred Wegner Institute (AWI), Germany.

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- Airborne radar and laser campaigns, LaRa 2002, CryoVEx 2003, CryoVEx 2004 and Bay of Bothnia 2005 in order to develop validation strategies.
- ASIRAS level 1b test data delivery to CVRT in May 2005 plus availability of other campaign data sets (LaRa 2002 and CryoVEx 2003, see §3.1).
- A future programme of verification & validation campaign activities planned at regular intervals throughout 2006 and 2007 (during mission operations).
- In place national funding of CVRT member activities with ESA funding for the airborne campaigns.

With good reason we believe the CryoSat-1 CryoVEx Cal/Val model would have been a successful one.

In the rest of this paper we review in Section 2 current and previous space & air borne radar altimeters and explain the improvements that were designed into the CryoSat radar altimeter, SIRAL and its airborne validation counterpart, ASIRAS. In Section 3 we describe the approach used by the CryoSat project and validation teams towards developing a fully functional and tested verification and validation strategy. In Section 4 we present some key results from campaigns using the air-borne test radar altimeter (ASIRAS), laser scanner and other *in-situ* measurements.

2. Past and Future Space and Air borne Radar Altimeter missions

2.1. Spaceborne Altimeter Missions

The history of Ku-band pulse-width limited space-borne radar altimetry is well documented beginning with the ocean/gravitational science communities needs in the 1960's. This can be typically summed up by the statement from *Heiskanen and Moritz*, 1967:

As a matter of fact, we can only estimate the covariance function [of the gravity field] from samples distributed over the whole Earth. But even this is not quite possible at present, because of the imperfect or completely missing gravity data over the oceans.

Progress was made during a conference held in 1969 at Williamstown, USA, were the proposal was made for the testing of a space borne radar altimeter (*Kaula*, 1969). It was therefore with anticipation the American S-193 radar was tested on-board Skylab (*McGoogan*, 1974). Subsequently McGoogan described a range of mainly ocean based applications for altimeters following this experiment (*McGoogan*, 1975). The first space borne *proof of concept* mission, GEOS-C, was launched in 1975 and space borne radar altimetry then took a leap forward with the short lived SEASAT-A in 1978 (*McArthur*, 1976) designed with the full de-ramp pulse-width limited method (see also *McArthur*, 1976 for a comparison between S-193, GEOS-C and SEASAT altimeters) which has been the basis for all future altimeter designs. The military satellite Geosat followed in 1985 operated initially with an ~18 month drifting orbit specifically to improve knowledge of the marine geoid before being placed into an exact repeat mission for ocean studies. The ocean targeted Topex followed in 1992 which also included a C-band channel to improve corrections for the ionosphere. Completing the list of American missions is Geosat follow-on (GFO) in 1998. It is worth noting the platform containing the payload Topex also contained the CNES solid state Poseidon altimeter. CNES has continued its programme of building Ku-band altimeters with a number of successful follow-on Poseidon-class instruments launched in their own right (e.g. Jason-1) and are continuing this heritage with development of Ka-band altimeters (AltiKa).

ESA's involvement in radar altimetry commenced in the 1980's with the development of ERS-1 with geodetic and exact repeat phases and ERS-2 missions. These missions were launched in 1991 and 1995 respectively.

The RA-2 on-board EnviSat (launched in 2002) was developed with Ku and S-band channels also for the intention of improving ionospheric corrections. As will be described later the design of the instrument and ground processors provided the secondary opportunity to improve retrieval of surface elevation for non-marine purposes.

One further advantage of the RA-2 was the option to allow, in parallel with the science data stream, short duration bursts of individual echoes to be transmitted to ground. This data stream allows phase and amplitude derivable information to be computed (from de-ramped I and Q time domain complex samples, see *Chelton*, 1989, for a useful description of generic altimeter functionality). This on-board storage restricted feature allows a potential reduction in echo blurring via a range migration correction given a good knowledge of datation, geometry and use of sinc function interpolation of the complex echoes (*Roca et al*, 2005). By nominal design the short time segments of individual I/Q echoes generated by EnviSat RA-2 are also generated at low instrument pulse repetition frequency (PRF) such that echoes are not phase coherent. Hence, further use of this data is restricted to a limited number of experiments.

A final improvement of the RA-2 over its predecessors was the inclusion of 3 tracking modes for use over topography. With bandwidths of 320, 80 and 20 MHz (tracking windows of ~60, 240 and 960 metres and range bin resolutions of ~0.47, 1.87 and 7.5 metres respectively) the system is designed to automatically switch between modes depending on surface elevation variability thus improving coverage. However, when tracking in a reduced resolution mode, science returns are also restricted to that resolution.

The primary science objectives of these missions were to improve knowledge of the marine geoid and allow the study of ocean characteristics. Despite valiant attempts to improve data usage over non-ocean surfaces these missions still have or had limitations when dealing with analysis over the cryosphere either by technology restrictions or by Earth coverage due to orbital characteristics and other mission constraints.

With sea-ice analysis the along-track resolution poses the major difficulty. Processing of sea-ice altimetry to extract freeboard and ice thickness (for use in climate models, see *Gregory et al*, 2002, for example) is a complex process (*Peacock and Laxon,* 2004) requiring knowledge of the ocean surface elevation at regular intervals along-track. This is achieved by discriminating between lead, sea-ice and ocean echoes (see for example, *Drinkwater*, 1991; *Fetterer et al.*, 1992 and *Peacock and Laxon*, 2004), however, along-track resolution using a pulse-limited altimeter is such that it is very difficult to resolve leads within sea-ice; in general a lead echo is contaminated by sea-ice returns. The CryoSat proposal (*Wingham et al*, 1998) identified the improvement of altimeter along-track resolution and sampling as a primary concern. As will be described later, along-track resolution can be improved by increasing the altimeter PRF such that echoes become phase coherent allowing the use of along-track unfocused synthetic aperture processing; otherwise known as Doppler beam sharpening (see for example, *Curlander*, 1991 and *Raney*, 1998), before range migration correction and incoherent averaging of echoes is used to reduce noise fluctuation.

With land-ice two fundamental shortfalls exist since we are dealing with surfaces with topography. The first concerns inability to resolve the echo point of surface scattered return (*Wingham*, 1995). One way to solve this (as is the case with EnviSat RA-2 level 2 processing for Antarctica and Greenland, for example) is to use slope models derived from DEM's. However, this relies on the accuracy of the slope model (in particular over ice sheet margins) and is not an optimum solution. The second reason is the inability of pulse-width limited altimeters to recover elevations for surface slopes greater than the half power beam-width of the antenna also resulting in a poor knowledge in elevation of ice sheets around the margins of Greenland and Antarctica, for example. The CryoSat proposal identified the use of interferometry via the introduction of a second radar antenna and receiving chain. Here the on-board Attitude and Orbit Control System would steer the interferometer baseline such that it would always be orthogonal to the ground-track (based on yaw steering and local normal pointing). SIRAL on-board tracking of topographic surfaces is achieved via an improvement of the RA-2 method. Whilst in SARIn mode a tracking range window of ~480 metres (derived from 40 MHz bandwidth) is provided, however, science measurements are still available with range bin resolution of ~0.46 metres with a range window of about 240 metres (512 samples). Land ice studies would also benefit from improved along-track resolution required for sea-ice processing.

Use of phase coherent instrumentation appears to commence with the airborne military system designed and successfully tested in 1957 (*Cutrona*, 1962). Following this we know of the RA-P altimeters on-board Venera 15 & 16 with missions to Venus in 1983 (*Aleksandrov et al*, 1988), which generated phase coherent pulses and allowed digital Doppler processing to take place with the telemetered data improving along-track resolution. *Barbarossa and Picardi*, 1990, describe an interplanetary radar altimeter using the SAR technique whilst the NASA Venus mission, Magellan, mapping the surface between 1990 and 1994 also had an altimeter mode within its SAR allowing short bursts of pulses to be transmitted (*Ford and Pettengill*, 1992).

It is finally worth noting *Elachi*, 1988, also describes a number of altimeter based concepts intended for use over topography. *Hartl and Kim*, 1990, describe the concept of SAR with an altimeter and the interferometric technique by adopting the use of two antennas separated in the across-track direction. This instrument was tested on land with the intention of spaceborne usage. *Jensen*, 1999, describes the interferometric principle in detail with respect to pulse-limited altimeters.

In the mid 1990's the Johns Hopkins University Applied Physics Laboratory (JHU-APL) proposed their Delay/Doppler altimeter concept (*Raney*, 1995) and provide a detailed description in *Raney,* 1998 using the Topex mission as a baseline for the design.

2.2. Airborne Radar Altimeters

Airborne radar altimeters have been used to map surface backscatter and elevation prior to the first complete description of radar return by *Moore and Williams* (1957) and whilst *Cutrona* (1962) describes the first non-pulse limited phase coherent airborne system in 1957 it was not until later in the 1980's that a conceptual phase coherent full-deramp pulse limited airborne instrument was designed for the objective of Earth observation and in particular with use over non-ocean surfaces as described in *Purseyyed & Griffiths*, 1988 and *Griffiths*, 1988 and then with a functioning instrument described in *Griffiths and Purseyyed*, 1990.

There have been a number of other airborne radar altimeters using other techniques for mapping topography, for example, the Rutherford Appleton Laboratory (RAL) built an altimeter (See *McIntyre et al*, 1986 and *Griffiths*, 1986) which was flown on-board a NASA Convair 990 aircraft over a variety of Arctic surfaces in 1984 for the Marginal Ice Zone Experiment (MIZEX). This system was the first to apply a twin-antenna concept, aligned in the along-track direction for investigating improved methods of tracking steep, variable ice-sheet topography.

As mentioned in the previous section, having improved along-track sampling resolution the problem of resolving across-track echoing point was provided by interferometry with the addition of an additional cross-track aligned antenna (see Fig. 1 and *Jensen*, 1999).

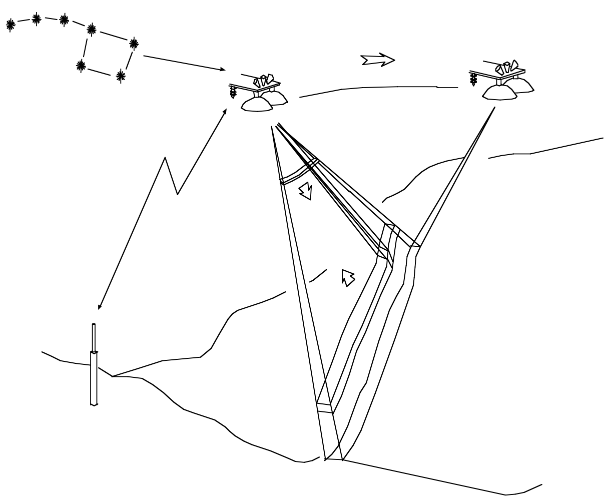

Figure 1 CryoSat Interferometric SAR concept (taken from Wingham, 2004).

In the late 1990's, through the NASA Instrument Incubator Programme, the JHU-APL built and tested (in Greenland) the D2P, a combined airborne synthetic aperture and interferometer using the delay/Doppler concept described in the previous section. Impressive results from these tests are available on the JHU website (*Raney and Jensen,* 2000).

Meanwhile ESA instigated hardware and simulation studies for a high spatial resolution radar altimeter in 1997 (*Phalippou et al*, 1998) combining, like the D2P, SAR and interferometry within the one instrument. ESA then commenced CryoSat "phase A" feasibility studies in 2000 and the full development of ESA's airborne demonstrator, ASIRAS, followed in 2002.

2.3. Future Radar Altimeter Missions

Other non-cryospheric uses of the radar altimeter based SAR technique for oceanographical purposes have been identified with respect to WITTEX (*Raney and Porter*, 2000, *Raney and Porter* 2001 and *Porter et al*, 2003). Improvement in bathymetry models have been described (*Raney et al*, 2003c) and gravity field modelling would also benefit in conjunction with ESA's GOCE mission. There are many other uses of SAR/Interferometric missions that have been identified in the literature but are not described here.

ESA will potentially include one of more SAR based radar altimeters with supporting instrumentation primarily for ocean (including sea-ice) purposes on the Global Monitoring for Environment and Security (GMES) based Sentinel-3 mission (*Drinkwater et al*, 2005a). Early planning for this mission identifies 2010 as an earliest launch date. Undoubtedly, as with earlier missions, data acquired from such a mission would be adopted for research of the cryosphere dependent on mission characteristics.

Current planning indicates CryoSat-2 will be a clone of the original design in order to reduce costs although some inevitable modifications can be envisaged based on experience from the original phase C/D activities and ESA programmatic priorities.

2.4. Description of ESA SAR and Interferometric Altimeters

2.4.1. CryoSat

CryoSat's primary mission objectives (*Wingham*, 1999) were to reduce uncertainties in the knowledge of sea ice thickness (*Laxon et al*, 2003), its role in radiative balance (§7.5.3 of *IPCC*, 2001) and improve understanding of mass balance of the major land ice fields (see §11.2.3 and §11.6.4 of *IPCC*, 2001). In order to achieve the scientific requirements the platform incorporated a range of instrumentation and was to be placed into a near polar circular orbit of 92° inclination (*Ratier et al*, 2005 and *Drinkwater et al*, 2005b). The payload consisted of:

- Synthetic Interferometric Radar Altimeter (SIRAL) with 3 science modes of operation
    - o Low Rate pulse limited mode (LRM) for use over land ice sheet interior – typical of an ocean altimeter.
    - o Synthetic Aperture Radar Mode (SAR) for use over sea ice
    - o Synthetic Aperture & Interferometer Mode (SARIn) for use over the ice sheet margins
    - o Plus several internal calibration modes.
- Use of the DORIS and beacon network for precise orbit determination (POD).
- Laser Retro Reflector to assist with POD.
- Three star trackers for precise SIRAL interferometer baseline orientation determination.

CryoSat was able to meet all its objectives without the need for additional microwave radiometer or dual-channel altimeter payloads.

The ground segment (described in *Francis et al*, 2005) contained the payload data segment (PDS) housed in Kiruna (the location of the only X-band measurement data downlink) where the instrument processing, monitoring, quality control and user data delivery facilities were also housed. Flight operations and dynamics were housed at ESOC with the reference planning facility in ESRIN. Other facilities covered the DORIS processing in CNES, expert support from University College London with the Orbit and Altimeter Validation group based at ESA and Delft University of Technology. The numerous retrieval validation groups are listed in Section 3.

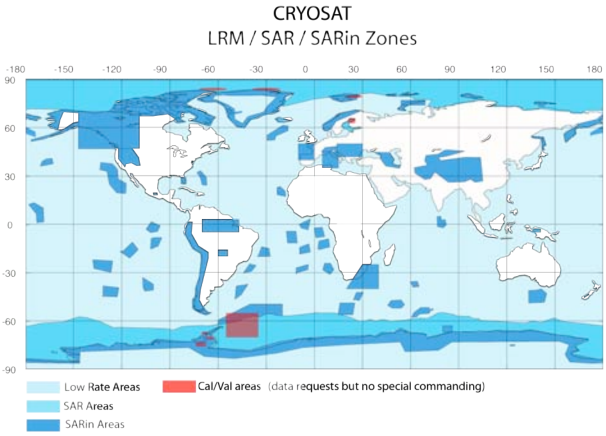

Figure 2 CryoSat Cal/Val measurement masks and AO zones used here to show the science community had a keen interest in using the CryoSat acquisitions over all surface types. Since CryoSat was ruled by strict mass memory and X-band downlink budgets (a single ground station was located in Kiruna) it was unfortunately necessary that planning was undertaken not to record data over most land surfaces. Low rate mode acquisitions over ocean was a pre-requisite to support precise orbit determination.

One of the cost budget drivers of the mission was the use of the single ground station in Kiruna shared with EnviSat. Though one would have liked to record acquisitions covering the whole Earth using the SARIn mode it simply was not possible via the single X-band downlink bandwidth combined with limited on-board mass memory size. Hence, mode switching was implemented as a geographic mode mask governed by the primary science objectives. Margins were built into the system for supporting activities such as calibration, via calibration zones, and a requirement for ocean LRM data to be integrated in POD activities.

Following announcements of opportunity (AO) to the scientific community the expected interest in non-cryosphere related exploitation became apparent with requests using SAR/SARIn modes over some regions of land and ocean based on the remaining margins. The geographic mode mask installed in the reference planning facility at CryoSat launch is shown in Fig. 2.

Other CryoSat related documentation is available for download on the ESA living planet web site (http://www.esa.int/esaLP/LPcryosat.html).

2.4.2. ASIRAS

In the late 1990's JHU-APL built the D2P airborne demonstrator with a 360 MHz bandwidth full de-ramp pulse-width limited phase coherent radar altimeter system with interferometric capability.

Initial D2P test results acquired over Greenland in 2000 (published on the JHU web site, *Raney and Jensen*, 2000) provided evidence of inter-annual layering in the processed waveforms over regions of Greenland. With the D2Ps range resolution of ~40 cm it became clear that if one could improve on this value then it would be possible to provide a better opportunity to understand radar pulse penetration within the first few metres of snow pack and therefore provide a better tool for validating the CryoSat retrievals.

Hence, the decision was taken to design ASIRAS with 1 GHz bandwidth (range resolution of ~8.7 cm following processing and range interpolation). The instrument was developed by Radar Systemtechnik (RST) and installed on Deutschen Zentrum für Luft- und Raumfahrt (DLR) aircraft (Polar-4) by AWI & Optimare in order to make a number of initial test flights in the region of Bremerhaven, Germany and the North Sea during 2003. In one test ESA was able to demonstrate pulse-to-pulse phase coherence from reflections obtained from cranes when bad weather prevented a direct corner reflector over flight. In 2004 the instrument was tested in the field for 2 significant Arctic campaigns.

In early 2005 an extra measurement mode was added to ASIRAS allowing the combined use of ASIRAS with laser scanners, which have operating ranges below 600 m, to characterise the penetration of the radar signal. This mode (LAM-SAR) was tested in the field in March 2005 in a dedicated test in the Bay of Bothnia.

The current and future operational processing of the ASIRAS raw and auxiliary data is conducted by AWI using a level 1b processor developed in-house at ESA. This processor is very similar in architecture to the CryoSat Level 1b processor (*Cullen and Wingham*, 2002) with added features to assist with data interpretation, for example, it became clear that users would require information regarding aircraft attitude and approximate surface elevation provided by a simple non-model re-tracker. Hence, the ASIRAS Level 1b product is different in structure to that of CryoSat's. There is currently no plan for an ESA level 2 processor for the ASIRAS data.

Key results from the CryoVEx 2004 campaign comparing ASIRAS elevation retrievals with laser scanner derived DEMs and *in-situ* neutron probe density profiles are presented in Section 4.

Land ice uncertainties	
Uncertainty	**Proposed CAL/VAL activity**
Error in spatially averaged ice sheet imbalance (Containing 4 elements)	
1. Covariance of snowfall fluctuation	New ice core observations etc.
2. Covariance of near surface density	Improved modelling, etc.
3. Covariance of elevation trend error	Defined sub-uncertainties
4. Post glacial rebound error	Model inter comparison
Sea ice uncertainties	
Error in spatially averaged sea ice thickness (Containing 4 elements)	Moored and submarine measurements EM bird thickness measures Borehole measures
1. Covariance of uncertain snow loading	Re-appraisal of snow depth records
2. Covariance of ice density	EM thicknesses and freeboard sounding.
3. Error covariance due to sampling of thick floes	Joint PDF of floes area thick ness, etc
4. Ice freeboard error covariance	Defined sub-uncertainties

Table 1 Land/Sea ice high-level uncertainties taken from (CSAG, 2001). Top level uncertainties are indicated in red and uncertainties in blue indicate they are broken up in sub-categories in the document.

3. CryoSat as a Model for Altimetry Mission Validation

As with all Earth observations missions, validation of retrievals are key to overall mission success. The CVRT was set up 3 years prior to CryoSat launch and met on a regular basis in order to:

- Develop optimum strategies to tackle scientific uncertainties.
- Obtain full aircraft installation certifications.
- Develop and test logistical mechanisms, methods of communication and learn from pre-launch campaign experiences.
- Plan cost and science effective field campaigns on land and sea ice.

A list of uncertainties to be investigated by the CryoSat Science Advisory Group (CSAG) extracted from *CSAG*, 2001 is provided in Table 1.

3.1. Verification & validation campaigns

Whilst ESA commenced the design and implementation of ASIRAS in 2001 (*Lentz et al*, 2002) the American D2P and ATM laser were made available (See Table 1 for a full list of campaign activities) for a joint ESA/NASA funded Laser/Radar altimeter (LaRa) campaign in spring 2002 (*Raney*, 2003a/b) operated on a NASA P-3. The following year in spring 2003 an ESA funded and CVRT coordinated campaign saw DNSC (then KMS) operating their laser scanner (with auxiliary instrumentation) combined with the JHU operated D2P on-board an Air Greenland Twin Otter. This campaign known as CryoVEx 2003 covered a significant coverage of land ice in Greenland and Svalbard and sea ice around the Fram strait, Svalbard and north of Alert, Greenland. Results of this campaign have been published (*Keller et al*, 2004 and *Raney & Leuschen*, 2004).

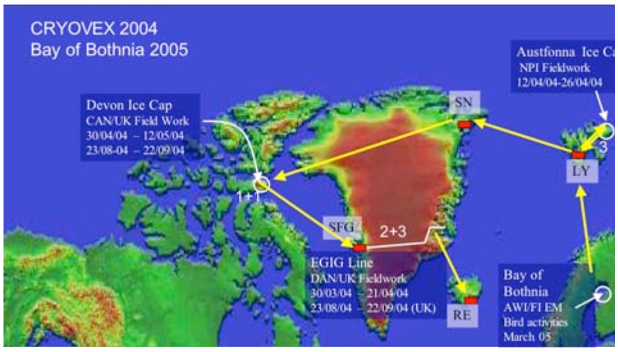

Figure 3 CryoVEx 2004 and Bay of Bothnia 2005 campaign sites and traverses. Devon Ice cap traverses took place along an EnviSat ground track in preparation for validation activities with CryoSat. (Courtesy of Alfred Wegner Institute)

ASIRAS was tested in the Arctic in March 2004 with a pre-campaign in Svalbard using corner reflectors and over flights of Austfonna ice cap. This was immediately followed by the spring and autumn Arctic campaigns over Svalbard, Greenland and Devon Island. This logistically demanding campaign incorporated for the first time several surface teams placed at various sites conducting *in-situ* activities listed in Table 2. Also the opportunity was available to test the ASIRAS radar penetration via the use of test corner reflectors (see Fig. 4) positioned a few metres above the snow surface and installed prior to ASIRAS over flight with accurate positioning communicated to the ASIRAS flight team (led by AWI) in order to plan the over flight to within 5 metres. Other instruments used to assess radar penetration are listed in Table 2.

Figure 4 Corner reflector being erected on Bay of Bothnia sea ice on March 14th 2005 (courtesy of AWI).

Following a necessary hardware modification allowing the use of ASIRAS at low (300-1100 metre) aircraft elevation a test campaign was conducted in March 2005 by AWI and the Finish Institute for Marine Research (FIMR) over sea ice in the Bay of Bothnia. This combined ASIRAS with laser scanner and helicopter based electromagnetic (EM) measurements with surface teams conducting *in-situ* corner reflector positioning and drilling. All these campaigns were designed in the context of developing CryoSat validation strategies.

3.2. Other Cal/Val Methods

Other cal/val methods planned for CryoSat included:

- Transponders used to provide interferometric phase difference and σ^o calibration:
  - The RAL developed transponder used for studies with ERS was refurbished, shipped and installed in Svalbard in 2005. Following loss of CryoSat an EnviSat pass on Nov. 11th 2005 provided a successful test opportunity of the Svalbard transponder.
  - An optional transponder located in Crete was also planned for use.
  - The reference planning facility was designed to automatically tele-command SIRAL to operate in SARIn mode within a certain overpass distance from the transponder.
  - Three transponder data processors were developed to help investigate instrument and processor characteristics and assist in other commissioning phase activities. Processors underwent detailed testing using simulated data.
- Natural land targets such as salar de Uyuni, Boliva would provide possibilities for interferometer baseline calibration and cross-calibration with RA-2.
- 'Flat' ocean targets. Regions of the ocean considered to be stable with low backscatter/elevation variability were to be used to assist in interferometric baseline characterisation.
- Inter mode biases. As with all altimeters it was expected that range biases may exist between LRM, SAR and SARIn science modes. An averaged 1 Hz pulse limited echo computation was built into the level 1b processors such that this bias would be observed by switching through the 3 modes over stable surfaces.
- Commissioning phase satellite rolls of a few degrees over the Pacific to further assist with interferometric baseline characterisation.
- Cross-calibration with IceSat and EnviSat RA-2.
- Internal calibration modes designed to compensate the science data for:
  - Instrument transfer function imperfection in phase and amplitude.
  - Variation of echo phase & amplitude over a burst of 64 echoes over period of 11.7 mS.
  - Chain dependent instrument path delay.

LaRa 2002		
JHU	D2P radar acquisition + processing ATM laser altimeter NASA P-3 aircraft	Greenland Svalbard land + sea
CryoVEx 2003		
JHU	D2P acquisitions + processing	
DNSC	Lidar acquisition Aircraft operation	
AWI	Polarstern, EM Bird Drilling	
CryoVex 2004 (spring/autumn)		
AWI/ Optimare	ASIRAS ASIRAS processing LD90 (Lidar) ALS (laser scanner)	Austfonna, EGIG Greenland, Devon island
RST	ASIRAS operation	
DLR	Do-228 Polar 4 aircraft ops	
Geological survey of Canada, Univ. Alberta (Ca), Univ of Aberdeen.	Skidoo Corner reflector Snow Pits, rocket launchers, coffee cans, ice cores, Stakes, Weather station	Devon island
Univ. Glasgow (UK)	Corner Reflector GPR, ice core	EGIG T05/T01 Greenland
Scott Polar Research Institute (UK)	T21 CR Snow pits, Neutron probe, GPS measures, coffee can	T05-T41 EGIG Greenland
Norwegian Polar Institute (NPI) + Univ. Oslo	6 Corner reflectors Skidoo traverses Pits, GPR, Stakes, ice cores	Austfonna
Bay of Bothnia 2005		
AWI/ Optimare/FIMR	ASIRAS operation & processing. LD90 & ALS Corner reflector, EM-Bird Sea ice drilling	
DLR	Do-228 D-Code operation	

Table 2 List of activities, teams and locations relating to LaRa 2002, CryoVEx 2003 & 2004 and Bay of Bothnia campaigns.

4. Results Obtained From CryoVEx 2004

There are a number of results that have been produced from the CryoVEx campaigns. Here we present some of the key results from the 2004 experiments.

The algorithms in the ASIRAS L1b processor are described elsewhere (*Cullen and Wingham*, 2002 and

Wingham et al, in press), however, it is worth explaining a few terms:

- *Burst*: The radar transmits a burst of phase coherent pulses at high PRF. For CryoSat this was fixed at 64 pulses. For ASIRAS the instrument generates pulses with a constant PRF; here received echoes are formed into bursts within the ground processing.
- *Beam Formation*: Bursts of phase coherent echoes are azimuth processed via the use of an FFT. Since beam echoes are contaminated with thermal and speckle noise and in order to assist with slant range migration correction CryoSat and ASIRAS ground processors pre-determine fixed locations at an approximation to the surface (provided by on-board tracker).
- *Stack:* All beam echoes steered to a fixed location (or target) are known as a stack. Beam echoes steered to a target are generated from different bursts and are incoherent. Depending on aircraft elevation, PRF and speed of aircraft the number of beams in a stack can vary. For a nominal pointing aircraft (and antennae bore sight) over a flat surface providing, *N*, beam echoes; echo 0 is the first echo generated as the aircraft approaches the fixed location, beam *N/2* is the beam echo formed as the aircraft is directly above the fixed location and beam *N-1* is the furthest backward looking beam as the aircraft moves away from the target location (see Fig. 1).
- *Multi-look*: In order to reduce thermal and speckle noise fluctuation a stack of echoes are averaged to produce level 1b echoes. The multi-looking process involves looping through each range window sample and integrating all incoherent beam echoes providing a single range window power echo for SAR mode and power, interferometric phase difference and coherence for SARIn.

Having briefly described the processing terms we turn to the results. In Fig. 5 a stack is plotted for data acquired close to T21 on the Greenland EGIG line. At range bin ~90 the radar response from the surface can be observed with an amplitude modulation being a function of beam (or beam angle) and is due to a combination of surface response and real antenna pattern. One can also see the effect of speckle in the signal; hence, integrating all incoherent beam echoes reduces the noise fluctuation and provides the final level 1b echoes (power, interferometric phase and coherence). The main issue that arose from this plot was to understand why linear features at range bin ~120, 175 and 210 were in the signal. In particular was this evidence of annual layering, instrument artefact or simply processor error.

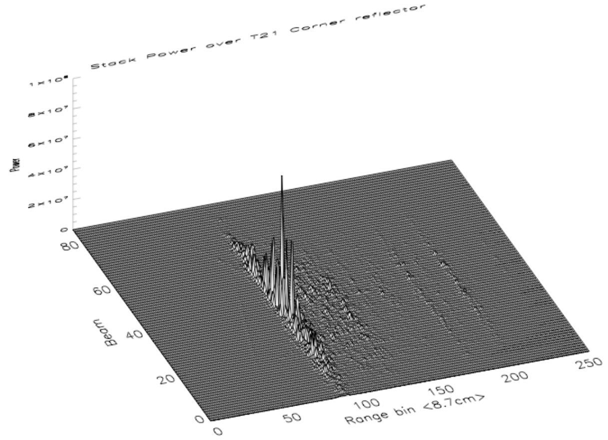

Figure 5 Stack of ASIRAS echoes steered to a fixed location processed from an over flight on Sept. 14th 2004 close to the T21 location on the EGIG line, Greenland. The x-axis is the range window in units of ~8.7 cm (ASIRAS SARIn, ~11cm for LAM-SAR), the y-axis is the beam number and z-axis is the power. One can see the stack is contaminated by speckle. Since beam echoes are incoherent, a summing of each beam echo reduces noise fluctuation providing a single range window echo. See text for further description.

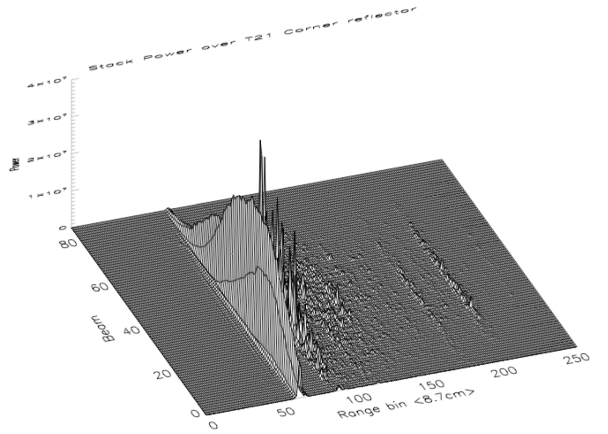

Figure 6 A stack of echoes gathered at a fixed location containing a corner reflector close to the T21 location on the Greenland EGIG line during Sept. 14th 2004 over flight of ASIRAS. See text for full description.

Fig. 6 shows a stack of ASIRAS beam formed power echoes for a surface region containing a corner reflector erected ~ 2 metres above the snow surface. The corner reflector response can be seen at range bin ~ 60. The asymmetry in beam was due to installation of the antennae on the aircraft with an unavoidable mis-pointing of the antennas occurring in the forward direction by ~2.5º.

The breakthrough in validating the potential layering seen in Fig. 5 and Fig. 6 came from analysis of the ASIRAS level 1b power echoes acquired during the over flight of the EGIG T21. At the time of the over flight a team from the Scott Polar Research Institute measured *in-situ* density profiles using a neutron probe (*Hawley et al*, 2006). Fig. 7 shows the comparison of the two independent data sets and clearly the ASIRAS radar is capable of retrieving several metres of sub-surface profiles from multi-year annual layering in the dry-snow zone of Greenland. The CVRT is also currently analysing quite different echo shapes retrieved from the percolation zone of Greenland near the T05 site of the EGIG line. There are numerous other experiments currently being conducted that will further prove the use of this instrument and value its data having lost CryoSat.

With respect to the validation of ASIRAS data, ESA and AWI are in the final stages of analysing the ASIRAS level 1b and laser scanner derived DEM's to determine instrument biases and the radar penetration depth, see Fig. 8.

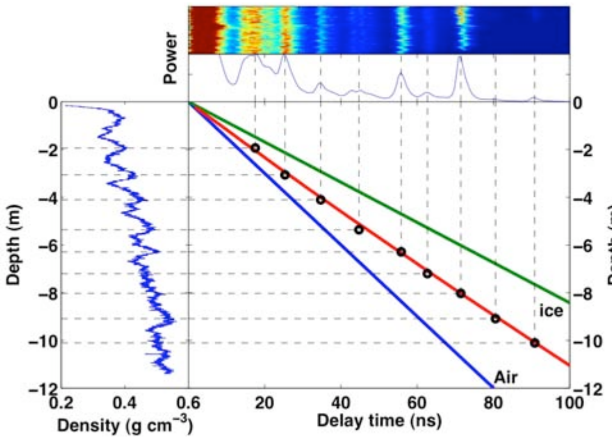

Figure 7 (Taken from Hawley et al, 2006) ASIRAS and neutron probe data acquired at the T21 site in the dry-snow zone of the EGIG line, Greenland. (Top) ASIRAS processed SARIn power waveforms with, directly below, a power trace computed from an average of 30 waveforms with respect to the delay time and (left) neutron probe density profile. Three diagonal lines display (Blue) depth-travel time in air, (Green) in solid ice and (Red) computed for snow using the neutron probe densities. One can see a direct one to one correspondence between the peaks in the densities and those of the averaged ASIRAS power waveform.

5. Conclusions

Despite the loss of CryoSat we have shown that all mechanisms were in place for a successful validation with CVRT being able to undertake and test a large number of cost effective, logistical and scientifically demanding validation challenges. The model developed is transferable for an opportunity mission such as CryoSat-2 and other potential ESA operational radar altimeter missions such as Sentinel-3, for example.

A compensation for the CryoSat interested science community comes from 4 years of ESA led (joint with NASA for LaRa) campaigns from which CVRT has acquired and processed a large repository of laser and radar altimeter airborne campaign data combined with surface acquired *in-situ* measurements. ESA and CVRT are in the process of interpreting this data.

ASIRAS related campaign activities re-commence in March 2006 with a brief test campaign to check and obtain certification for the ASIRAS installation on a Air Greenland Twin Otter with a number of additional tests to improve understanding of LAM mode data acquisitions.

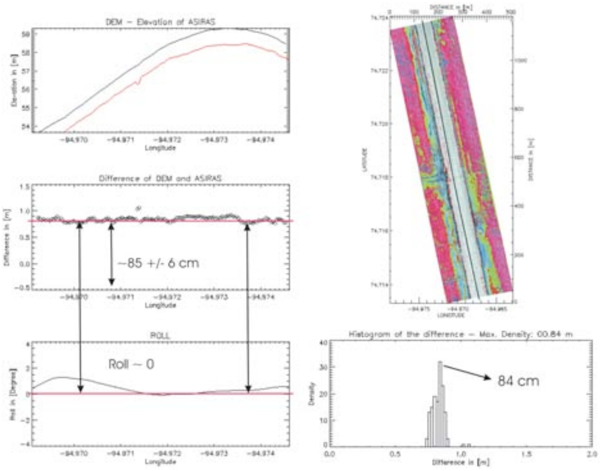

Figure 8 An early comparison of ASIRAS retrieved level 1b surface elevations and laser Scanner derived DEM's from data acquired at Resolute Bay (Canada) on 2nd May 2004 (Courtesy of AWI).

This test flight will be followed by an extensive Arctic grand tour covering land ice (Austfonna ice cap, EGIG line & Devon ice cap, see Fig. 9) supported by land teams with corner reflectors, neutron probe and Ground Penetration Radar (GPR), for example.

The tour will also cover a number of sea ice regions supported by helicopter borne EM thickness profiling and sea-ice drilling teams, for example.

With the combined efforts of ESA and the international science community (stretching beyond the membership of the CVRT) carrying out the coordination of CryoSat campaigns, data acquisition and analysis, critical issues relating to the exploitation of radar altimeter and laser signals over land-ice, sea-ice and ocean continue to be addressed. In terms of the cryosphere, analysis of issues such as signal penetration (both spatially and temporally), correlation of radar signals with known snow & ice properties, density of near-surface snow pack layers and snow loading on sea ice will contribute to more accurate future ESA ocean, land and cryosphere related radar altimeter missions, such as CryoSat-2 and Sentinel-3, thus improving scientific exploitation of their data.

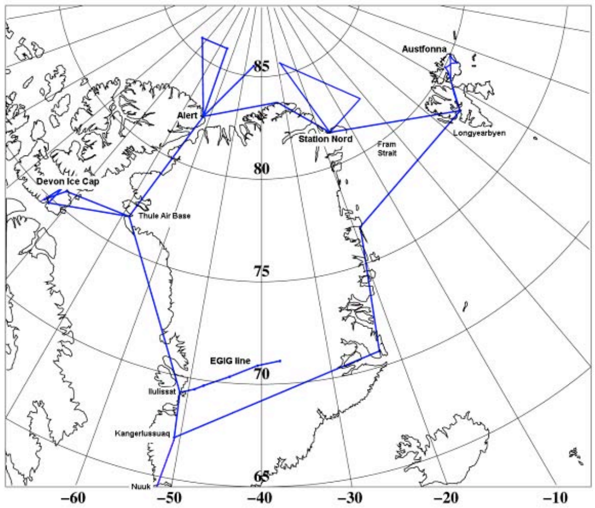

Figure 9 Flight plan for CryoVEx 2006 activities for April/May 2006. Showing land ice flights over Devon Island, EGIG line, Greenland, Austfonna ice cap and sea ice flights north of Station Noord and Alert (Courtesy of Danish National Space Centre).

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