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First Results of Recovery of Short Wavelength Gravity Field Signals from CryoSat-2 Data

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ABSTRACT BOOK

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ESA/ESTEC, THE NETHERLANDS

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ESA/ESTEC, THE NETHERLANDS

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University College London, UNITED KINGDOM

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Laxon, S; Ridout, A; Giles, K; Willatt, R
University College London, UNITED KINGDOM

A primary objective of the CryoSat mission is to determine trends in Arctic winter time sea ice thickness. This is achieved by making direct measurements of sea ice freeboard, from measurements of ice and ocean elevation, and from which sea ice thickness can be calculated. We present an initial evaluation of CryoSat performance over the Arctic in measuring both ice and ocean elevation along with preliminary findings with respect to ice freeboard. We provide recommendations with respect to both the CryoSat data, and for in-situ observations required to validate the mission performance.

Calibration and Validation Results

CryoSat Validation Activities

Davidson, MWJ[1]; Wingham, D[2]; Cullen, R[3]
[1]ESA, NETHERLANDS; [2]UCL, UNITED KINGDOM; [3]ESA, UNITED KINGDOM

The overall objective of all CryoSat validation activities 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 has been through dedicated, independent, ground-based and airborne campaigns along with detailed investigations of retrieval methods applied to the satellite measurements. The Calibration, Validation and Retrieval Team (CVRT) composed of members selected through two ESA CryoSat cal./val. Announcements of Opportunity plays an important role in the mission validation. The CVRT has helped ESA elaborate details of coordinated Cal/Val strategy and contributes through experiments and data analysis to Cal/Val efforts, providing feedback to ESA on the results. The presentation will cover the scope of the CryoSat validation experiments and an overview of the planning and expected feedback from post-launch validation work. Synergies with parallel NASA activities and ESA/NASA collaboration will be highlighted.

Airborne Campaigns for CryoSat Prelaunch Calibration and Validation

Skourup, Henriette[1]; Forsberg, Rene[1]; Hanson, Susanne[2]; Hvidegaard, Sine Munk[1]; Morris, Elizabeth M.[3]; Nienow, Peter[4]; Poulsen, Stine Kildegaard[1]; Stenseng, Lars[1]
[1]National Space Institute, DTU Space, DENMARK; [2]Danish Meteorological Institute, DENMARK; [3]Scott Polar Research Institute, UNITED KINGDOM; [4]University of Edinburgh, UNITED KINGDOM

After the successful launch of CryoSat-2 in April 2010, the first direct validation campaign of the satellite is planned for spring 2011. DTU Space has been involved in ESA’s CryoSat Validation Experiment (CryoVEx) with airborne activities since 2003. To validate the prelaunch performance of the CryoSat radar altimeter (SIRAL), an airborne version of the SIRAL altimeter (ASIRAS) has been flown together with a laser scanner in 2006 and 2008. Of particular interest is to study the penetration depth of the radar altimeter over both land- and sea ice. This can be done by comparing the radar and laser measurements with *in situ* observations.
Here is given an overview of the prelaunch airborne campaigns together with results of the ASIRAS performance over land- and sea ice. The observations, used in this study, are obtained from the Greenland ice sheet and from both multiyear and first year sea ice.

CryoSat-2 SIRAL Calibration using an ESA Transponder: DATATION, RANGE and INTERFEROMETRIC BASELINE (angle of arrival)

Roca, M.[1]; Fornari, M.[2]; Reche, M.[3]; Garcia, P.N.[4]; Cullen, R.[2]
[1]isardSAT, POLAND; [2]ESTEC/ESA, NETHERLANDS; [3]isardSAT, SPAIN; [4]isardSAT, CUBA

A transponder can be seen by a radar as a point target. Transponders are commonly used to calibrate absolute range from conventional altimeter waveforms. As a uniquely defined terrestrial reflection surface, a transponder is deployed within the footprint of the radar altimeter. The waveforms corresponding to the transponder distinguish themselves from the other waveforms resulting from natural targets in power and shape.
One transponder is available for the CryoSat project (a refurbished old ESA transponder developed for the ERS-1 altimeter calibration). It is deployed at the ESA Svalbard station: SvalSAT.
We are using the ESA CryoSat transponder to calibrate SIRAL's range, datation, and interferometric baseline (or angle of arrival). In these calibrations, we are using 3 different types of data: the raw Full Bit Rate data; the stack beams before they are multi-looked (stack data), and the single multi-looked echo of the L1b data.
The comparison between (a) the theoretical value provided by the well known target, and (b) the measurement by the instrument to be calibrated; provides us with the error the instrument is introducing when making its measurement. If this error can be assumed to be a constant error, regardless the conditions, it will provide the bias of the instrument. If, on top of that, this measurement is repeated after a certain period of time, it can also provide an indication of the instrument drift. In particular for the interferometric baseline, the study will be completed during the operations phase to monitor its behaviour and correlate it with temperature.
Here we will present the results obtained during the Commissioning phase and beyond, and the plans for the routine phase.

Accuracy of Surface Elevation derived from the Airborne SAR Interferometric Radar Altimeter System (ASIRAS)

Helm, Veit[1]; Hendricks, Stefan[1]; Steinhage, Daniel[1]; Cullen, Rob[2]
[1]Alfred Wegener Institute, GERMANY; [2]ESA/ESTEC, UNITED KINGDOM

The Airborne SAR Interferometric Radar Altimeter (ASIRAS) was designed to simulate the CryoSat SAR Interferometric Radar Altimeter (SIRAL) for reasons of pre-launch and simultaneous accuracy studies by using a similar instrument. The purpose of the ASIRAS calibration and data validation is to provide confidence in estimates of the uncertainty of the ASIRAS data products namely the surface elevation. Error estimates of the ASIRAS surface elevation in different snow zones were assessed using simultaneously acquired reference surface heights from an airborne laser scanner (reference digital elevation model). We present results of the combined ASIRAS/Laserscanner measurements during the CryoVEx campaigns in the Arctic and Antarctic and will present first comparisons with CryoSat-2 data at the North Greenland Drilling site (NEEM).

Calibration and Validation of CryoSat-2 Low Resolution Mode Data

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[1]TUDelft, NETHERLANDS; [2]Altimetrics, LLC, UNITED STATES

Running ahead of the continuously growing need for operational use of sea level products, TUDelft started off the Radar Altimeter Database System RADS many years ago. This system attends to a global international sea-level service. It supports, on one hand, science, like studies on ocean circulation, El Niño, sea level change, and ice topography, and on the other hand (offshore) operations, like delivery of ocean current information, wind- and wave statistics, ice detection and ice classification. At present, the database is used by a large scientific community throughout the world, and is daily maintained and developed by Altimetrics LLC, TUDelft and NOAA. It contains all historic altimeter data, and now has to be updated with the data from ESA's ice mission CryoSat-2, which was launched successfully in April 2010. These new data are important to augment the dataset and by that to improve the estimates of sea level change and its contributors. For this the data have to be validated and calibrated, necessary corrections added and improved (including modelling of corrections that are not directly available from the CryoSat-2 platform), and the orbit accuracy verified and if possible the orbits brushed up. Subsequently, value-added ocean and ice products need to be developed in synergy with all the other satellite altimeter data. During the commissioning phase we primarily looked at the sanity of the available level-1b and level-2 Low Resolution Mode (LRM) data. For the 2011 CryoSat Validation Workshop we present the results of our absolute and relative calibration of LRM L2 data by comparison of CryoSat-2 with other satellites (global crossover and grid analyses) and with tide gauge data. We provide estimates on range and timing biases.

Ice Thickness and Surface Roughness Validation from Aircraft Observations

Crocker, R. I.; Maslanik, J. A.
University of Colorado, UNITED STATES

High resolution observations of sea and land ice are important for investigating the ice geophysical evolution and identifying various surface characteristics and their apparent signatures in CryoSat-2 data. Ice thickness, roughness, ridging, crevassing, and melt pond extent are indicators of the ice age, the climate forcing to which the ice has been exposed, and the overall stability of the ice. As such, it is critical to understand how these properties will be expressed, and subsequently identified, in the CS-2 data. High resolution observations from manned and unmanned aircraft (UA) flights offer one method for identifying and validating ice surface properties detected by CS-2. With proper coordination between the CS-2 calibration, validation and retrieval team, NASA's Operation IceBridge (OIB), and researchers at the Norwegian Institute for Air Research, The Norwegian Polar institute, and Norut, it will be possible to collect a significant amount of ice elevation and roughness measurements and surface imagery that are coincident with the CS-2 retrievals. In this paper we present sea and land ice topography measurements and visible and synthetic aperture radar imagery that were collected during UA campaigns that were carried out in Greenland and Svalbard in the summers of 2008 and 2009. These high resolution data depict an array of ice surface properties and exemplify future CS-2 calibration and validation datasets. Additionally, we present the sea ice topography data that were collected during the OIB underflight of CS-2 on 20 April 2010, and discuss the potential for future collaboration with the aforementioned Norwegian institutes to collect additional topographic and image data in 2011 during their UA flight campaigns in Svalbard and Greenland.

Validation of CryoSat-2 Products in Antarctica by GPS Ground Surveys

Dietrich, Reinhard[1]; Knoefel, C.[1]; Ruelke, A.[2]; Schwabe, J.[1]
[1]Institut für Planetare Geodäsie, Technische Universität Dresden, GERMANY; [2]Federal Agency for Cartography and Geodesy, GERMANY

One main objective of the European ice radar altimeter mission CryoSat-2 is the determination of the surface geometry of the continental ice sheets with a few centimeters accuracy which is an important input for studies on ice mass balances. In this context detailed information on the error budget of the mission are essential for the interpretation of ice mass changes obtained from CryoSat-2 observations. Therefore, investigations of the error budget and the validation of CryoSat-2 products are an essential part of a successful mission. As location for the calibration / validation experiment a blue ice area south of the Schirmacher Oasis, Dronning Maud Land, East Antarctica (11.0° -14.5° East, 70.5° -71.4° South) is chosen. It has a size of about 110 km x 50 km. Since 1991 the Institut fuer Planetaere Geodesie of TU Dresden has been working successfully in this area. Earlier extensive ground observations along traverses revealed a surface height decrease of the area of up to -20cm/year.

We will present the results of the CryoSat-2 cal/val pre-launch campaign 2008/2009 in this area. During that campaign ice elevations have been determined by kinematic differential GPS observations. On the one hand repeated observations of already existing tracks had to be performed, on the other hand dense grids located directly in the subsatellite track of a planned CryoSat-2 orbit have been observed. The observed kinematic GPS data have been analyzed with respect to a static reference antenna. It will be shown that the accuracy of the determined kinematic GPS heights is in the level of a few centimeter.

During the Antarctic summer season 2010/2011 a second CryoSat-2 cal/val campaign will be performed. Therefore, the same areas as in 2008/2009 will be observed. In addition, areas covered by actually realized CryoSat-2 ground tracks will be subject of the ground survey. The determined observations shall be used for comparisons with the results based on CryoSat-2 observations obtained during the same time. These comparisons will provide accuracy estimates for the anticipated determination of long-term elevation changes

by CryoSat-2. It will be shown that the ground-based measurements are closely linked to the AWI cal/val activities based on the POLAR 5 aircraft. This aircraft is equipped with the ASIRAS radar altimeter as well as with a laser scanner and will be used for airborne surveys of the area. We will report about the status of the ongoing cal/val campaign in Antarctica and give an outlook on the expected results.

Early Results from CryoSat-2 over Devon Ice Cap, Canada

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[1]Geological Survey of Canada, CANADA; [2]Natural Resources Canada, CANADA; [3]University of Alberta, CANADA

Preliminary analysis of CryoSat-2 L1b data acquired in the fall of 2010 over the Devon Ice Cap reveals good potential for retrieval of surface elevation from the interior regions (percolation zone) of small polar ice caps where melting is absent and surface slopes are low. The wave-forms of the radar returns over the lower slope regions in the centre of the Devon Ice Cap clearly show good signal-to-noise ratio, satisfactory leading edge shape, highlighting the success and value of the along-track focusing utilized for the SARInM data sets. Work reported on will thus include an initial attempt to use the differential phase to map the point-of-closest approach and check the derived elevation with any available recent topographic data. In this talk, results of our analyses of CryoSat-2 (L1b and L2) over the Devon Ice Cap will be presented in the light of data on meteorological and snow conditions coupled with prior knowledge of surface and near-surface radar scattering from ASIRAS and surface GPRs. The CryoSat data and the preliminary analysis will be timely in helping to guide our plans for the spring 2011 cal/val campaign which will also be presented.

Land Ice Validation in East Antarctica: Law Dome and Totten Glacier Area

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[1]University of Tasmania, AUSTRALIA; [2]The Australian National University, AUSTRALIA; [3]Australian Antarctic Division, AUSTRALIA; [4]University of California, San Diego, UNITED STATES; [5]CNRS, LEGOS, FRANCE

The Australian TotCal project contributes to the validation of the CryoSat-II mission through investigations of two adjacent important regions on the coastal fringe of East Antarctica. The first focuses on the Totten glacier, one of the key outlet glaciers in the East Antarctic, for which recent satellite altimetry and gravity observations show significant surface lowering and mass loss. The second area comprises the coastal slopes and varied accumulation profile across Law Dome behind the Australian Casey Station. The 2010/11 austral summer is the first field season for this project.

We seek to validate four aspects of CryoSat data through the use of airborne radar and laser observations together with in-situ GPS, meteorological and firn measurements. The first component of the project seeks to validate the integrated water vapour content of the atmosphere (as provided by the ECMWF product used to calculate the signal delay in the CryoSat-II data stream), using our network of six in-situ GPS sites deployed over the summer period throughout the Law Dome / Totten Glacier region. Second, we will assess the SAR-In mode of the SIRAL altimeter in an area of significant across-track slope through comparison with detailed topographic and radar return data collected using the scanning LiDAR and ESA ASIRAS aboard the AWI Polar-5 aircraft. The in situ GPS sites deployed in the region also serve to provide reference stations for the precise positioning of the Polar-5 trajectory, as well as skidoo-based GPS surveys that will enable the validation of the airborne data. Third, we will compare CryoSat estimates of dH/dt over a range of magnitudes including the dynamic upper Totten glacier region against those determined from our 10/11 field measurements combined with historic survey data, other satellite altimetry results and future seasons of field observations. Finally, we will improve inferences of mass change in this part of Antarctica by better resolving the spatial and temporal variation of firn density through analysis of the ASIRAS radar data and in-situ measurements of shallow cores.

In this contribution, we detail the above planning contributions to the validation of CryoSat-II and review progress made over the 2010/11 austral summer field season.

Australian CryoSat-2 Cal/Val Efforts in the East Antarctic Sea Ice Zone

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[1]Antarctic Climate & Ecosystems CRC, AUSTRALIA; [2]Australian Antarctic Division, AUSTRALIA

The Australian Antarctic program is deploying an integrated airborne imaging system in the East Antarctic to assist in the calibration and validation of CryoSat-2 products. The system consists of a scanning LiDAR (Riegl LMS-Q240i) in combination with a high resolution digital still camera (Hasselblad H3D-II) and an IR pyrometer (Heitronics KT-19). It will be deployed both in the sea ice zone and over terrestrial outlet glaciers over the next few years.

The scanning LiDAR measures surface elevation (i.e. freeboard in case of sea ice) from which ice thickness can be estimated. The still photos are used to derive surface characteristics and provide visual reference. The pyrometer measures skin surface temperature of the snow/ice surface and open water in leads or polynyas.

The airborne instrument package was first used in the East Antarctic sea ice zone during the international and multi-disciplinary sea ice research cruise SIPEX (Sea Ice Physics and Ecosystem eXperiment) on board Australian RSV Aurora Australis in austral spring 2007. During SIPEX we demonstrated the good agreement of LiDAR derived sea ice thickness estimates and in-situ measurements with overflights over drilled transects on sea ice stations.

In late October/early November 2010 the first field deployment for the collection of CryoSat-2 cal/val data will take place in the East Antarctic sea ice zone between about 75¢ª E and 90¢ª E. There we aim for coincident space- and air-borne data collection utilising ship based helicopters off the Australian RSV Aurora Australis.

This paper will present preliminary results from the voyage, and provide details of the airborne instrument package, project design, and capabilities.

Sea Ice Comparisons of Icebridge Data for Snow Thickness with CryoSat-2 Sea Ice Elevation

Holt, B[1]; Perkovic, D.[1]; Kwok, R[1]; Leuschen, C[2]; Panzer, B[2]
[1]Jet Propulsion Laboratory, UNITED STATES; [2]University of Kansas, UNITED STATES

On April 20, 2010, sea ice observations were obtained by the IceBridge mission along an early CryoSat-2 track in the Arctic Ocean. This paper will present results from the snow radar (2-6 GHz), Ku-band radar altimeter, and airborne lidar (ATM) for penetration of snow on sea ice and resulting estimates of snow thickness from both the snow radar and the combined observations from the radar and laser altimeters. We then plan to compare these aircraft snow thickness observations with the CryoSat-2 Ku-band sensor derivations of sea ice elevation.

Observations of Ku-band radar penetration into snow cover on sea ice.

Willatt, R C[1]; Laxon, S[1]; Giles, K[1]; Cullen, R[2]; Haas, C[3]; Helm, V[4]
[1]CPOM, UCL, UNITED KINGDOM; [2]ESA/ESTEC, NETHERLANDS; [3]University of Alberta, CANADA; [4]Alfred Wegener Institute for Polar and Marine Research, GERMANY

Measuring sea ice thickness using satellite radar altimetry provides basin-wide coverage and has been used to examine long term trends in Arctic sea ice thickness. This technique requires a knowledge of the radar penetration characteristics through the snow cover on the sea ice. The radar is assumed to penetrate to the snow/ice interface in the Arctic, where the winter snow cover is cold and dry, in light of supporting laboratory experiments. We present measurements of Ku-band radar penetration into snow on sea ice from the CryoVEx campaigns in the Arctic, as well as discussing results from sledge-borne and satellite radar altimeter data obtained over Antarctic sea ice.

CryoSat-2 Precision Orbit Determination with Doris and Satellite Laser Ranging, Validation with the SIRAL LRM Data

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CryoSat-2 was successfully launched on April 8, 2010 to map the cryosphere with an advanced microwave altimeter system. The mission goal is to observe the freeboard of sea ice and the topography of ice sheets for a nominal period of 3 years. Precision orbit determination of CryoSat-2 relies on DORIS Doppler tracking and ground based satellite laser ranging. During this talk we will show preliminary results obtained by precision orbit determination. We will focus on the comparison of independently computed trajectories to those provided by the CNES to ESA's CryoSat-2 project, and we will use independent data acquired from CryoSat's SIRAL radar altimeter over ocean surfaces to assess orbit quality.

CryoSat Processing Prototype, LRM Processing on CNES Side and a Comparison to DUACS SLA

Boy, F; Picot, N
CNES, FRANCE

In the frame of Sentinel3 project, CNES is involved in the overall topography payload product quality. Like CryoSat, Sentinel3 embarks a Doppler altimeter, while there is a long experience of LRM processing, SAR nadir looking data are new and will need in depth validation. Thanks to CryoSat project, 2 long acquisitions of SAR data were performed early June 2010 over the Indian ocean. Those SAR data will be very useful to assess the quality of the SAR processing methods currently under development.

A CryoSat Processing Prototype (C2P) has been developed on CNES side to prepare the CNES SAR ocean retracking study. In order to validate our prototype, the analysis has been conducted on the LRM data. C2P uses directly the LRM telemetry files and perform the whole processing steps required to derive sea surface information. It is so independent from the IPFs products. The C2P has been validated thanks to the use of Jason-2 data and the C2P CryoSat products will be compared with DUACS SLA estimates.

CryoSat Orbit Accuracy Assessment based on Multi Satellite Cross over Reduction Technic over Ocean

Picot, N1; Boy, F1; Dibarboure, G2
1CNES, FRANCE; 2CLS, FRANCE

CryoSat LRM data has been processed with the processing prototype developed by CNES. CryoSat Processing Prototype (C2P) has been developed internally to prepare the SAR processing study over ocean. In that frame, the LRM processing was also included and validated thanks to Jason-2 data. We will analyse the CryoSat LRM

data over ocean and feed those data inside the CNES CalVal multi mission tool to assess the orbit quality compared to Jason-2 operational orbit.
This CalVal analysis is based on the computation of multi satellite cross overs over ocean and compute the orbit error estimates by spline functions. As Jason-2 orbit quality has a quality of 1-2 centimetres (depending on the orbit latency) this will allow to analyse the CryoSat obit quality. MOE and POE orbit qualities will be presented.

On the Performance of CryoSat-2 SAR Mode over Water Surfaces

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[1]National Oceanography Centre Southampton, UNITED KINGDOM; [2]Starlab, SPAIN; [3]ESRIN, ITALY; [4]Johns Hopkins University, Applied Physics Laboratory, UNITED STATES; [5]Satellite Oceanographic Consultants Ltd, UNITED KINGDOM

This paper presents analyses of L1B waveforms in SAR and LRM mode over water surfaces, both from numerical simulations from the CryoSat Mission Performance Simulator (CRYMPS) and from CryoSat2 satellite measurements. This work was performed as part of the ESA project "Development of SAR Altimetry Studies and Applications over Ocean, Coastal zones and Inland waters (SAMOSA)". The project aims to determine the performance of SAR altimeters over the ocean and the coastal zone, compared to those of conventional pulse-limited altimeters. The performance for range and wave height retrieval in SAR mode is assessed with the help of the SAMOSA theoretical waveform retracker developed in the SAMOSA contract to retrack peaky SAR mode waveforms (Gommenginger et al., 2010). The SAMOSA retracker will form the basis of the operational SAR altimeter retracker to be implemented for Sentinel-3 STM.

In this paper, we present a comparative assessment of the properties of L1B waveforms in LRM and SAR mode over water surfaces in the coastal and the open ocean in different wave height conditions. Results of the retracked range accuracy in LRM and SAR mode are compared with earlier results by Jensen & Raney (1998).

Gommenginger , C., Martin-Puig , C., Srokosz, M., Caparrini, M., Dinardo, S., and Lucas, B.: Detailed Processing Model of the Sentinel-3 SRAL SAR altimeter ocean waveform retracker, Version 1.3.1, 21 June 2010. ESRIN Contract No. 20698/07/I-LG "Development of SAR Altimetry Mode Studies and Applications over Ocean, Coastal Zones and Inland Water" (SAMOSA), 63 pages, 2010.

Jensen, J. R. & R.K. Raney: Delay Doppler radar altimeter: Better measurement precision. Proceedings IEEE Geoscience and Remote Sensing Symposium IGARSS'98. Seattle, WA, IEEE: 2011-2013, 1998.

Study on the Relationship between Radar Power Waveforms and Snowpack Structure across the Greenland Ice Sheet.

de la Peña, Santiago[1]; Nienow, Peter[1]; Shepherd, Andrew[2]; Duncan, Wingham[3]
[1]University of Edinburgh, UNITED KINGDOM; [2]University of Leeds, UNITED KINGDOM; [3]University College London, UNITED KINGDOM

Radar altimetry signatures present unexpected variability when operating over the interior of ice sheets. The variability in echo power is of particular importance because a direct correlation between changes in measured elevation and changes in the radar signal power has been observed. Additionally, recent investigations suggest substantial changes in accumulation patterns over parts of Greenland while an increase in the area experiencing melting has also been observed. To accurately estimate mass loss by remote sensing techniques, there is a pressing need both for high resolution snow accumulation estimates, and to determine the extent to which seasonal snow densification is occurring caused by surface melt that percolates and subsequently refreezes in the snowpack and firn. High bandwidth radar altimeters, operating in the Ku-band, can penetrate several meters into the snowpack and firn revealing subsurface horizons. In the percolation zone, these horizons are associated with spatially extensive ice layers formed by the refreezing of surface melt water. In the dry snow zone, they result from differential snowpack densities associated with the annual formation of hoar layers. Here, we present an analysis of power waveforms acquired by CryoSat-2 and by the ASIRAS airborne radar altimeter in conjunction with CalVal field observations to assess the relationship between the backscatter radar signals and different snow and firn facies across a wide elevation range in the Greenland Ice Sheet.

Snow densification in Greenland

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As part of the calibration and validation experiments for CryoSat snow density profiles have been measured along the EGIG line from Spring 2004 to Summer 2010. Repeated measurements at the same site allow the development of the characteristic stratigraphy of the dry snow zone to be observed and the rate of densification to be measured directly. Densification rates below the surface layer are found to be compatible with a physics-based grain boundary sliding model (Alley, 1987) but near-surface rates are enhanced.

Data Processing, Product Quality and Outlook for Improvement

CryoSat 2 performance monitoring and product QA

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The SIRAL instrument on-board CryoSat 2 has been successfully commissioned and is working well within specifications. The instrument has been characterised on the ground, and in-flight by the Cal/Val campaign. As with any Earth Observation mission it is important to continue to monitor instrument performance in-flight in order to detect any anomalous behaviour and to detect signs of measurement drift due to component ageing. During the commissioning phase a team at UCL-MSSL developed a set of tools to monitor certain aspects of instrument performance. Other tools were implemented to provide routine QA for important product parameters. We present an overview of these tools and discuss the performance features and trends observed to date. These tools will continue to operate throughout the mission as part of the expert support given to ESA by MSSL. The outputs can be viewed by interested users and serve to support confidence in the interpretation of data from the altimeter measurement system.

Assessing the Performance of CryoSat-2 over Rugged Glacier Terrain

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[1]University of Leeds, UNITED KINGDOM; [2]University of Edinburgh, UNITED KINGDOM

Data acquired by the ASIRAS airborne prototype of the CryoSat-2 SIRAL instrument have demonstrated that it is possible to retrieve glacier elevation measurements across the ground-track in regions where the surface slope is sufficiently steep. In such conditions, the instrument operates as a conventional synthetic aperture radar and the elevation measurements can be determined using interferometry. Differences in the system performance and imaging geometry mean that it is not certain that CryoSat-2 will present the same opportunity for data collection in interferometric mode. In this paper, we investigate the extent to which similar observations can be retrieved from CryoSat-2 observations.

Global Data Quality Assessment of the CryoSat-2 Altimetric System over Ocean

Faugere, Yannice; Labroue, Sylvie
CLS, FRANCE

CryoSat-2, was launched on 8 April 2010, is dedicated to precise monitoring of the changes in the thickness of marine ice floating in the polar oceans and variations in the thickness of the vast ice sheets overlying Greenland and Antarctica, as well as of continental glaciers. But, it also designed to provide accurate Sea Surface Height (SSH) estimation over Ocean.

This paper thus concerns the global data quality assessment of the CryoSat-2 altimetric system over ocean from available user's products. This consists in assessing main altimeter parameters (global statistics, maps) and in analyzing the SSH performances at crossovers and along-track. Data coverage and valid SSH measurements are also analyzed thoroughly.

Exploitation of CryoSat Data

Comparison of Radar and Laser Altimetry measurements for Antarctic ice sheet mass balance

Remy, F.1; Flamand, T.1; Blarel, F.1; Benveniste, Jérome2
1LEGOS, FRANCE; 2ESA, ITALY

Since the launch of ERS-1 Altimeter we have nearly 20 years of data to monitor Antarctic ice sheet mass balance. CryoSat-2 is extending this series. Because of the difference between CryoSat and previous classical altimeters, some investigations will be needed to compare the series. We will investigate the effect of the altitude of the spacecraft, the non-repeat orbit and the polarisation of the radar antenna. Some IceSat, Envisat Extended mission and HRS SPIRIT data will be used to infer these effects. References: Remy, F., Legresy, B., & Benveniste, J., 2006. On the azimuthally anisotropy effects of polarization for altimetric measurements. Ieee Transactions on Geoscience and Remote Sensing, 44(11), 3289□]3296. Korona, J., Berthier, E., Bernard, M., Remy, F. and Thouvenot, E., 2009. SPIRIT. SPOT 5 stereoscopic survey of Polar Ice: Reference Images and Topographies during the fourth International Polar Year (2007-2009). ISPRS Journal of Photogrammetry & Remote Sensing, 64: 204-212.

Sensitivity of Elevations observed by Satellite Radar Altimeters over Ice Sheets to Variations in Backscatter Power

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Recent studies show that radar-altimeter-measured surface elevations over ice sheets are sensitive to changes in the surface backscatter power that vary temporally and geographically. A correction is needed to extract the real elevation change (dh/dt) from the altimetry-measured ranges (Wingham et al., 1998; Li et al., 2003; Davis and Ferguson, 2004; Zwally et al., 2005) using either the backscatter coefficient (sigma0) or the Automatic Gain control (AGC) as measure of the backscatter power. AGC is highly correlated to radar altimeter measured surface elevation. The sensitivity of calculated elevation change to the measured backscatter power may vary from satellite to satellite, due to different instrument characteristics. We derive sensitivities between observed changes in elevation and changes in the backscatter power using 3 methods (short-term, long-term, and mixed term), which give similar sensitivities but somewhat different correlation coefficients. We review our method for correcting the dh/dt for the ERS and Envisat altimeters. The resulting corrected h(t) series show significant differences from the observed h(t). In particular, the apparent seasonal cycle in the corrected h(t) is much smoother and smaller in amplitude. Also, in some locations the derived dh/dt from the corrected h(t) is quite different than from the uncorrected h(t). In this study, we also apply our method to CryoSat-2 elevation data, examine the derived sensitivities of the elevation to backscatter power, and provide a preliminary correction to the observed elevations.

Application of SAR Retracking Techniques to CryoSat-2 Data over West Iberian Coast and Tyrrhenian Sea

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In the framework of the ESA-funded research and development project named SAMOSA, a novel analytic model for mean return power of the radar altimeter echo in SAR mode has been derived.

Parallelly, an alternative and independent numerical solution for SAR waveform modelling problem, developed essentially for the purposes of the SAMOSA model validation, has been drawn out inside ESA/ESRIN exploitation team.

Such retracking techniques have been devised principally to be applied to S-3 ground segment where the SAR oceanographic products are destined to become operational over coastal areas but nevertheless, given the strong similarity between the two instruments, they remain still valid and easily adaptable to CryoSat-2 altimeter configuration.

With regard to the scopes of CryoSat-2 SAR oceanographic products quality assessment, in the present work, the afore-mentioned SAR retracking techniques have been applied over open sea regions.

The application region is twofold: an internal basin, as the Tyrrhenian Sea, where moderately calm sea conditions are expected and an open ocean stretch off the Western Iberian Coast where high sea levels are encountered, in order to assess the techniques over the full sea state spectrum.

Particular attention has been dedicated to the results validation process. That shall be accomplished either with a comparison of the sea state multi-mission grid maps in the analyzed regions at the observation time either with a novel and more original approach: indeed the SAR L1b products originate from the CryoSat-2 Full Bit Rate (FBR) data; these shall be reduced to LRM-equivalent level (also known as pseudo-LRM) and retracked

hence by means of conventional altimetry retracking schemes; afterwards, such results shall be contrasted with the results coming from L1b SAR data and obtained applying the afore-mentioned SAR retracking techniques.

The results from SAR L1b are expected to match or ideally over-perform the pseudo-LRM outcomes.

That shall allow even to quantify the benefits of the SAR altimetry with respect the pulsewidth-limited altimetry.

First Results of Recovery of Short Wavelength Gravity Field Signals from CryoSat-2 Data

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A number of geophysical phenomena in the open ocean are still unresolved by conventional 1 Hz altimetry, but could be observed through the potential improvements offered by SAR, or Delay-Doppler (DD), altimetry. The DD altimeter offers the following benefits with respect to conventional satellite altimetry: Factor of 20 improvements in along track resolution. Along-track footprint length that does not vary with wave height (sea state). Improved precision in sea surface height measurements / sea surface slope measurements. These improvements are studied with respect to retrieval of short wavelength geophysical signal related to mainly bathymetric features. The combination of upward continuation from the sea bottom and smoothing the altimeter observations resulted in the best recovery of geophysical signal for simulated 5-Hz DD observations.

The first validation of these theoretical modeling results with respect to resolution and noise are presented using various CryoSat-2 data and evaluation against conventional Radar altimeter data from older GM missions onboard ERS-1 is presented. A comparison of L2 products for LRM, SAR and SAR-in data are carried out with re-tracked L1 data for the same data types.

International Context Including Synergies with Programmes from Other Space Agencies

MABEL: The ICESat-2 airborne simulator

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Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) is scheduled to launch in early 2016 and will carry the Advanced Topographic Laser Altimeter System (ATLAS), which represents a new approach to spaceborne determination of surface elevations. Specifically, the current ATLAS design uses a micropulse, multibeam, photon-counting laser altimeter with lower energy, a shorter pulse width, and a higher repetition rate relative to the Geoscience Laser Altimeter (GLAS), the primary payload on ICESat. Given the new and untested technology associated with ATLAS, airborne altimetry data is necessary (1) to test the proposed ATLAS instrument geometry, (2) to validate instrument performance models, (3) to assess the atmospheric effects on high repetition-rate altimeters, and (4) to develop algorithms for surface retrieval, and (5) provide a means for future calibration of ICESat-2 data. To these ends, we have developed an airborne ICESat-2 simulator: the Multiple Altimeter Beam Experimental Lidar (MABEL). MABEL is a multi-beam, variable repetition rate, photon-counting lidar designed for the ER-2. With a nominal flight altitude of 20 km, the ER-2 flies above ~95% of the earth's atmosphere, allowing MABEL to collect nearly ICESat-2 like data. We will collect data in advance of the launch of ICESat-2 over sea ice and land ice targets in conjunction with the ongoing Operation Ice Bridge, which deploys lidars at lower elevations. We also anticipate under-flying CryoSat-2 if possible. During the first year of ICESat-2 operations, we expect to deploy MABEL more frequently over a variety of targets to assist with calibration and validation of ICESat-2 data. In this presentation, we present the MABEL concept, results of preliminary tests, and plans for ICESat-2 cal/val activities.

The ICESat-2 Mission: Laser Altimetry of Ice, Clouds and Land Elevation

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The ICESat mission used a state-of-the-art at the time laser altimetry system to measure changes in the Greenland and Antarctic ice sheets, document changes in sea ice thickness distribution, and has been used to derive important information about the interactions between ice sheets and climate. ICESat stopped collecting data in October 2009, while the IceBridge and CryoSat-2 missions continue these important observations. The well-documented and ongoing dramatic and rapid changes in the Earth's ice cover have only strengthened the need for sustained observations beyond what CryoSat-2 and IceBridge are expected to provide. Following recommendations from the National Research Council for an ICESat follow-on mission, the ICESat-2 mission is now under development for launch in late 2015. The primary aims of the ICESat-2 mission are to continue measurements of sea-ice thickness change, and ice sheet elevation changes at scales from outlet glaciers to the entire ice sheet. Unlike ICESat, which used a laser operating at 40 Hz and an analog detection system to record reflected laser energy in the infrared as a waveform, ICESat-2 is expected to employ a photon-counting approach. The current concept uses a high repetition rate (10 kHz) low power laser in conjunction with single-photon sensitive detectors to measure range using ~532nm (green) light. This approach also makes use of multiple beams unlike the single-beam of ICESat, while the higher repetition rate generates dense along track sampling. Combining ICESat-2 data with existing and forthcoming altimetry data will yield a 15+ year record of elevation change. In this presentation, we will present the current design for the ICESat-2 mission, as well as concepts and challenges for a combined ICESat-IceBridge/CryoSat-2-ICESat-2 ice sheet and sea ice time series.

A comparison of CryoSat-2 and ICEBridge Altimetry from April 20, 2010 over Arctic Sea Ice

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It is widely known that climate-driven loss of Arctic sea ice has occurred in the past decade. And in just the past few years a synoptic view of significant ice thickness changes (dominated by thinning and volume loss) across the Arctic Ocean has been provided by various investigations using ICESat and Envisat altimetry. Continued Arctic-wide observation of this (presumably secular) thinning, or other thickness changes, will be provided for the next 3 to 5 years by the Synthetic Aperture Interferometric Radar Altimeter (SIRAL) onboard CryoSat-2 as well as the suite of airborne instruments used by NASA's Operation IceBridge. On April 20 - just 12 days after the CryoSat-2 launch - during the IceBridge Spring 2010 campaign and in coordination with ESA, the NASA DC-8 flew precisely along some 670 km of a CryoSat-2 ground-track in the northernmost Arctic Ocean. The DC-8 collected scanning laser Airborne Topographic Mapper (ATM) data as well as a number of other measurements including DMS imagery, gravity, lidar and radar altimetry, including snow radar, which are virtually coincident and nearly simultaneous with SAR-mode SIRAL data collected by CryoSat-2. We will present initial comparative analyses of these CryoSat-2 data and the coincident airborne ATM data along with other

IceBridge data including digital imagery. We will identify leads and floes in both the CryoSat and ATM data. Discrimination between leads, floes, and ridges as well as identification of recently refrozen leads in the CryoSat SIRAL data is the first step towards precise estimates of sea ice freeboard.

Usefulness of CryoSat data in the SSALTO/DUACS system contributing to the MyOcean Sea Level center

Dorandeu, J1; Dibarboure, G1; Picot, N2
1CLS, FRANCE; 2CNES, FRANCE

The CryoSat mission is operating over ocean surfaces providing a new source of valuable altimeter measurements. It represents an additional altimeter ocean mission complementary to existing Envisat, Jason-1 and Jason-2 missions in the operational multi-mission processing chain of the SSALTO/DUACS system. The crucial importance of this new mission is particularly evidenced in the frame of the Near Real Time processing contributing to the GMES MyOcean project. Indeed in the current altimetry context, both ENVISAT and Jason-1 missions have extended their nominal duration: redundancy of some components does not exist anymore onboard Jason-1. ENVISAT, having lost its S-band measurements, is now moved to another ground track inducing lower accuracy measurements. Consequently, the previous multi-mission configuration would have been degraded without the complementary CryoSat measurements. Even if not fully suited for ocean signals (single altimeter frequency, no radiometer wet troposphere measurement), the CryoSat mission is clearly an opportunity for improving the multi-mission ocean products. Results of the benefit of the CryoSat mission are shown from actual situations in which Near Real Time CryoSat data improve the ocean circulation mapping

Poster Session – Data Processing, Quality and Outlook for Improvement

Swath Processing SIRAL Interferometric Mode Data to determine Across-Track Elevation Profiles.

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CryoSat-2's Synthetic-Aperture Interferometric Radar ALtimeter (SIRAL) uses dual receive antennas to overcome some of the limitations of pulse-limited altimeters. In a normal interferometric-mode SIRAL measurement, the range and across-track direction of a scatterer are determined using the phase difference between the antennas.

We extend this technique to include the echoes acquired from the remainder of the coherent backscattered echo waveform, thus resolving elevation points across a swath orthogonal to the instrument ground track in regions of steep terrain, such as ice-sheet margins. At each location sampled within the waveform, the phase measurement provides the look angle and the time delay provides the range to the scattering surface. It is then a geometric translation, knowing the attitude of the antenna baseline, to determine the elevation of the ground location from which echoes are returned.

When applied to data from the airborne prototype altimeter ASIRAS, this method achieved a 75-fold increase in measurement density compared to conventional radar altimetry. We apply this method to new data from CryoSat-2's SIRAL instrument, and assess the effectiveness of using this "swath processing" to increase elevation measurement density in the presently undersampled steep margins of the ice sheets.

Features of CryoSat Level 2 Processing

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CryoSat is the first Radar Altimetry mission primarily designed to retrieve geophysical parameters from ice sheets rather than oceans. It embarks an advanced instrument with two operating modes (SAR and SARin) which are not found on traditional pulse-limited radar altimeters. The differences in surface targets and instrument design have required implementation of on-ground processing chains that have significant changes from previous missions.

The operational CryoSat level 2 processing chains have been developed and delivered by a team from MSSL with design input from scientists at UCL's Centre for Polar Observation and Modelling (CPOM). This talk will present an overview of the CryoSat level-2 processing chains, explain the new algorithms and high-light other differences compared to preceding processing schemes. We will also describe some particular features and fundamental differences of the associated level 2 data products.

First Assessment of the CryoSat-2 LRM Altimeter Measurements over Ocean

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CLS, FRANCE

To meet the challenges of measuring ice, CryoSat-2 carries a sophisticated radar altimeter called SIRAL (Synthetic Aperture Radar Interferometric Radar Altimeter) which is based on heritage from existing instruments, but with several major enhancements designed to overcome the difficulties intrinsic to the precise measurement of ice surfaces. Siral is a Ku-band instrument operating in three modes: Low Resolution Mode, SAR mode and SAR interferometric mode.

This paper proposes to make an overview of the results obtained in the low resolution mode at the instrumental level (calibrations, waveforms, altimeter estimates derived from the waveforms, corrections, ...). The main parameters will be assessed and their performances will be detailed mainly in terms of biases and noises. The LRM instrument being a replica of the Jason-2 altimeter, it is natural to compare these results with what is currently observed on Jason-2 altimeter and to point out similarities and discrepancies in relation with instrumental and processing characteristics.

Plans were for CryoSat to operate over the oceans for validation purposes, in low-resolution mode. An overview of the LRM instrumental performances seems thus of main interest to fully characterize the oceanic performances of the mission.

Assessment of the Current NRT Orbit Solution Quality

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Diode on board orbit solution software was created by Cnes in 1991. It is an integrated software to the Doris instrument that calculates real-time location and very precise velocity of the satellite. Since Diode was onboard the Spot 4 satellite on an experimental basis, this software fits out all altimetry satellites since Jason-1.

DIODE ephemeris are used for NRT processing. On Jason-2 mission a performance of the level of 3-4 centimeters on the radial component was demonstrated in orbit. On CryoSat-2 mission, the nadir performance demonstrated during the calval phase is of the order of about 10 cms. We intend to review the performance for the whole time life and review the way to further improve the nadir quality.

Improving Met File Processing for Ice Caps and Inland Bodies

Picot, N1; Obligis, E2
1CNES, FRANCE; 2CLS, FRANCE

CryoSat meteorological corrections (wet and dry) are derived thanks to the processing approach adopted for ENVISAT and Jason-1/2 missions.

This is based on the sum of the ECMWF model layers from the top of the atmosphere down to the surface of each ECMWF Gaussian grid model location. If this approach is fully acceptable over flat surfaces, this generates processing limitations over other surfaces. For example over ice caps, the ECMWF grid point altitude will not match the real altitude of the measurement location. This can be due to the grid resolution limitation: currently the processing is based on the use of the N400 resolution grids. Or to the error in the surface evolution used to define the Gaussian grid model elevation.

A Gaussian grid is rectangular. The gridpoints along the longitudes are equally spaced, while they are unequally spaced along the latitudes, where they are defined by their Gaussian quadrature. The N400 grid used includes 1600 grid points at the equator, so the resolution is 0.225 degrees which can be translated to about 25 kms.

We will analyse the limitation raised by such a processing approach and proposed a new method, experienced during PISTACH project for inland water bodies..

PDS LRM Product compared to CNES CryoSat Processing Prototype Outputs

Picot, N
CNES, FRANCE

CryoSat LRM data has been processed with the processing prototype developed by CNES. CryoSat Processing Prototype (C2P) has been developed internally to prepare the SAR processing study over ocean. In that frame, the LRM processing was also included and validated thanks to Jason-2 data.

C2P products are fully independent from the PDS official products and have been validated thanks to a comparison with Jason-2 operational products. This analysis was performed over ocean and the sea level differences are below 1 cm.

We will compare the PDS LRM Level2 products and propose a first assessment of the differences between those operational products with regard to the C2P products.

On the Need of Instrumental Correction Tables for LRM Processing over Ocean

Picot, N; Boy, F; Desjonqueres, JD
CNES, FRANCE

MLE retracking algorithms developed in the ENVISAT and/or Jason(1/2) ground processing approaches are based on the Hayne model (Hayne 1980), which is a refined analytical ocean return model derived from the Brown model and assumes that the instrumental Point Target Response (PTR) can be adjusted with a Gaussian function. To account for that Gaussian approximation, Look-up Correction Tables (LUT) are used on Jason1/2 missions while an Hamming window is used on ENVISAT mission.

Jason1/2 LUT are computed from Monte Carlo simulation of altimeter performance. This simulation tool is representative of the hardware and software complexity of the real altimeter. In this simulation tool, the real PTR of the altimeter is accounted for to generate realistic echoes, while a Gaussian approximation is considered in the retracking algorithm. LUT are statistically computed from thousands of simulations and are provided for range, significant wave height and sigma0. Specific LUT have to be derived for each retracking algorithm and they have to be updated whenever the PTR characteristics (e.g., power, width, and positions of main and side lobes) are significantly modified. We will present the impact of the Jason1/2 LUT on the retracking estimates and assess the need to implement such a table on CryoSat mission.

Using Radiometer flying Data to provide Accurate Wet Tropospheric Correction

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As CryoSat satellite dos not embark a radiometer, the wet tropospheric correction is derived from the ECMWF model.

Thanks to recent analysis conducted in the frame of the SWOT mission preparation, we will present another way to derive higher accurate wet tropospheric correction.

Indeed, the wet tropospheric correction (WTC) can be derived thanks to the use of AMSU flying data (AMSR-E water vapor observations). AMSR-E measurements are used to compute daily maps of the WTC which are then used to compute the CryoSat WTC. We will assess the quality of such a processing method thanks to a comparison on Jason-2 mission. The correction quality will be assessed with regard to the radiometer as well as to the ECMWF correction over ocean.

Operational Quality Control for CryoSat-2 Data performed by IDEAS

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As the main instrument of the CryoSat-2 mission, SIRAL will measure changes in the thickness of continental ice sheets and marine ice cover with unprecedented accuracy using three modes of operation. The performance and quality of the instrument and the data products are assessed by the routine operations activities of the IDEAS (Instrument Data quality Evaluation and Analysis Service) team. The main objective is to assure, on an operational basis, that the quality of the data products delivered to users meets their requirements. All information concerning product quality and data processing is then conveyed to the scientific and user community in order to allow them to use the CryoSat-2 data with confidence. This poster presents the different quality control checks which are performed by IDEAS for SIRAL in addition to details on how the quality reports may be accessed by users.

CryoSat-2 SIRAL Elevations, Waveforms, and Backscatter over Sea Ice and open Water

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We are currently examining the elevations, waveforms, and backscatter from the SIRAL mode over sea ice and open water in the data products released to the CryoSat-2 CVRT. Discrimination of ice and water is aided but the detection of openings in near coincident Envisat Synthetic Aperture Radar (SAR) imagery. We will show the sensitivity of the retrieved SIRAL range to expected changes in the surface elevation, and changes in the waveform characteristics associated with transitions from thicker sea ice floes to thin ice/open water.

Poster Session – Tools Available to PI's

Basic Radar Altimetry Toolbox: Tools and Tutorial to Use Radar Altimetry for the Cryosphere

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ESA and CNES had the Basic Radar Altimetry Toolbox developed a few years ago, and are improving and upgrading it to fit new missions, in particular the new ESA CryoSat-2 mission, and the growing number of uses of altimetry . The Basic Radar Altimetry Toolbox is an "all-altimeter" collection of tools, tutorials and documents designed to facilitate the use of radar altimetry data. The software is able: - to read most distributed radar altimetry data, from ERS-1 & 2, Topex/Poseidon, Geosat Follow-on, Jason-1, Envisat, Jason- 2, CryoSat and is ready for the future Saral/Altika and Sentinel-3 missions, - to perform some processing, data editing and statistics, - and to visualize the results. It can be used at several levels and in several ways: - as a data reading tool, with APIs for C, Fortran, Matlab and IDL - as processing/extraction routines, through the on-line command mode - as an educational and a quick-look tool, with the graphical user interface As part of the Toolbox, a Radar Altimetry Tutorial gives general information about altimetry, the technique involved and its applications, as well as an overview of past, present and future missions, including information on how to access data, additional software and documentation. It also presents a series of data use cases, covering all uses of altimetry over cryosphere, ocean and land, showing the basic methods for some of the most frequent manners of using altimetry data. It is an opportunity to teach remote sensing with practical training. It has been available from April 2007, and had been demonstrated during training courses and scientific meetings. About 1250 people downloaded it (September 2010), with many "newcomers" to altimetry among them, including teachers and professors. Users' feedback, developments in altimetry, and practice, showed that new interesting features could be added. Some have been added and/or improved in version 2. Others are under development, some are in discussion for the future. Data use cases on cryosphere applications will be presented. BRAT is developed under contract with ESA and CNES. It is available at earth.esa.int/brat and www.altimetry.info

CUT - CryoSat User Tool

Wu, Stephen; Martin Crespo, Felipe; Macrì, Francesco
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The CryoSat User Tool (CUT) is a light tool to help users to access the CryoSat dissemination ftp server for product selection and downloading. The CUT is a Windows stand-alone application that allows browsing and transferring of products from the archive incorporating a modern and intuitive Google Earth™-like interface. The product locations are graphically displayed on a 3D map as well as a timeline (Gantt chart). The user is assisted in product identification by such features as filtering on time and geographic areas which can be defined or imported from external sources.

Poster Session – Calibration and Validation Results

High-Altitude Glacier Observatory - Ground Truth for CryoSat-2

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The continuous monitoring of hydrometeorological and glaciological parameters including ice mass balances is essential to the observation of the cryosphere and their effect to the global climate change. CryoSat-2 with its SIRAL altimeter is well suited to monitor glaciers and glacier dynamics in high mountains. However, monitoring of the stability of the altimetric measurements and the ground truthing for year-around studies is the prerequisite for building long-term climate records.

In 2009, a glacier observatory was installed at the Inylchek Glacier (Kyrgyzstan) in the Tian Shan mountain area. In the first year, the observatory consisted of only one station measuring GPS and basic meteorology components. In 2010 it was extended by further stations with a wide range of hydrometeorological sensors. The monitoring stations automatically measure parameters such as air temperature, air pressure, relative humidity, precipitation, wind speed and direction, solar radiation and snow parameters including the snow depth as well as high-rate GPS data. In addition, a kinematic station was directly installed at the glacier surface. This station measures the kinematic glacier motion, changes in glacier heights and, additional, the snow depth.

With the wide range of sensors, the data is used for several applications like glacier mass balance, monitoring of geodynamic processes and water resources management in Central Asia. As the stations provide snow coverage and ice thickness data from a glacier in Central Asia where hardly hydrometeorological stations are existing, the observatory is, therefore, well suited to provide the necessary long-term ground truthing and calibration for CryoSat-2.

Digital Elevation Models from Ground-Based GPS as Validation Areas for Satellite Altimetry on the Greenland Inland Ice

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A long-term geodetic project on the Greenland inland ice is performed in order to determine elevations, elevation change, flow velocity, and deformation of the ice surface in the western part of the Greenland ice sheet. There are two main research areas. The first research field at Swiss Camp (ETH/CU-Camp) was started in 1991. Until 2008 a total of 10 measuring campaigns were carried out.

The second research field (ST2) was established in 2004. It is situated 170 m lower than Swiss-Camp. Here we have now four campaigns in 2004, 2005, 2006 and 2008. The 3D-coordinates of the snow and ice surfaces were measured by ground-based static and kinematical GPS survey. As a result very precise ellipsoidal heights (WGS84) of distinctive points and digital elevation models of the research areas are available.

The digital terrain models can be used as ground control areas for satellite altimetry. As an example, they were used for evaluation and validation of ICESat satellite elevation data. Height comparisons along one track show in average a discrepancy of 0,13 m +- 0,06 m.

Due to their very high accuracy, the measured areas can also be used as control areas for CryoSat. The next field measurements are planned in summer 2011. The location of the ground measurements will be coordinated with predicted tracks for CryoSat.

Summer 2010 in Situ Data in Pacific Arctic Sector, Potentially Valuable for Cal/Val of CryoSat Sea Ice Thickness

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The Fourth Chinese National Arctic Research Expedition (CHINARE) from July 1 to Sep. 20, 2010, conducted ocean-ice-ecosystem-atmosphere study in the Pacific Arctic sector, in particular between 150°W to 180°W to 88.5°N. Sea ice thickness measurements were performed at 8 short-term ice stations and one long-term ice station using electromagnetic induction sounding (EM31). At each point, two data are recorded, one with the instrument's longitudinal direction parallel to the walk direction and the other with the instrument's longitudinal direction perpendicular to the walk direction. The mean of the two readings in one point is counted as the point reading. The reason for doing this is to deal with the thickness heterogeneity of sea ice in different extents. The EM-estimated thicknesses were compared with borehole-drilling thicknesses. The error found is between 3-7%. In each short-term ice station, one or more profiles covering the work zone were surveyed with a fixed sampling interval of approximately one meter (two steps). In the long-term ice station (~86.92°N-87.33°N), a grid of 8 profiles of 100 meters in work zone 2 and two other profiles (200m and 125m) in work zone 3 were surveyed with repeat intervals of 3 to 4 days. A mean of 1.6cm per day in ice melting (primarily bottom melting) is obtained at the long-term station from Aug 10-19. The mean sea ice thickness at the long-term ice station is ~1.8m, while it is from 1.2-2.1m for the 8 short-term ice stations. Those thicknesses data are valuable in calibrating/validating CryoSat sea ice thickness, if available for the time and for the region.

First Experiences with CryoSat-2 LRM Data

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Although not part of the basic mission objectives the use of CryoSat-2 LRM data acquired over ocean is of particular interest for the cross-calibration with other altimeter systems and the spatial and temporal densification of their measurements. The available Level 2 LRM data of CryoSat-2 is taken to check its consistency with Jason-1, Jason-2, and ENVISAT measurements, to perform a preliminary cross-calibration, and to assess the accuracy of CryoSat-2 radial component.

Satellite Calibration and Validation Experiments over Arctic Sea Ice in the Vicinity of Svalbard

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Combined satellite surveys and in situ sea ice observations are crucial for the calibration and validation of data retrieved from satellite products. However, coordinated campaigns with both high resolution satellite surveys, and ground and airborne sea ice surveys are rare. In August and September 2010, in situ observations on Arctic sea ice were performed at the end of the summer melting season north of Svalbard at the edge of the Arctic Basin, and in the Fram Strait. High resolution Radarsat-2 SAR images were obtained with both dual and quad polarizations. Simultaneously, data about sea ice and snow thickness, ice topography, and the area of melt ponds was collected, along with ship-based regular ice observations. A helicopter performed ice thickness surveys using an electromagnetic device, accompanied with automatic digital photography and laser altimetry. The electromagnetic method was also used for the calibration and validation of data from the new CryoSat-2 radar altimetry satellite. Data on snow and sea ice properties including densities, thicknesses, freeboard, have been collected over several years for calibration of satellite altimetry. These are necessary background data for estimating the sea ice thickness from the measured freeboard. The preliminary results indicate the improved possibilities for ice type classification from SAR satellite imagery. Data collected for CryoSat-2 calibration and validation will contribute to improved data quality in the derivation of ice thickness from freeboard measurements, to be retrieved from the satellite measurements during the coming years.

Impact of the LRM Waveform Centering on Retracking Estimates

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Over an ocean surface, the echo waveform has a characteristic shape that can be described analytically (the Brown model). Surfaces which are not homogeneous, which contain discontinuities or significant slopes, such as some land surfaces, make accurate interpretation more difficult.

Over land ice surfaces, the echo waveform complies also often to the Brown model. The ocean retracking algorithm developed for ENVISAT and called ocean1 is so commonly used.

In this paper, we will address the impacts of the LRM waveforms centering on the ocean1 estimates (MLE3 retracking based on Brown model).

First an analysis will be conducted on ENVISAT and CryoSat flying data to compare the mean wave form centering value over ice surfaces. Then the potential data quality impact will be assessed on simulated data.

SIRAL Internal Calibration: Commissioning and Beginning of Operation Phase Results

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SIRAL performs regularly 4 types of calibrations: (1) CAL1 in order to calibrate the internal path delay and peak power variation, (2) CAL2 in order to compensate the instrument transfer function, (3) CAL4 to calibrate the interferometer and (4) AutoCal, a specific sequence in order to calibrate the gain and phase difference for each AGC setting. An additional calibration has been added in order to calibrate the ADC (Analogic to Digital Converter) phase difference distortion at low power. Results during commissioning phase reveal high stability of the instrument which makes possible a reduction of the calibration frequency during operation with the initial planning.

Internal calibration data are processed on ground by the CryoSat-2 Instrument Processing Facility (IPF) and then applied to science data.

Here we will present both (a) the results obtained so far from instrument point of view (raw data) and (b) the

key calibration parameters extracted/computed by the IPF1, their stability over time and their application to the science data

First Impressions and Operational use of CryoSat-2 Data over Oceans

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Since December 2010, the CryoSat-2 Low Resolution Mode (LRM) data have been fed operationally into the RADS altimeter data base. This data base, developed and maintained jointly by NOAA, Altimetrics and TU Delft, contains 1-Hz data for all altimeters since Geosat, in a common format, with common standards and intercalibrated so that the data can be used easily by experts and non-experts alike.

Apart from the measurement and model data found on the original Geophysical Data Records (GDRs), RADS features a multitude of additional data fields, common across all mission, current and historical, to facilitate verification of the various data fields from the GDRs and facilitate cross-calibration of the various missions. Special attention has been paid to ensure that the GDR data fields are according to specification.

Currently, CryoSat-2 data is pushed into RADS twice-daily and is already used by various RADS users to augment the data take from Jason-1, Jason-2 and Envisat. Because of the common data format, virtually no additional work had to be done by these users to add CryoSat-2 as data input to their modelling efforts.

The CryoSat-2 data (range, sigma0 and SWH) has been cross-calibrated against the other current missions and sea level records have already been verified against tide gauges. Although 2-3 months of data is short, a first glimpse at a sea state bias model will be provided.

LRM Processing over Ice Inland Bodies, first Analysis using Local DEM and a Comparison to ENVISAT Data

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The altimeter LRM mode is used over major part of the ice inland bodies. This includes the Antarctica and the Greenland interiors. Altimeter ground processing of those data includes the MLE3 ocean1, one of the retracking solutions implemented. This processing, based on brown model, has also been used on ENVISAT.

We will compare the retracking estimates between CryoSat and ENVISAT and also compare the PDS LRM products elevation with regards to digital elevation models like the Bamber model.

The Calibration of CryoSat-2 using a new Microwave Transponder

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The Gavdos calibration facility has been operational as of 2004 for satellite radar altimeters. The site has been used for the calibration of Jason-1 and Jason-2 as well as of the Envisat satellite altimeters. Up to now, different techniques have been applied for determining the absolute biases of oveflown satellites using in-situ observations made by tide gauges, GPS receivers, meteorological and other sensors in conjunction with the precise values of geoid undulations. In addition, a microwave transponder has been also used for satellite calibration.
In 2009-2010, a new transponder has been developed for the calibration of CryoSat-2 not only to determine the altimeter bias but also to establish the orientation and the baseline length of the interferometer in orbit. This paper will describe the technical characteristics of the new microwave transponder and will outline the software procedures to be followed during a calibration process for the determination of the interferometer and altimeter biases for CryoSat-2.

Global Monitoring and Validation of the CryoSat-2 Ocean Wind and Wave Products

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The plan is to present the global validation of the CryoSat-2 ocean wind and wave products. The comparison will be done against ECMWF model products as well as available buoy products and the altimeter products of other missions. Till now we have not received any ocean data. We hope to have enough data well before the start of the workshop.

Potential for Improving Global Marine Gravity from CryoSat and Jason-1

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Marine gravity anomalies derived from radar altimeter measurements of ocean surface slope are the primary data for investigating global tectonics and seafloor bathymetry. The accuracy of the global marine gravity field is limited by the availability of non-repeat altimeter data. Current models, having accuracies of 3-5 milligals (e.g., S&S V18 and DNSC08), are based on the non-repeat data collected by Geosat (18 mo.) and ERS-1 (12 mo.) which use altimeter technology from the 70's and ', respectively. The next opportunities for significant improvements in marine gravity will come from CryoSat and perhaps Jason-1 if it is placed into a non-repeat orbit. In addition to complete ocean coverage, the three attributes needed for improved gravity are improved range precision, optimal satellite inclination, and long mission duration. Range precision is established through a coherence analysis of repeating profiles. We will use these standard methods to assess the range precisions of CryoSat and Jason-1 in relation to Geosat, ERS, Topex, and Envisat. We expect that the higher PRF's of the newer altimeters will provide a square root of 2 improvement in range precision. The low inclination of the Jason-1 orbit offers the best opportunity for improvement in the E-W variations in gravity, especially at low latitude. The hopefully, long mission duration of CryoSat provides the best opportunity for reducing the noise due to ocean surface roughness from swells. Data from these two missions may eventually result in a factor of two improvement in the accuracy of the marine gravity field and geoid at scales less than 100 km.

Ku-Band Radar Penetration into Snow over Arctic Sea Ice

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Results from airborne validation campaigns of the CryoSat Validation Experiment (CryoVEx) over sea ice in the Arctic are presented. For the estimation of sea ice volume trends, precise ranging of the CryoSat-2 altimeter over snow covered sea ice is essential. We use ASIRAS, an airborne version of SIRAL in conjunction with a sidescanning laser-altimeter to estimate freeboard, the height of sea ice floating above the water level for both wavelengths. The difference of both altimeters can be used as a measure for the penetration of Ku-Band radar waves into the snow pack since the laser is always reflected at the top snow surface. In addition, high resolution digital elevation models of the laserscanner are used to estimate sub-footprint scale surface roughness and its impact on the radar range retrieval. With extensive airborne surveying, we were able to cover a large area with different sea ice types and surface conditions in the Arctic Ocean. We find a regional variable penetration of the radar signal at late spring conditions, where the difference of the radar and the reference laser range measurement was always less than the expected snow thickness. In addition, a rough surface can lead to biases of the airborne validation dataset, since the radar overestimates the amount of open water and thin ice as well the freeboard of heavy ice deformation zones.

Poster Session – Exploitation of CryoSat Data

Initial Results of CryoSat-2 Data from the Arctic

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DTU Space exploits CryoSat-2 data both for sea-ice and land-ice applications. We will show some examples of processed data and present comparisons to earlier cal/val data with focus on sea-ice.

We apply CryoSat-2 data to detect open leads in the area north of Greenland at the Fram Strait, and compare the results with Envisat ASAR images. Corrections for the drift of sea-ice are done with drift vector estimates for overlapping SAR swaths. We will furthermore, classify the sea-ice from computed freeboard values and evaluate the coherence between the SAR backscatter and the CryoSat-2 data.

Sea Ice Measurements with CryoSat-2 and SAR

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Sea ice is an integral and sensitive part of the Arctic climate system. At the same time simulated sea ice in the Arctic shows high uncertainties in climate models. This is partly due to differences in large scale circulation, regional Arctic non-linear interaction and the parameterizations within the sea ice model component. Recent changes in the Arctic sea ice cover have illustrated the need for increased simulation capabilities. For climate modelling, a pressing need for Arctic climate projections on the five-to-ten year time scale (decadal prediction) has become more obvious.

In a project formed to validate the coupled ice-ocean model RCO-HELMI, the possibility to use data from CryoSat-2 SIRAL, Envisat ASAR and ALOS PALSAR to estimate thickness, concentration and drift of the ice is of great importance. Data acquired is intended to be used for the validation of the multi-category sea-ice model and for initialization of the sea ice field.

Combined altimeter and SAR data will be used to derive the state and variability of the Arctic sea ice volume through measurements of sea ice thickness, sea ice concentration and sea ice drift. The project will focus on the important regions of the Arctic Sea, i.e. the Fram Strait between Greenland and Svalbard. The preferred approach will be to model altimeter and SAR backscatter from sea ice and to make comparisons with laser mapping by helicopter. The long term goal is to contribute to the development of products that can be used for data assimilation in climate models and earth system models. The first task will be to review the user needs with respect to the performance of SIRAL.

Constraining Ice Sheet mass Balance Trends using CryoSat-2 and Laser Altimetry

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The mass balance of the Antarctic and Greenland is required to assess their contribution to sea level rise as well as evaluate their sensitivities to variable future forcings. There is general agreement that the ice sheets are losing mass and that loss may be increasing. However, the range of estimates and the uncertainty in those estimates is in many cases, larger than the signal measured, particularly in a regional sense. CryoSat-2 will improve on the legacy satellite measurements from ERS-1 and -2 by using its interferometric model to determine elevation on steep slopes and through it's greater across "C track resolution. The new technique will overcome many of the limitations of previous radar altimeters but elevations will still suffer from variable penetration in the firn and errors due to short-wavelength roughness. This poster will introduce a new project to explore these possible issues. We will use NASA Operation Ice Bridge to assess biases in absolute elevation and elevation rates from CryoSat2 data. We will focus on the first 12\18 months of the mission so that variability in penetration and echo shape due to seasonal temperature, melt and accumulation variations can be assessed. The aim will be to quantify biases and develop algorithms to correct for them. This will allow us to determine the likely improvement in mass balance estimates from CryoSat-2 as compared to legacy datasets as well as to create the higher accuracy elevation datasets needed to improve mass budget estimates of mass balance and needed for InSAR and stereo-photogrammetry studies.

The Role of Firn in the Interior Part of the Greenland Ice Sheet - Correction of Surface Elevation Measurements

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In the interior part of ice sheets, firn is compressed by the overburden pressure. This process of converting snow into ice is known as firn densification. Changes in the compaction rates of the firn have been shown by Sorensen et al. 2010 to be the most prominent correction factor when converting the volume change measured by ICESat into equivalent mass changes of the Greenland ice sheet. Knowledge of the stratification and changes in density of the interior part of the Greenland ice sheet becomes even more important when radar altimetry is used. Since the measured elevation of the ice sheet depends on the density of the surface material.

Here we present a model for estimating the firn densification and the resulting stratification of the upper part of the Greenland ice sheet. This model can be used to give a better estimate of elevation changes of the Greenland ice sheet using CryoSat. We will also outline how the CryoSat can be used to estimate present mass loss of the Greenland ice sheet.

Citation: Sorensen, L. S., Simonsen, S. B., Nielsen, K., Lucas-Picher, P., Spada, G., Adalgeirsdottir, G., Forsberg, R., and Hvidberg, C. S.: Mass balance of the Greenland ice sheet - a study of ICESat data, surface density and firn compaction modelling, The Cryosphere Discuss., 4, 2103-2141, doi:10.5194/tcd-4-2103-2010, 2010.

Surface Movement and Mass Balance at the NEEM deep Drilling Site, North Greenland, and Comparison with Satellite Data

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In this work we present preliminary results from a surface GPS survey near the NEEM drill site in North Greenland, and compare the resulting surface movement and calculated mass balance with data from the ICESat, GRACE, and CryoSat satellite missions.

The NEEM deep drilling site (77.45□‹N 51.06□‹W) is located at the main ice divide in North Greenland. A strain net has been established around the NEEM site in 2007 and re-surveyed with GPS in 2008, 2009, and 2010. The strain net consists of a reference pole and 12 poles placed in three diamonds at distances of 2.5, 7.5 and 25 km, respectively, from the reference pole. The reference pole has been measured each year to provide the horizontal and vertical movement from 2007 to 2010. Preliminary data show that the ice flow along the ice divide is W-NW with an average horizontal surface velocity at NEEM of 5.8□}0.3 m/a along the ridge, and we estimate surface strain rates at NEEM to be (3.6□}1.9)·10^{-5} a^{-1} (longitudinal) and (13.1□}0.4)·10^{-5} a^{-1} (transverse), i.e. flow is divergent and slightly extending along the ridge. Radar layers along the ridge upstream from NEEM have been analyzed and inverted to provide upstream accumulation rates, basal melt rates, and velocity depth profiles. Surface velocities and velocity depth profiles provide an estimated ice flux used to infer the local rate of ice thickness change from the depth-integrated continuity equation. Using preliminary results, we estimate the local rate of ice thickness change to be □ÝH/□Ýt = (-0.01□}0.17) m/a. We find agreement between our estimate and the surface elevation change in the NEEM area obtained by the ICESat mission.

We combine all available data, including surface strain rate data at NEEM and at NorthGRIP (previous drill site 1996-2003 located at the main ridge 365 km upstream from NEEM) and internal radar layers between NorthGRIP and NEEM, to discuss the flow pattern along the ridge and in particular the surface movement at the NEEM site. We compare our results with observations of the Greenland ice sheet from the ICESat, GRACE, and CryoSat satellite missions, and discuss the mass balance and possible implications for the dynamic stability of the ice sheet in this region.

Recent Trend and Interannual Variability of the Sea Ice Cover Modeled by a Global ¼° OGCM

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The Mercator Ocean modeling team designed the new global ¼° configuration for the Mercator reanalysis (1992-2009) launched in fall 2010. Among others changes, this update comprised a shift from NEMO1 to the NEMO3 code, the explicit implementation of the diurnal cycle in the air/sea and air/ice exchanges and the use of the CORE bulk formulation. An ensemble of modifications (tagged 'LIM2-EVP') has also been implemented in the sea ice model LIM2. In order to avoid the peculiar trends present in the ECMWF analysis forcing, and also to take into account the recent improvements made by ECMWF, we used the ERA-interim reanalysis products. A method of correction towards the Gewex satellite data has been applied on the downwelling surface radiative fluxes. This correction is made from 65°N to the Antarctica. Then, atmospheric ad-hoc corrections over the high latitudes are described and implemented. With all these changes, we performed a 21-years runs over the ERA-interim period (1989-2009). The results are discussed in terms of trends, interannual variability and seasonal cycle of the sea ice cover in both hemispheres. Validation of the experiment is made with comparisons with satellite observations. Results are focused on the sea ice fraction and the sea ice drift, quantities which are identified as control variables (in the state vector) for the future Mercator Océan sea ice assimilation system. Strong interannual variability correlations (up to 0.9) of both sea ice fraction and sea ice speed are found between the experiments and the observations. Even if the experiment shows an overestimation of the melting processes during the recent summers, it is able to capture the extremes events. Based on these positive results discussions are made on the long term trend obtained with the modeled Arctic sea ice volume. Conclusions present the feasibility for integrating the CryoSat data in the Mercator operational system in real time analysis and hindcasts (reanalysis) purposes.

Altimeter as a high resolution Imager of the Surface Backscatter over sea ice and ice sheets

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1IFREMER, FRANCE; 2CNES, FRANCE

High resolution (20 Hz) altimeter waveforms contain a wealth of information that is not yet fully exploited. Over sea ice as well as ice sheets, land or rivers (if the topography is smooth enough) an altimeter can be seen in a first order approximation as an imager of the surface backscatter whose pixels are annular and not rectangular. Each element of a waveform is thus the sum of all the surface elements backscatter which has the same range. The imaging matrix of an altimeter only depends on the geometrical characteristics of the orbit and of the sensor. It is possible to compute this matrix which represent and over-determined linear system and can thus be inverted. A group of high resolution altimeter waveforms, can thus be inverted to infer the surface backscatter at a resolution of some hundred meters. The method can be applied to analyze the time and space variability sea ice at high resolution and for example to discriminate between first and multi-year ice. The analysis of the difference between the estimated Ku- and C or S-band high resolution backscatters can also be used to better discriminate the ice characteristics. Over ice sheets (such as the Greenland one) the topography is smooth enough to allow the inversion and can be used to estimate the presence of liquid water. The high resolution backscatter surface fields from Jason-2 or Envisat altimeters are very complementary to the CryoSat data and could help to better understand the small scale variability of se ice and ice sheets.

The DTU10 Mean Sea Surface for and with CryoSat-2

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The DTU10MSS mean Sea Surface (MSS) is a new mean sea surface particularly useful for CryoSat-2 altimetry. The DTU10MSS is the state of the art mapping of the mean sea surface height of the world's oceans, derived from a combination of 17 years of satellite altimetry from a total of 8 different satellites covering the period 1993-2009. It is the first and only global MSS without a polar gap including all of the Arctic Ocean by including 17 epochs of lowest level filtered ICESat mission and adjusted geoid data from the ArcGP to close the Polar gap above 86N.

The DTU10MDT Mean Dynamic Topography (MDT) is the quantity that bridges the geoid and the mean sea surface constraining large scale ocean circulation. Here we present a new high resolution 1 minute global MDT called DTU10MDT derived from the slightly smoothed difference between the DTU10MSS and the EGM2008 geoid.

The first test with CryoSat-2 data LRM and SAR mode data are presented in the Arctic Ocean where the data will be used to validate the DTU10MSS in the Arctic Ocean particularly along the 82 and 86 parallels where altimetry from ENVISAT and ICESat, respectively cease to cover.

Poster Session – International Context Including Synergies with Programmes from Other Space Agencies

SAR Data over Ocean, CNES Proposed Processing Strategy and Continuity with LRM Data

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The nadir looking SAR altimeter concept has been studied in parallel in ESA and the US since the mid 1990s. This concept is now implemented in SIRAL instrument operating on board CryoSat-2 mission launched early 2010, and dedicated to ice topography observations. However, this novel altimeter concept can be very advantageous for observation of ocean surfaces, as it promises improved altimetric precision and better along-track resolution than conventional pulse-limited altimeters. This will allow to achieve high-resolution high-accuracy altimetric mapping of the ocean in regions of high mesoscale variability and in coastal areas. Several studies are ongoing to develop and test suitable processing algorithms for this new altimeter mode. This paper will present the ongoing study on CNES side using simulated tools and CryoSat-2 flight data provided by the CryoSat project. In particular the continuity between SAR and LRM products will be addressed.