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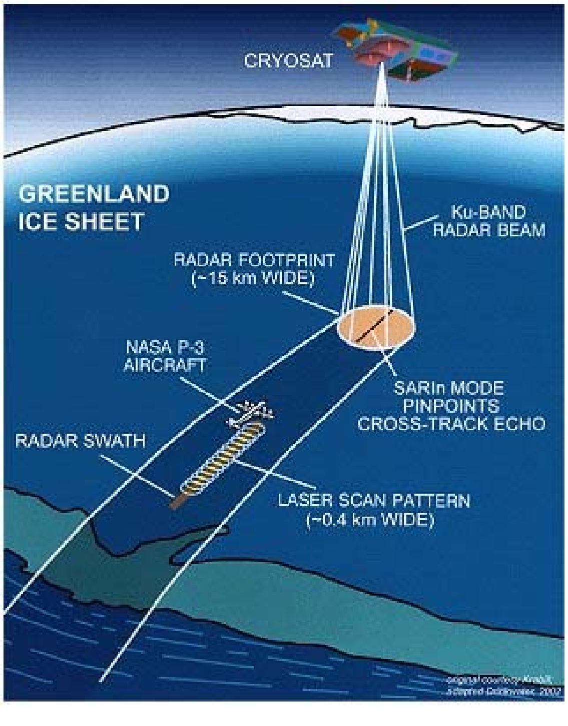
CRYOSAT PLANNING DOCUMENT FOR NORWEGIAN PRE-LAUNCH ACTIVITIES



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Sammendrag på norsk

CRYOSAT, som er ESA's første Earth Explorer Opportunity Mission med planlagt oppskying in september 2004, er den første satelitt med "Beam-limited" radar altimeter til å måle høyder og topografi på jordoverflaten. Instrumentet kan operere i tre ulike moder: som konvensjonell "pulse-limited" altimeter over åpent hav, som Syntetisk Apertur Radar altimeter (med 300 m oppløsning langs banen) over sjøis, og med interferometrisk prosessering på tvers av banene over isbreer. Det er de to siste modene som er innovative og gjør CRYOSAT særlig interessant for nøyaktig høydemålinger over isbreer og for beregning av tjukkelse av havis via måling av fribord. Et tilsvarende altimeter (D2P) har vært bygd og prøvd i fly av Johns Hopkins University Applied Physics Laboratory. Eksperimentelle målinger har vært gjort med dette instrumentet over Grønlandsisen, over havisen i Svalbardområdet og over isbreen på Nordaustlandet. Videre informasjon fines på web-sidene http://fermi.jhuapl.edu/d2p/.

Et annet forhold som gjør CRYOSAT interessant er at NASA har skutt opp IceSat i desember 2002 med et laser altimeter (GLAS) som vil være komplementær til CRYOSAT. Dette gjør at både havis,

isbreer og andre terrestriske prosesser som krever nøaktige høydemålinger vil få tilgang på både laser altimeter (532 og 1064 nanometer bølgelengde) og radar altimeter (Ku-bånd) data.

En norske CryoSat gruppe ble etablert i løpet av høsten og vinteren 2001-2002 med 10 - 15 personer. I "pre-launch" fasen inntil 2004-2005 er det først og fremst representater fra forskning og operasjonelle institusjoner som har vært aktive siden det er betydelige FoU aktivtiter som må gjennomføres før data produkter som er nyttige for brukere kan leveres. Etterhvert vil gruppen utvides med deltagere fra brukermiljøer, industri og andre som ser muligheter i utnyttelse av dataene, ikke bare innen landis og havis, men også andre anvendelsesområder som trenger nøyaktige høydemålinger

En workshop ble avhold den 7 februar 2002 med ca 15 deltagere og med Prof. Duncan Wingham som invitert foredragsholder. Prof. Wingham er vitenskapelig leder av CryoSat programmet. Deltagerne gav presentasjoner og leverte stoff til bruk i plandokmentet. Fokus for workshopen var å diskutere hvordan norske institusjoner skulle respondere på CalVal AO utlysingen for CryoSat. Fram mot 15 april ble flere norske CalVal forslag med feltarbeid utarbeidet og innsendt til ESA. Resultatet var at to norske forslag ble akseptert, et på havis og et på landis, slik at det nå er betydelig norsk deltagelse i "CalVal Research Team" (CVRT) for CryoSat.

I perioden mai - september 2002 har fokus vært å forberede søknader til Norges forskningsråds PolarKlima utlysing hvor utvikling av JO-metoder for anvendelse i polarområdene er eksplisitt nevnt. Flere søknader ble innlevert til fristen 15. september hvor fjernmåling inngår, herunder også CrySat-relaterte aktiviteter. Ingen av de CryoSat relaterte søknadene ble innvilget i denne runden.

I løpet av høsten 2002 og vinteren 2003 ble det første CryoSat CalVal eksperimentet planlagt og gjennomført i regi av ESA hvor flybåren laser og radar altimeter (D2P fra John Hopkins University Applied Physics Laboratory). Eksperimentet, som ble kalt CRYOVEX, hadde flyvninger over Grønland, i Framstredet og over Austfonna i peioden 5 – 21 April 2003. Mer informasjon om eksperimetet finnes på http://www.esa.int/export/esaLP/cryosat.html. Det var norsk deltagelse i både havis ekserperimentet hvor feltmålinger fra isgående fartøy ble utført og i landis ekseprimentet over Nordaustlandet. Videre aktiviteter vil være å analysere resultater fra CRYOVEX og planlegge videre feltarbeid i Svalbard området.

Innsamling og analyse av valideringsdata for dokumentering av algoritmer og målenøyaktighet vil være den viktigste aktiviteten i løpet av de neste årene. Dette skal brukes til promotering og demsontrasjoner mot aktuelle bruker grupper. Etter 2005, når CryoSat etter planen skal levere data og produkter på regulær basis, vil CRYOSAT-relaterte aktiviteter gå inn i en ny fase med intensiv data analyse, publikasjon av resultater og promotering mot nye potensielle bruker grupper.

En ny "Announcement of Opportunity" utlysing er planlagt i 2003- 2004, hvor datautnyttelse er hovedformålet. Her vil det være viktig at norske miljøer som potensielt kan tenke seg å bruke data deltar i søknader for å sikre seg tilgang på data. I forhold til den forrige CalVal-utlysingen, vil dette være en mer generell utlysing som åpner for mange ulike typer anvendeser av CryoSAt datene.

CryoSat aktivtene vil kreve dedikert finansiering fra flere kilder, blant annet fra Norges Forskningsråd Utvikling og bruk av CryoSat og IceSat data er således nevnt i Strategi plan for forskning i Arktis 2003 – 2007 som er under utarbeidelse av Nasjonalkomiteen for polarforskning.

Innenfor operasjonell observasjon av havis og overvåking av isbreer, vil det være behov for å ta i bruk produkter fra CryoSat så snart de er tilstrekkelig validert. Dette betyr at institusjoner med avsvar for operasjonell overvåking bør støtte utvikling og validering av informasjonsproduktene som kommer fra CryoSat of IceSat.

Contents

1. INTRODUCTION TO CRYOSAT

The CryoSat mission was selected, in June 1999, as the first mission in the Earth Explorer Opportunity Mission series. The Earth Explorer missions have the fundamental aim of contributing to the provision of data essential to the study of the various processes involved and the extension of the existing hierarchy of models of the Earth System. They are also intended to help establish the feasibility of new space-based observation techniques of potential application in operational observing systems.

The concept of an Opportunity Mission is tailored for more focused scientific applications with smaller satellites and a minimum set of observation instruments. This should allow a faster implementation schedule and a quicker response to evolving situations or areas of immediate environmental concern. The time from mission selection (1999) to launch (2004) is about 5 years for CryoSat.

The CryoSat mission has been defined in order to determine fluctuations in the mass of the Earth's major land and marine ice fields. Predicting future climate and sea level depends on knowledge of these fluctuations, but present observations are deficient in time and space.

The cryosphere has a central role in the Earth's radiation budget. As a consequence of this feedback a loss of sea ice is predicted to cause a larger greenhouse-gas warming in the Arctic than the rest of the Earth. Ice sheets and glaciers together comprise one of the largest uncertainties in the potential sources of global sea-level rise. Variations in these components of the Cryosphere can have a significant controlling influence upon sea-level variations.

The goals of CryoSat are to measure variations in the thickness of perennial sea and land ice fields to the limit allowed by natural variability, on spatial scales varying over three orders-of-magnitude. The natural variability of sea and land ice depends on fluctuations in the supply of mass by the atmosphere and ocean, and snow and ice density. CryoSat measurement requirements are determined from estimates of these fluctuations.

The measurement requirements of the CryoSat system have been formulated in terms of the uncertainty in the measurement of perennial ice thickness change due to all contributing elements, including satellite performance, ground processing etc. They are expressed in units of cm yr^{-1} over certain specific averaging areas.

- Over sea ice the averaging area of interest is 10^5 km^2 and a minimum latitude of 50° is assumed; the required system measurement uncertainty is 1.6 cm yr^{-1}.
- Over ice-sheet margins an averaging area of 10^4 km^2 and a minimum latitude of 72° is assumed, being sufficient to cover the margins of Antarctica; the required system measurement uncertainty is 3.3 cm yr^{-1}.
- Over the interiors of the ice-sheets the averaging area is 13.8 $x10^6$ km^2 (the surface area of Antarctica) and a minimum latitude of 63° is assumed which will include all of Antarctica and most of Greenland; the required system measurement uncertainty in this case is 0.7 cm yr^{-1}.

The CryoSat system is required to perform measurements over three full years in order to establish secular trends. More details on the CryoSat mission and its objectives can be found in the *CryoSat Science and Mission Requirements Document*[1]

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[1] Report edited by D. Wingham, UCL, 21. September 1999, 56 pp.

The CryoSat satellite is illustrated in Fig. 1.

Figure 1. Illustration of CryoSat currently under construction by Astrium in Friedrichshafen. The two radar antennas are oriented cross-track and will be used for synthetic aperture interferometric (SARIn) processing over steep ice sheet margins.

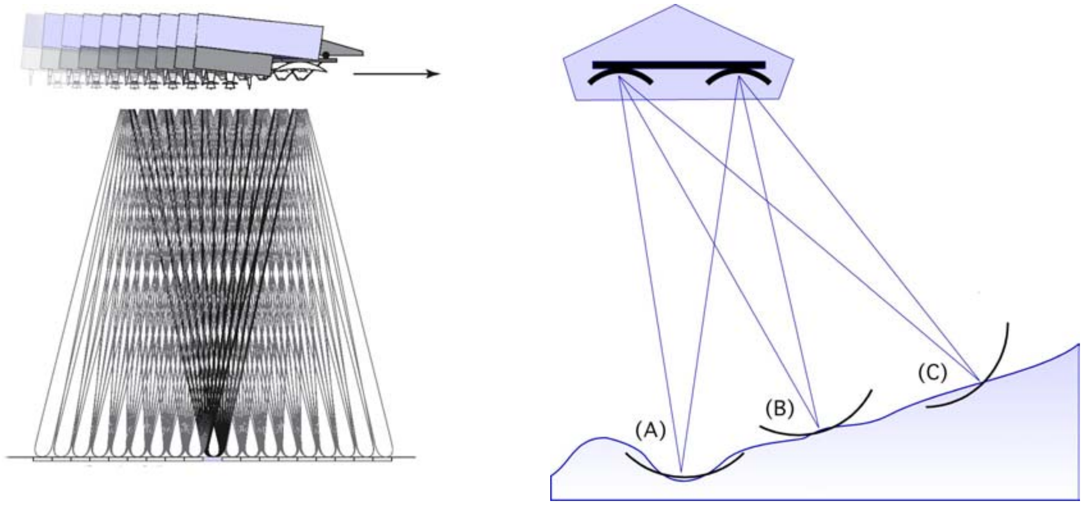
The primary instrument on CryoSat is a radar altimeter (SIRAL) with extended capabilities to meet the observation requirements for ice sheet elevation and sea ice freeboard estimates. SIRAL is based on the Poseidon Altimeter developed for the French-US Topex/Poseidon Mission. The new operations modes are based on the development of the delay/Doppler radar altimeter of the Johns Hopkins University in Maryland (Raney, 1998). SIRAL will have three operative modes:

- Conventional pulse limited operation for the ice sheet interiors and open ocean.
- Synthetic aperture (SAR) operation for sea ice.
- Dual-channel synthetic aperture/interferometric (SARIn) operation for ice sheet margins with more topography than the relatively flat ice sheet interiors

Over sea ice the new *Synthetic Aperture* mode will use the entire (beam-limited) along-track signal history to retrieve height measurements rather than only the much smaller pulse-limited area. Stated another way, the altimeter uses much more of the instrument's radiated energy than does a conventional beam-limited altimeter. Another important property of the synthetic aperture processing will be to obtain enhanced resolution along track, about 250 m, as shown in Fig. 2a. This will improve the capability to observe freeboard of sea ice significantly compared with the ERS altimeter with about 7 km footprint. The enhanced along-track resolution will be important for improved ice thickness estimates.

The *SAR-Interferometric* mode of SIRAL is intended for improved elevation estimates over ice sheets with variable topography. Generally, over ice sheets the surface is not plane, and a method for determining the echo location is required. A second synthetic aperture system is added and used to form an interferometer across the satellite track (Fig. 2 b). The angle of the echo at each range may be determined, and this, together with the range, determines the elevation and across-track location of the surface.

The global geographical coverage of the three modes is show in Fig. 3. More information can be found at http://www.esa.int/export/esaLP/cryosat.html



a

b

Fig. 2 Principle Operation Modes of the SIRAL altimeter. a): SAR-Mode over sea ice, where the arrow shows the flight direction. b): SARIn-Mode over steep ice sheet terrain, showing the capability to measure across track slope of the terrain.

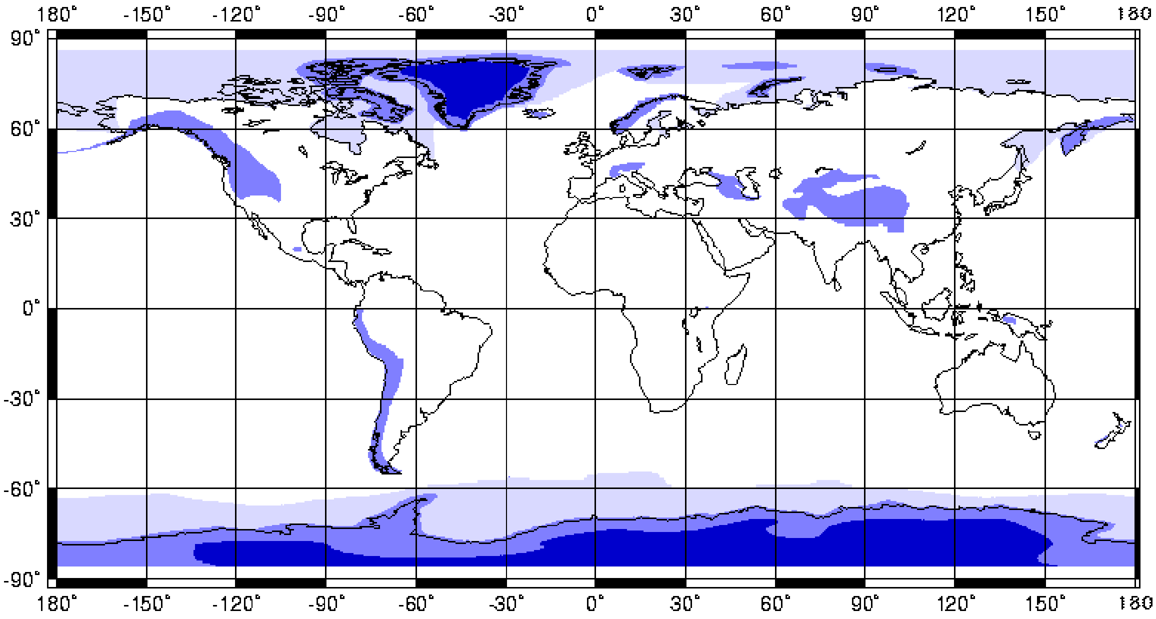


Figure 3. Geographical mask showing the SIRAL operation modes. Dark blue and white areas shows low-resolution pulse-limited mode, medium blue shows the SARIn mode for ice sheet margins and glaciers, and light blue shows the sea ice areas where SAR mode will be used.

2. CALIBRATION AND VALIDATION ACTIVITIES

2.1 CalVal objectives and concepts

European Space Agency (ESA) has initiated a validation program aimed at the validation of CryoSat products. An Announcement of Opportunity (AO) in Calibration, Validation and Retrieval for the CryoSat mission was issued on November 16, 2001. Following the acceptance of their proposals the scientists were invited to become members of the CryoSat Calibration, Validation and Retrieval Team (CVRT). From Norway, NERSC, NPI and University of Oslo are represented in the CVRT.

The overall objective of the Cryosat validation campaigns is to assess and quantify uncertainty in the CryoSat measurements of sea ice thickness and land ice thickness change. The principal means for carrying out this program is through dedicated independent, ground-based and airborne campaigns along with detailed investigations of retrieval methods applied to the satellite measurements.

Specific areas for which validation activities are planned include

- Validation experiments to further the understanding of the interaction of the radar echo with sea ice, land ice and snow cover.
- Validation experiments providing independent measurements of sea ice thickness and land ice elevation change.
- Validation of ice thickness and ice elevation retrieval algorithms (level 1b and 2 data products).

A deeper understanding of the interaction of the Cryosat radar echo with land and sea ice has been shown to be especially important for the validation of Cryosat products. Previous studies have shown that radar-snow interaction varies strongly over an annual cycle due to changes in the snow and ice properties with time. Overall, the change in scattering processes over time in turn leads to time-variant errors in the retrieved heights by the Cryosat instrument.

The objective for validation campaigns, in this context is to improve the understanding of time changes in radar scattering, leading to methods for removing the time dependence in the signal and thus improving the tracking of ice thickness changes by the Cryosat instrument. This requires repeated experiments at different locations and times of the year. The preferred time period for experiments are the months of April and October which represent the maximum and minimum ice thickness within the seasonal cycle. In terms of instrumentation the preferred approach is to combine airborne laser and radar altimeter with detailed in-situ measurements of snow properties.

A second important objective of the Cryosat validation campaigns is to provide independent measurements of sea ice thickness and land ice elevation change and additional data required for the interpretation of the results. For sea ice independent measurements of sea ice thickness are provided mainly through helicopter based electromagnetic sounding instruments. These can then be compared with airborne laser and radar based retrievals, and finally with Cryosat retrieved ice thicknesses. Additional spot measurements of snow thickness, ice and snow density and other variables will provide the necessary background data for the interpretation of the retrieval results. Land ice independent measurements of ice elevations can be provided by a combination of airborne laser and radar altimeters with additional ground measurements to help with the interpretation.

Other objectives of Cryosat validation campaigns include assessing the bias in retrieved ice thickness due to preferential selection by the radar instrument of scattering from large flows and improving mass-imbalance estimates for land ice flows. The objectives can generally be met using the same campaign activities as above.

A detailed discussion the Cryosat validation requirements can be found in the *CryoSat Calibration and Validation Concept*[2]

After instrument launch, it is planned that the data users (called "wider scientific users") will be given application-ready values of the desired geophysical ice-parameters as derived from the CryosSat measurements. Also a good estimate of the uncertainty (that is: the expected error of the ice-parameters) should be given. A main object for the pre-launch Cal-Val activities is to find reliable estimates of these uncertainties (errors) together with good methods of ice-parameter derivation.

Calibration is defined as to find the primary measured physical value (the surface-distance or surface-height) together with its uncertainty. Before launch, this must be derived from the specified instrument parameters and properties. After launch, measurement over selected calibration-targets and inter-comparison with other altimeters (called "verification") can be used.

Validation is defined as to find the ice-parameters of interest (e.g. the average thickness of old ice) from the measured distances. Also, the uncertainties of the geophysical parameters are wanted. This requires good models of the relation between the measured surface-height and the desired geophysical parameter. E.g. the measurement sampling scheme relative to the variations of the ice is important. To obtain reliable and relevant ground-truth data for the validation process .will be very important.

The calibration must be derived from given characteristics of the platform and the instrument. Its part of the total ice-parameter error is called the system error. To carry out the validation, a wide range of surface measurements of ice parameters (type and geometry) and their change in time and space will be required. This will be supplied by polar scientists using existing and planned measurement campaigns in the polar regions. This part of the total error is called the retrieval error Finally, the two parts should be combined for the total error.

In the case of land ice, the main parameter will be the long-term temporal change (trend) of the ice mass in a given area. In the case of sea ice, the main parameter will be the spatial average in ice thickness in a given larger area. Here also, the long-term change is wanted. One important error sources for both cases is the uncertainty in position of the main electromagnetic reflecting layer within the vertical air-snow –(firn)-ice profile. Another is due to limitations in the models of atmospheric effects, ocean tides and gravity fields.

For land ice, a known error source from the ERS 1 –2 comparison is in the retrieval error. For sea ice, a bias-type error will arise du to the preferred radar return from the thicker (and larger) ice floes relative to water and thin ice. Work on the joint probability density of floe area and ice thickness will be needed (e.g. by using visual, thermal or radar data from existing satellites).

2.2 CalVal Schedule

CryoSat is due for launch in Autumn 2004. Pre-launch calibration and validation activities for Sea Ice will take place in Spring 2003 and for Land Ice in 2004. Post launch *in situ* and airborne measurements will take place in 2005 for Sea Ice and 2006 for both Land and Sea Ice. Multiple measurement periods will take place to highlight logistical and other problems that can then be addressed at the later period.

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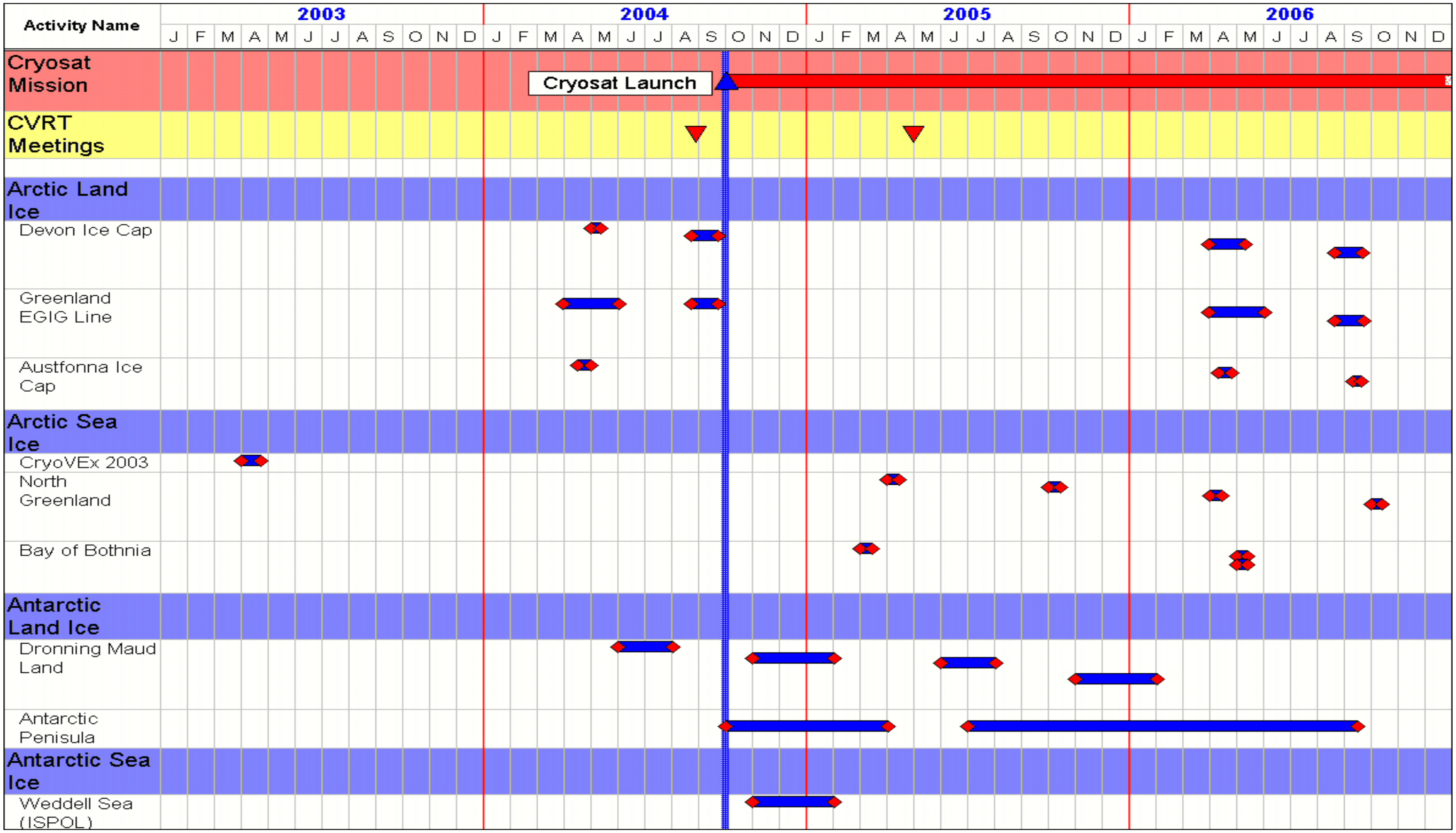
[2] Report edited by D. Wingham, UCL, 14. November 2001, 96 pp

In addition, to meet the validation requirement of assessing and quantifying CryoSat errors during the periods of maximum and minimum ice thickness, arctic *in situ* and airborne measurements are scheduled both during the Spring (April) and Autumn (August/September). Antarctic activities are generally programmed for both winter and summer months in the southern hemisphere.

The schedule shown in Table 1 covers the entire foreseeable period of the calibration and validation exercise.

***Table 1. Overall validation schedule*[3]**



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[3] From CryoSat Validation Implementation Plan, edited by M. Davidson (Draft, October 2003).

2.3 Key CryoSat validation sites

CryoSat validation activities encompass both land and sea ice measurements in the Arctic and the Antarctic. Table 2 summarises the key sites for coordinated validation activities and details the relation of the planned experiments at each site to the overall validation objectives. The locations of the experiments are illustrated on the maps on the following page (Fig. 4).

Table 2. CryoSat validation sites

Site	**Location**	**Land/Sea Ice**	**Validation Issues Addressed**
1) Devon Ice Cap	Canadian Arctic	Land Ice	Snowfall Fluctuation Near Surface Density Time-varying penetration
2) EGIG Line	Central Greenland	Land Ice	Snowfall Fluctuation Near Surface Density Time-varying penetration
3) Austfonna Ice Cap	Spitsbergen, Norway	Land Ice	Snowfall Fluctuation Near Surface Density
4) Dronning Maud Land	Antarctica	Land Ice	Snowfall Fluctuation Near Surface Density
5) Fram Strait	Greenland Spitsbergen	Sea Ice	Prelaunch validation of experimental concept Snow loading Ice density Geometric and penetration errors Preferential sampling
6) Bay of Bothnia	Baltic States	Sea Ice	Geometric and penetration errors Preferential sampling
7) North Greenland	Arctic Sea	Sea Ice	Snow loading Ice density Geometric and penetration errors Preferential sampling
8) Dronning Maud Land	Antarctica	Land Ice	Snowfall Fluctuation Near Surface Density Time-varying penetration
9) Antarctic Peninsula	Antarctica	Land Ice	Snowfall Fluctuation Near Surface Density Time-varying penetration
10) Weddell Sea	Antarctica	Sea Ice	Snow loading Ice density Preferential sampling

Physical issues are associated with the reflection from ice surface both at land and sea. Snow layers are unavoidable when observing ice surfaces, and the influence they have on the observations to be made by CryoSat have to be assessed very carefully if we are to verify any trend towards thicker or thinner ice over the lifespan of the mission. Other complications arise from the density profiles in the ice layers and sea ice floes as well as the wetness of the upper snow layer and how all these parameters can vary over a certain area. These issues can only be tackled by taking direct measurements in the polar regions. This means actually going there with ships and aircraft and conducting appropriate experiments with a broad range of instrumentation so that the data received from the altimeter on CryoSat can be calibrated and verified with data taken in-situ.

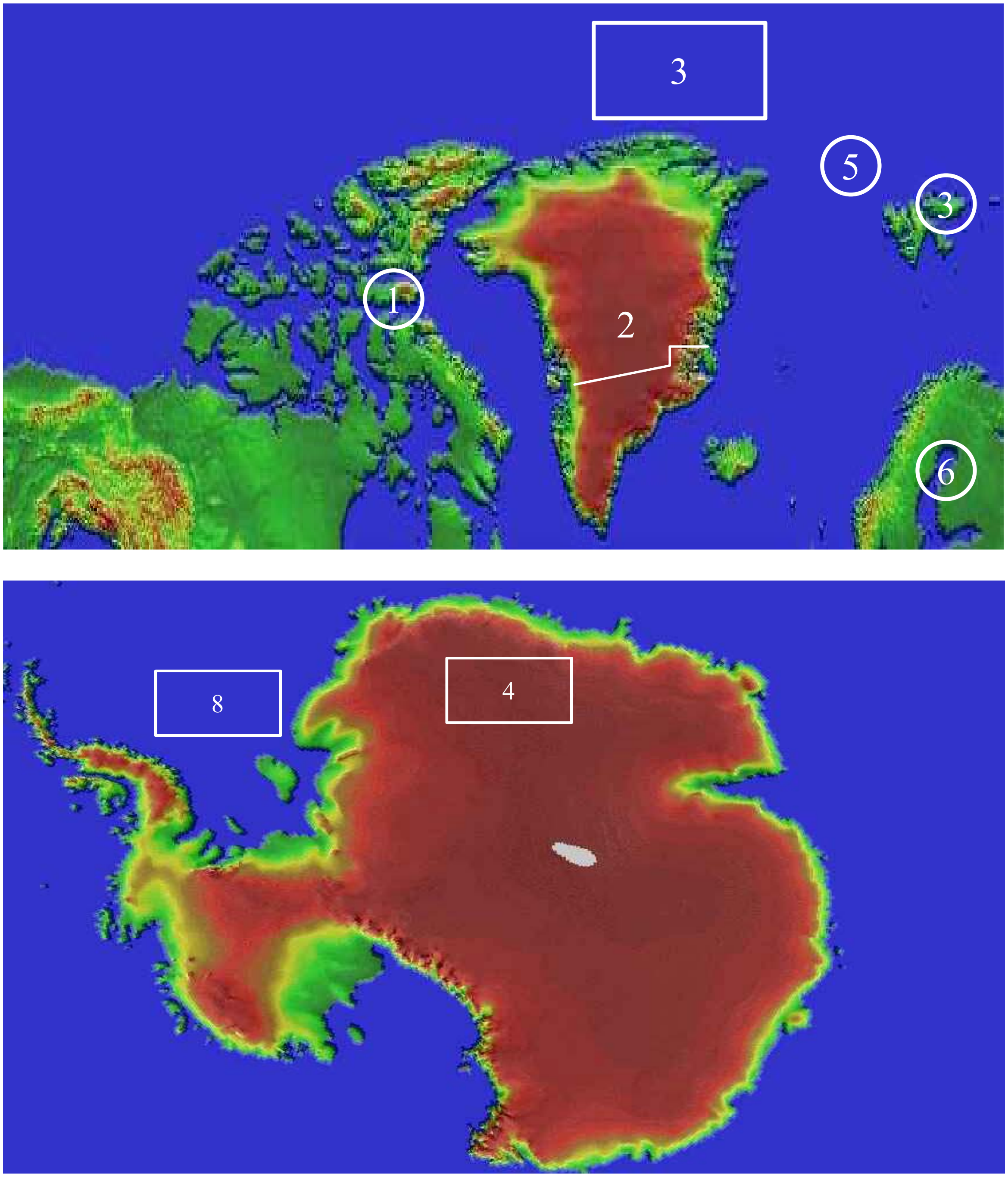

Figure 4. Maps of the CalVal sites in the Arctic (upper figure) and the Antarctic (lower figure). The number of the sites corresponds to Table 2.

2.4 Norwegian contribution to the CalVal activities

The Calibration, Validation and Retrieval Team (CVRT) is an international consortium with more that 50 scientists, with Norwegian participation primarily from NERSC (S. Sandven), NPI (J.-G. Winter, S. Gerland), and University of Oslo, Geographical Institute (J. O. Hagen). Other institutions will be involved as needed, depending on availability of relevant data. The main platforms for the sea ice experiments are ice-going research vessels such as Polarstern from Germany, Lance from Norway and others. Polarstern is the main vessel which serve as the operations platform for experiments on sea ice. Laser profiling from helicopters, carrying special electromagnetic sensors, which allow thickness estimates to be made of individual ice floes, will examine ice properties. In addition, ice core drilling and subsequent laboratory analysis will be carried out.

Aircraft from Denmark, Germany and the US with radar and laser altimeters will measure ice sheet profiles so that they can be compared with the results from CryoSat. This will include the first flight with the airborne version of the CryoSat altimeter (ASIRAS), currently under development. US scientists will look for opportunities to acquire Upward Looking Sonar sea ice thickness data from US Navy submarines. Several field campaigns are in preparation in Greenland and Antarctica during which intensive periods of measurements of snow and ice properties on glaciers and ice caps will take place.

Sea validation

Objectives:

1. To obtain and to combine sea ice measurements (ice thickness, density, freeboard, snow cover, etc.) from various instruments on field expeditions in the Arctic (from ships, aircraft), including ULS (Upward Looking Sonars for ice draft) and ASAR for sea-ice maps and ice classification.
2. To use the resulting ice parameters for pre-launch characterization of SIRAL simulated data (derived altitude and surface character from pulse shape), to derive data on the probable accuracy of the satellite measurements.
3. To use the resulting ice parameters for post-launch comparison with the SIRAL measured ice parameters.

Validation issues:

The ice thickness is the overall Cryosat parameter to be derived from the measurements. Its relation to the SIRAL-measured ice freeboard is a main issue in the Cryosat validation. The proposed project will study also the other ice/snow parameters in the basic equation between these two, that is: measure /estimate ice draft, ice density, snow load. The coupling (co-occurrence) within the various parameters and their co-variation in space and time will be addressed based on the observations made available by the Team.

ULS have been moored by NP for about 15 years in the Fram Strait, a major area for the Project. Statistical theory is used to minimise errors of the draft measurement, and to separate leads from ice floes.

Satellite SAR images has been used at NERSC since 1991 to characterize and map sea ice, using a number of developed classification and ice motion algorithms. With the availability of ASAR multi-polarization images, the separation between: 1) the thicker ice types on one side, and 2) the thin ice types including the open leads on the other, is expected to be significantly improved. New multi channel (that is: multi-polarization) algorithms will be tested and used to generate ice maps the during Project experiment periods, and later analysed.

Operational ice mapping, and in-situ ice and snow measurements made from arctic stations, are both provided by DNMI. Ongoing work includes a coupled sea ice and ocean model. Ice thickness is a model parameter that will be compared with the simulated or the actual SIRAL derived ice thickness data. Snow cover is another model parameter planned to be studied in this connection.

CalVal of land ice (Austfonna)

Objectives

The overall objective of the Austfonna cal-val activities is to measure spatial variations in nearsurface density, snow pack layering and snowfall fluctuations over the ice cap. These measurements will be obtained along transects crossing Austfonna from west to east and from north to south. Additionally, a detailed measurement program will be carried out at the summit. GPR radar, DGPS, snow pit stratigraphy, coffee-cans and electrical measurements on shallow ice cores will be used to obtain this validation data set.

Validation issues

The validation exercise will characterise retrieval errors due to:

- temporal changes in snow surface caused by densification and snowfall;
- complex topography that potentially affects the recovered elevation when the sensor is in interferometric mode.

CryoSat altimeter data will be validated by obtaining accurate ground-based measurements of snowpack properties relevant to electromagnetic scattering and monitoring elevation changes due to snowfall fluctuations and snow/firn densification processes.

Of the three established Norwegian Polar Institute (NPI) fieldwork sites in Svalbard, Austfonna (centred at 79.5 deg N, 25 deg E; elevation 0-800m a.s.l.) is the largest (8,200km^2) and most suitable for CryoSat validation activities. Access to this remote icecap during summer and early autumn, the largest in Europe, will be via NPI's 'R/V Lance', which visits the area regularly (*e.g.* to establish a depot in summer 2003). During the 2004 spring campaign the field party will be flown to the depot site. Post-launch experiments are planned in 2006.

3. CRYOVEX 2003

The CRYOVEX campaign in spring 2003 was the first pre-launch CalVal experiment over land ice as well as sea ice. The objective of the campaign was to collect simultaneous laser and radar measurements from aircraft with coincident *in situ* measurements of sea ice parameters using Polarstern. Previous campaigns, such as LaRA-2002, have clearly demonstrated the potential value of cross-calibrated simultaneous laser and radar altimetry over ice for retrieval error assessment.

3.1 Airborne Measurements

The Geodynamic Department of the National Survey and Cadastre (KMS), Copenhagen, Denmark, provided a Twin Otter aircraft, equipped with the John Hopkins University D2P scanning radar altimeter and the KMS scanning laser altimeter. The D2P instrument is a Ku band (13.9 GHz) radar altimeter providing along track (doppler) and interferometer across track measurements. It behaves as a conventional beam-limited radar altimeter when operated at the planned low altitude (i.e. 300m). With an interferometric baseline of 15cm, centimetre height accuracy can be achieved over both sea and ice sheets. The KMS scanning laser system provides a swath of height measurements at a scan rate of 8 kHz. The scan-angle is +-30 degrees and the expected height accuracy 10-15cm. The flight tracks of the airborne measurements are shown in Fig. 5 and a a summary of the flights are shown in Table 3.

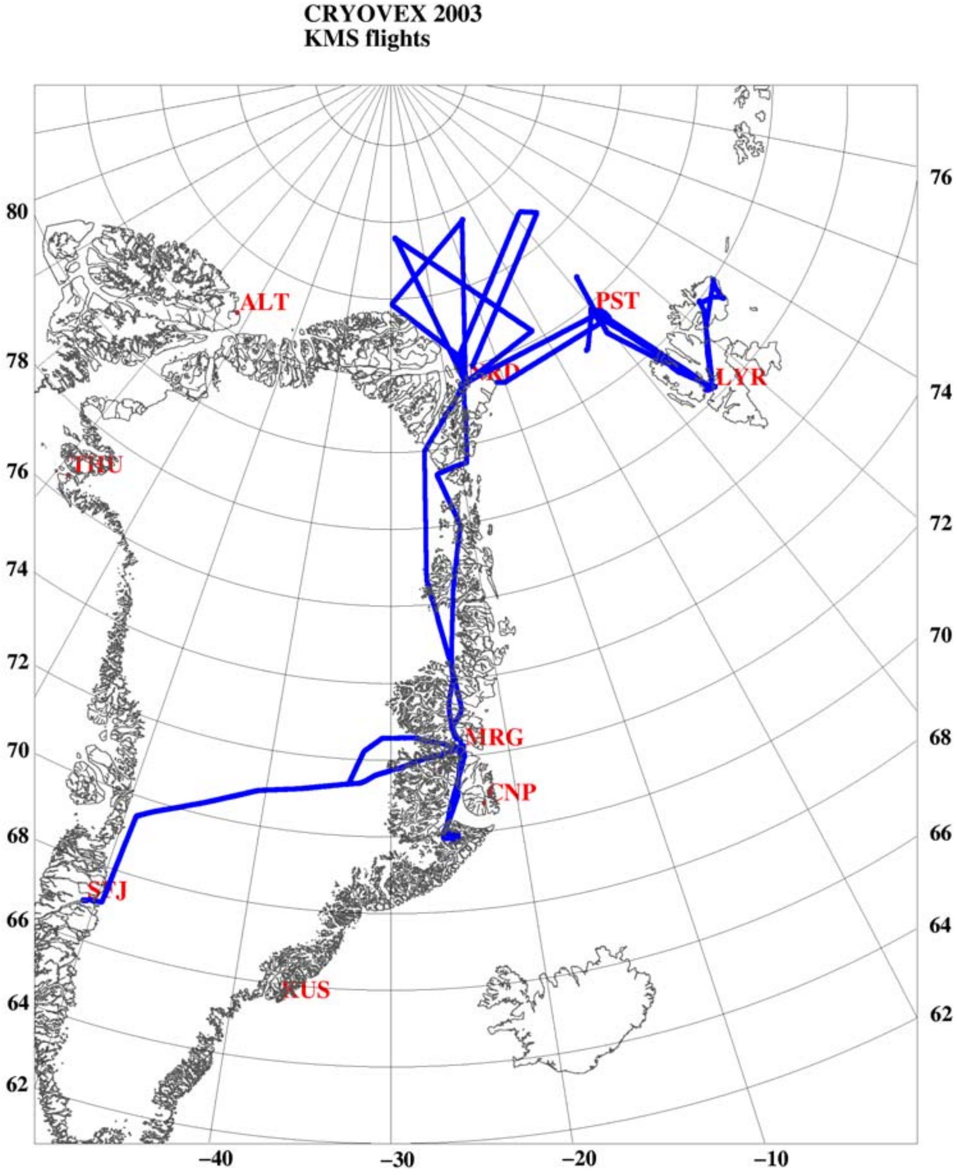

Figure 5: Flight pattern during the CryoVex campaign from 5 to 19 April 2003.

Table 3. Flight overview.

Flight No.	Waypoints	Duration
#1	SFJ – SFJ Test Flight	1hr
#2	SFJ – EGIG – CNP	6hr
#3	CNP – B - NRD	5hr 30
#4	NRD – F – NRD	6hr
#5	NRD – D – NRD	5hr 15
#6	NRD – N – LYR	3hr 35
#7	LYR – PST (P3/4) – LYR	5hr
#8	LYR – PST (P5/6) - LYR	5hr
#9	LYR – PST (grid) – LYR	4hr 30
#10	LYR – PST (P1 – P2) – NRD	3hr 40
#11	NRD – E – NRD	5hr 15
#12	NRD – CNP	5hr 30
#13	CNP – A – KUS KUS – K -SFJ	4hr 10 3hr 15
#14	CNP – Geikie – CNP	2hr 45
Total		66hr 25

Figure 6. Air Greenland's Twin Otter used by KMS for the CryoVex campaign

Post-flight radar altimeter processing will include the generation of Level 1b (height waveforms), and Level 2 (height profiles) data products, with ancillary navigation and calibration data sufficient to co-locate the radar footprint with laser data. Post-flight processing of laser altimeter data and EM bird data will include the generation of Level 2 data: height profile data in the case of the laser altimeter and sea ice thickness profiles in the case of the EM bird.

Example of airborne scanning laser data from the CryoVex flights is shown in Fig. 7.

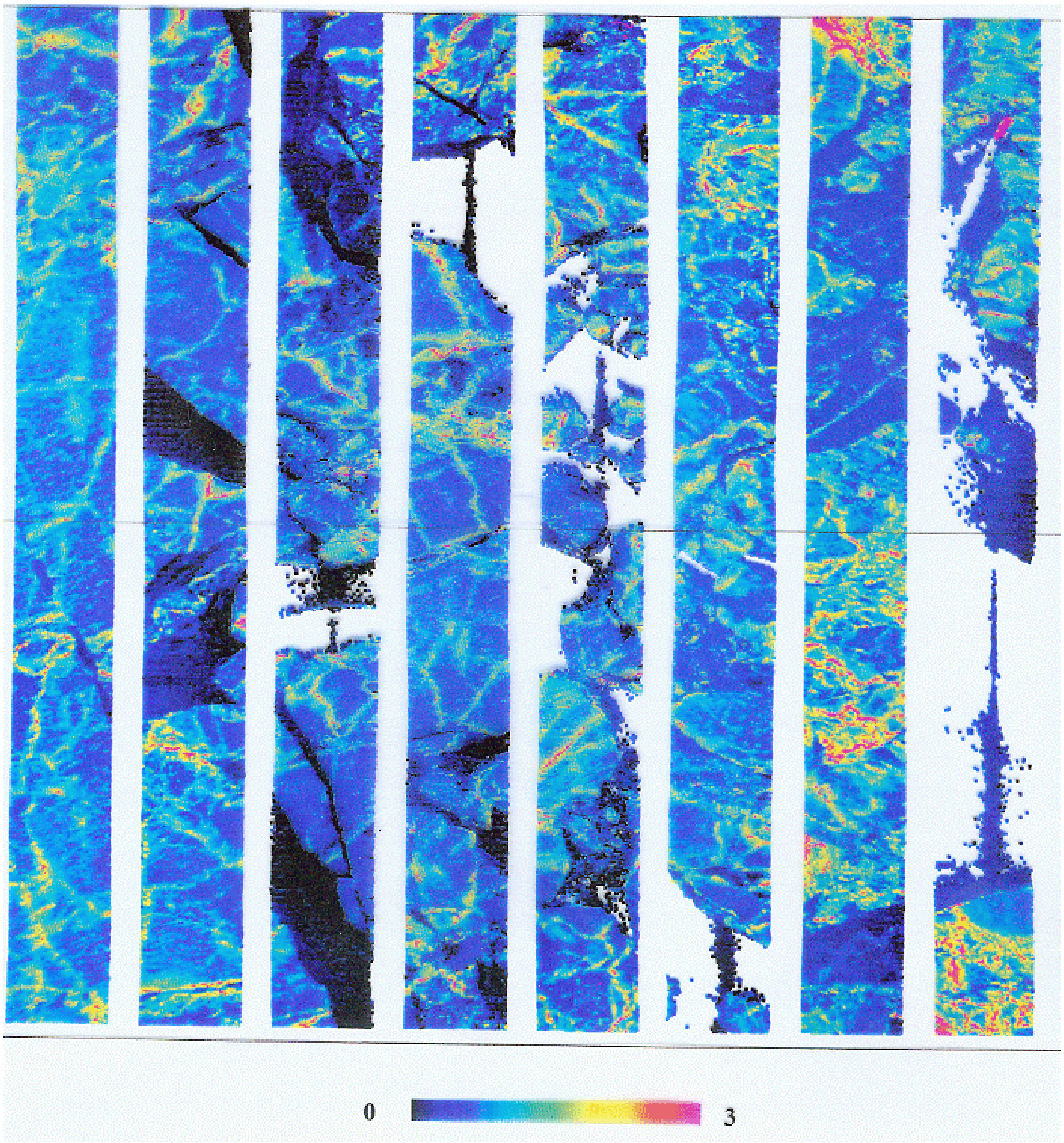

Figure 7. The scanning laser data from the aircraft are obtained in long stripes of 300 m width. By use of GPS the height of the ice surface above sea level can be retrieved and plotted as

shown in the example above. Sea level, which can be open water or very thin ice, is represented by dark blue, whereas ridges of 2 - 3 m height are shown in yellow-red. The distribution of ridges corresponds to ice thickness distribution, using a conversion factor to be determined from the HEM data. Note that leads and floes are readily observed in the laser image data. The white areas represent saturation of the reflected signal.

3.2 AWI - EM Bird (with laser)

The EM Bird is a helicopter-sensor combination, which is able to provide independent precise measurements of actual sea ice thickness. The system consists of an electromagnetic sensor ('HEM Bird'), which uses electromagnetic induction to determine sea ice thickness. The sensor is towed underneath the helicopter at heights of between 10-20m above the ice surface as illustrated in Fig. 8 a. The HEM Bird also includes a laser altimeter to measure the distance to the ice surface. This also provides additional information about surface roughness and pressure ridge statistics. The helicopter has a typical range of 300 nautical miles and typically flies at a speed of approximately 100km/h.

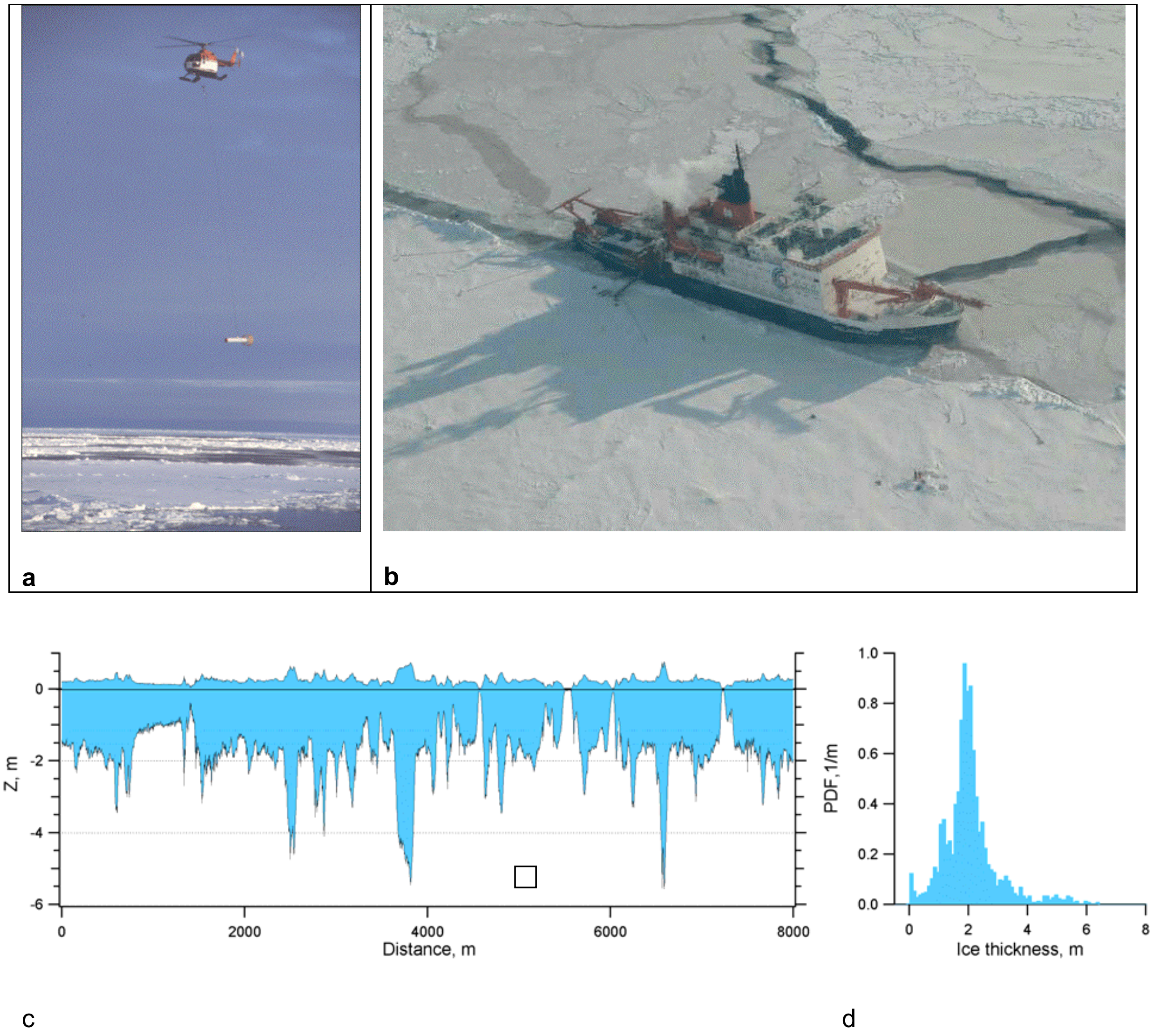

Figure 8. The upper pictures show the HEM system in operation (a) with base at Polarstern (b). The lower graphs are example of data from the HEM system, providing high-resolution

profiles of ice draft and surface height along the flight line (c), leading to the Probability Density Function (d) for ice thickness measured by the HEM system.

3.3 In situ measurements and ENVISAT ASAR acquisition

In situ ice and snow measurements were performed during the Polarstern cruise, by transferring field teams onto ice floes from the ship or by helicopter. Daily deployments during the main campaign period (5 – 19 April) yielded data along the cruise track, with representative information on regional ice thickness distributions and other ice properties.

Helicopter measurements were performed using the EM ice thickness sensor (EM Bird), laser profiling and a video camera. This enabled extrapolation of some of the *in situ* measurements over a much larger area. The EM bird profiles also included data on thin ice and open water fractions, which were difficult to measure on the ground.

Nansen Environmental and Remote Sensing Center (NERSC) coordinated and acquired ENVISAT ASAR data supporting the ship and aircraft measurements in addition to collecting *in situ* data from drilling holes and helicopter measurements of ice thickness and ice topography. These resources was coordinated with the EU funded project SITHOS (Sea Ice Thickness Observing System).

The observing methods are summarized in Table 4.

Table 4. Overview of in situ observing methods using during CRYOVEX 2003

No.	**Measurement Technique**	**Properties to be Measured**	**Coverage/Frequency**
1	Snow and Ice Coring, including dielectric resonance (Snow Fork)	Vertical profiles of snow/ice density, salinity, grain size and wetness (Snow Fork)	Daily, at one or more locations on a floe
2	Surveying using laser levelling equipment	Ice freeboard Metre scale roughness	Along profiles a few hundred metres in length (at spacings of 1 -5m)
3	Ruler stick	Snow thickness	At every site where helicopter landed on ice
4	Helicopter towed EM system (EM Bird)	Ice thickness	Profiles of several hundred km
5	Helicopter towed nadir-looking laser profiler	Ice roughness and pressure ridge distribution	As above
6	Helicopter mounted nadir-looking video camera	Ice concentration, floe size distributions, melt pond fractions	As above
7	Ku band scatterometer (optional)	Radar penetration and interaction with the snow and ice surface	Daily, at one or more locations on a floe
8	Upward Looking Sonar (ULS) from moorings	Sea ice draft	Time series at fixed locations in the Fram Strait

3.4 Expected Results

The results from the Cryovex 2003 campaign will contribute to a pre-launch assessment of CryoSat sea ice retrieval errors during a period of maximum snow load. In particular the campaign will help quantify CryoSat retrieval errors arising from snow loading on sea ice, errors due to penetration and volume scattering within the snow/ice layers, variations in ice density and errors due to the preferential sampling of larger ice flows by the CryoSat satellite.
The campaign will also provide important feedback on the feasibility of collecting co-located airborne, helicopter-borne and *in situ* measurements above drifting ice surfaces. This will help with the preparation and organisation of future CryoSat validation experiments, which are based on similar sensor and platform configurations. Co-located data sets were obtained northwest of Svalbard as shown in Fig. 9.

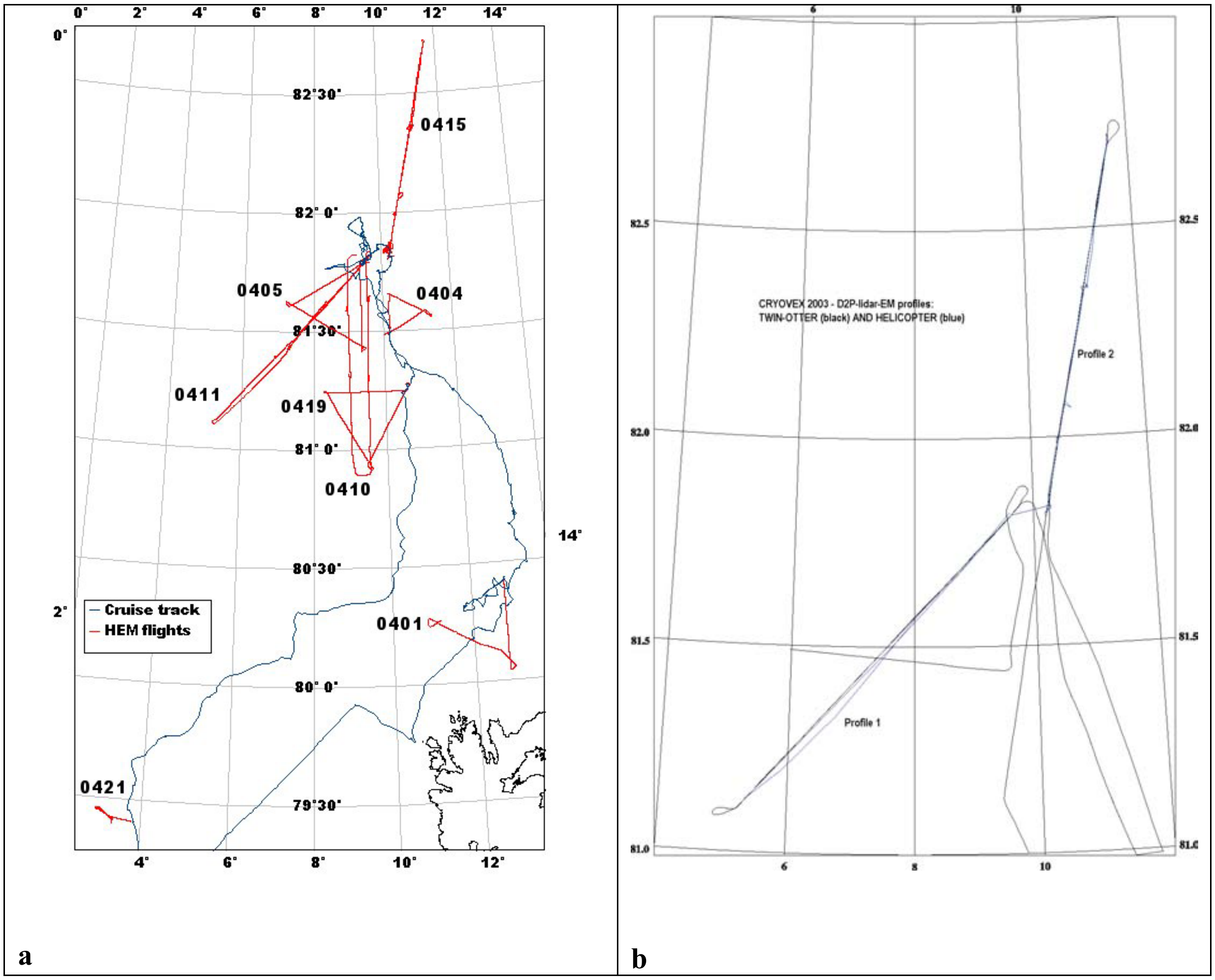

Figure 9. Map of simultaneous tracks of (a) helicopter HEM flights, Polarstern ship track and (b) aircraft flights.

The analysis of the dataset will help determine seasonal and interannual variability of sea ice thickness and volume, which can only be achieved if the accuracy of ice thickness retrievals are known. The combination of airborne laser and radar altimeter data, co-located with *in situ* ice thickness measurements provided by the EM Bird and ground survey data points, will permit a quantitative assessment of retrieval errors as a function of sea ice surface conditions.

Additional information will be provided by the ENVISAT ASAR SAR images. These are expected to provide useful information on floe size, ice types, leads, polynyas, ridges and surface roughness, ice drift and help in sea ice-water discrimination.

4. DATA PRODUCTS

The overall scientific data products from CryoSat will be maps of variations in sea and land ice fluxes. The principal output of the SIRAL altimeter will be raw waveforms describing the surface reflection. A multi-stage processing chain is under development to derive useful geophysical information from the raw data stream.
The following data products will be generated:

- Level-0: raw telemetry source packets, filtered for errors, time ordered, and tagged with time and telemetry quality information; note that this includes instrument data, but also raw house-keeping telemetry parameters, to be forwarded to the FOS
- Full-Bit-Rate (FBR): functionally same information as Level-1b, but before the averaging on SAR and SARIN modes. The expected data volume will be very high with 430 Gbit/day.
- Level-1b: containing instrument echo wave-forms; in the case of the SAR and SARIN operation modes, these wave-forms are averaged, so the data rate is much lower than the FBR above.
- Level-2: containing elevations along the orbit track
- scientific monitoring data: scientific performance of the SIRAL will be monitored systematically, resulting in e.g. trend plots, statistics data

The provision of CryoSat data products requires numerous calibration and correction steps which are part of the processing chain from a Level 0 up to Level 2 data product. The processing chain is illustrated in Fig. 10 where the blue part is ESA responsibility, whereas the brown part (level 2 and higher) will be the responsibility of one or more service providers outside of ESA. The data products are also summarised in Table 5.

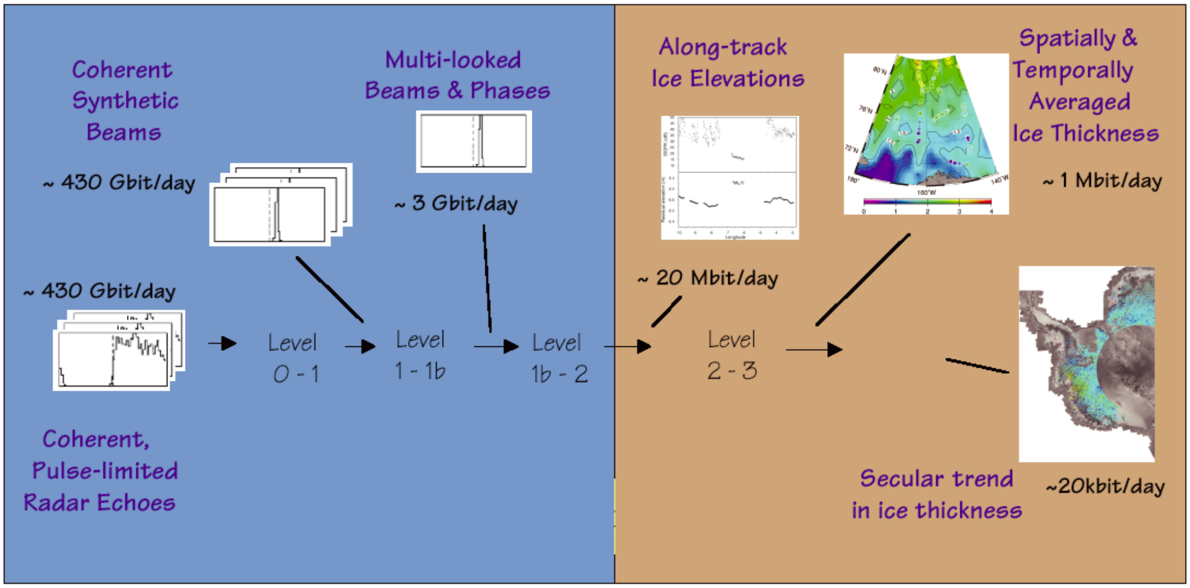

Fig. 10: Principal processing chain for CryoSat

Table 5: CryoSat Data Products

Data Type	Description	Purpose of data	Data Volume
Full bit rate data (= Level 0 with housekeeping data removed)	Fully-engineering and geophysical corrected data with acquisition and other non-science data removed, and orbit and datation information added.	- Detailed scattering behaviour - Beam forming - Calibration - Instrument trouble-shooting	430 Gbit/day
Level 1 b data	Fully-engineering and geophysical corrections applied. Beam formation and phase and amplitude multi-looking performed.	- Scattering behaviour - elevation retrieval methods over land and sea ice - Calibration & Validation - Instrument trouble-shooting	3 Gbit/day
Level 2 data	Along-track elevation and backscattering 'coefficient' estimate.	- Ice fluxes and other geohysical phenomenon - Validation	20 Mbit/day
Monitoring data	A subset of with degraded orbit and datation information	- Instrument health - Instrument long-term monitoring	5 Mbit/day

There will be no near real time delivery of CryoSat data except for specific needs during calibration or validation activities. For Level 1 and 2 data it will be possible for users to order data by describing a space-time window. Tailored software for data access and conversion will be provided to users. Data distribution will be handled with CD-ROM discs and FTP transfers where feasible. Data delivery up to level 2 is planned to be within one week.

Table 1 describes the distribution requirements. Data latency is the time delay between data acquisition and distribution. The min/max duration values specify the minimum and maximum interval of continuous satellite operation for which a data product is available.

Table 1: CryoSat Data Distrbution Requirements

Data	Latency	Minimum Durartion	Maximum Duration	Users
Full bit rate data	< 1 week	10 min	10 min	Cal/Val Teams, . Subject to resource limitations
Level 1b	< 1 week	10 min	none	Cal/Val Teams & Requests from data exploitation AO
Level 2	< 1 week	1 orbit	none	Cal/Val Teams & Requests from data exploitation AO

5. DATA UTILISATION

5.1 Sea ice data utilisation

Ice thickness data is lacking in operational sea ice monitoring both on regional and global scale. The Norwegian Meteorological Institutes (met.no) sea ice service produce ice charts for the area from West Greenland to the Kara Sea every week-day. These charts are based upon AVHRR scenes from the NOAA satellites, SSM/I from DMSP and O&SI SAF products, which are based on AVHRR, SSM/I and scatterometer data from QuikScat. SAR data is planned to be included in met.no's ice service to provide higher resolution ice charts. It is foreseen that CryoSat will fill an important gap in ice observations and be valuable supplement to information from other satellite systems. Met.no also has in situ observations of ice concentration, ice type, formation of the ice, and snow layer on the ice outside the stations at Bear Island, Jan Mayen Island and Hopen Island. At Hopen they also measure the ice thickness and snow layer height by manually drilling holes in the ice. These recordings are point recordings taken at certain distances from the shore regularly throughout the ice season. As an operational sea ice monitoring service met.no plan to use Cryosat data in to add ice thickness information to the ice charts. Although the CryoSat data will be offline data which are not available in near real-time, they are expected to be useful to update ice thickness information on weekly to monthly time scale.

In addition to ice charting service, it is envisaged that CryoSat data will be useful as input to sea ice models. NERSC and met.no's R&D Dep. are running a pre-operational coupled ice-ocean model system where sea ice thickness data are scarce and not sufficient for model validation. The most useful sea ice thickness data products from CryoSat will be monthly fields gridded at about 100 by 100 km. These fields will primarily be useful for assimilation in large-scale models and for validation of climate models where the seasonal ice volume variability and fluxes in the Arctic is not well documented by observations. For climate studies it is planned to use ice thickness data from CryoSat in combination with ULS data provided by NPI in the Fram Strait to better estimate ice volume flux in this strait. NERSC has carried out studies of ice thickness data assimilation in coupled ice-ocean model system as a pre-cursor to CryoSat (Sandven et al., 2001). The usefulness of CryoSat data in operational sea ice forecasting is a question, but this will be investigated by NERSC and met.no from 2005. In sea ice dynamics studies, it is foreseen that ice freeboard, ice topography and ice thickness from CryoSat will be very important supplementary data to SAR-derived ice information, where convergence/divergence of the ice field can be estimated through the mapping of leads and ridges. This information will be useful for further development of sea ice rheology models needed for ice modelling and forecasting on regional and local scale.

5.2 Land ice data utilisation

Norwegian Polar Institute has proposed to use CryoSat data to investigate snowfall fluctuations and snow/firn densification in glaciers in Svalbard and in Antarctica. Studies will be conducted in the easy-accessible Holtedalsfonna ice cap on Svalbard (~ 250 km^2 – centered around 79°N, 13°30' E). Furthermore, similar studies are planned on the Jutulstraumen ice stream in Dronning Maud Land, Antarctica (the drainage basin of Jutulstraumen is 124,000 km^2 and is located around 72°South, 0°E/W). The studies will include use of CryoSat/IceSat data in combination with field observations using: i) measurements of surface elevation using precision GPS, ii) relative surface elevation changes measured by an acoustic sensor, iii) snow and air temperatures, iv) density, grain size and stratigraphy obtained by measurements in snow pits, v) electromagnetic measurements (i.e., ECM and DEP) on shallow ice cores and vi) ground penetrating radar profiling. The studies will also include intersatellite comparisons between altimeter data from CryoSat, ICESat and ENVISAT in both areas.

Norwegian Water Resources and Energy Administration (NVE) has proposed to use CryoSat data for studies of temperate glacier and lakes in Norway. Experiments are planned over a temperate icecap at about 66 degrees North and 13 degrees East, at Svartisen, which is one of the largest glaciers in Norway. The 200 km^2 large test site includes a test area (20 km^2) over the icecap's accumulation area, the glacier Engabreen (38 km^2), and the Storglomvatn reservoir (15 km^2). These areas have been studied for more than 30 years, and CryoSat data will support current activities in the OMEGA project where all available remote sensing methods for glacier and snow surface elevation and velocity monitoring are studied.

The experiments will concentrate on measuring the surface elevation using precision GPS over the test areas co-located with CryoSat orbits. Two 14-days campaigns under the 2-days cal-val orbit is proposed, one in April (dry snow surfaces/volumes, maximum snow accumulation, and an ice-covered lake) and one in September (wet snow and glacier ice surfaces, and lake level changes). The campaigns will be implemented to quantify not only the surface elevation but also relevant near-surface snow and ice properties on a daily basis over both the glaciers and the lake. A set of precision GPS receivers, a dual-frequency ground penetrating radar, manual snow density and depth profiling, fixed stake networks and snow/ice-coring equipment are to be deployed.

The Norwegian Computing Centre and NORUT IT have proposed to carry out a land snow variability study using CryoSat data. Of particular interest is the retrieval of snow depth (SD) and snow water equivalent (SWE). The Heimdalen test site in Jotunheimen is proposed as primary study area as there exist detailed ancillary data for the area, like very accurate DEM and vegetation maps. The site is about 100 km^2, but can easily be extended to about 500 km^2. It is located at 9°0' east, 61°25' north with elevations in the range 1000-1850 m a.s.l. Field measurements will be carried out using CryoSat and other remote sensing data, as well as measurements of snow density, wetness, grain size, layering, air and snow temperature. The proposers have had project activities in the area since 1997 and have currently projects funded for the area until 2005.

In addition to CalVal work in Svalbard described in chapter 2, the Geographical Institute at University of Oslo has proposed to carry out fine-scale climate studies of glacier mass balance in Norway in a joint consortium with several other partners. The aim of this proposal is to develop advanced methodologies for determining the effect of climate change on the mass balance of Norwegian glaciers and ice caps. The project will concentrate on the use of satellite remote sensing to monitor glacier mass balance, on the use of high-resolution atmospheric and subsurface models to simulate the mass balance, and on the use of ice flow models to describe the effects of climate change on glacier extent. All these approaches require ground calibration or validation and a substantial field campaign, on Hardangerjøkulen ice cap in central southern Norway, will be implemented to address this.

Satellite data in various forms can be combined to give detailed information on glacier mass balance and relevant glaciological features on a large spatial scale and at high spatial resolution. However, verification of the retrieval algorithms, which are used to convert remote sensed data into useable physical parameters, has often been a weak point in the application of satellite remote sensing for glaciological studies. The approach taken here is to verify the remote sensing analysis with in depth field measurements and to assess the most appropriate methodologies needed to retrieve this information.

Atmospheric models, coupled with subsurface models, are the most advanced tools available for simulating glacier mass balance. These have never been applied at high spatial resolution to glaciers before, yet they offer the most physically based methodology available for simulating accumulation and surface melt, the essential components of glacier mass balance.

Glacier mass balance has generally been calculated using parameterised models, tuned to observational data. This has been necessary due to the lack of data required to run more complicated models. However, advances in computing capacity and in modelling techniques now allows the use of complex atmospheric and subsurface models to describe these processes directly. High-resolution atmospheric models, driven at their boundaries by regional scale models, and coupled to subsurface models, provide an improved methodology for determining the mass balance and can be applied in regions where little or no observational data are available.

Glacier advance and retreat is the result of changes in mass balance and can be described using ice flow models. With improved mass balance distribution these models can be used to predict changes in glacier extend as the result of future climate change.

The primary objectives of this proposed project are:

- Determine future trends in glacier mass balance using physically based high-resolution atmospheric and subsurface models, forced by regional climate scenarios (RegClim).
- Develop and apply satellite-based observation techniques for (1) validation of glacier and mass balance modelling results, and (2) monitoring of key indicators of climate change effects on glaciers, such as glacier extent and mass balance.
- Determine the future extent of glaciers and ice caps using numerical modelling techniques.

To obtain these objectives a number of sub-objectives will also be achieved:

- Develop and validate coupled atmospheric and subsurface models for use in mass balance studies in complex terrain.
- Determine the spatial and temporal distribution of precipitation and melt for glaciated regions on time scales from days to decades.
- Improve our understanding of the physical processes that govern glacier mass balance.
- Carry out comparative studies of mass balance models with an emphasis on their climate sensitivity.
- Develop the retrieval algorithms required for the analysis of satellite remote sensed data in a glaciological context.
- Develop techniques for mapping glacier extent (perimeter) and its changes through time using high-resolution optical data
- Develop techniques for mapping the position of the snow and firn edges on glaciers and its changes through time using high-resolution optical and SAR data
- Carry out *in situ* observations of key meteorological variables for the determination of the surface energy balance and validation of atmospheric models.
- Carry out *in situ* observations of key snow and ice parameters such as albedo, snow line, snow characteristics, glacier surface facies and geometry coincident with satellite data acquisitions.
- Validate the use of subsurface models in mass balance studies with *in situ* observations and remote sensed data to determine snow properties such as albedo, liquid water content and density.
- Establish Hardangerjøkulen and Svartisen as key glaciers for validation of altimeter data from ICESat and CryoSat.
- Propose a scheme for the monitoring of glaciers with combined use of field measurements and satellite data regularly available in the future.
- Develop a GIS-database where all data and results obtained during the project can be compared, correlated and analysed.

This proposal will lay the foundation for future work in several other environmental studies. The development of coupled high-resolution atmospheric and subsurface models will enable hydrological studies to be carried out of catchment scale regions, including flood prediction, as such a prognostic model can be applied to determine daily discharge rates. It will also be applicable to avalanche research and can be used to identify regions and situations of potential avalanche threat. The techniques developed here for remote sensing will be applied to future monitoring of glaciological features and mass balance.

6. CONCLUDING REMARKS AND NEXT STEPS

In the period up to 2005 – 2006, before CryoSat data becomes available for scientific and operational users, the main activities will be to prepare and implement CalVal experiments as outlined in chapter 2 and 3. This is particular important since SIRAL represent a new generation radar altimeter data, and the experience of using this kind of data to retrieve land and sea ice parameters is very limited. In fact, only aircraft data from the D2P instrument exist which are comparable to the CryoSat data. The results of the D2P flights have only recently been published.

The Norwegian participation in the CalVal activities is quite significant, where resources in the Svalbard area are of special relevance for the CalVal programme. The first extensive CalVal experiment (CRYOVEX) was carried out in Svalbard and Fram Strait in April 2003. According to the CryoSat Validation Implementation Plan (Davidson, 2003) there will be validation campaigns with Norwegian participation in 2004, 2005 and up to October 2006, two years after the launch of CryoSat. The purpose of the calval activities is not only to establish reliable data products, but also to train scientist in using the data for monitoring of cryospheric parameters.

For user who are not interested in the retrieval and validation of parameters, should take the opportunity to submit proposal for to the second Announcement of Opportunity (Data Utilisation AO), planned for 2003-2004, to get data for studies and application beyond the more strictly defined CalVal programme. Level 2 and 3 products, tentatively available from mid – 2005, allow user to obtain these products and use them in further research and monitoring activities. Several proposed projects, outlined in chapter 5, will contribute to the exploitation of CryoSat data in combination with other satellite data.

Funding of projects related to CalVal or Data Utilisation need to be established by the institutions that have expressed interest in the CryoSat data. Since CryoSat represents a new type of satellite data, R&D work is necessary before regular use as part of operational services can be expected.

The Norwegian CryoSat group will work to increase the interest in using the CrySat data among Norwegian institutions, including research, operational institutions and others.

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CryoSat Data Processing Concept, 2001, ESA/UCL

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Wingham, D.J., Johannessen, O., Lemke, P., Tscherning, C., Picardi, G., Sandven, S., Vaughan, D., Laxon, S. and R. Scharroo, 1998, CryoSat: Response to the ESA Earth Explorer Opportunity Mission AO, UCL.

Wingham, D.J. 1999, The First of the European Space Agency's Opportunity Missions: CryoSat, Earth Observation Quarterly, 63, ESA

Useful links:

ESA CryoSat web site: http://www.esa.int/export/esaLP/cryosat.html.

German CryoSat web site: http://www.awi-bremerhaven.de/CryoSat/CryoSat.html

APPENDICES: TECHNICAL INFORMATION ABOUT ALTIMETER SYSTEMS

A1. Airborne Delay / Doppler Phase Monopulse Radar (D2P)

The Delay / Doppler Phase Monopulse Radar (D2P) is an aircraft instrument built and run by Johns Hopkins University Applied Physics Laboratory It intend to demonstrate the use of two enhancement techniques to current satellite radar altimeters. The basic satellite altimeter concepts (pulse-limited with 2 –3cm precision) is in use for Topex (NASA), Geosat (US Navy) and ERS (ESA). The two added techniques are:

1. Doppler phase-coherence processing (analog to SAR) for better resolution in the along-track direction,
2. Interferometric (delay) phase-angle processing using two antennas for better resolution in the cross-track direction.

These enhancement techniques will be especially useful over glacier ice with moderate slopes (> 1-2degree) where the current satellite instruments cannot be used. Both techniques will be used in the CryoSat satellite altimeter. Frequency is 13.9GHz. Many parameters are different from those used for satellite, but the basic concepts and performance can be established.

Test flights over the Greenland ice-sheet was made on 3 days in June 2000 and in May 2002. Also measurements over the sea-ice in Davis Strait were made. Included were nadir video imagery and aircraft position and attitude data. More information is available on http://fermi.jhuapl.edu/d2p

Example of SARIn processing over ice sheet

Color coded images have been assembled from the processed D2P radar data along profiles over the Greenland ice sheet (Fig. A1). The upper colored edge of each waveform indicates the elevation of the surface over which the radar data was collected. Each position is coded with an intensity that indicates the strength of the radar return. The color indicates the angle of the surface area relative to the nadir direction. Yellow is roughly at nadir and shows that the radar scattering occurs directly below the aircraft. The color coding for other angles is shown in the color bar. Red is to the left of nadir. Green is to the right. See Fig. 2 for illustration of the cross track slope measurements.

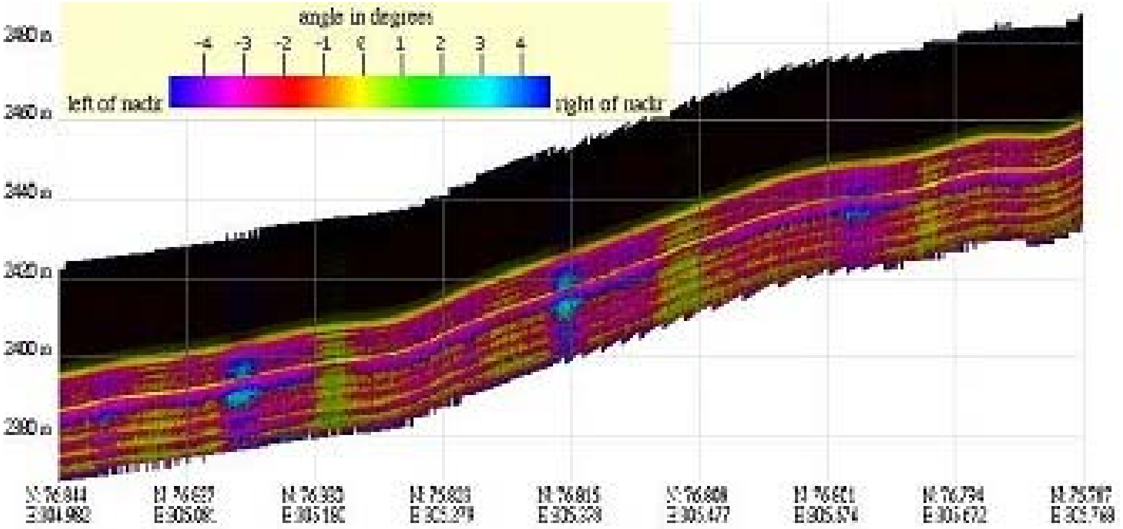


Figure A1. Radar profile from LaRa with SARIn Processing indication reflections from different snow/ice layers (Raney et al., 2002).

Each vertical raster in the images is normalized to the peak power at a given time. In places where the nadir return is very strong, such as specular scattering over lakes, this normalization suppresses the returns from greater ranges. This normalization is not necessary, but it results in more features and variations of the surface characteristics being visible than if a common normalization scale had been used. The intensity is logarithmically scaled from full intensity to 10% of the full intensity.

The radar directly measures the returned power as a function of distance from the aircraft. Therefore, while the upper colored edge shown in the images corresponds to the surface elevation, the power below the upper edge is a result of surface reflections from a greater distance from the aircraft and not necessarily reflections from a lower elevation. For example, data collected over water, where there is no significant penetration of the surface, show a bright yellow corresponding to the water surface below the aircraft. The power reflected from points that are away from the nadir point on the left and right sides of the aircraft is from a greater range than the nadir point and so appear below the bright yellow line. In some cases, topography and penetration of the surface do result in reflections that are at lower elevations than the upper edge of the waveform.

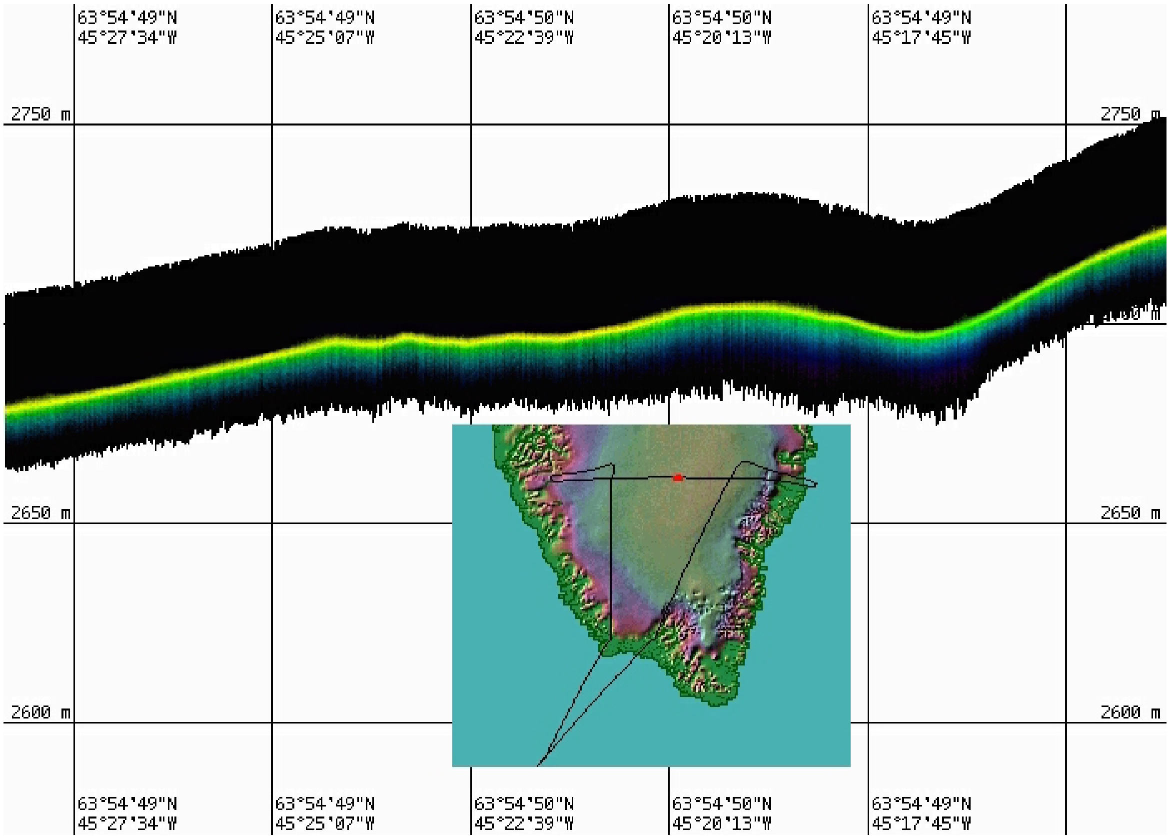


Fig. A2. Example of SARIn data from the Greenland Ice sheet summit area with more flat topography compare to Fig. A1.

Only the color of the upper edge of the waveform (the point of first reflection from the surface) is unambiguous. When the leading edge of the radar pulse first meets the surface, it does so in a small area that expands until the trailing edge of the waveform reaches the surface. The angle measurement for this initial scattering event is well defined. At later times, the radar is simultaneously observing surface points that are widely separated and that have different reflectivities. The angle measurement that results from this does not have a simple geometrical meaning.

A range interval in which data is collected is adjusted by the radar as it flies over the Greenland surface. This range interval is adjusted again during processing of the radar data. The black area above the colored waveform is the leading edge of the range interval. The lower edge of the waveform in the images is the farthest point that has an intensity of at least 10% of the peak intensity.

At some times, the data is interrupted because the radar has lost tracking of the surface due to aircraft maneuvers or steep slopes of the surface that exceed the radar beamwidth (4 degrees in the along-track direction).

A2. General properties of radar altimeter signal over water and sea-ice

The radar altimeter measures the return signal that is backscattered 180° within the footprint. The pulse-limited altimeter on ERS has a IFOV (=instantaneous field-of-view, also sometimes called footprint) diameter that is dependent on the meter-scale surface-roughness. Over ocean it may range from less than 4km for smooth (<1m waves) up to more than 10km for very rough sea (large waves). This roughness defines the width of the return-pulse leading edge. The return-pulse height and shape of trailing edge both depends on the cm-scale surface-roughness. Over water, the cm-scale roughness will increase with the wind speed, leading to scattering in a broader solid angle. Pulse max. height (the backscatter intensity) will then generally decrease with increasing roughness (that is: increasing wind), and for all but the lowest wind, the signal will thereafter decrease only slowly (called the pulse trailing edge) within the footprint.

Ice will have a range of type of the scattered signals, depending very much on the ice type. First, any flat (on cm-scale) surface within the antenna-lobe that is perpendicular to the pulse-direction will give a strong and nearly transmit-pulse-like return. (The lobe has a ground diameter of about 14km at –3dB) This may happen for very smooth (on cm-scale) ice. In the pack-ice this will be the case for thin, undeformed, newly frozen winter-ice. Most other forms of sea ice will be either broken (as small floe pieces or as rafted or ridged ice), or the ice will be volume-scattering (as the thicker and older ice). In these cases the signal will resemble a windy water signal, with a low maximum height and a slowly decreasing trailing edge.

Areas with smooth ice (that is: thin, undeformed) are found during cold weather in newly opened pack-ice leads and also in newly frozen melt ponds on floes. These areas can then be expected to a give different signal from their surroundings and thus be measured based on signal shape, assuming unique (not mixed) IFOV.

Alternatively, a difference in the pulse-delay-time can be measured between the thick ice and the thin ice/open water (generally named “leads”). On thick ice in winter, the dry snow - ice interface is expected to give the major return signal, and the total ice thickness may be derived from comparison with the signal from leads (or water level). This is called the “freeboard” measurement, and knowing the ice specific weight, ice thickness is derived. Suitable assumptions must be made about the effect of the snow load. In summer, the main signal return is from the air - wet snow surface, and it will be more difficult to compensate for the snow layer to find the ice thickness due to large difference in specific weight.

A3. SIRAL on CryoSat

Some description of the SIRAL instrument is given in chapter 1. In this section addition information is given. The altitude of CryoSat will be near 715km and inclination 92 degrees. The orbit will change between a Validation Phase and a Science Phase. The Validation Phase may be used for a one-month period near the beginning and again near the end of the mission depending on the requirements from the CVRT.

The Science Phase has repeat period of 369 days with a subcycle of 30 days, allowing provision of monthly averaged products. The Validation Phase has only 2 days repeat, and fixed measurement systems can be deployed on the ground track. Technical specifications for the three operating models of SIRAL are given in Table A1.

Table A1: Key instrument parameters of SIRAL

Instrument Mode	Pulse limited	SAR	SARIn
Receive chain	1	1	2
Samples per echo	128	128	512
Range window	60 m	60 m	240 m
Bandwidth	350 MHz	350 MHz	350 MHz
PRF	1970 Hz	17.8 kHz	17.8 KHz
TX pulse length	51 µs	51 µs	51 µs
Useful echo length	44.8 µs	44.8 µs	44.8 µs
Burst length	-	3.6 ms 3.6 ms	
Pulses per burst	-	64	64
Burst repetition interval	-	11.7 ms	46.7 ms
Azimuth looks (46.7 ms)	92	240	60
Tracking pulse bandwidth	350 MHz	350 MHz	40 MHz
Samples per tracking echo	128	128	128
Size of tracking window	60 m	60 m	480 m
Aver. tracking pulses (46.7 ms)	92	32	24
Data rate	51 kbps	12 Mbps	2x12Mbps
Power consumption	100 W	135 W	130 W

A4. IceSat

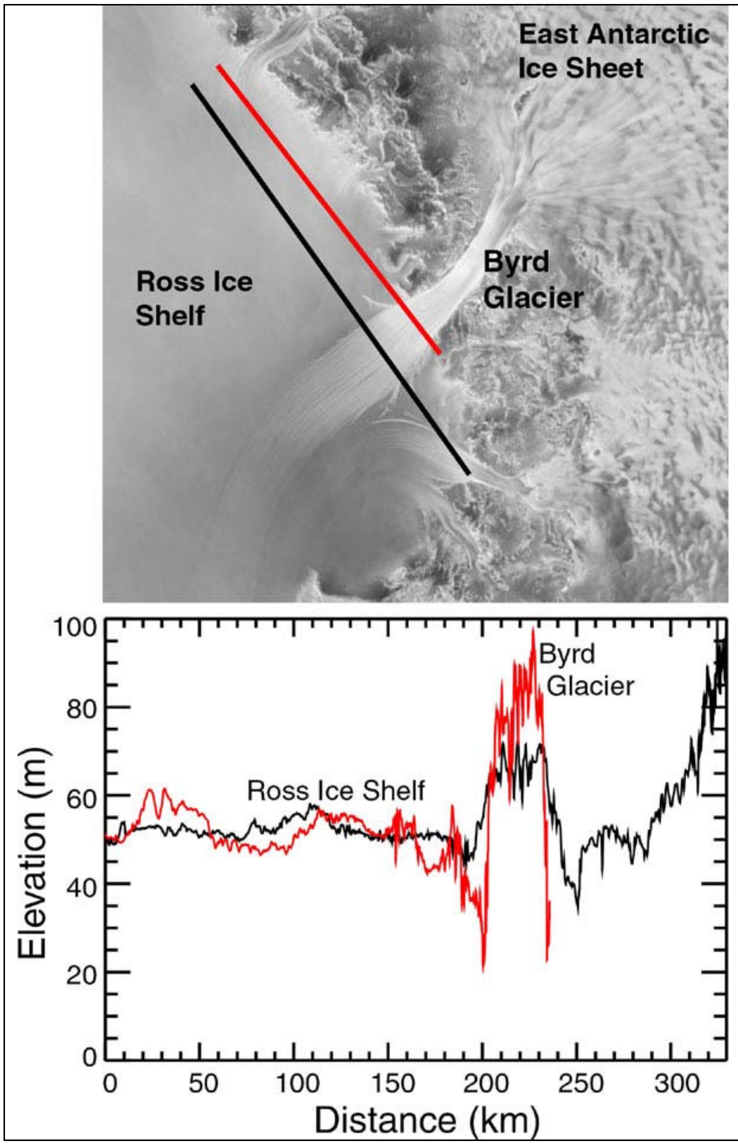
IceSat (Ice, Cloud and Land Elevation Satellite) carrying laser altimeter was launched in December 2002. IceSat is part of the NASA EOS system. Expected lifetime is 3 –5years, it will be followed by successive spacecrafts to acquire the 15-year dataset planned for EOS.

Spacecraft altitude is 600 km, inclination is 94 degree, which will cover 96% of the cryosphere. The onboard laser lidar instrument is named GLAS (= Geoscience Laser Altimeter System). GLAS will transmit 4ns pulses in the IR (1064 nm) and in the green (532 nm) spectral bands toward nadir. The IR signal is used for altimetry and the green signal for atmospheric profiling. On the ground, spots of 70m diameter are illuminated at 175 m intervals (40 pulses per sec). The return signal is collected by a 80 cm diameter telescope. Accurate satellite position /attitude is measured by GPS and a star-tracker system, as to locate the measurement position to down to 10 m accuracy.

It is primarily planned to measure: 1) glaciers and ice-sheet elevation, 2) cloud height and the profiles of atmospheric optical properties, 3) land surface elevations, 4) vegetation height. Over polar ice sheets, most instantaneous surface height measurements will have accuracy of about 15cm. By averaging, accuracy near 1cm/year in elevation temporal variation over mission duration (3 –5 years) is expected. Science data will be provided for these parameters. Expected land elevation accuracy is 1m –10m depending on slope. Vegetation height is measured by separating the reflections from ground and treetops. A vegetation index can be derived using both IR and green signals. Sea ice is mentioned, but without specifying the measurements. Also open ocean topography measurement is mentioned. From analysis of the return signal shape, other ground parameters can be found (e.g. roughness).

IceSat will measure <1 cm/yr average ice-thickness change, and the main application will be for climate research. Reflectivity accuracy expected is 10% (land) and 5% (snow). Cross-over analysis technique will be used for the ice data, with a spatial grid denser than 10km (down to 1km over local regions with 5 years of data). Elevation error is 15cm for <1deg. slope, 22cm for 1 –3deg. slope. Clouds and large slopes will give 50% loss of data over glacier ice. Repeated mapping is planned with a period of 1/2 year (183 days). Within this period, track separation will vary from 15km at equator to 2.6km at 80deg latitude. Interleaving tracks may be added during IceSat lifetime. Further information is found on http://icesat.gsfc.nasa.gov.

New results of IceSat measurements of Antarctic glaciers



Byrd Glacier, shown in a radar image from RADARSAT (top), is the largest outlet glacier draining ice from the East Antarctic Ice Sheet through the Trans-Antarctic Mountains into the Ross Ice Shelf. The ice sheet is grounded on bedrock and the ice shelf is floating on the ocean. Two ICESat profiles across the glacier show details of the troughs formed on the sides of the glacier as it plows into the ice shelf. The differences between the elevations and widths of the glacier at the inner (red) profile and the outer (black) profile show how the glacier thins and spreads as it merges with the ice shelf. With time, ICESat's measurements of small changes in the elevations of the ice sheets, outlet glaciers, and ice shelves will provide information on whether the rate of ice discharge into the ocean is increasing or decreasing and thus influencing sea level. Credit: NASA

Figure A3. Laser profiles of Byrd Glacier from IceSat data