

ABSTRACT BOOK

## **North-American CryoSat Science Meeting**

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## 2 Committees

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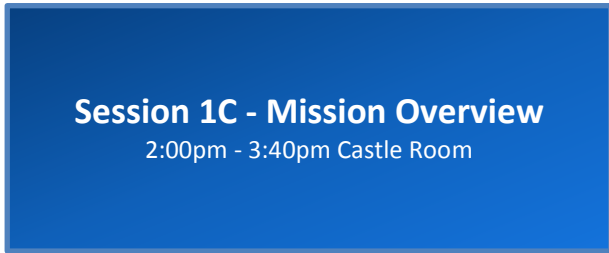
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### 3 Abstracts



#### **CryoSat Mission. 7 years in Operations: Status and Achievements**

*Tommaso Parrinello, CryoSat Mission Teams  
ESA, Italy*

CryoSat mission will reach its 7th years of operational life in April 2017. Since its launch, it has delivered high quality products to the worldwide cryospheric and marine community that is increasing every year. Scope of this paper is to describe the current mission status and programmatic highlights on the next scientific development of the mission in its extended period of operations.

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#### **Cryosat - Scientific Highlights**

*Andrew Shepherd  
University of Leeds*

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#### **Cryosat - Validation Campaigns**

*Mark Drinkwater  
European Space Agency*

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#### **CryoSat Product Evaluation & Evolution after 7-years in Operation**

*J rome Bouffard<sup>1</sup>, Tommaso Parrinello<sup>2</sup>, Pierre F m nias<sup>2</sup>  
<sup>1</sup>RHEA c/o ESA, Italy; <sup>2</sup>ESA*

CryoSat, the 1st Polar European Mission, is equipped with a Ku band radar altimeter, operating in 3 modes (LRM, SAR, SARin). The main mission objectives are to measure the regional and basin-scale changes in the thickness of sea-ice and, in the elevation of the ice sheets and mountain glaciers. Beside its ice-monitoring objective, CryoSat also provides valuable observations for ocean scientific and operational applications. To achieve these goals, the CryoSat data are processed by ESA both over the Ice and the Ocean surfaces with two independent processors. The ice products are generated with the Baseline C ice processors, including processor upgrades such as an improved retracker

optimized for the freeboard retrieval. The CryoSat Ocean data are currently generated with the Baseline B CryoSat Ocean Processors (COP), operating since April 2015. The CryoSat ice and ocean products have to meet the highest performance. In this respect, the ESA operational data need to be routinely Quality-Controlled and thoroughly Validated (QCV). Based on the QCV outcomes from ESA multi-national partners and the feedback from the Scientific user Community, the data products continuously evolve in order to accommodate a wide range of users focused on the Sea ice, Land Ice and Ocean domains. The main objectives of this paper are to give an overview of main QCV results and product improvements made possible over the past 7-years; as well as to present the processing algorithm upgrades being implemented for future ice and ocean Processing Baselines.

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#### **The Sentinel-3 Altimetry Land Mission: Overview and Status of Operations**

*Pierre F m nias, Susanne Mecklenburg  
ESA ESRIN, Italy*

The Copernicus Programme, being Europe’s Earth Observation and Monitoring Programme led by the European Union, aims to provide, on a sustainable basis, reliable and timely services related to environmental and security issues. The Sentinel-3 mission forms part of the Copernicus Space Component. Its main objectives, building on the heritage and experience of the European Space Agency’s (ESA) ERS and ENVISAT missions, are to measure sea-surface topography, sea- and land-surface temperature and ocean- and land-surface colour in support of ocean forecasting systems, and for environmental and climate monitoring. The series of Sentinel-3 satellites will ensure global, frequent and near-real time ocean, ice and land monitoring, with the provision of observation data in a routine, long-term (up to 20 years of operations) and continuous fashion, with a consistent quality and a high level of reliability and availability.

The Sentinel-3 mission is jointly operated by ESA and EUMETSAT. ESA is responsible for the operations, maintenance and evolution of the Sentinel-3 ground segment on land related products and EUMETSAT for the marine products. All facilities supporting the Sentinel-3 operations are in place and operational:

- Data acquisition and near real time (NRT) product generation, including data downlink and processing (NRT and offline) will be performed at Svalbard station,
- Processing and Archiving Centres (PAC), which will perform the Sentinels’ systematic non-time-

critical data processing, the on-the-fly data processing for specific cases and the reprocessing in case of processing algorithms or calibration parameters upgrades:

- OLCI processing and archiving will be performed at DLR,
- SRAL processing and archiving will be performed at CLS,
- SLSTR and Sentinel-3 synergy products processing and archiving will be performed by ACRI,
- EUMETSAT's marine centre acts as PAC for marine products.
- Missions Performance Centre (MPC): Operational Quality Control, Expert Support Laboratories (ESL), Calibration and Validation
- Sentinels POD Service, which generate the orbit products for the Sentinels-1, -2 and -3 missions and perform the performance monitoring of the GNSS sensors.

The Sentinel-3 ground segment systematically acquires, processes and distributes a set of pre-defined core data products to the users. For a detailed description of the core data products please see <https://earth.esa.int/web/sentinel/missions/sentinel-3/data-products>.

This paper will provide an update on the status of the ground segment operations for the Sentinel-3 mission since launch, including an outlook on the performances of the Altimetry Land products and ground processing.

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**Invited - Keynote: Understanding Inter-annual Variability, and Long Term Trends, in Polar Sea Ice using Satellite Laser and Radar Altimetry: Current Achievements and Future Prospects**

*Sinead Farrell  
NOAA Affiliate*

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**Monthly Variability of Sea Ice Thickness from CryoSat-2**

*Ron Kwok  
Jet Propulsion Laboratory, California Institute of Technology, United States of America*

Monthly changes in CryoSat-2 sea ice thickness can be separated into changes due to dynamics and ice growth using estimates of ice deformation calculated from large-scale ice drift. Over a region of persistent convergence north of the coasts of Greenland and the Canadian Arctic Archipelago, divergence and shear explain up to 69% monthly thickness variability in CryoSat-2 thickness estimates. The estimated area-averaged growth of  $0.12 \pm 0.03$  m/month compares with measurements from ice mass balance buoys of about 0.14 m/month. It can be seen in the mechanical redistribution process that areas covered by ice  $< 3$  m are reduced, while areas of thicker ice ( $> 3$  m) increased. Ice convergence near the Arctic coasts of Greenland and the Canadian Arctic Archipelago (CAA) is a source of some of the thickest ice in the Arctic and alters the response of the ice cover to atmospheric and oceanic forcing at different time and space scales. The thicker, more deformed ice adds to the variability and challenges the predictability of the ice cover in during summer melt. The signature of ice convergence on the behavior of the summer ice cover is discussed.

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**Drop of Arctic Sea-Ice Growth in Winter 2015/16 Observed with Merged CryoSat-2/SMOS Data Record**

*Robert Ricker<sup>1,2</sup>, Stefan Hendricks<sup>1</sup>, Fanny Girard-Arduin<sup>2</sup>, Lars Kaleschke<sup>3</sup>, Camille Lique<sup>1</sup>, Xiangshan Tian-Kunze<sup>3</sup>, Marcel Nicolaus<sup>1</sup>, Jennifer King<sup>4</sup>, Christian Haas<sup>1</sup>, Stephan Paul<sup>1</sup>*

*<sup>1</sup>IFREMER, France; <sup>2</sup>AWI, Germany; <sup>3</sup>University of Hamburg, Germany; <sup>4</sup>Norwegian Polar Institute, Norway*

A new record low in Arctic sea-ice maximum winter extent has been observed in 2016, associated with an anomalous warm winter. The high winter temperatures lead to reduced thermodynamic ice growth associated with a thinner first-year sea-ice cover in spring. This can also have consequences for the melt season, since, in addition to the summer conditions, it is crucial how thick and resistant the ice cover is in spring, at the end of the freezing period. Previous studies have shown that preconditioning through a thinned ice cover substantially contributed to the ice extent record minimum in September 2012. Sea-ice thickness on global scale is derived from different satellite sensors using independent retrieval methods. Due to the sensor and orbit characteristics, such satellite retrievals differ in spatial and temporal resolution as well as in the sensitivity to certain sea-ice types and thickness ranges. Satellite altimeters, such as ICESat or CryoSat-2, sense the height of the ice or snow surface above the sea level, and can be converted into sea-ice thickness assuming hydrostatic balance. However, relative uncertainties associated with this method are largest over thin ice regimes, where surface elevations are small. Another retrieval strategy is realized by the evaluation of surface emissivity in L-band, obtained from the Soil Moisture and Ocean Salinity (SMOS) satellite, which is restricted to the thin

first-year sea-ice thickness range, where relative uncertainties are smaller than those of altimetry-based retrievals. In addition, the SMOS retrieval provides complete coverage in conjunction with a better temporal resolution over sea ice in lower latitudes. Here, we use the first joint data fusion of CryoSat-2 and SMOS ice thickness retrievals to investigate how the Arctic-wide anomalous warm winter in 2016 has affected the thermodynamic ice growth and the sea-ice thickness in spring. We evaluate ice thickness and volume anomalies in 2016 with respect to previous years, also considering the role of ice dynamics.

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**Towards Climate Data Records of Arctic and Antarctic Sea Ice Thickness from CryoSat-2 and Envisat Radar Altimetry**

*Stefan Hendricks<sup>1</sup>, Eero Rinne<sup>2</sup>, Stephan Paul<sup>1</sup>, Robert Ricker<sup>1</sup>, Henriette Skourup<sup>3</sup>, Stefan Kern<sup>4</sup>, Stein Sandven<sup>5</sup>*

*<sup>1</sup>Alfred Wegener Institute, Germany; <sup>2</sup>Finish Meteorological Institute, Finland; <sup>3</sup>Danish Technical University, Denmark; <sup>4</sup>Universität Hamburg, Germany; <sup>5</sup>Nansen Environmental and Remote Sensing Center, Norway*

The CryoSat-2 mission has demonstrated the value of radar altimetry to assess the interannual variability and short-term trends of Arctic sea ice over the existing observational record of 7 winter seasons. CryoSat-2 is a particularly successful mission for sea ice mass balance assessment due to its novel radar altimeter concept and orbit configuration, but radar altimetry data is available since 1993 from the ERS-1/2 and Envisat missions. Combining these datasets promises a decadal climate data record of sea ice thickness, but inter-mission biases must be taken into account due to the evolution of radar altimeters and the impact of changing sea ice conditions on retrieval algorithm parameterizations. Particular challenges are the classification of surface types and freeboard retrieval based on radar waveforms because of the significantly varying footprint sizes of the instruments involved. However, consistent decadal time series from radar altimetry has the prospect for cross-calibration of sea ice thickness estimates from CryoSat-2 and ICESat and for investigation of decadal trends of sea ice thickness.

The ESA Climate Change Initiative on Sea Ice aims to extent the list of data records for Essential Climate Variables (ECV's) with a consistent time series of sea ice thickness from available radar altimeter data. We will report first results and uncertainty estimates for sea ice thickness retrieval in the Arctic and Antarctic Oceans from CryoSat-2 and Envisat and the planned release cycle of the sea ice thickness climate data record.

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## Session 2A – Sea-ice thickness retrieval and validation #1

8:30am - 10:10am Castle Room

**Impact of Ice and Snow Properties on Freeboard Retrieval and Sea-Ice Thickness Calculation from ALS, ASIRAS and CryoSat-2**

*Jennifer King<sup>1</sup>, Henriette Skourup<sup>2</sup>, Sine M. Hvidegaard<sup>2</sup>, Gunnar Spreen<sup>3</sup>, Anja Rösel<sup>1</sup>, Sebastian Gerland<sup>1</sup>, Veit Helm<sup>4</sup>, Chris Polashenski<sup>5</sup>, Glen E. Liston<sup>6</sup>, J. Wilkinson<sup>7</sup>, M. Granskog<sup>1</sup>*

*<sup>1</sup>Norwegian Polar Institute, Norway; <sup>2</sup>DTU Space, Denmark; <sup>3</sup>University of Bremen, Germany; <sup>4</sup>Alfred Wegener Institut, Bremerhaven, Germany; <sup>5</sup>U.S. Army Cold Regions Research and Engineering Laboratory – Alaska, USA; <sup>6</sup>Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University, USA; <sup>7</sup>British Antarctic Survey*

Current freeboard and associated sea-ice thickness retrievals from the SIRAL radar altimeter on the CryoSat-2 satellite rely on the premise that the return signal measured is from the ice surface. However, it has been indicated that where a thick, or wet, snow cover is present this return may arise from somewhere within the snowpack rather than from the snow-ice interface. We present a case study in which co-located freeboard measurements from airborne laser scanner (ALS), the Airborne Synthetic Aperture and Interferometric Radar Altimeter System (ASIRAS) and CryoSat-2 are compared to ice thickness measurements from both helicopter-borne and ground based electromagnetic-sounding, and to point measurements of ice properties (ice thickness, density, and freeboard; and snow thickness and density). This case study was performed in the Arctic Ocean in April 2015 in the region north of Svalbard as part of a joint campaign between the N-ICE2015 expedition and the 2015 ICE-ARC airborne campaign.

This case study adds to a body of evidence that documents the complexity of sea-ice freeboard retrievals from radar altimetry. It particularly highlights that radar penetration of the snow on sea-ice can be low and variable even at temperatures as low as -15°C. Whilst this knowledge has far-reaching consequences for radar based sea-ice thickness and consequently total Arctic sea ice volume estimates, we can use this information to improve altimetry processing routines, reduce uncertainty assessments for freeboard retrievals, and thus increase the accuracy of derived ice thickness information.

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**Novel Measurements of the Snow Depth Distribtuion on Sea Ice in Support of Polar Altimetry**

*Sinead L Farrell<sup>1</sup>, Jacqueline Richter-Menge<sup>2</sup>, Marissa Dattler<sup>1</sup>, Thomas Newman<sup>1</sup>*

*<sup>1</sup>University of Maryland, United States of America; <sup>2</sup>USACE-ERDL-CRRELL, United States of America*

The growth and retreat of the polar sea ice cover is influenced by the seasonal accumulation, redistribution and melt of snow on sea ice. Knowledge of the snow depth distribution is critical for understanding sea ice mass balance and thus the heat and energy budgets of the polar climate system. Snow loading on sea ice is also a key variable in the derivation of sea ice thickness from altimeter measurements collected over the polar oceans.

An ultra-wideband, frequency modulated-continuous-waveform airborne radar altimeter system, known as the snow radar, and flown onboard NASA’s Operation IceBridge mission, provides annual measurements of snow depth on Arctic sea ice. We describe recent advances in the processing techniques used to interpret airborne radar waveforms, to produce accurate and robust snow depth results across basin scales. We present the results of seven years of radar measurements collected over Arctic sea ice at the end of winter, just prior to melt. Our analysis provides the snow depth distribution on both seasonal and multi-year sea ice, allowing us to understand its relationship with the parent ice cover. We will discuss the outcome of a number of validation experiments where temporally and spatially coincident in situ measurements were gathered during many IceBridge over-flights. These data provide a means to improve our understanding of the impacts of instrument design and the geophysical environment on snow radar echograms, and the associated, derived snow depth.

Our results provide perspective on new airborne radar systems being developed and deployed for future sea ice investigations. They also provide new insights on snow loading and its inter-annual variability, which will inform algorithm development for current and future altimeter missions, including CryoSat-2, ICESat-2 and Sentinel-3.

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**Deriving Snow Depth for Arctic Sea Ice Thickness Retrievals: Can We Trust Precipitation Estimates from Reanalyses?**

*Linette Nicole Boisvert<sup>1,2</sup>, Alek Petty<sup>1,2</sup>, Melinda Webster<sup>2</sup>, Thorsten Markus<sup>2</sup>*

*<sup>1</sup>Earth System Science Interdisciplinary Center (ESSIC), UMD; <sup>2</sup>NASA Goddard Space Flight Center, Cryospheric Sciences Lab*

Snow depth on sea ice is the biggest source of uncertainty in the retrieval of sea ice thickness from airborne and satellite altimeters (e.g. CryoSat-2 and IceSat-2). The seasonal and interannual variability of snow depth on sea ice varies due to precipitation, snowmelt, sublimation, and wind-driven redistribution. Precipitation, however, is one of the most uncertain variables in Arctic reanalyses and climate models due to the lack of in situ validation data [Walsh et al., 1998], which limits our confidence in the application of derived snow accumulation estimates in scientific investigations.

The decline in Arctic snow depth [Webster et al., 2014] has been linked to sea ice loss and changes in surface fluxes (e.g. evaporation/precipitation) and atmospheric circulation patterns, yet precipitation is projected to increase in the Arctic by the end of this century [Christensen et al., 2007; Overland et al., 2011; Singarayer et al., 2006; Deser et al., 2010; Bintanja and Selten, 2014] with peaks in autumn and winter. Bintanja and Selten [2014] showed that increased Arctic precipitation is strongly influenced by increased evaporation in fall and winter due to warming and loss of sea ice cover, and that transport from lower latitudes played a lesser role. Uncertainties in Arctic precipitation in climate models and reanalysis are large, and could be greatly improved with reliable remotely-sensed observations.

As part of the Precipitation, Accumulation and Snow Thickness in the Arctic (PASTA) project, we will use moisture fluxes, atmospheric moisture content and other atmospheric variables from satellite instruments to compare with reanalysis and modeled precipitation estimates. Specifically, moisture fluxes and atmospheric moisture content over the Arctic can be retrieved from NASA’s Aqua AIRS data [Boisvert et al., 2013; 2015a,b], passive microwave retrievals of snow depth and precipitable water estimates from NOAA AMSU-B data [Markus et al., 2006] will be synthesized to constrain uncertainties in precipitation fields from global climate models and reanalyses products. Improving our understanding of precipitation estimates in the Arctic offers a vital step forward in assessing the variability and uncertainty in snow accumulation and hence snow depth over Arctic sea ice.

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## Consistent CryoSat-2/Envisat Waveform Interpretation Over Sea Ice

Stephan Paul<sup>1</sup>, Stefan Hendricks<sup>1</sup>, Eero Rinne<sup>2</sup>, Robert Ricker<sup>1</sup>

<sup>1</sup>Alfred Wegener Institute, Germany; <sup>2</sup>Finish Meteorological Institute, Finland

CryoSat-2 showcased the potential of radar altimetry for sea-ice mass balance estimation over the last years. However, its precursor altimetry missions such as Envisat's Radar Altimeter 2 (RA2) have not been used to the same extent and success. Combining these two data sets in order to acquire a decadal data set poses a challenging task, especially due to different foot-print sizes from either pulse-limited (2-10km, Envisat-RA2) or beam-sharpened (0.3 x 1.6 km, CryoSat-2) radar acquisitions. Based on most recent surface-type classification scheme and applied retracers from ESA's Sea Ice Climate Change Initiative Phase 1 (SICCI1) using the Envisat-RA2 Sensor Geophysical Data Record (SGDR), the resulting sea-ice freeboard showed rather large biases and a limited overall freeboard range compared to estimates from CryoSat-2 for both hemispheres. The SICCI1 surface-type classification is solely based on rather strict pulse-peakiness thresholds, resulting in only a very limited number of classified waveforms as either leads or sea ice. Therefore, Envisat SICCI1 freeboard estimates were unable to reproduce any regional features seen in CryoSat-2 freeboard estimates during the overlap period from November 2010 to March 2012. While the range limitations partly result from the much larger RA2 footprint, the use of inconsistent surface-type classifications and retracers between the two different sensors is likely to further enhance these differences. In the here presented study, we implemented a common surface-type classification scheme for both sensors based on pulse peakiness, leading-edge width and sea-ice backscatter. This surface-type classification scheme was iteratively tuned to fit Cryosat-2's lead and sea-ice fractions. Furthermore, in order to achieve a consistent retracking procedure, we adapted the Threshold First Maximum Retracker Algorithm to Envisat-RA2. Based on these changes and by utilizing a new surface-roughness correction, we are for the first time able to produce a consistent freeboard data set for the overlap period of Cryosat-2 and Envisat. This new data set features a spatial resolution of 25km x 25km and 50km x 50km for the Arctic and Antarctic, respectively.

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## Validation Of CryoSat Sea Ice Thickness Retrievals

Christian Haas<sup>1,7,9</sup>, Steve Baker<sup>2</sup>, Justin Beckers<sup>1</sup>, Malcolm Davidson<sup>3</sup>, Sinead Farrell<sup>4</sup>, Rene Forsberg<sup>5</sup>, Sebastian Gerland<sup>6</sup>, Stefan Hendricks<sup>7</sup>, Sine Munk Hvidegaard<sup>5</sup>, Jennifer King<sup>6</sup>, Robert Ricker<sup>7,8</sup>, Henriette Skourup<sup>5</sup>, Gunnar Spreen<sup>9</sup>

<sup>1</sup>York University, Canada; <sup>2</sup>Mullard Space Sciences Lab/University College London, UK; <sup>3</sup>ESA ESTEC,

NL; <sup>4</sup>NOAA/University of Maryland, USA; <sup>5</sup>Danish Technical University, DK; <sup>6</sup>Norwegian Polar Institute, NO; <sup>7</sup>Alfred Wegener Institute, DE; <sup>8</sup>IFREMER, FR; <sup>9</sup>University of Bremen, DE

Since April 2010 the CryoSat-2 mission with its innovative Synthetic-Aperture Radar Altimeter has produced sea ice thickness data of unprecedented accuracy and regional coverage. However, sea ice thickness retrievals require numerous processing steps to convert the altimeter's range measurements first to ice freeboard and then to thickness. Each of these steps can introduce uncertainties in the resulting thickness estimate, thus requiring careful validation. Various studies have used a range of coincident submarine and airborne ice thickness observations for validation of CryoSat thickness retrievals at spatial and temporal scales of  $\geq 10000$  km<sup>2</sup> and  $\geq 1$  month, respectively. These show correlation coefficients of 0.6-0.8 and rms errors of 0.3-0.6 m between CryoSat and other thickness retrievals.

Here we first review the CryoSat sea ice thickness retrieval error budget and then show results from the ESA supported CryoSat Sea Ice Validation project: CryoVal-SI. CryoVal-SI used coincident airborne freeboard and thickness retrievals from ESA's CryoVex and NASA IceBridge validation campaigns to validate CryoSat freeboard and thickness retrievals at the CryoSat footprint and orbit scale. Such comparisons allow better identification of the main error sources along the CryoSat orbits although they are limited by a lack of complete across-track footprint coverage. Airborne observations include ice freeboard derived from laser altimetry and ESA's Airborne Synthetic Aperture Radar Altimeter System (ASIRAS) as well as total ice thickness obtained from electromagnetic sounding.

Results show that the main potential sources of error in freeboard retrievals are due to: 1) interpolation of sea surface height anomalies in areas of small lead coverage, in regions where errors remain in geoid or mean sea surface models; and 2) unknown radar penetration into the snow layer. Conversion of freeboard to thickness is mostly affected by uncertainties in the snow thickness distribution and the densities of snow and ice. Several research groups who have created ice thickness products have suggested different solutions to address these errors and uncertainties.

Results of the direct comparison of airborne and CryoSat data at the footprint scale show very low correlation coefficients and large rms errors. These are due to the instrument and speckle noise of CryoSat retrievals and the insufficient airborne coverage of across-track sea ice variability within the CryoSat footprint. Results improve with longer along-track averaging intervals resolving regional thickness gradients.

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## Session 2B – Sea-ice thickness retrieval and validation #2

10:40am - 12:20pm Castle Room

### Validation of CryoSat-2 Sea Ice Thickness with Upward-Looking Sonar Measurements in the Eastern Canadian Arctic

Ingrid Peterson, Yongsheng Wu, Jim Hamilton  
Fisheries and Oceans Canada, Canada

Sea ice thickness estimates from CryoSat-2 are compared with ice draft measurements collected with Upward-Looking Sonar (ULS) moorings in Davis Strait and in the Canadian Arctic Archipelago (Barrow Strait) in 2010-2013. In western Davis Strait, the mean ice thicknesses inferred from the ULS ice draft measurements in spring (March-April) 2012 and 2013 were 2.8 m and 2.4 m respectively. The mean CryoSat ice thickness to the north in Baffin Bay was also higher in 2012 than in 2013. However the magnitude of the ULS measurements was about 50% higher than the CryoSat estimates, probably due in large part to the close proximity of the mooring to the coast. The difference in ice thickness between the two years is consistent with a higher winter North Atlantic Oscillation (NAO) index in 2012 than in 2013. Differences in spring CryoSat ice thicknesses in Baffin Bay for all years between 2011 and 2016 are also discussed. In Barrow Strait, the mean ULS ice thicknesses in fall 2010 and spring 2011 were 0.9 and 1.6 m respectively, and were in reasonable agreement with the mean CryoSat ice thicknesses in the surrounding area.

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### The Development of a Dynamic Snow Load for Cryosat-2 Sea Ice Thickness Retrievals

Rachel Tilling, Andy Ridout, Michel Tsamados, Isobel Lawrence, Andrew Shepherd  
University of Leeds, United Kingdom

CryoSat-2 data are now being used internationally to produce estimates of Arctic-wide sea ice thickness and volume [1-5]. However, current estimates rely (to varying degrees) on the use of a snow climatology in the conversion of ice freeboard to thickness, and this is currently the largest source of error in sea ice thickness and volume estimates [6, 7]. To reduce this uncertainty we have developed a dynamic snow load for application with our sea ice processor. The snow load is initialised using precipitation and evaporation data from the ERA-Interim reanalysis [8], and developed

with a dependence on sea ice concentration, drift, and atmospheric temperature. This enables us to apply a snow load that varies in space and time, rather than relying on a constant monthly snow climatology. To perform an initial evaluation of our dynamic snow load, we compared estimates of sea ice thickness that we obtained using the climatological and dynamic snow loads, to ice thickness measurements from NASA's Operation IceBridge (OIB) campaign. Although both of our sea ice thickness datasets agree well with OIB in the region north of Greenland, there is some spatial variation in the thickness differences at lower latitudes. This presentation will summarise the development, application, and evaluation of the new snow load in relation to our sea ice thickness estimates and comment on future considerations.

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[6] R. L. Tilling, A. Ridout, A. Shepherd, and D. J. Wingham, "Increased Arctic sea ice volume after anomalously low melting in 2013," *Nature Geoscience*, vol. 8, pp. 643-646, 2015.

[7] R. L. Tilling, A. Ridout, and A. Shepherd, "Near Real Time Arctic sea ice thickness and volume from CryoSat-2," *The Cryosphere*, vol. 10, pp. 2003-2016, 2016.

[8] D. P. Dee, S. M. Uppalaa, A. J. Simmons, P. Berrisford, P. Polia, S. Kobayashib, *et al.*, "The ERA-Interim reanalysis: Configuration and performance of the data assimilation system," *Quarterly Journal of the Royal Meteorological Society*, vol. 137, pp. 553-597, April 2011.

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## Using Ice Thickness Distribution from Cryosat to Initialise Sea Ice Models

Michel Tsamados<sup>1</sup>, David Schroeder<sup>2</sup>, Daniel Feltham<sup>2</sup>, Andy Ridout<sup>1</sup>

<sup>1</sup>University College London, United Kingdom; <sup>2</sup>University of Reading, UK

We extract for the first time the local sea ice thickness distribution (ITD) from the along track Cryosat individual thickness measurements and compare these distributions with high resolution airborne data from Operation IceBridge.

We use the state of the art sea ice model CICE that was previously used to successfully forecast September sea ice extent from the melt onset pond coverage in May to assess its sensitivity to a sub-grid scale ITD initialised from a distribution derived from Cryosat.

CICE model runs initialized from a Cryosat ITD in November and April are compared with the corresponding model runs without initialisation and with the observed Cryosat thickness maps for the following April (lead time of 6 and 12 months respectively).

We demonstrate that this type of ITD initialisation from Cryosat thickness data shows potential to improve sea ice forecast both in term of its concentration and thickness With lead times of up to a year.

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## A Physical Approach for Freeboard Computation from CryoSat-2

Jean Christophe Poisson<sup>1</sup>, Pierre Thibaut<sup>1</sup>, Duc Hoang<sup>1</sup>, Amandine Guillot<sup>2</sup>, François Boy<sup>2</sup>, Nicolas Picot<sup>2</sup>

<sup>1</sup>Collecte Localisation Satellite, France; <sup>2</sup>Centre National d'Etudes Spatiales

The Arctic region is an important component of the climate system and its exact influence is still not clearly understood today. For several years, radar measurements from Low Resolution Mode (LRM) satellite altimetry missions have been processed in Arctic sea ice region, providing valuable data on the sea ice freeboard and its evolution. However, the observation in these areas is not simple due to the presence of multiple surface types which make LRM altimetry measurements very complex with multiple off-nadir reflections that degrade the surface height retrieval. With the arrival of delay-doppler altimetry embarked onboard the CryoSat-2 mission (and Sentinel-3), this new technique has provided very promising results opening a new area for the observation of the sea ice regions.

For several years, specific processings have been developed to extract and monitor sea ice extent, sea level in the leads and freeboard height of the ice covered ocean. In the CS-2 ground segment, the methods developed for the LRM altimetry, although empirical, have been adapted to SAR waveforms with

their robustness but also with their drawbacks. In this talk, we propose to present a new physical approach to classify and retrack the sea ice waveforms combined with a lead-oriented method to compute the freeboard heights. The retrievals are then compared with the results obtained with the same physical approach applied on SARAL/AltiKa and Sentinel-3A data.

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## Retrievals of Lake Ice Thickness Using CryoSat-2

Justin Francis Beckers<sup>1</sup>, J. Alec Casey<sup>1,2</sup>, Christian Haas<sup>1,2,3</sup>

<sup>1</sup>Department of Earth and Atmospheric Sciences, University of Alberta, Canada; <sup>2</sup>Department of Earth and Space Science and Engineering, York University, Canada; <sup>3</sup>Alfred Wegener Institute for Polar and Marine Sciences, Germany

Satellite observations have revealed decreases in the duration of the seasonal snow and ice coverage of lakes in northern Canada and modelling studies suggest that these decreases will continue and that there will be an associated decrease in ice thickness. However, there is limited ice thickness information for these lakes due to their remoteness. Here we present and validate a method to retrieve lake ice thickness using CryoSat-2 L1B waveform data. Under optimal conditions, the CryoSat-2 signal penetrates through the freshwater ice and is scattered from both the snow-ice and the ice-water interfaces, with returns from each interface being of sufficient power to be detected. The distance between the scattering horizons is used to determine the ice thickness, similar to ground-penetrating radar profiling. The observed seasonal evolution of ice thickness of Great Bear Lake and Great Slave Lake agrees well with in-situ measurements, modelled ice thicknesses, and previous studies. Thickness retrievals of thin ice are limited by a minimum waveform peak separation of 2 range bins, approximately 0.26 m in ice. A comparison of maximum waveform power to lake ice thickness is also presented for the retrieval of phenological ice and snow information. Although not designed for lake ice observations, CryoSat-2 and future SAR satellite altimeter missions offer new possibilities to monitor the ice and water levels of climatically sensitive and influential lakes.

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## Session 2C – New application frontiers over polar ocean

14:00pm - 15:40pm Castle Room

### Iceberg Detection and Analysis using Cryosat Modes

Jean Tournadre<sup>1</sup>, François Boy<sup>2</sup>, Dinardo Salvatore<sup>3</sup>

<sup>1</sup>IFREMER, France; <sup>2</sup>CNES, France; <sup>3</sup>Eumetsat, Germany

Conventional pulse limited (LRM) altimetry is a powerful tool to detect and characterize small (<3km) icebergs and to measure the profile of large ones (>16km). The Cryosat-2 SIRAL is the first altimeter that can operate in two new modes over the ocean besides the classical LRM: the Delay Doppler or SAR and the SAR Interferometric (SARin) modes. It offers thus a unique opportunity to test, validate and compare the capabilities of the three modes for the detection and analysis of small icebergs and the estimation of large iceberg topography. Over most of the ocean, SIRAL operates in LRM mode and the classical iceberg detection algorithm can be applied without modification. It can also be applied to the pseudo-LRM data, i.e. sequence of echoes derived from reducing SAR or SARin data into a sequence which looks like LRM data.

SAR altimeters have high pulse repetition frequency to ensure pulse-to-pulse coherence. The correlation of the returning echoes is used by the data processor to separate the echoes into strips arranged across the track by exploiting the slight Doppler frequency shifts, in the forward- and aft-looking parts of the beam. The strips laid down by successive bursts can therefore be superimposed on each other and averaged to reduce noise. This leads to an along-track resolution around 300m, improved SNR and enhanced ranging performance. The reduction of the noise level of the thermal noise part of the waveform used for detection facilitates the iceberg detection. The iceberg signatures, i.e. parabolas in the classical altimetry waveform space, reduce to bright spots in SAR waveform. They can be easily detected using classical image processing connected components and region properties algorithms. The iceberg area can be estimated using the signature's along-track and across-track lengths.

SARin is the most advanced mode, primary used around the ice sheet margins. SIRAL performs synthetic aperture processing and uses a second antenna as an interferometer to determine the across-track angle to the earliest radar returns. The SARin mode provides the exact surface location being measured. SAR and pseudo-LRM echoes can be used to detect icebergs. Coherence can be used to further improve the

detection by limiting the probability of false alarm and by insuring the presence of a surface above the sea surface. In this mode the range analysis window (240m) is four times larger than that in LRM and SAR mode, which double the altimeter's detection swath. The main interest of SARin mode is the possibility, for the first time for a satellite sensor, to precisely locate the surface scatterer and to allow the estimation of the iceberg free-board from the phase difference and thus the iceberg volume. The high across-track accuracy allows to map the iceberg topography at an unprecedented resolution.

In SARin mode, the interferometric capabilities also allows to estimate the topography of large icebergs with an unprecedented resolution. Several passes over the B17A icebergs have been analyzed and the evolution of the surface topography has been analyzed during the last year of life of the iceberg.

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### Scientific Applications of Fully-Focused SAR Altimetry

Alejandro Egido<sup>1</sup>, Walter H.F. Smith<sup>2</sup>

<sup>1</sup>NOAA / UMD, United States of America; <sup>2</sup>NOAA, United States of America

The delay/Doppler algorithm implemented in CryoSat-2 and Sentinel-3 applies a coherent processing the 64 echoes within each burst (about 3.5 milliseconds of flight), which allows narrowing the footprint in the direction along the track to about 300 m. However, by accounting for the phase evolution of the targets in the scene, it is possible to focus the complex echoes along the aperture, and perform inter-burst coherent integration potentially as long as the target illumination time. This process, similar to SAR imaging systems, reduces the along-track resolution down to the theoretical limit equal to  $L/2$ , where  $L$  is the antenna length. We call this the fully focused SAR (FF-SAR) Altimetry processing. For the development of the technique we have used the CryoSat-2 SAR Mode data, but our methods could also be used with similar data from Sentinel-3 or Sentinel-6/Jason-CS.

The footprint of an FF-SAR altimeter measurement is an elongated strip on the surface, which is pulse-limited across-track and SAR focused along-track. The technique has been demonstrated using transponder data, showing an achievable along-track resolution of 0.5 meters. Despite the asymmetry of the altimeter footprint, the fully focused technique may be useful for applications in which one needs to separate specific targets within highly heterogeneous scenes, such as in the case of sea-ice leads detection, hydrology, and coastal altimetry applications. Applying this technique on CryoSat-2 data over land and sea-ice, we can correctly measure the along-track extent of water bodies and ice-leads only a few meters long in the along-track dimension. On a random rough surface, independent FF-SAR waveforms can be obtained, potentially, every 0.5 meters, leading to an increase on

the effective number of looks that can be obtained of the surface, with respect to delay/Doppler altimetry.

This paper concentrates on the cryospheric applications of the FF-SAR altimetry technique, and reviews the results that we have obtained so far from CryoSat-2 SAR mode observations over sea-ice, where a consistent performance improvement of square root of 2 with respect to the ESA L2 product is obtained for sea surface height estimates from sea-ice leads. In addition, due to the finer along-track resolution obtained with FF-SAR altimetry, we are now able to precisely determine the width of sea-ice leads from a nadir-looking altimeter. The performance improvement is, in any case, lower than expected for an ideal FF-SAR, as the closed burst operation mode of the CryoSat-2 SIRAL instrument imposes a lacunar sampling of the Doppler spectrum. This results in side lobes in the full along-track point target response, which introduces correlation in the successive looks of the ocean. This effect and possible mitigation strategies are also discussed in this work.

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#### **As Assessment of Sea Ice Freeboard Derived from Fully-Focussed SAR Altimetry**

*Thomas Armitage<sup>1</sup>, Alejandro Egado<sup>2</sup>, Walter Smith<sup>2</sup>, Ron Kwok<sup>1</sup>*

<sup>1</sup>NASA Jet Propulsion Laboratory; <sup>2</sup>NOAA Laboratory for Satellite Altimetry

We assess the performance of fully-focussed synthetic aperture radar (FF-SAR) altimetry from CryoSat-2 over Arctic sea ice. The altimeter onboard CryoSat-2 is operated in a closed-burst configuration, whereby coherent bursts of 64 echoes are processed to form 64 'beams' in the along-track direction. The aperture duration of 3.5ms narrows the along track footprint to around 300m, and successive looks at the same strip on the ground are summed (multi-looked) as the satellite passes overhead. On the other hand, by accounting for the phase evolution of scatterers in the scene, the FF-SAR technique applies an inter-burst coherent integration, potentially over the entire duration that a scatterer remains in the altimeter footprint. It has been demonstrated that applying FF-SAR processing to CryoSat-2 data can narrow the along track resolution to just 0.5m, or half the antenna diameter (the theoretical limit for SAR imaging). Further, the effective number of looks for the multi-looked echoes is approximately doubled, leading to better precision in the retrieved geophysical parameters.

Here, we explore the potential for FF-SAR processing to improve sea ice freeboard retrievals from radar altimetry. Further narrowing of the along-track footprint, and increasing the number of waveforms, allows more stringent waveform filtering, and retention of only the 'cleanest' lead/floe waveforms and smaller leads should become resolvable. For the SSH retrieval we will investigate whether this has the potential to reduce contamination by off-nadir leads, which can

bias the SSH retrieval low. The increased effective number of looks should also improve the local sea level and sea ice elevation precision. We compare the freeboard retrieval from FF-SAR against the conventional Level-1b SAR data from CryoSat-2 and we make use of a coincident Operation IceBridge underflight to assess the results.

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#### **Deriving IMO Polar Code Risk Index Outcome from Cryosat-2**

*Eero Rinne<sup>1</sup>, Heidi Sallila<sup>1</sup>, Antti Kangas<sup>2</sup>, Stefan Hendricks<sup>3</sup>*

<sup>1</sup>Finnish Meteorological Institute, Finland; <sup>2</sup>Finnish Meteorological Institute, Ice Service, Finland; <sup>3</sup>Alfred Wegener Institut, Germany

We present different methods to derive Polar Operational Limit Assessment Risk Indexing System (POLARIS) Risk Index Outcomes (RIO) from CryoSat-2 data. This work contributes towards the use of satellite radar altimeters in operation planning and tactical sea ice navigation.

The International Maritime Organization (IMO) adopted the international code for ships operating in polar waters or Polar Code in 2014. The polar code covers several aspects of navigation in ice covered seas spanning from ship design to training and environmental impacts. An important part of the polar code is the POLARIS system. The core of POLARIS is a number called Risk Index Outcome or RIO, which is an easy to interpret index depending on ship's ice class and sea ice conditions. Mathematically POLARIS is a 2d look-up-table of risk values (RV) for different ice conditions and ship ice classes. RIO is then calculated as a mean of these RV's weighted with their partial ice concentrations. RIO also takes into account potential ice breaker assistance and summer ice decay. RIO is easy to interpret with RIO > 0 standing for "operation permitted" and -10 > RIO > 0 and RIO < -10 for limited operation permitted and operation not permitted consequently.

Cryosat-2 thickness estimates are not trivial to interpret as RIO values. Gridded CryoSat-2 thickness products are averages of successful thickness retrievals falling within the averaging grid cell and do not include information on thickness distributions or lead detections. This information however is present in the L2 CryoSat-2 products. We present different approaches for deriving RIO from CryoSat-2 L2 products from the Pysiral software and compare them to RIO values calculated directly from the Canadian Ice Service operational ice charts. First we present methodology to derive RIO from CryoSat-2 L2 files from the ESA CCI Pysiral processor. We then explore the possibility to use a coupled sea-ice-atmosphere model NEMO-LIM3 for spatial interpolation of Cryosat-2 derived ice information. Finally we present a possibility to use an unsupervised classifier to derive adjusted IMO ice

classes from Cryosat-2 data and convert these into RIO values.

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### **An Assessment of the State-of-the-Art Mean Sea Surface and Geoid Models of the Arctic Ocean: Implications for Sea Ice Freeboard Derivation**

*Henriette Skourup<sup>1</sup>, Sinead Farrell<sup>2,3</sup>, Stefan Hendricks<sup>4</sup>, Robert Ricker<sup>4,5</sup>, Tom Armitage<sup>6</sup>, Andy Ridout<sup>6</sup>, Ole Baltazar Andersen<sup>1</sup>, Christian Haas<sup>7,4,8</sup>, Steven Baker<sup>9</sup>*

<sup>1</sup>National Space Institute, DTU Space, Denmark; <sup>2</sup>NOAA Center for Weather and Climate Prediction, College Park, MD, USA; <sup>3</sup>ESSIC, University of Maryland, College Park, MD, USA; <sup>4</sup>Alfred Wegener Institute, Bremerhaven, Germany; <sup>5</sup>IFREMER, Brest, France; <sup>6</sup>CPOM, University College London, UK; <sup>7</sup>York University, Canada; <sup>8</sup>University of Bremen, Germany; <sup>9</sup>Mullard Space Sciences Lab/University College London, UK

State-of-the-art Arctic Ocean mean sea surface (MSS) models and global geoid models (GGMs) are used to support sea ice freeboard estimation from satellite altimeters, as well as in oceanographic studies such as mapping sea level anomalies and mean dynamic ocean topography. However, errors in a given model in the high frequency domain, primarily due to unresolved gravity features, can result in errors in the estimated freeboard. These errors are exacerbated in areas with a sparse lead distribution in consolidated ice pack conditions. Additionally model errors can impact ocean geostrophic currents, derived from satellite altimeter data, while remaining biases in these models may impact longer-term, multi-sensor oceanographic time-series of sea level change in the Arctic.

Here we present results arising from the ESA CryoVal Sea Ice project, focusing on an assessment of four state-of-the-art Arctic MSS models (UCL13, DTU15/13/10) and a commonly used GGM (EGM2008). We describe errors due to unresolved gravity features and inter-satellite biases and their impact on the derivation of sea ice freeboard based on data obtained from CryoSat-2. The latest MSS models, incorporating CryoSat-2 sea surface height measurements, show improved definition of gravity features, such as the Gakkel Ridge. The differences between the models are analyzed and the results can be used to support improvements in future models. We find that the impact of MSS or GGM errors on freeboard can reach several decimeters in some parts of the Arctic. The maximum observed freeboard difference was 0.59 m (UCL13 MSS minus EGM2008 GGM).

So far the impact of the ocean mean dynamic topography (MDT) has largely been neglected in the freeboard processing chain, since existing MSS models have been so divergent. However, improvements in our ability to measure the sea surface height of the polar oceans with advanced altimetry techniques has improved our knowledge and the precision of the MDT. We compare Arctic MDT based on the differences

between the MSS and GGM models, to understand the impact on MDT quality derived from historical versus current models. The results support algorithm decision for deriving freeboard from current and future missions such as CryoSat-2, Sentinel-3 and ICESat-2.



### **The Great Value of Cryosat-2 SAR-in for Coastal Sea Level Monitoring**

*Ole Baltazar Andersen<sup>1</sup>, Martina Idzanovic<sup>2</sup>, Vegard Ophaug<sup>2</sup>, Adil Abulaitijiang<sup>1</sup>*

<sup>1</sup>DTU space, Denmark; <sup>2</sup>NMBU, Norway

Cryosat-2 operates in SAR-in for selected coastlines in the world. We perform an evaluation and cross-comparison with conventional altimetry and coastal tide gauges to demonstrate the great step forward in accurate coastal sea level mapping that Cryosat-2 SAR-in data can provide.

The investigation of SAR-in data in Greenland adds an entire new dimension to coastal altimetry. An amazing result of the investigation is the ability of Cryosat-2 to detect and recover sea level even though the coast (sealevel) is up to 15 km away from the nadir location of the satellite.

This ability of capture and use returns from outside the main (-3Db) loop in theory enables Cryosat-2 SAR-in to map sea level height of fjords more frequently than the 369 days repeat.

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### **Evaluating the Performance of Sentinel-3 SRAL SAR Altimetry in the Coastal and Open Ocean, and Developing Improved Retrieval Methods – The ESA SCOOP Project**

*David Cotton<sup>1</sup>, Thomas Moreau<sup>2</sup>, Eduard Makhoul Varona<sup>3</sup>, Paolo Cipollini<sup>4</sup>, Mathilde Cancet<sup>5</sup>, Francisco Martin<sup>6</sup>, Luciana Fenoglio-Marc<sup>7</sup>, Marc Naeije<sup>8</sup>, M Joana Fernandes<sup>9</sup>, Marco Restano<sup>10</sup>, Américo Ambrósio<sup>11</sup>, Jérôme Benveniste<sup>12</sup>*

<sup>1</sup>Satellite Oceanographic Consultants, United Kingdom; <sup>2</sup>Collecte Localisation Satellites, France; <sup>3</sup>isardSAT, UK; <sup>4</sup>National Oceanography Centre, UK; <sup>5</sup>Noveltis, France; <sup>6</sup>Starlab, UK; <sup>7</sup>University of Bonn, Germany; <sup>8</sup>Delft University of Technology, The

Netherlands;<sup>9</sup>University of Porto, Portugal;<sup>10</sup>SERCO / ESRIN, Italy;<sup>11</sup>DEIMOS / ESRIN, Italy;<sup>12</sup>ESA-ESRIN, Italy

The ESA Sentinel-3 satellite, launched in February 2016 as a part of the Copernicus programme, is the second satellite to operate a SAR mode altimeter. The Sentinel 3 Synthetic Aperture Radar Altimeter (SRAL) is based on the heritage from Cryosat-2, but this time complemented by a Microwave Radiometer (MWR) to provide a wet troposphere correction, and operating at Ku and C-Bands to provide an accurate along-track ionospheric correction.

SCOOP (SAR Altimetry Coastal & Open Ocean Performance) is a project funded under the ESA SEOM (Scientific Exploitation of Operational Missions) Programme Element, started in September 2015, to characterise the expected performance of Sentinel-3 SRAL SAR mode altimeter products, in the coastal zone and open-ocean, and then to develop and evaluate enhancements to the baseline processing scheme in terms of improvements to ocean measurements. There is also a work package to develop and evaluate an improved Wet Troposphere correction for Sentinel-3, based on the measurements from the on-board MWR, further enhanced mostly in the coastal and polar regions using third party data, and provide recommendations for use.

At the end of the project recommendations for further developments and implementations will be provided through a scientific roadmap.

In this presentation we provide an overview of the SCOOP project, highlighting the key deliverables and discussing the potential impact of the results in terms of the application of delay-Doppler (SAR) altimeter measurements over the open-ocean and coastal zone. We also present the initial results from the project, including:

- Key findings from a review of the current “state-of-the-art” for SAR altimetry,
- Specification of the initial “reference” delay-Doppler and echo modelling / retracking processing schemes,
- Evaluation of an initial Test Data Set in the Open Ocean and Coastal Zone, processed from Cryosat FBR data, using a processing scheme designed to be equivalent to the Sentinel-3 baseline processor
- Overview of modifications planned to the reference delay-Doppler and echo modelling/ retracking processing schemes.

This work builds on findings from the Cryosat Plus for Oceans (CP4O) study, in which new processing schemes for Cryosat SAR mode data were developed and evaluated with a view to supporting a range of open ocean and coastal zone applications, and continues to be highly relevant to further exploitation of Cryosat data in these applications.

The SCOOP test data sets and relevant documentation are available to external researchers on application to the project team.

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## Using Cryosat to Improve the Observation of Global Oceanic Internal Tides

Zhongxiang Zhao

University of Washington, United States of America

Our recent work demonstrates the usefulness of Cryosat altimeter data in observing global oceanic internal tides (Zhao 2016 JGR). It has long been known that TOPEX/Poseidon (T/P) can detect internal tides via their centimeter-scale sea surface height (SSH) displacements, which correspond to tens of meters of subsurface displacements. T/P altimetric observations, however, are limited to 254 discrete tracks, leaving most of the ocean unsampled. Even worse, the cross-track spacing of T/P (200~300 km) is wider than the wavelength of M2 internal tides (~150 km). For comparison, Cryosat has a much higher spatial resolution with 10688 tracks around the globe; this orbit configuration determines that Cryosat is superior to T/P for monitoring global internal tides.

Traditional harmonic analysis is incapable of extracting internal tides from Cryosat altimeter data. The Cryosat data series at any given point is short, due to its 369-day-long repeat period. We take up this challenge by developing a plane wave fit method (Zhao 2016 JGR). Using our new technique, we extract internal tides by fitting plane waves in large horizontal windows covering multiple tracks, instead of at individual points. We demonstrate that M2 internal tides can be extracted using 4 years of Cryosat data from 2011 to 2014 (CryoSat4yr). Likewise, M2 internal tides are extracted using 60 satellite years of SSH measurements made by exact-repeat missions (T/P--Jason-1/2, ERS-1/2--Envisat, and GFO) from 1992 to 2012 (MultiSat20yr). CryoSat4yr and MultiSat20yr are in good agreement in the central North Pacific, although they are from satellite data of different sampling patterns (1998 versus 10688 tracks) and different observational periods (60 versus 4 years). Further comparisons reveal that the internal tide field is subject to significant seasonal and interannual variability.

Internal tides have drawn great research interest in recent years, because they play an important role in a variety of ocean processes. The satellite altimeter's near global coverage offers a great improvement over moored and shipboard measurements. Previous studies mainly observe global internal tides using exact-repeat satellite altimeter missions. The unique Cryosat dataset, combined with the newly developed analysis technique, has a potential to better observe internal tides on a global scale.

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## Session 3A – Ice Sheet elevation time records

08:30am - 10:10am Castle Room

### Invited - Keynote: Dynamic Features of the Ice Sheets (Subglacial Lakes and Ice Shelves)

*Helen Amanda Fricker*

*Scripps Institution of Oceanography*

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### Ice Shelf Thickness Change from CryoSat-2

*Anna Hogg<sup>1</sup>, Andrew Shepherd<sup>1</sup>, Lin Gilbert<sup>2</sup>, Alan Muir<sup>2</sup>*  
*<sup>1</sup>CPOM, University of Leeds, United Kingdom; <sup>2</sup>Mullard Space Science Laboratory, University College London, UK*

Floating ice shelves that fringe the majority (74%) of Antarctica's coastline provide a direct link between the ice sheet and the surrounding oceans, and changes in their constitution have been shown to influence the flow of inland ice due to their buttressing effect. This process has become increasingly important over recent decades as Antarctic ice shelves have thinned, retreated, and collapsed – events that have been recorded largely by European satellites. At the Antarctic Peninsula, ice shelf retreat has been observed throughout the satellite era (18% over 50 years), and large sections of the Larsen-A, Larsen-B, and the Wilkins Ice Shelf collapsed, catastrophically in 1995, 2002, and 2008, respectively. In the Amundsen Sea, ice shelves at the terminus of the Pine Island and Thwaites glaciers have thinned at rates in excess of 5 meters per year for more than two decades. Both signals are indicative of long-term changes in the regional climate, and have impacted on the ice inland. CryoSat-2 has repeatedly surveyed 49% of the coastal margins of Antarctica six or more times within the first three years of operation. That is six and five times more than ENVISAT (8%) and ICESat (10%), and will continue to be improved on if CryoSat-2 continues to live beyond its original mission lifetime. Further to this the CryoSat-2 synthetic aperture radar interferometry (SARIn) mode has a smaller footprint size (~300m by 1km) than previous radar altimetry missions, increasing the spatial resolution of the measurements made by radar altimeters. We use CryoSat-2 to map ice thickness change on Antarctic ice shelves by exploiting the dense spatial sampling and repeat coverage provided by the SARIn mode data acquired by CryoSat-2 from 2010 to the present day. We find that ice shelf thinning rates exhibit large fluctuations over short time periods, and the improved spatial resolution of CryoSat-2 enables us

to resolve the spatial pattern of thinning with ever greater detail in Antarctica.

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### Elevation Changes of the Greenland Ice Sheet from 2013 to Present - CryoSat-2 vs. SARAL/ALtiKA

*Sebastian B. Simonsen<sup>1</sup>, Louise Sandberg Sørensen<sup>1</sup>, Kirill Khvorostovsky<sup>2</sup>, Lars Stenseng<sup>1</sup>, Rene Forsberg<sup>1</sup>*

*<sup>1</sup>DTU Space, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark; <sup>2</sup>Nansen Environmental and Remote Sensing Center, 5006 Bergen, Norway*

For more than six years, CryoSat-2 has measured elevation changes of the Greenland Ice Sheet. The nature of the onboard Ku-band radar enables CryoSat-2 to measure climate dependent changes in the upper snow/firn cover of the interior parts of the ice sheets. Hence, the retrieved waveform is a convolution of both surface scattering and volume scattering. This hampers the direct interpretation of surface elevation change, and further ice sheet-wide mass balance. However, if the surface and volume signals can be de-convoluted, CryoSat-2 would provide the most comprehensive record of the state of the Greenland Ice Sheet in the present warming climate. Since Ku-band radar altimeters are sensitive to snow characteristics, CryoSat-2 could provide information about firn densification, a crucial parameter for the conversion from volume change to mass balance. Changes in the firn densification is usually modelled, and independent observations are needed to validate this product.

To capture the many different regimes of firn conditions on the Greenland Ice Sheet, we use data from the French/Indian satellite SARAL. The altimeter ALtiKA, onboard SARAL, operates in Ka-band frequency that reduces surface penetration comparing to Ku-band altimeters. Initial studies have shown trend difference in the derived 3-year elevation changes for the two satellites. Understanding the differences in detail is the key to utilizing the full potential of CryoSat-2 data to both provide detailed surface elevation changes and the climate dependent changes in the firn. We focus our investigation on the difference in 3-year trend and time series of the elevation change over selected areas of the Greenland ice sheet. The interpretation of the differences will be supported by firn modeling, which previously has been used to derive Greenland mass balance from ICESat data. This firn model is further developed to also provide conceptual knowledge of possible penetration depths of the CryoSat-2 Ku-band altimeter.

Finally, this 3-year record of coinciding measurements from the two satellites may shed light on the needs for future multi-sensor satellite missions, to assess the state of the Greenland Ice Sheet and eventually to improve the elevation change products of the ongoing ESA Greenland Ice Sheet CCI project.

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## Extending Antarctic Ice Shelf Height Change Time Series using Cryosat-2

Susheel Adusumilli<sup>1</sup>, Matthew Siegfried<sup>1</sup>, Fernando Paolo<sup>1</sup>, Helen Fricker<sup>1</sup>, Laurence Padman<sup>2</sup>

<sup>1</sup>*Scripps Institution of Oceanography, La Jolla, California;* <sup>2</sup>*Earth & Space Research, Oregon, USA*

Continuous time series of surface height observations derived from satellite radar altimetry over the Antarctic ice shelves show significant and complex patterns of interannual variability. Such changes, which have been shown to correlate with climatic drivers (such as the El Niño-Southern Oscillation), can potentially impact the dynamics of the grounded ice sheet behind the floating ice shelves. It is, therefore, vital to continue the currently available 18-year observational record (1994-2012) from the ERS 1/2 and Envisat missions through the CryoSat-2 (CS-2) period (2010-present). However, due to the differences in instrumentation and orbit configuration between CS-2 (carrying a Delay/Doppler altimeter) and Envisat (which carried a conventional altimeter), the same processing techniques are not optimal for deriving height changes from CS-2 measurements. Here, we evaluate the potential of several processing methods, and present time series for various Antarctic ice shelves. We use the ~2-year overlap period between Envisat and CS-2 records to validate the independently derived height changes. We also compare the measured elevations with lidar observations from Operation IceBridge (2009-present). We present a case study on the Larsen-C ice shelf, which shows significant variability over decadal timescales up to the present time, to demonstrate the importance of continuous and long-term observations.

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## Satellite Altimetry of Greenland and Antarctic Ice Sheets: 40 Years of Advances and Challenges

*H Jay Zwally*

*NASA Goddard SFC, United States of America*

Following the early suggestion of using satellite radar altimetry for mapping ice-sheet elevations (Robin, 1969) and for measuring elevation changes to determine ice-sheet mass balance (Zwally, 1975), both of these goals have been achieved using satellite radar and laser altimeter measurements (e.g. Shepherd et al., 2012 and Zwally et al., 2015). Measurements of ice-sheet elevations to  $\pm 65$  began with the ocean-radar altimeters first on GEOS-3 in 1975 (Brooks et al., 1987) and to  $\pm 72$  on SeaSat in 1978 (Zwally et al., 1983) and GeoSat in 1985 (Zwally et al., 1989). The effect of off-nadir returns within the radar beam-limited footprints on causing slope-induced elevation errors (Robin, 1969) was shown in the measurements (Brooks et al., 1987), followed by approximate corrections made to SeaSat data (Brenner et al., 1983). Range errors in the altimeter's automatic range-tracking algorithm were first corrected for SeaSat data with a waveform-fitting procedure called retracking (Martin et al., 1983), which was later applied more universally to ocean and ice

measurements. The radar altimeter on ERS-1 and ERS-2 was the first with improvements for ice measurements including more adaptive range tracking and an ice mode with wider range gates. Some of the first papers to describe elevation change measurements with estimates of ice sheet mass balance included Zwally, 1989 using SeaSat and GeoSat data and Wingham et al., 1998; Zwally et al., 2005; and Davis et al., 2005 using ERS-1 and ERS-2 data. Wingham et al., 1998 was the first to apply a backscatter-based correction for seasonal and interannual variations in the penetration depth of the radar signal into the ice-sheet firn. The depth-penetration correction was further developed (Zwally et al., 2005; Yi et al., 2011) and its success is demonstrated by the close agreement of  $dH/dt$  over Lake Vostok in East Antarctic with that from ICESat laser altimetry (2.02 vs 2.03 cm/yr) (Zwally et al., 2015). ICESat (Zwally et al., 2002) with a laser altimeter and CryoSat-2 (Wingham et al., 2006) with an advanced multi-mode radar altimeter were the first satellites specifically designed for ice measurements and flown in near-polar orbits. Remaining challenges include: 1) developing more successful penetration-depth corrections for EnviSat and CryoSat that account for the complications of the interactions of their linear-polarized radar signals (oriented cross-track to the satellites) and the directions of the surface slope (e.g. Remy et al., 2012) and 2) developing long-lifetime laser-altimeter missions.

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## Session 3B – Ice Sheet retrieval and techniques

10:40am - 12:20pm Castle Room

### Cryosat-2 and Sentinel-3 SAR-Mode Altimetry Performance over the Antarctic Ice Sheet

*François Boy<sup>1</sup>, Jérémie Aublanc<sup>2</sup>, Thomas Moreau<sup>2</sup>, Frederique Remy<sup>3</sup>, Denis Blumstein<sup>1</sup>, Nicolas Picot<sup>1</sup>, Pierre Thibaut<sup>2</sup>*

<sup>1</sup>CNES, France; <sup>2</sup>CLS, FRANCE; <sup>3</sup>LEGOS, FRANCE

During the past 30 years, Earth's polar region has been continuously monitored by satellite altimetry. Thanks to their wide spatial coverage and relatively high temporal sampling, radar altimeters have greatly improved our knowledge of the ice-sheets topography and our understanding of the ice sheets dynamics. Over that time period, all radar altimeter missions flying over ice-sheet surfaces (GeoSat to Altika) have been operating in conventional Low Resolution Mode (LRM). Despite constant improvements in resolution and precision, LRM instruments still suffer from several limitations and uncertainties, notably due to their large radar footprint: 10km to 20km (depending on mission).

Unlike its predecessors, the Cryosat-2 and Sentinel-3A satellites carry on-board a new generation of radar altimeter instrument operating in a Synthetic Aperture Radar (SAR) mode. This mode allows reducing the alongtrack resolution to 300 meters, that would make it possible to capture finer-scale topographic variations of icesheet surfaces. The SAR-mode performances have been thoroughly analyzed in open ocean with Cryosat-2 data. However their abilities in monitoring of ice-sheet surfaces have still to be assessed.

SAR-mode radar altimeter data have been recently analyzed over the Antarctica continent, with sporadic Cryosat-2 acquisitions performed in winter 2014 and Sentinel-3A SRAL data acquired in spring 2016. Those data have been processed through the CNES prototype chains (the CPP for Cryosat-2 and the S3PP for Sentinel-3A) and the use of innovative and dedicated algorithms to this particular surface. This paper presents a comprehensive study of the SAR-mode performance over ice-sheet surfaces in comparison with LRM one, focusing on analyses of the waveform shapes, the accuracy of the retrieved surface elevation, its sensitivity to surface slope and penetration effects into the snow/ice layers. This work clearly demonstrates the improved icesheet surface measuring capability offered by SAR-mode altimetry with respect to conventional radar altimetry.

To finish, we will present a R&D study driven by CNES which aims at building a Digital Elevation Model over Antarctica by exploiting data from Cryosat-2, Sentinel-3 and Altika missions. In this part, we will focus on the different challenges adressed through this initiative.

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### Comparison of Interferometric and Non-Interferometric SAR Altimetry over Ice Sheets

*Malcolm McMillan<sup>1</sup>, Andrew Shepherd<sup>1</sup>, Alan Muir<sup>2</sup>, Julia Gaudelli<sup>2</sup>, Robert Cullen<sup>3</sup>*

<sup>1</sup>University of Leeds, United Kingdom; <sup>2</sup>University College London, United Kingdom; <sup>3</sup>ESA, ESTEC, The Netherlands

The launch of CryoSat-2 in April 2010 provided the first spaceborne interferometric SAR altimeter measurements over the Polar Ice Sheets. The mission's novel interferometric mode of operation was specifically designed to enable monitoring of rapidly-changing coastal regions of Greenland and Antarctica, where complex topography has limited the reliable retrieval of geophysical signals by past altimeter missions. In the 6.5 years since launch, CryoSat-2 has demonstrated the utility of interferometric altimeter systems for polar monitoring, and their value for establishing the contribution of ice sheets to global sea level rise. Given that CryoSat-2 had a design lifetime of 3.5 years, and has been in extended operations since October 2013, there is a need to investigate the expected performance of other sensors. In particular, as the requirement for continuity of long term measurements grows, it is important to assess the capacity of a non-interferometric mission to retrieve estimates of ice sheet elevation and elevation change. Here we present the results of the CryoSat Follow-on SAR trade-off study, a 6 month project funded by ESA to investigate the relative performance of CryoSat-2 interferometric and non-interferometric altimetry. By processing CryoSat-2 SARIn data without interferometric information, and relocating the echoing point using an external slope model, we emulate ice sheet margin SAR retrievals from the CryoSat-2 system. In total, we generate 4 years of CryoSat-2 pseudo-SAR data covering the entire Antarctic Ice Sheet margin. We compare these measurements to interferometric retrievals spanning the same period, to assess the relative accuracy and precision of estimates of ice sheet elevation and elevation change derived from the two modes of operation.

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**Influence of Retracker on Ice-Volume and Mass Change Estimates of Greenland and Antarctica**

*Veit Helm<sup>1</sup>, Angelika Humbert<sup>1,2</sup>, Stefan Ligtenberg<sup>3</sup>, Peter Kuipers Munneke<sup>3</sup>*

*<sup>1</sup>Alfred Wegener Institut, Germany; <sup>2</sup>University of Bremen, Germany; <sup>3</sup>Institute for Marine and Atmospheric research Utrecht (IMAU), Utrecht University, The Netherlands*

Recent contribution of ice sheets to sea level change is topic with relevance for the society and a challenging topic for glaciologists. For the assessment of the contribution of ice sheets to sea level change robust, consistent processing, as well as the estimation of uncertainties is important. For this purpose we analyse altimeter data of the two ESA satellites CryoSat-2 and ENVISAT covering a time period from 2002 to 2017 and will present a time series of volume change and as a final product mass change estimates using a firn densification model provided by IMAU. This presentation focuses on large differences arising from using different re-tracker strategies applied to data acquired over the Greenland and Antarctic ice sheets. We will present a set of estimates derived from three different re-tracking approaches. To verify our results we will compare our radar-altimetry elevation change rates with rates obtained from ICESat data covering the same time period (2003 to 2009), as well as ENVISAT using the same interpolation approach. Additionally, we will compare our altimetric derived mass change estimates with the time series observed by GRACE.

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**On a Path Towards the Reassessment of Antarctic Volume Change: Synthesis of ESA CryoSat-2 Radar and NASA Airborne and Satellite Laser Altimetry Observations**

*Johan Nilsson, Alex Gardner*

*Jet Propulsion Laboratory, California Institute of Technology, United States of America*

The West Antarctic Ice Sheet has experienced rapid changes in its surface elevation in response to glacier thinning that results from accelerated flow of glaciers feeding into the Amundsen and Bellingshausen Seas. Changes in the surface elevations over the East Antarctic Ice Sheet and over "stable" ice shelves are much more subtle (~ ± 1 cm a<sup>-1</sup>) and approach the limit of detectability from space. Here we present a reassessment of changes in grounded ice volume for the Antarctic Ice Sheet using a new technique to merge radar and laser altimetry, from both airborne and satellite data, to produce long-term and robust assessments of elevation change rates for the Antarctic Ice Sheet. The applied merging procedure allows the local solution to estimate the inherent elevation bias between laser and radar-derived elevations, due to signal penetration of the radar wave into low-density firn in the upper strata of the ice sheets surface.

To determine the volume change of the Antarctic Ice Sheet a total of five altimetry missions were used, consisting of both airborne and satellite observations. Airborne surface elevations were gathered from NASA's Operation IceBridge (Land, Vegetation, and Ice Sensor (LVIS), Airborne Topographic Mapper (ATM) and the Riegl Laser Altimeter from University of Texas) and satellite derived elevations in the form of the Ice, Cloud, and land Elevation Satellite (ICESat) and ESA's CryoSat-2 mission. These multi-temporal surface elevations, spanning the time period of 2003-2016, were then merged locally at 1-km resolution using an adaptive least-squares minimization, accounting for both the spatial and temporal data availability in the solution. This point wise solution provides ice sheet wide estimates of elevation change with accompanying time series that were then gridded to 5 km resolution using optimal interpolation.

The quality of the merged solution was further judge by local comparison of elevation change rates estimated over the same time period from multi-mission satellite crossover analysis. Finally, the derived volume change rates are placed in the context of other published estimates of Antarctic Ice Sheet volume change spanning the time period of 2003-2016.

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**Combining Data Sets to Improve the Vertical and Spatial Resolution of Cryosat-2 Elevation-Change Mapping.**

*Benjamin E. Smith<sup>1</sup>, Alex Huth<sup>2</sup>*

*<sup>1</sup>University of Washington APL, United States of America; <sup>2</sup>University of Washington Dept. of Earth and Space Sciences, United States of America*

CryoSat-2 is currently unique for providing dense, well-located measurements of elevation and elevation change throughout coastal Greenland and Antarctica. The point-of-closest-approach (POCA) measurements allow seasonal recovery of elevation and elevation change at horizontal resolutions of a few km, with sub-meter precision, but recovering smaller-scale features, at higher spatial or temporal resolution, can be difficult using these data alone. In this presentation, we discuss techniques to include additional data in global solutions for elevation and elevation change. Additional sources of information include swath-processed Cryosat-2 returns, laser-altimetry data, stereo-photogrammetry DEMs (digital-elevation models), and surface-slope information from sunlit optical imagery. As an example, CryoSat-2 data can be used to estimate biases in DEMs from Worldview stereo pairs, allowing their use in estimating elevation and elevation change in areas where other control data are not available. We provide examples for how each type of data can be used in glaciological problems, including outlet glacier elevation change, ice-shelf change mapping, and subglacial lake discharge mapping.

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## Session 3D – CryoSat2-IceSat2 synergy towards future polar missions

14:00pm - 15:40pm Castle Room

### ICESat-2, its Retrievals of Ice Sheet Elevation Change and Sea Ice Freeboard, and Potential Synergies with CryoSat-2

Thorsten Markus<sup>1</sup>, Thomas Neumann<sup>1</sup>, Benjamin Smith<sup>2</sup>, Ronald Kwok<sup>3</sup>

<sup>1</sup>NASA, United States of America; <sup>2</sup>University of Washington, United States of America; <sup>3</sup>JPL, United States of America

Understanding the causes and magnitudes of changes in the cryosphere remains a priority for Earth science research. Over the past decade, NASA's and ESA's Earth-observing satellites have documented a decrease in both the areal extent and thickness of Arctic sea ice, and an ongoing loss of grounded ice from Greenland and Antarctic ice sheets. Understanding the pace and mechanisms of these changes requires long-term observations of ice-sheet mass, sea-ice thickness, and sea-ice extent.

ICESat-2 has three pairs of beams, each pair separated by about 3 km across-track with a pair spacing of 90 m. The spot size is 17 m with an along-track sampling interval of 0.7 m. This measurement concept is a result of the lessons learned from ICESat. The multi-beam approach is critical for estimating cross-track slope around the margins of Greenland and Antarctica enabling the calculation of elevation change on a seasonal basis. For sea ice, the dense spatial sampling (eliminating along-track gaps) and the small footprint size are especially useful for sea surface height measurements in the, often narrow, leads needed for sea ice freeboard and ice thickness retrievals.

Currently, algorithms are being developed to calculate ice sheet elevation change and sea ice freeboard from ICESat-2 data. The talk will present an overview of algorithm approaches and how ICESat-2 and Cryosat-2 data may augment each other.

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### Possible Extensions for the ESA Ice Mission CryoSat-2: Exploiting the CryoSat-2/ICESat-2 Synergies

Javier Sanchez<sup>1</sup>, Xavier Marc<sup>2</sup>, Gerald Ziegler<sup>3</sup>, Miguel Angel Martin Serrano<sup>3</sup>, David Fornarelli<sup>4</sup>, Elia Maestroni<sup>2</sup>

<sup>1</sup>GMV GmbH at the European Space Operations Centre (ESOC), Germany; <sup>2</sup>European Space Agency (ESA), European Space Operations Centre (ESOC), Germany; <sup>3</sup>SCYSIS GmbH at the European Space

Operations Centre (ESOC), Germany; <sup>4</sup>Rhea Group at the European Space Operations Centre (ESOC), Germany

The CryoSat-2 satellite was successfully launched on the 8th of April 2010 on a Dnepr rocket from the Baikonur Cosmodrome in Kazakhstan. The mission is dedicated to the precise monitoring of changes in the thickness of marine ice floating in the polar oceans as well as variations in the thickness of the vast ice sheets that overlie Greenland and Antarctica. The CryoSat-2 satellite is operated following a near-polar reference orbit, with a 92 degrees mean inclination of the orbital plane and a repeat cycle of 5344 orbits in 369 nodal days. The spacecraft is equipped with two redundant pairs of 40 mN cold gas thrusters to execute orbit maintenance manoeuvres.

In nearly 7 years of operations the CryoSat-2 satellite has successfully produced a wealth of data in a field of growing scientific interest. Now, the excellent state of the platform and the load of remaining propellant (31.5 kg from its initial 36.7 kg) enable the extension of operations even further. As for the activities foreseen for the coming years, an opportunity has been identified by acquiring a ground-track pattern close to that of NASA mission ICESat-2. The ICESat-2 spacecraft is set for launch in 2018 and will be operated following a near polar reference orbit. The purpose of this paper is to analyse the feasibility of a CryoSat-2 re-orbiting and orbit maintenance in order to support combined operations with the ICESat-2 mission. Likewise, its aim is to trigger the interest among the scientific community on potential benefits of this type of operations and to stimulate users of both missions into exploiting the synergies that this possibility can offer.

In the general case, the acquisition of a new reference orbit for CryoSat-2 implies: the adjustment of the orbital plane inclination, in order to acquire the same areas in the polar regions; the selection of a new orbital period, which satisfies the needs of the combined ICESat-2/CryoSat-2 operations; the correction of the eccentricity vector and the acquisition of the right phasing.

The execution of inclination changes via Out-Of-Plane manoeuvres presents an exceptional challenge for the CryoSat-2 mission. This manoeuvre type requires a 90-degree attitude slew in order to perform a delta-V perpendicular to the orbital plane. In addition to this, the performances of the cold gas thrusters lead to a relatively low delta-V, which forces the split of the necessary inclination changes into several manoeuvres. The implementation of inclination control for the CryoSat-2

mission was not foreseen in the original requirements and feasibility analysis and has never been attempted in flight. The impact on the space segment of this type of operations will be analysed in depth. This paper details the baseline to acquire the target inclination, as well as

its maintenance during the combined operations period. Also, results of the initial operational feasibility assessment will be presented.

Concerning the change in orbital period, two options have been analysed in this study. The purpose of these examples is to illustrate the performances that can be achieved in terms of synchronization of the grid of equatorial nodes of both missions. However, different solutions can be found in this respect depending on the specific requirements for combined operations of both payloads.

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### **Continuation of Service for CryoSat using the Sentinel-6 Heritage Platform with an Interferometric SAR Altimeter**

*Bjoern Barthen<sup>1</sup>, Klaus Koebler<sup>1</sup>, Robert Cullen<sup>2</sup>, Pierrick Vuilleumier<sup>2</sup>, Daniel Sausen<sup>1</sup>, Frank Blender<sup>1</sup>, Inge Vanschoenbeek<sup>1</sup>, Florian Reuscher<sup>1</sup>*

<sup>1</sup>Airbus DS GmbH; <sup>2</sup>European Space Agency

In view of the international user needs to have a long term climate data record of land and marine ice sheet retrievals we have investigated the constraints to launch a potential follow-up mission to CryoSat-2. Situated in a non-Sun-synchronous, near-polar orbit with an altitude just over 700 km and an inclination of 92 deg, CryoSat-2 successfully concluded its nominal mission in October 2013 and is continuing to provide valuable data post its extended.

At perfect health and more than 6 years in orbit, CryoSat-2 provides unique data of the cryosphere. In order to ensure continuation of this data, one must think, however, beyond CryoSat-2. Building a new satellite takes a long time and bears development risks both jeopardising the successful continuation of the CryoSat mission. This article presents the possibility of refitting the Sentinel-6 spacecraft with an interferometric SAR altimeter, minimising development time and risk towards the continuation of CryoSat.

Already prior to the launch of CryoSat-2, ESA initiated a study focusing on the continuation of the well-recognized series of TOPEX/Poseidon and Jason-1, 2 and Jason-3 while relying on the CryoSat platform concept, which eventually became the Jason-CS/Sentinel-6 mission. The Sentinel-6 platform itself is the result of studying the possibility to re-use CryoSat while making required adaptations. Adaptations were made in order due to cope with a far more severe radiation environment, hosting payloads supporting the new oceanographic mission, ensuring space environment sustainability by performing de-orbiting after the nominal mission and coping with obsolescences of the CryoSat platform.

It is only logical that the Sentinel-6 platform is by itself perfectly suited to host a new SIRAL-3 instrument, requiring only few modifications. This new satellite will meet permit continuing CryoSat with exiting or surpassing performances. Observation of continental

ice sheets and ocean can be performed in SAR burst and no longer Low Resolution Mode. Next to DORIS and the laser retro reflector, a GNSS receiver can be used for orbit determination additionally. An increase in lifetime can be expected due to Sentinel-6 being designed for a longer mission in a radiation critical Low Earth Orbit.

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### **Evolutions of the SIRAL instrument for the Cryosat Follow-On mission**

*Yves Le Roy<sup>1</sup>, Eric Caubet<sup>1</sup>, Pierluigi Silvestrin<sup>2</sup>, Erik De Witte<sup>2</sup>, Robert Cullen<sup>2</sup>*

<sup>1</sup>THALES ALENIA SPACE, France; <sup>2</sup>ESA-ESTEC

This paper presents the outputs of recent studies which have been carried out by Thales Alenia Space (TAS) to support ESA in the definition of the SIRAL instrument for the Cryosat Follow-On (FO) mission. The SIRAL-2 instrument of the currently in-orbit Cryosat-2 mission was under TAS responsibility.

The SIRAL-2 instrument is a nadir-looking Ku-Band radar altimeter with interferometric capability. The radar supports three different modes which are switched according to the surface type, the conventional Low Resolution mode (LRM) as well as the SAR and SAR Interferometric (SARIn) modes, these two modes being operated in closed-burst fashion. The first objective of the SIRAL Follow-On radar is to meet, as a minimum, the existing Cryosat-2 requirements. For this, the SAR and SARIn modes providing the same performances as SIRAL-2 are proposed as a baseline in order to ensure continuity in the SIRAL-2 measurements. The SARIn interleaved mode operated with a PRF of 18 kHz is proposed as an enhanced mode in order to improve the azimuth resolution over sea ice surfaces and provide better detection of sea ice freeboards. The instrument architecture which responds to these requirements is based on the Jason-CS/Poseidon-4 architecture whose development is in progress as well as on the SIRAL-2 heritage. This leads to a cost-efficient flexible solution including state of the art technologies while ensuring optimum continuity in the altimeter product line.

Snow loading on sea ice has proved to alter the accuracy of sea ice thickness retrieval in Ku-Band. The addition of a Ka-band nadir channel would improve the retrieval of ice elevation and snow thickness by taking advantage of deterministic snow penetration rates in Ku- and Ka-Band. This is supported by the comparisons made by scientists between the SIRAL measurements in Ku-Band and the Alti-Ka measurements of the SARAL mission. Furthermore, ionospheric corrections can also be performed by using the dual Ku/Ka measurements in order to improve the Sea Surface Height accuracy. The Ka-Band functionality, which is built on top of the Ku-Band without modifying its original performances, allows simultaneous acquisitions in the dual band, with reduced impacts on the instrument architecture and a

reasonable increase of mass and power consumption budgets.

The architecture and the performances of the radar in the baseline configuration and with the enhanced functionalities (SARIn interleaved mode in Ku-Band, addition of Ka-Band) will be presented and discussed.

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### **AltiCryo: A CNES Altimetry Concept Study for Cryosphere Monitoring**

*Amandine Guillot<sup>1</sup>, Frédérique Rémy<sup>2</sup>, François Boy<sup>1</sup>, Jean-Luc Courrière<sup>1</sup>, Anne Lifermann<sup>1</sup>*

<sup>1</sup>CNES, France; <sup>2</sup>LEGOS, France

The cryosphere monitoring is crucial for environment and climate studies. Alongside Cryosat-2, another altimetry mission has contributed to advances in cryosphere studies: SARAL/AltiKa, developed by CNES and ISRO mission, and launched in 2013. First, SARAL/AltiKa flew on the orbit as Envisat until last July, providing continuity of topography measurement on the ground track monitored by ERS1,2 and ENVISAT since 1992. Second, the AltiKa instrument provides active (altimeter) and passive (radiometer) measurements in Ka-band, which is valuable to understand the ice and snow properties (Frédérique Rémy, Thomas Flament, Aurélie Michel & Denis Blumstein (2015) Envisat and SARAL/AltiKa Observations of the Antarctic Ice Sheet: A Comparison Between the Ku-band and Ka-band, Marine Geodesy, 38:sup1).

Based on the SARAL/AltiKa feedback over cryosphere, the French space agency (CNES) has initiated a study to propose an altimetry concept optimized for the cryosphere scientific needs. This concept will be derived from AltiKa and has to be compact and cost-effective. This paper will describe the objectives and the organization of this study.

The first step of the study is to document user needs for cryosphere, based on the actual knowledge acquired with current missions (both SARAL and Cryosat) and physical measurement skills. The orbit choice will also be discussed.

The second step consists in the definition of an instrumental configuration which will satisfy the user needs. A first concept to be studied is a dual frequency Ka/Ku altimeter, operating in LRM or SAR mode. Based on the SARAL/AltiKa experience, some instrument parameters will be tuned to optimize the cryosphere observation. Moreover, the AltiKa radiometer function could be maintained, to help characterizing surface properties over ice, as well as providing wet tropospheric correction over ocean.

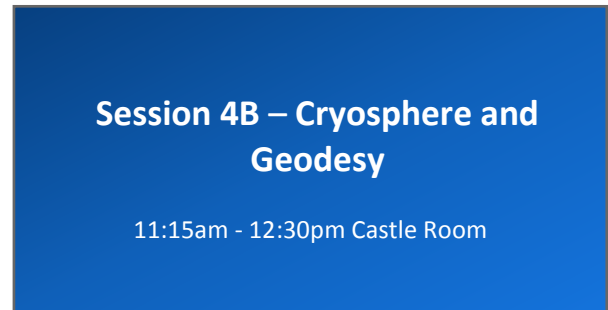
Once the instrumental configuration will be set up, the associated end-to-end performance will be assessed, including ground processing up to the product level. In particular, the impact of Ku-Ka band combination will be studied. The advantages and drawbacks of this

configuration will be also compared with the Cryosat-FO concept.

Lastly, the impacts on the platform will be listed.

The AltiCryo study should run until July 2017.

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### **Large Precipitation Event Influences Sub-Glacier Hydrology and Ice Flow of Recovery Ice Stream, East Antarctica**

*Indrani Das<sup>1</sup>, Nicole Schlegel<sup>2</sup>, Ted Scambos<sup>3</sup>, Bea Csatho<sup>4</sup>, Greg Babonis<sup>4</sup>*

<sup>1</sup>Columbia University, United States of America; <sup>2</sup>Jet Propulsion Laboratory, NASA, California, USA; <sup>3</sup>University of Colorado in Boulder, Boulder, USA; <sup>4</sup>University at Buffalo, Buffalo, New York, USA

We observe a period of anomalous net positive accumulation of several gigatons over Recovery Ice Stream in 2006 using both GRACE and climate model data. The accumulation anomaly, manifest by higher-than-average precipitation, reversed the sign of Recovery Ice Stream mass balance over a period of a few months as observed by GRACE within the course of a year. ICESat and IceBridge laser altimetry data confirmed a thickening signal corresponding to the precipitation event. The timing of the precipitation event was correlated with movement of water in subglacial lakes over the Recovery Ice Stream. We propose that the large precipitation event caused a significant change in the ice overburden pressure at the base of the ice sheet, prompting subglacial water movement. This anomalous precipitation event may not be an isolated incident; climate models and reanalysis data suggest events of similar magnitude may occur a few times in a decade. We will present preliminary results using satellite and airborne laser altimetry and modeling.

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### **Estimate of Regional Glacial Isostatic Adjustment in Antarctica Considering a Lateral Varying Earth Structure (ESA-STSE Project REGINA)**

*Ingo Sasgen<sup>1</sup>, Alba Martín-Español<sup>2</sup>, Alexander Horvath<sup>3</sup>, Volker Klemann<sup>4</sup>, Elizabeth J. Petrie<sup>5</sup>, Bert Wouters<sup>6</sup>, Martin Horwath<sup>7</sup>, Roland Pai<sup>3</sup>, Jonathan L.*

Bamber<sup>2</sup>, Peter J. Clarke<sup>8</sup>, Hannes Konrad<sup>9</sup>, Mark R. Drinkwater<sup>10</sup>

<sup>1</sup>Division of Climate Sciences, Alfred Wegener Institute, Bussestraße 24, 27570 Bremerhaven, Germany.; <sup>2</sup>School of Geographical Sciences, University of Bristol, University Road, Clifton, Bristol BS8 1SS, United Kingdom.; <sup>3</sup>Institut für Astronomische und Physikalische Geodäsie, Technische Universität München, Arcisstraße 21, 80333 München, Germany.; <sup>4</sup>Department of Geodesy, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany.; <sup>5</sup>School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, United Kingdom.; <sup>6</sup>Institute for Marine and Atmospheric Research, Utrecht University, Princetonplein 5, 3584 CC, Utrecht, The Netherlands.; <sup>7</sup>Institut für Planetare Geodäsie, Technische Universität Dresden, Helmholtzstr. 10, 01069 Dresden, Germany.; <sup>8</sup>School of Civil Engineering and Geosciences, Newcastle University, Newcastle, NE1 7RU, United Kingdom.; <sup>9</sup>School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, United Kingdom.; <sup>10</sup>Mission Science Division, European Space Agency, European Space Research and Technology Centre, Keplerlaan 1, Noordwijk 2201 AZ, The Netherlands.

The mass balance of the Antarctic ice sheet from satellite gravimetry, and to a lesser extent altimetry, observations remains uncertain due to the poorly known correction for the glacial isostatic adjustment of the solid Earth (GIA). Although much progress has been made in consistently modelling ice-sheet evolution, related bedrock deformation and sea-level change, predictions of GIA remain ambiguous due to the lack of observational constraints in Antarctica. Here, we present an improved GIA estimate based on the joint inversion of GRACE, Envisat/ICESat and GPS measurements, making use of the different sensitivities of the satellite observations to surface-mass and solid Earth processes. We base our joint inversion on viscoelastic response functions to a disc load forcing, allowing us to account for lateral variations in the lithosphere thickness and mantle viscosity in Antarctica. Our estimate is able to reproduce extreme GPS-measured uplift rates (up to 3 cm yr<sup>-1</sup>) in the Amundsen Sea Embayment, indicating that large parts of the uplift are caused by GIA induced by recent load changes in the presence of a low-viscosity upper mantle. We compare our GIA inversion estimate with the prediction obtained with a coupled model of the ice sheet and solid Earth, as well as with published estimates. We evaluate its impact on the determination of ice-mass balance in Antarctica from gravimetry and altimetry. The results presented here are the final results of the Support To Science Element Project REGINA and its Supplementary Study of the European Space Agency, [www.regina-science.eu](http://www.regina-science.eu).

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## Arctic Gravity Field from Cryosat-2

Ole Baltazar Andersen, Per Knudsen, Adili Abulaitijiang, Simon Holmes  
DTU spac, Denmark

Cryosat-2 data offers a unique possibility to derive the Arctic gravity due to its near geodetic orbit of 369 days repeat. Its the only satellite besides the old ERS-1 flown 20 years ago which provide satellit altimetry of geodetic quality in the Arctic Ocean.

We will present and evaluate our new DTU15 global marine gravity field as well as our pre-releasable DTU17 arctic gravity field in the Arctic Ocean.

Both are based on retracked altimetry from Cryosat-2 and ERS-1 in the Arctic Ocean. In the Arctic Ocean we are testing an new combined empirical/physical retracking system that uses physical retracking of the LRM data using a reduced parameter system in combination with empirical retracking of the SAR and SAR-In data in particularly high latitude regions.

An advantage of the Cryosat-2 is its ability of provide new accurate sea surface height information for gravity field determination in the northernmost part of the Arctic Ocean upto 88N where no altimeters have measured before.

Also the first evaluation of the use of Cryosat-2 SAR data in a few relative narrow fjords of Greenland will be presented.

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## High-Resolution Mass Changes of the Greenland and Antarctica Ice Sheets from Combined CryoSat and GRACE Inversion

Rene Forsberg, Sebastian Simonsen  
DTU Space, Denmark

The combination of space-based remote sensing data, especially gravity field changes from GRACE and elevation changes from CryoSat, may yield time series of Greenland and Antarctica mass balance with both high temporal and spatial resolution, highlighting the varying individual mass loss behaviour of major glaciers systems, while still keeping a “correct” overall ice sheet wide mass loss, within the uncertainty of the glacial-isostatic effects. Although the GIA-related errors continue to be large in Antarctica, the temporal changes in mass balance are well determined, and show significant acceleration both over the Antarctic Peninsula and the Pine Island/Thwaites glacier systems. For Greenland the large yearly melt event of 2012 followed by extraordinary cool summers have meant that the Greenland ice sheet mass loss have been slightly decreasing during the CryoSat period 2010-16, with large variations between individual glaciers and ice streams.

In the presentation we outline change results from CryoSat and GRACE 2010-2016, for both Greenland and Antarctica, and outline the basis of a high resolution point mass estimation method, and the associated use



firm compaction and density models. We also include estimates of the northern Canadian ice cap changes to reduce GRACE leakage errors for Greenland. We estimate an overall mass balance of Greenland around -265 GT/yr and for Antarctica -145 GT/yr, representing nearly a doubling of Antarctica mass loss since 2002, while Greenland show only relatively small overall accelerations, with large regional melt region variations, clearly pointed out by CryoSat.

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### High Mountain Asia Glacier Mass Balance Estimates Using Satellite Geodetic Observations

Jian Sun

Ohio State University, United States of America

The 2013 Intergovernmental Panel for Climate Assessment (IPCC) Fifth Assessment Report (AR5) concluded that the observed and explained geophysical causes of global geocentric sea-level rise, 1993–2010, is much closer towards closure. However, the discrepancy reveals that up to approximately 30% of the observed sea-level rise remains *unexplained*, despite contemporary reports on *reconciled* mass balance estimates of ice-sheet and mountain glaciers during the early 21<sup>st</sup> century. This discrepancy is primarily attributable to the wide range of estimates of respective contributions of Greenland and Antarctic ice-sheets and mountain glaciers to sea-level rise. In particular, the High Mountain Asia glacier systems remains a focus of public and scientific debate, as the uncertainty of its mass balance estimates and its future projection have a significant implication of water resource problems affecting 1.5 billion people in the region. It is also not clear, in the case of the High Mountain Asia glacier system that glacier ablation would instantaneously contribute to sea-level rise, as melt water is largely dammed up resulting from anthropogenic activities in the region. The use of satellite altimetry for glacier elevation change has been problematic primarily because of steep terrains causing grossly inaccurate gradient corrections hindering the ability to generate ice elevation time series. Here we use available DEMs developed using the Indian Cartosat-1 (2.5 m resolution) and the KH-9 Hexagon, and ALOS PALSAR and Envisat ASAR InSAR measurements over glaciers, such as the Siachen Glacier system in the East Karakoram for gradient corrections to generate altimetry-based glacier elevation time series. In particular, we use ICESat and multi-mission radar altimeter data including TOPEX, ERS-1/-2, Envisat, SARAL/Altika, CryoSat-2, as well as GRACE gravimetry data, and improved mountain glacier masks developed using optical/IR and SAR data, to provide an update of the glacier mass balance estimate in the High Mountain Asia region.

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## Session 4C – Ice sheet dynamics

14:00pm - 15:20pm Castle Room

### Measuring Surface Processes for the Interpretation of CryoSat-2 and IceBridge Altimetry in the Accumulation Zone of Greenland.

Santiago de la Peña<sup>1</sup>, Ian Howat<sup>1</sup>, Alberto Behar<sup>2</sup>, James Crowell<sup>2</sup>

<sup>1</sup>The Ohio State University, United States of America; <sup>2</sup>Arizona State University, United States of America

Inter-annual fluctuations in the firm volume of the Greenland Ice Sheet have been observed in recent years by repeated altimetry from CryoSat-2. Although an order of magnitude smaller than ice thinning rates measured in some areas at the margins of the ice sheet, these short-term departures in surface elevation trends occur over most of the accumulation zone of Greenland. Changes in the thickness of the firm column are influenced by variability in surface mass balance, firm compaction, and abrupt seasonal densification near the surface caused by refreezing at depth of variable amounts of surface meltwater produced during the summer. These processes and dynamic thinning cannot be differentiated from each other by altimetry alone.

Here we use direct, continuous measurements of firm density and surface mass balance along with annual estimates of firm ice content used to assess observed elevation change in the percolation zone of western Greenland in relation to firm processes. Since 2012, autonomous in-situ firm compaction sensors have monitored several sites in the catchment area of Jakobshavn Isbrae, and since 2015 surface mass balance and surface displacement has been measured continuously using a combination of sensors. In addition to identify the different components in the altimetry signal, the temporal resolution of the data acquired provide a means to monitor short-term changes in the near-surface firm, and identifying individual events causing surface elevation displacement independently from ice dynamics in western Greenland.

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### Swath Processing of CryoSat-2 for Improved Coverage of the Grounding Zone

Geoffrey Joseph Dawson, Jonathan Bamber  
University of Bristol, United Kingdom

The synthetic aperture radar interferometric (SARin) mode of CryoSat-2, which uses a cross-track

interferometer to determine the origin of off-nadir reflections, has performed better over steeper margins of the ice sheets compared to previous conventional radar altimetry. In the grounding zone of ice sheets where there is generally a break in slope, measurements based on the point of closest approach (POCA) are limited as the POCA points tends to be clustered upslope of the grounding line, reducing coverage in this critical zone. Swath processing maps the time-delayed footprint beyond the POCA allowing us to obtain downslope elevation estimates close to nadir. In this study, we focus on the Antarctic Peninsula and the Ross Ice Shelf to investigate the accuracy and potential for improved coverage using swath processing compared to the POCA data around the grounding zone. We compare the results with ICESat to assess the accuracy, and with the POCA data to assess the improvement in coverage.

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**Fourteen Years of Subglacial Lake Activity in Antarctica from Multi-Mission Altimetry**

*Matthew R. Siegfried, Helen A. Fricker  
Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, United States of America*

The ability to infer the movement of water beneath the Antarctic ice sheet using remote sensing techniques has fundamentally altered our perception of the subglacial environment. What used to be considered system in steady-state is now known to be a dynamic environment, with inferred variability on timescales ranging from sub-annual to multi-century or longer. The changing basal environment has direct implications on regional glaciological parameters (e.g., ice flow and grounding line dynamics), as well as on boundary conditions for other disciplines (e.g., freshwater flux to the ocean and global carbon cycling). Our understanding of subglacial hydrological variability on timescales likely important for the near-term prediction of ice sheet fluctuations driven by global climate change (multi-year to decadal) is limited by the short temporal window of our current record of active subglacial hydrology (2003-2008). Here we extend the record of subglacial lake activity for all lakes covered by CryoSat-2 SARIn mode-data, to generate a fourteen year time series. We reassess the ice surface height anomalies and explore what we can infer about Antarctic subglacial hydrologic processes and variability from this extended time-series.

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**Comparison of Regional Scheme Techniques for Estimating the Canadian Arctic Archipelago Land Ice Mass Changes from ICESat**

*Iliana Tsalis, Michael Sideris  
University of Calgary, Canada*

Mountain glaciers and ice caps of the Canadian Arctic Archipelago (CAA) - sensitive indicators of climate change - have recently been characterized as significant contributors to the sea level rise. Therefore, our goal is to estimate the elevation changes of the land ice covered area of the North and South Canadian Arctic Archipelago (NCAA and SCAA), using high spatial resolution satellite laser altimetry data from the ICESat satellite. In order to estimate the mass variations, we seek a spatial correlation scheme for predicting the elevation change values in the unmeasured off-track glaciated areas, convert them to volume changes, and then into mass changes.

Our focus lies on applying and comparing the deterministic method of inverse distance weighting and the geostatistical method of ordinary kriging for investigating the variability of the regional volume changes. The data used are the GLAS/ICESat L2 Global Land Surface Altimetry data (product GLA14) of release 34, referring to the period from 2003.02.20 until 2009.10.10. Repeat-track method is followed for estimating the elevation rates, after gross error detection. The glaciated areas of the CAA are defined as refined polygons of glaciers and ice caps obtained from the GLIMS Glacier Viewer.

We evaluate our results by performing cross-validation comparison on the implemented techniques on a dense and a sparse measurement sampling of the NCAA and the SCAA respectively. Our results show that although both methods are giving similar ice mass change estimates, approximately ~40 Gt/year for the NCAA and ~25Gt/year for the SCAA, in agreement with previous studies, ordinary kriging is the preferred method for estimating the mass balance of ice caps and glaciers, since it can work with noisy data and provide uncertainties in the predicted results.

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**Session 4D - Ice-caps and  
Glaciers**

16:10pm - 17:50pm Castle Room

**Invited - Keynote: Monitoring and Modelling Glacier Changes in Western Canada**

*Shawn Marshall<sup>1</sup>, Brian Menounos<sup>2</sup>  
<sup>1</sup>University of Calgary, Canada; <sup>2</sup>UNBC*

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## Near Real-Time Mass Balance of Arctic Ice Caps from the CryoSat-2 Radar Altimeter

David Burgess<sup>1</sup>, Laurence Gray<sup>2</sup>, Luke Copland<sup>2</sup>

<sup>1</sup>Natural Resources Canada, Canada; <sup>2</sup>University of Ottawa

Canada is a circumpolar nation which collectively holds the largest reserve of land ice on the planet outside of the ice sheets of Greenland and Antarctica. Since the early 1960's, reference glaciers in the Queen Elizabeth Islands (QEI) have been measured annually to provide a multi-decadal time series of glacier mass balance as an indicator of climate change. Unprecedented warming across this region since the early 2000's has resulted in strongly negative glacier mass balances, causing this region to become the largest non-ice sheet contributor to eustatic sea level rise. This recent shift towards strongly negative mass balance, combined with predictions of enhanced warming for the Arctic to at least 2100 (IPCC), has increased demand for more timely information pertaining to annual glacier mass balance from the Arctic region. In this study we present seasonal height changes of the Meighen, Devon, and Barnes ice caps in the Canadian Arctic using CryoSat-2 SARIn mode 'Point of Closest Approach' (POCA) measurements. Independent validation through comparison with in-situ mass balance and NASA ATM data highlights the effectiveness of CryoSat-2 for obtaining near-real time glacier mass balance information from one of the fastest warming regions on Earth.

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## Validation of CryoSat-2 for Elevation-Change Detection Over Glaciers on Svalbard and Ice Rises in Antarctica

Geir Moholdt, Laurence Gray, Thorben Dunse, Kirsty Langley, Kenichi Matsuoka, Thomas V. Schuler, Bert Wouters

Norwegian Polar Institute, Norway

Precise applications of CryoSat-2 over glaciers and ice sheets can be hampered by variable signal penetration and backscatter in snow and ice, particularly during the transition from a cold winter snowpack to a melt-affected summer snowpack. In this study, we use dense networks of GPS surface profiles to validate CryoSat-2 elevation estimates from ESA's Level 2 product and alternative processing techniques using Level 1b data. We consider surface elevations from both the point-of-closest-approach (POCA) and the full swath of the interferometric mode. We investigate the variability in signal penetration by analysing the seasonal evolution of derived surface elevations in respect to climate parameters. The main study targets are Austfonna ice cap on Svalbard and three ice rises in Dronning Maud Land, East Antarctica, where extensive ground-truth data are available. We find that the results of POCA and swath processing complement each other very well: POCA locations concentrate along ice divides whereas the swaths give good coverage in gentle slopes which are not resolved by POCA. A combined approach has

the potential to improve current DEMs in coastal Antarctica and increase the coverage of elevation-change measurements at the margins of ice sheets and glaciers where most of current mass losses take place.

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## Swath Processing of CryoSat-2 for the Study of Ice Caps and Mountain Glaciers

Noel Gourmelen<sup>1</sup>, Paul Tepes<sup>1</sup>, Albert Garcia<sup>2</sup>, Maria Jose Escorihuela<sup>2</sup>, Jan Wuite<sup>3</sup>, Luca Foresta<sup>1</sup>, Thomas Nagler<sup>3</sup>, Monica Roca<sup>2</sup>, Andrew Shepherd<sup>4</sup>, David Brockley<sup>5</sup>, Steven Baker<sup>5</sup>

<sup>1</sup>University of Edinburgh, United Kingdom; <sup>2</sup>isardSAT, Spain; <sup>3</sup>ENVEO, Austria; <sup>4</sup>Center for Polar Observation and Modeling, University of Leeds, UK; <sup>5</sup>MSSL, University College London, UK

Satellite altimetry has been used extensively in the past few decades to observe changes affecting large and remote regions covered by land ice such as the Greenland and Antarctic ice sheets. Glaciers and ice caps have been studied less extensively due to limitation of altimetry over complex topography. However their role in current sea-level budgets is significant and is expected to continue over the next century and beyond (Gardner *et al.*, 2011), particularly in the Arctic where mean annual surface temperatures have recently been increasing twice as fast as the global average (Screen and Simmonds, 2010).

Radar altimetry is well suited to monitor elevation changes over land ice due to its all-weather year-round capability of observing ice surfaces. Since 2010, the Synthetic Interferometric Radar Altimeter (SIRAL) on board the European Space Agency (ESA) radar altimetry CryoSat (CS) mission has been collecting ice elevation measurements over glaciers and ice caps. Its Synthetic Aperture Radar Interferometric (SARIn) processing feature reduces the size of the footprint along-track and locates the across-track origin of a surface reflector in the presence of a slope. This offers new perspectives for the measurement of regions marked by complex topography.

More recently, data from the CS-SARIn mode have been used to infer elevation beyond the point of closest approach (POCA) with a novel approach known as "swath processing" (Hawley *et al.*, 2009; Gray *et al.*, 2013; Foresta *et al.*, 2016). Together with a denser ground track interspacing of the CS mission, the swath processing technique provides unprecedented spatial coverage and resolution for space borne altimetry, enabling the study of key processes that underlie current changes of ice caps and glaciers.

In the frame of the CryoSat+ Mountain Glacier project, we use CS swath observations to generate global maps of ice elevation change over ice caps and glaciers. Here we present results over most of the world's ice caps and selected glaciers and discuss the benefit of swath processing for assessing glaciers and ice caps changes and their contribution to changes in sea level.



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### **Cryosat-2 Altimetry of BC Coastal Mountain Glaciers**

*Jim Gower<sup>1</sup>, Stephanie King<sup>2</sup>*

*<sup>1</sup>Institute of Ocean Sciences, North Saanich, BC, Canada; <sup>2</sup>Sea This Consulting, Nanaimo, BC, Canada*

Cryosat-2 altimetry for the period July 2010 to January 2016, shows wide-spread melting of glaciers in the southern part of the British Columbia (BC) Coastal Mountain range in western Canada. The SARIN altimeter on Cryosat-2 is in synthetic aperture mode in this area, recording elevations of suitably-sloping targets out to about 5km cross-track from nadir and hence giving full coverage between tracks separated by 5km. Average height change rates were computed for small, overlapping sub-regions covering the study area. Sub-regions at altitudes less than 1500m showed rates clustered symmetrically about zero. These targets could be confirmed by visual inspection to be from rock, soil or vegetated targets. Above 2000m more than half the targets show a broader distribution, indicating reducing altitudes (melting) by up to 2m.year<sup>-1</sup>. This second distribution is from the surface of glaciers. Melt rates above 1500m decrease with increasing altitude and are lower before the start of 2013 than in the three years afterwards. Absence of negative melt rates (i.e. growing glacier heights over the full study period) is especially striking. Results show the capability of Cryosat-2 to measure individual and average melt rates on a time scale of 2-3 years.

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**Session 5A - Glaciers: multisensory observations and simulations**  
16:10pm - 17:50pm Castle Room

### **Challenges and Approaches to Altimeter-Data Analysis of Rapidly Changing and Heavily Crevassed Glacier Systems: The Bering Bagley Glacier System, Alaska, During Surge in the View of CryoSat-2, ICESat-2 and Airborne Altimetry**

*Ute Christina Herzfeld<sup>1</sup>, Thomas Trantow<sup>1</sup>, Veit Helm<sup>2</sup>, Kelly Brunt<sup>3,4</sup>, William Cook<sup>4</sup>*

*<sup>1</sup>University of Colorado Boulder, United States of America; <sup>2</sup>Alfred Wegener Institut, Bremerhaven, Germany; <sup>3</sup>University of Maryland, United States of America; <sup>4</sup>NASA Goddard Space Flight Center, Greenbelt, United States of America*

As a complex and large mountain glacier system with surging and non-surging glaciers, the Bering-Bagley Glacier System (BBGS) is both glaciologically very interesting and a great test bed for satellite-observation ground truthing and algorithm development aimed at advancing the limits of altimetry. Bering Glacier and the eastern Bagley Ice Field surged in 2011-2013, after the launch of CryoSat-2, while the western Bagley Ice Field was not affected by the surge. The signatures of the surge that result from sudden mass transfer, changes in the hydrological system and acceleration and are observable with altimetry include elevation changes and crevassing. Challenges result from the specific combination of large elevation changes occurring over very short time frames, the spatially complex and changing dynamics of the surge in the BBGS and the size range of spatial signatures as well as coincident changes in surface reflectance. In this paper we investigate the possibilities for utilizing altimeter data to study the surge. Three data types are available: CryoSat-2 data (in several forms of processing), airborne laser altimeter data collected by our group in 4 airborne campaigns in 2011-2013, and observations collected with the ICESat-2 simulator instrument MABEL (Multiple Altimeter Beam Experimental Lidar) in July 2014.

Following spatial statistical analysis, comparison to flight data and detailed error analysis, we find that CryoSat-2 data provide time series of elevation and elevation change at 6-month intervals and hence can be used to monitor the complex mass transfer during the surge and is the only data available for this purpose. The relevance of CryoSat-2-based ice-surface observations as a constraint in modeling the surge dynamics will be presented in a companion paper. However, information on crevasse fields is not registered in CryoSat-2 data. High-resolution airborne altimetry reveals spatial characteristics of crevasse fields that result from different types of deformation, as will be illustrated for different times and ice provinces. Using an algorithm specifically designed for the analysis of micro-pulse photon-counting lidar altimeter data as will be collected by ICESat-2, we demonstrate that similar information on crevassed surfaces can be derived from MABEL data and hence from future ICESat-2 data. The presentation will conclude with glaciological implications of the altimeter-data analysis.

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### **Numerical Experiments of Surface Crevassing during the Surge of the Bering-Bagley Glacier System in 2011-2013 and Sensitivity to CryoSat-2 Processing**

*Thomas Trantow, Ute Christina Herzfeld*

*University of Colorado Boulder, United States of America*

Glacier acceleration is one of the main sources of uncertainty in global sea-level rise estimates according

to the IPCC 5th Assessment. Glacier surging is one type of acceleration found in ice systems around the world yet is still incompletely understood. After a long period of quiescent flow, a surge-type glacier will suddenly and rapidly advance resulting in large-scale elevation change and significant surface deformation. Crevasses are the most conspicuous manifestations of the surge dynamics and provide a source of geophysical information that allows reconstruction of deformational processes. The recent surge of the Bering-Bagley Glacier System (BBGS), Alaska, in 2011-2013 provides an excellent test case to study the surge through airborne and satellite observations together with numerical modeling.

A full-Stokes finite element model of the BBGS has been created using the Elmer/Ice software for structural and dynamical investigations of the surge. A von Mises condition is applied to modeled surface stresses so as to predict where crevassing might occur during the surge. The model is constrained by surface and bottom topography with associated boundary conditions all of which affect experiments investigating the glacier surface structure. CryoSat-2 measurements provide a time series of elevation at six-month intervals which are used as inputs for the numerical model. Satellite and airborne imagery of the BBGS during the surge provides us with observations for model-data comparisons with respect to the model's ability to predict surface crevassing. Sensitivity of results to different types of CryoSat-2 processing is investigated. As a result, the model-data comparison can be employed as a means for evaluation of CryoSat-2 processing.

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**Calibration and Use of the Interferometric Mode of the CryoSat Radar Altimeter to Measure Height Change in the Periphery of the Greenland Ice Cap**

Laurence Gray<sup>1</sup>, David Burgess<sup>2</sup>, Luke Copland<sup>1</sup>, Thorben Dunse<sup>3</sup>, Kirsty Langely<sup>4</sup>, Moholdt Geir<sup>5</sup>

<sup>1</sup>University of Ottawa, Canada; <sup>2</sup>Geological Survey Canada; <sup>3</sup>University of Oslo; <sup>4</sup>Asiaq, Greenland; <sup>5</sup>Norwegian Polar Institute

Geocoded heights derived from the interferometric mode (SARIn) of CryoSat are compared with surface heights from calibration-validation sites on Devon Ice Cap and West Greenland. Comparisons are included for both the heights derived from the first return (the 'point-of-closest-approach' or POCA) as well as heights derived from delayed waveform returns ('swath' processing). Using these results, we show that the pre-launch interferometric baseline coupled with an additional roll correction (~0.0075°), or equivalent phase correction (~0.0435 radians), provides an improved calibration of the interferometric SARIn mode.

The periphery of Greenland represents an important area for the use of the CryoSat SARIn mode: The ice

loss in this area is significant and hard to quantify at high spatial resolution with existing satellite sensors. We show that the CryoSat SARIn mode can provide useful information on the summer melt through waveform signature and height change estimates, including height change of supraglacial lakes. An adaption of swath processing is used in this work and height accuracies of ~0.5 m are possible for the supraglacial lakes when they are positioned very close to the sub-satellite track.

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**Session 5A - Glaciers:  
multisensor observations and  
simulations**

16:10pm - 17:50pm Castle Room

**Markov Random Field Based Waveform Retracking Solved by the Graph Cuts Technique**

Omid Elmi, Mohammad J. Tourian, Nico Sneeuw  
Institute of Geodesy, University of Stuttgart, Germany

Application of satellite altimetry over inland water bodies requires a postprocessing algorithm known as retracking. This study introduces a new retracking algorithm that benefits from information about spatial and temporal variation of waveforms over the selected region. We stack the waveforms over a selected water body into radargrams for each overpass of altimetry, which we then segment and label into two distinct parts (before and after retracking gate) with the help of returned power and the contextual and temporal correlation in the radargram. The separation line between two segments is referred to as "retracking line" which consists of the retracking gate for each waveform.

Markov random fields (MRF) can express a wide variety of spatially and temporally varying behaviors. To take advantages of this property, we define a MRF framework by specifying conditional distributions regarding the returned power and the labels. In order to find the retracking line in the radargram, the Maximum A Posteriori (MAP) estimate of the defined MRF must be sought. Since the high computational effort of finding a global solution is a serious concern, the problem is reshaped as an energy minimization problem. The minimum energy solution is found by the graph cuts technique, which is fast and able to find either the exact minimum or an approximate minimum solution. We apply our method to waveforms of the missions ENVISAT and CryoSat-2 over the Niger River at

Lokoja and validate the corrected water level time series against in situ water level and discharge.

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### **Water Level Estimation Along The Mekong River Using Cryosat-2 SAR Multi-Look Stack Data**

*Eva Boergens<sup>1</sup>, Karina Nielsen<sup>2</sup>, Ole B. Andersen<sup>2</sup>, Denise Dettmering<sup>1</sup>, Florian Seitz<sup>1</sup>*

*<sup>1</sup>Deutsches Geodätisches Forschungsinstitut, Technische Universität München, München, Germany; <sup>2</sup>Div. of Geodesy, DTU Space, National Space Institute, Kgs. Lyngby, Denmark.*

Cryosat-2 SAR data is especially useful for monitoring smaller inland waters thanks to the improved along track resolution compared to conventional LRM altimetry. However, the extraction of reliable water levels is still challenging for smaller rivers where only very few consecutive measurements over the water body are present. Maps or land-water-masks are usually too unreliable for identifying small water bodies. Instead, altimetry measurements themselves can be used to detect the water measurements by means of classification processes.

The SAR data of Cryosat-2 contains all multi-looks for one point on the Earth's surface in a so-called data stack. Each of the multi-looks is a returning waveform from a different looking angle. The SAR (multi-look) waveform is the averaged waveform of the stack. The assemblage of the mean power of each look is named RIP waveform. For our investigation, we use both quantities, i.e., the full stack data available for Cryosat-2 SAR, to classify the measurements and to identify the water returns. The classification is performed with a k-means clustering on features extracted from the waveform and the RIP waveform as well as the waveform and RIP waveform itself.

The classification approach is applied in the Mekong River basin. Out of ten clusters, those forming the water classes are identified in a test region with known river locations. These classes are used in a next step for grouping all measurements in the whole river basin in water and non-water measurements. The classified water measurements are used in a last step to generate water levels for each Cryosat-2 crossing with a river branch in the Mekong River basin.

The long repeat orbit of Cryosat-2, together with the complex topography of the region, hinders the extraction of water level time series at fixed virtual stations, which can be used for validation against in situ gauge data. Under the assumption of a very stable seasonal signal, which holds for the Mekong River, an internal validation of the data is possible. To this end, we compare, first, the water levels of consecutive passes (time difference 369 days) with each other and, second, water levels that are both close in location and close in season. The validation proves the success of the approach for the main river as well as for smaller tributaries.

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### **General Evaluation of the Performance of CryoSat-2 over Inland Water**

*Karina Nielsen, Ole B. Andersen, Lars Stenseng, Per Knudsen*

*Div. of Geodesy, National Space Institute, The Technical University of Denmark, Denmark*

CryoSat-2 has now been operating for more than six years with the new altimeter modes SAR and SARIn. For inland water, studies have shown that water levels based on SAR and SARIn have shown improved results compared to conventional altimetry for selected lakes.

Here we perform a thorough investigation of the quality of obtained water levels from the SAR and SARIn modes from CryoSat-2. As part of the evaluation, we compare with results from conventional altimetry such as Envisat. We estimate the along-track precision of the mean and compare with in-situ data when possible. The water level is evaluated for various water bodies of different types and sizes and in different settings.

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## Poster Session

### **CryoSat Interferometer: End-to-End Calibration and Achievable Performance**

Michele Scagliola<sup>1</sup>, Marco Fornari<sup>2</sup>, Jerome Bouffard<sup>3</sup>, Tommaso Parrinello<sup>3</sup>

<sup>1</sup>Aresys, Italy; <sup>2</sup>ESA ESTEC; <sup>3</sup>ESA ESRIN

The main payload of CryoSat is a Ku-band pulsewidth limited radar altimeter, called SIRAL (Synthetic interferometric radar altimeter). When commanded in SARin (synthetic aperture radar interferometry) mode, through coherent along-track processing of the returns received from two antennas, the interferometric phase related to the first arrival of the echo is used to retrieve the angle of arrival of the scattering in the across-track direction. In fact, the across-track echo direction can be derived by exploiting the precise knowledge of the baseline vector (i.e. the vector between the two antennas centers of phase) and simple geometry.

In order to monitor the performance of the CryoSat interferometer along the mission, in orbit calibration campaigns following the approach described in [1] have been periodically performed about once a year.

The end-to-end calibration strategy for the CryoSat interferometer, described in [1], uses the ocean surface as the known external target. In fact, the interferometer can be used to determine the across-track slope of the overflow surface and the slope of the ocean surface can be considered as known starting from the geoid. Denoting by  $\beta$  the across-track slope of the ocean and assuming that the knowledge error of the geoid slope is negligibly small,  $\beta$  can be compared with the across-track slope derived from CryoSat SARin Level1b products which results in  $\beta' = \eta(\theta - \chi)$  where  $\eta$  is a geometric factor,  $\theta$  is the angle of earliest arrival measured by the CryoSat interferometer and  $\chi$  is the baseline roll angle. By comparison of the expected across-track slope  $\beta$  and the measured across-track slope  $\beta'$ , the accuracy and the precision of the angle of arrival  $\theta$  measured by the CryoSat interferometer can be assessed. It is worth noticing here that the accuracy of the measured across-track slope  $\beta'$  is also dependent on the knowledge of the baseline orientation. As discussed in [1], starting from  $\beta$  and  $\beta'$  a calibration function  $F(\theta)$  for the angle of arrival can be computed.

In our analysis, the accuracy (i.e. the closeness of the measurement to the true value) and of the precision (i.e. the closeness of agreement among a set of measurements) of the CryoSat interferometer have been assessed starting from the residual errors on the measured angle of arrival, that have been obtained after compensation of the calibration function  $F(\theta)$ .

In addition, in this abstract it is presented a complementary approach for the calibration of CryoSat interferometer based on the analysis of the operational SARin acquisitions for small ocean patches in order to increase the number of calibration opportunities.

[1] Galin, N.; Wingham, D.J.; Cullen, R.; Fornari, M.; Smith, W.H.F.; Abdalla, S., "Calibration of the CryoSat-2 Interferometer and Measurement of Across-Track Ocean Slope," in *Geoscience and Remote Sensing, IEEE Transactions on*, vol.51, no.1, pp.57-72, Jan. 2013

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### **Evolutions of the Cryosat-2 Instrument Processing Facility (IPF)**

Pier-Luca Mantovani<sup>1</sup>, Michele Scagliola<sup>2</sup>, Stéphanie Urien<sup>3</sup>, David Brockley<sup>4</sup>, Steven Baker<sup>4</sup>, Jerome Bouffard<sup>5</sup>, Pierre Feménias<sup>5</sup>, Marco Fornari<sup>5</sup>, Tommaso Parrinello<sup>5</sup>, Rubunder Mannan<sup>6</sup>

<sup>1</sup>Advanced Computer Systems ACS S.r.l., Italy; <sup>2</sup>ARESIS; <sup>3</sup>CLS; <sup>4</sup>MSSL-UCL; <sup>5</sup>ESA; <sup>6</sup>Telespazio UK

Ever since the Cryosat-2 launch in April 2010, the on-ground facility devoted to process SIRAL data from Level 0 up to Level 2, i.e. the Instrument Processing Facility (IPF) has continuously evolved with the purpose to improve the quality of the production.

This goal has been pursued in two main ways: refinement of the products contents and increase of the products number.

The products contents have been enriched in terms of new fields and more accurate and precise figures computed by means of the algorithms continuously in evolution.

As to the most important changes the IPF processing of Level 1b has undergone it is worth mentioning: computation of refined attitude information from the same star tracker that is selected on-board by AOCS; Hamming windowing in beamforming; oversampling in range of the waveforms by factor 2 without reducing the range window; surface sample stack weighting to increase the clutter suppression on the L1b waveform. The level 2 processing has been updated to add sea-ice freeboard processing and phase-wrap detection for SARin ice-sheet margins.

The original Cryosat production, mainly devoted to ice scientists, was extended in March 2015 with the generation of products specific for the ocean community, which got interested in the exploitation of the Cryosat measurement for innovative research mainly in polar ocean, coastal seas and sea-floor mapping.

In this production, LRM and SAR L0 products are processed to generate Intermediate and Geophysical Ocean Products (IOP and GOP respectively). In Q2 2017, this production will be further improved by processing SARin L0 products and by using SAR retracers (SAMOSA)

Last but not least, ESA decided to add value to the Cryosat-2 production by changing the format of the products distributed to the users: the original Earth Explorer format, a binary format inherited by the ENVISAT mission, has been replaced by a new format based on netCDF (called CONFORM), which is easier to use and more flexible. These products are planned to be distributed in Q2 2017.

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### **Assessing IceBridge Snow Depth Retrievals over Arctic Sea Ice Using Estimates from Multiple Sources**

Ron Kwok<sup>1</sup>, Ludovic Brucker<sup>2</sup>, Sinead Farrell<sup>3,4</sup>, Jeremy Harbeck<sup>2</sup>, Stephen Howell<sup>5</sup>, Alvaro Ivanoff<sup>2</sup>, Joshua King<sup>5</sup>, Nathan Kurtz<sup>2</sup>, Carl Leuschen<sup>6</sup>, Joseph MacGregor<sup>2</sup>, Thorsten Markus<sup>2</sup>, Thomas Newman<sup>3,4</sup>, Jacqueline Richter-Menge<sup>7</sup>, Mark Tschudi<sup>8</sup>, Melinda Webster<sup>2</sup>

<sup>1</sup>Jet Propulsion Laboratory, Pasadena, CA, United States of America; <sup>2</sup>Goddard Space Flight Center/NASA, Greenbelt, MD, United States of America; <sup>3</sup>University of Maryland, College Park, MD, United States of America; <sup>4</sup>NOAA, College Park, United States of America; <sup>5</sup>Environment and Climate Change Canada, Toronto, Canada; <sup>6</sup>University of Kansas, Lawrence, United States of America; <sup>7</sup>Cold Regions Research and Engineering Laboratory, Hanover, NH, United States of America; <sup>8</sup>University of Colorado, Boulder, United States of America

The sensor suite of Operation IceBridge (OIB) includes an ultra-wideband snow radar that can measure snow depth over sea ice by resolving the range location of the air-snow and snow-ice interfaces. Since 2009, this instrument has acquired data in annual OIB campaigns conducted during the Arctic and Antarctic springs. Progressive improvements in radar hardware and data processing methodologies have led to improved data quality for subsequent analysis to derive snow depth. Five algorithms now exist for snow depth retrieval, and they differ in the way that the air-snow and snow-ice interfaces are detected and localized in the radar returns, and in how the system limitations (e.g., noise, resolution, etc.) are accounted for. In 2014, the Snow Thickness On Sea Ice Working Group (STOSIWG) was formed and tasked with investigating how radar data quality affect snow depth retrievals and how retrievals from the various algorithms differ. The ultimate goal is to understand the limitations of the estimates and to produce a well-documented, long-term record that can be used for understanding broader changes in the Arctic climate system. Assessments of retrievals are based on comparisons with field measurements from multiple ground-based campaigns, including BROMEX and the field program at Eureka, Nunavut (sponsored by Environment and Climate Change Canada), the Warren et al. (1999) climatology and snowfall from ERA-Interim reanalysis. Here, we report on the current status and the results from the assessment of different retrieval approaches, and our plans for improvement of data products based

on our current understanding informed by the inter-comparisons between approaches and by comparisons with field measurements.

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### **Improving CryoSat-2 Elevation Change Estimates using TanDEM-X**

Veit Helm<sup>1</sup>, Angelika Humbert<sup>1,2</sup>

<sup>1</sup>Alfred Wegener Institut, Germany; <sup>2</sup>University of Bremen, Germany

Estimating the contribution of ice sheets to sea level change is a major goal of glaciologists and of high interest for the society. Therefore, there is a strong need for robust volume change and in consequence mass change estimates of the ice sheets including reliable uncertainty estimates. There are numerous sources for uncertainties, ranging from instrumental errors, different processing approaches towards the interpolation between sparsely distributed data and especially for CryoSat-2 the combination of two different measurement modes is challenging. To our understanding the slope correction of the altimetry signal is one of the critical parameters for reliable elevation estimates of satellite-borne altimeters. For this purpose we analyse 6 years of CryoSat-2 altimeter data acquired from 2011 to 2017 in three to four different test sites characterized by different surface topography and covering CryoSat's LRM and SIN zones, respectively. We present the influence of different slope corrections applied to the CryoSat-2 data on derived volume change estimates. The slope corrections will be based on coarse resolution ice-sheet wide elevation models and high-resolution very precise elevation models derived from TanDEM-X.

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### **Quality Assessment of CryoSat-2 Ocean Altimetry**

Marc Naeije<sup>1</sup>, Ernst Schrama<sup>1</sup>, Jérôme Bouffard<sup>2</sup>, Pierre Féménias<sup>3</sup>

<sup>1</sup>Aerospace/TU Delft, The Netherlands; <sup>2</sup>RHEA/ESA, Italy; <sup>3</sup>ESRIN/ESA, Italy

CryoSat-2 has been monitoring the Earth's cryosphere and oceans with unprecedented accuracy and precision since its launch in 2010. In our paper we assess the quality of the CryoSat Ocean Processor (COP) LRM and pLRM products by cross-calibration with the LRM ocean altimeter data in the RADS database and by comparing the COP sea level data with a selected set of tide gauges. The goal is long-term monitoring; evaluating the stability of the measurement system and identifying biases & drifts. In summary we observe a very stable system which is on par with the Jason's ocean reference missions. Also we have been generating since 2010 precise orbits for CryoSat-2 and have cross-validated them with the CNES orbit given in the COP product. The orbits compare very well and can

be considered Jason-class with a difference standard deviation < 1.5cm.

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### **A Digital Elevation Model Of Antarctica Derived From 6 Years Of Continuous Cryosat-2 Observations**

*Thomas Slater<sup>1</sup>, Andrew Shepherd<sup>1</sup>, Malcolm McMillan<sup>1</sup>, Alan Muir<sup>2</sup>*

*<sup>1</sup>University of Leeds, United Kingdom; <sup>2</sup>University College London, United Kingdom*

Surface topography measurements of Antarctica are important datasets in the validation and initialising of numerical ice-sheet models, fieldwork planning, and the calculation of mass balance. In addition, accurate and current knowledge of ice-sheet topography is also required for InSAR measurements of ice velocity to distinguish between interferometric phase difference caused by topography and ice motion. Here we present a new digital elevation model (DEM) for the Antarctic ice-sheet, derived from 6 years of continuous Cryosat-2 radar altimetry. At a resolution of 2 km we find that CryoSat-2 provides an elevation measurement for 92% of the total ice-sheet area. We assess the accuracy of the generated DEM by comparison with airborne laser altimeter measurements from NASA IceBridge campaigns over the time period 2008-2015, in various locations across the Antarctic ice-sheet.

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### **Broadview Radar Altimetry Toolbox**

*Albert Garcia-Mondejar<sup>1</sup>, Roger Escolà<sup>1</sup>, Gorka Moyano<sup>1</sup>, Mònica Roca<sup>1</sup>, Miguel Terra-Homem<sup>2</sup>, Ana Friças<sup>2</sup>, Fernando Martinho<sup>2</sup>, Ernst Schrama<sup>3</sup>, Marc Naeije<sup>3</sup>, Americo Ambrozio<sup>4</sup>, Marco Restano<sup>5</sup>, Jérôme Benveniste<sup>6</sup>*

*<sup>1</sup>isardSAT Ltd., United Kingdom; <sup>2</sup>DEIMOS Engenharia, Portugal; <sup>3</sup>TU Delft, Faculty of Aerospace Engineering, The Netherlands; <sup>4</sup>Deimos/ ESRIN, Italy; <sup>5</sup>Serco / ESRIN, Italy; <sup>6</sup>ESA / ESRIN, Italy*

The universal altimetry toolbox, BRAT (Broadview Radar Altimetry Toolbox) which can read all previous and current altimetry missions' data, incorporates now the capability to read the upcoming Sentinel-3 L1 and L2 products.

ESA endeavoured to develop and supply this capability to support the users of the future Sentinel-3 SAR Altimetry Mission. BRAT is a collection of tools and tutorial documents designed to facilitate the processing of radar altimetry data. This project started in 2005 from the joint efforts of ESA (European Space Agency) and CNES (Centre National d'Etudes Spatiales), and it is freely available at <http://earth.esa.int/brat>. The tools enable users to interact with the most common altimetry data formats. The BratGUI is the front-end for the powerful command line tools that are part of the BRAT suite. BRAT can also be used in conjunction with MATLAB/IDL

(via reading routines) or in C/C++/Fortran via a programming API, allowing the user to obtain desired data, bypassing the data-formatting hassle. BRAT can be used simply to visualise data quickly, or to translate the data into other formats such as NetCDF, ASCII text files, KML (Google Earth) and raster images (JPEG, PNG, etc.). Several kinds of computations can be done within BRAT involving combinations of data fields that the user can save for posterior reuse or using the already embedded formulas that include the standard oceanographic altimetry formulas. The Radar Altimeter Tutorial, that contains a strong introduction to altimetry, shows its applications in different fields such as Oceanography, Cryosphere, Geodesy, Hydrology among others. Included are also "use cases", with step-by-step examples, on how to use the toolbox in the different contexts. The Sentinel-3 SAR Altimetry Toolbox shall benefit from the current BRAT version. While developing the toolbox we will revamp of the Graphical User Interface and provide, among other enhancements, support for reading the upcoming S3 datasets and specific "use-cases" for SAR altimetry in order to train the users and make them aware of the great potential of SAR altimetry for coastal and inland applications. As for any open source framework, contributions from users having developed their own functions are welcome. The Broadview Radar Altimetry Toolbox is a continuation of the Basic Radar Altimetry Toolbox. While developing the new toolbox we will revamp of the Graphical User Interface and provide, among other enhancements, support for reading the upcoming S3 datasets and specific "use-cases" for SAR altimetry in order to train the users and make them aware of the great potential of SAR altimetry for coastal and inland applications. As for any open source framework, contributions from users having developed their own functions are welcome. The first Release of the new Radar Altimetry Toolbox was published in September 2015. It incorporates the capability to read S3 products as well as the new CryoSat-2 Baseline C. The second Release of the Toolbox, in October 2016, will have a new graphical user interface and other visualisation improvements.

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### **CONFORM: CryOsat Netcdf FORmat Migration for Ice and Ocean Products**

*Pier-Luca Mantovanie<sup>1</sup>, Marco Fornari<sup>2</sup>, Michele Scagliola<sup>3</sup>, Stephanie Urien<sup>4</sup>, David Brockley<sup>5</sup>, Steven Baker<sup>5</sup>, Jerome Bouffard<sup>2</sup>, Pierre Féménias<sup>6</sup>, Tommaso Parrinello<sup>6</sup>, Rubinder Mannan<sup>7</sup>*

*<sup>1</sup>ACS, Italy; <sup>2</sup>RHEA c/o ESA; <sup>3</sup>ARESYS, Italy; <sup>4</sup>CLS, France; <sup>5</sup>MSSL, UK; <sup>6</sup>ESA, Italy; <sup>7</sup>IDEAS+/Telespazio, UK*

One of the major evolutions planned in 2017 for both CryoSat Ice and Ocean products is the switch to NetCDF, a much more user-friendly format than the current *Earth Explorer format* (EE). The EE format is no



more suited for today's evolution and maintenance needs whereas the netCDF format is the standard "de-facto" for most advanced and modern Earth Observation missions. The ongoing format migration activity for Cryosat products is called CONFORM (*CryOsat Netcdf FORmat Migration*). CONFORM has been designed considering the *Climate and Forecast* conventions as well as the guidelines used in other altimetric missions. One of the objectives is to ensure good homogeneity and harmonization between CryoSat and previous (reprocessed ERS1/2, Envisat-Phase F), new (Sentinel-3) and future (Sentinel 6) ESA altimetric missions. However, at the same time, the proposed design could also contribute to the definition of innovative conventions and standard for some particular fields specific to CryoSat, the first ESA ice-oriented mission. Demonstration of new ocean and ice CryoSat NetCDF products will be organized aside the presentation of this poster whereas CONFORM data sample will be made available –on demand - to all participants of the *North-American CryoSat Science Meeting*

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**CryoSat SAR/SARin Level1b Products: Assessment of BaselineC and Improvements towards BaselineD**

*Michele Scagliola<sup>1</sup>, Luca Maestri<sup>1</sup>, Marco Fornari<sup>2</sup>, Jerome Bouffard<sup>3</sup>, Tommaso Parrinello<sup>3</sup>*  
<sup>1</sup>Aresys, Italy; <sup>2</sup>ESA ESTEC; <sup>3</sup>ESA ESRIN

CryoSat was launched on the 8th April 2010 and is the first European ice mission dedicated to the monitoring of precise changes in the thickness of polar ice sheets and floating sea ice. Cryosat carries an innovative radar altimeter called the Synthetic Aperture Interferometric Altimeter (SIRAL), that transmits pulses at a high pulse repetition frequency thus making the received echoes phase coherent and suitable for azimuth processing. This allows to reach a significantly improved along track resolution with respect to traditional pulse-width limited altimeters.

CryoSat is the first altimetry mission operating in SAR mode and continuous improvements in the Level1 Instrument Processing Facility (IPF1) are being identified, tested and validated in order to improve the quality of the Level1b products. The current IPF, Baseline C, was released in operation in April 2015 and the second CryoSat reprocessing campaign was jointly initiated, taking benefit of the upgrade implemented in the IPF1 processing chain but also of some specific configurations for the calibration corrections.

In particular, the CryoSat Level1b BaselineC products generated in the framework of the second reprocessing campaign include refined information for what concerns the mispointing angles and the calibration corrections.

This poster will thus detail thus the evolutions that are currently planned for the CryoSat BaselineD SAR/SARin

Level1b products and the corresponding quality improvements that are expected.

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**Evolution of Fast Ice Thickness from Four Years of Cryosat-2 Data, a Case Study in Scar Inlet, Antarctica**

*Mahsa Sadat Moussavi<sup>1,2,3</sup>, Ted Scambos<sup>1,3</sup>, Erin Pettit<sup>4</sup>, Waleed Abdalati<sup>2,3</sup>*

<sup>1</sup>National Snow and Ice Data Center (NSIDC), United States of America; <sup>2</sup>Cooperative Institute for Research in Environmental Sciences (CIRES), United States of America; <sup>3</sup>University of Colorado, Boulder, United States of America; <sup>4</sup>University of Alaska, Fairbanks, United States of America

While the last substantial fragment of the former Larsen B Ice shelf, namely the Scar Inlet Ice Shelf, has undergone dramatic changes ever since the breakup of Larsen B in 2002, it has remained largely intact. A thin layer of frozen ocean ice fastened to the coastline, or 'fast ice', may be responsible for supporting the weakened ice shelf over the past few years. Some evidence from ice flow speed and direction changes measured on the shelf suggest this is the case. However, the degree to which the fast ice impedes the full collapse of the Scar Inlet Shelf is not well understood. One source of uncertainty is the lack of current fast ice thickness data, and moreover, data that would describe how the fast ice has evolved over the past several years. The European Space Agency's (ESA) Cryosat-2 radar altimeter is a new satellite sensor that has the potential to provide data on the evolution of the Scar Inlet Ice Shelf itself and the adjacent fast ice since 2013. We analyze four years (2013-2016) of Cryosat-2 data to determine the thickness of the fast ice and study its seasonal and annual variation patterns in relation to in-situ temperature measurements collected by the nearby weather stations. We apply automatic freeboard retrieval procedures to the ESA level-2 SAR Interferometric (SIN) mode data (Baseline-C) to estimate the ice thickness. To evaluate errors, we undertake a supervised lead detection procedure, through which we manually establish sea surface height from Cryosat-2 measurements over leads visible in imagery from the Moderate Resolution Imaging Spectrometer (MODIS). This study provides the first long-term satellite-based evaluation of fast ice thickness and offers insight into processes affecting ice shelf stability.

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**Finite-element GIA Estimations For Antarctica Based On A New Lithospheric Model**

*Bas Blank<sup>1</sup>, Haiyang Hu<sup>1</sup>, Wouter van der Wal<sup>1</sup>, Folker Papp<sup>2</sup>, Jorg Ebbing<sup>2</sup>*

<sup>1</sup>TU Delft, Netherlands, The; <sup>2</sup>CAU Kiel, Germany

The GRACE mission provided the scientific community an opportunity to observe mass transport processes

during a longer period than imagined. One of the most important mass transport processes in the last decades, is the melting of glaciers and ice caps. However, the melting of past ice caps induced Glacial Isostatic Adjustment (GIA) in these regions, which is also an important cause for mass transport in the Earth's mantle. GRACE cannot distinguish between ice cap melting and GIA. Therefore it is important that we are able to model the GIA process in order to extract the present-day ice mass loss from the GRACE data.

We are developing a GIA model based on finite-elements which is tailored towards GIA in Antarctica. This new GIA model is developed in cooperation with the ESA's GOCE+ "Dynamic Antarctic Lithosphere" project. Within the GOCE+ project a more accurate model of e.g. the lithosphere and upper mantle is developed, based on seismic tomography, satellite and airborne gravity data and realistic mantle composition. The lithosphere and mantle models will be implemented in the finite element based model of Antarctica, to investigate the influence of local variations in mantle and lithosphere parameters, in particular low viscosities in West Antarctica, on GIA in Antarctica.

A benchmark of the FE model has been done versus semi-analytic normal mode models. Test cases without ocean loading showed an error of less than 2% for deflection 10 kyear after unloading. However, the elastic response showed an error at the deflection bulge. A varying mesh was implemented to achieve a resolution of up to 50 km by 50 km at specifically targeted locations.

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### **GOCE and Cryosat-2 for Dynamical Coastal Topography and Tide Gauge Unification**

*Ole Baltazar Andersen<sup>1</sup>, Karina Nielsen<sup>1</sup>, Per Knudsen<sup>1</sup>, Micael Kern<sup>2</sup>, Chris Hughes<sup>3</sup>, Mederic Gravelle<sup>4</sup>, Luciana Fenoglio-Marc<sup>5</sup>, Guy Woppelmann<sup>4</sup>, Rory Bingham<sup>6</sup>*

<sup>1</sup>DTU space, Denmark; <sup>2</sup>ESA ESTEC, Noordwijk, The Netherlands; <sup>3</sup>University of Liverpool; <sup>4</sup>University La Rochelle; <sup>5</sup>University of Bonn; <sup>6</sup>Universtiy of Bristol

ESA has recently released a study on the investigation and using ocean levelling as a novel approach to the study of height system unification across the oceans taking the recent development in geoid accuracy through GOCE data into account.

The suggested investigation involves the use of measurements and modelling to estimate Mean Dynamic Topography (MDT) of the ocean along a coastline, which contributes/requires reconciling altimetry, tide gauge and vertical land motion. Close to the coast the determination of the MDT is problematic due to i.e., the altimeter footprint, land motion or parameterization/modelling of coastal currents.

The objective of this activity is to perform a consolidated and improved understanding and modelling of coastal processes and physics responsible

for sea level changes on various temporal/spatial scales. The study runs from October 2015 to march 2017 and involves the following elements

Develop an approach to estimate a consistent DT at tide gauges, coastal areas, and open ocean; Validate the approach in well-surveyed areas where DT can be determined at tide gauges; Determine a consistent MDT using GOCE with consistent error covariance fields; improving altimetry (SAR) along the coast for MSS/MDT improvement and finally connecting the global set of tide gauges and investigate trends

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### **Improved Oceanographic Measurements with CryoSat SAR Altimetry**

*David Cotton<sup>1</sup>, Pablo Garcia<sup>2</sup>, Mathilde Cancet<sup>3</sup>, Ole Andersen<sup>4</sup>, Paolo Cipollini<sup>5</sup>, Francisco Martin<sup>6</sup>, Marcello Passaro<sup>7</sup>, Marc Naeije<sup>8</sup>, Marco Restano<sup>9</sup>, Américo Ambrósio<sup>10</sup>, Jérôme Benveniste<sup>11</sup>*

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The ESA CryoSat mission is the first space mission to carry a radar altimeter that can operate in Synthetic Aperture Radar "SAR" (or delay-Doppler) and interferometric SAR (SARin) modes. Studies have confirmed the improved ocean measuring capability offered by SAR mode altimetry, through increased resolution and precision in sea surface height and wave height measurements, and have also added significantly to our understanding of the issues around the processing and interpretation of SAR altimeter echoes.

The objective of the CryoSat Plus for Oceans (CP4O) project was to develop and evaluate new ocean products from CryoSat data and so maximize the scientific return of CryoSat over oceans. The main focus of CP4O has been on the additional measurement capabilities that are offered by the SAR mode of the SIRAL altimeter, with further work in developing improved geophysical corrections.

This paper first presents a short overview of the major results from CP4O, and outlines a proposed roadmap for the further development and exploitation of these results in operational and scientific applications.

We then present results from an extension to CP4O in four themes, each investigating different aspects of the opportunities offered by this new technology.

The first two studies address the coastal zone. Firstly, a thorough analysis was made of the performance of "SAR" altimeter data (delay-Doppler processed) in the coastal zone. This quantified the performance, confirming the significant improvement over "conventional" pulse-limited altimetry. In the second study a processing scheme was developed with CryoSat



SARin mode data to enable the retrieval of valid oceanographic measurements in coastal areas with complex topography. Thanks to further development of the algorithms, a new approach was achieved that can also be applied to SAR and conventional altimetry data (e.g., Sentinel-3, Jason series, Envisat).

The third part of the project developed and evaluated improvements to the SAMOSA altimeter re-tracker as implemented in the Sentinel-3 processing chain. The modifications to the processing scheme should support improved performance in terms of accuracy and efficiency in retrieving oceanographic geophysical parameters from altimeter data.

Finally, we describe the development of a state of the art tidal atlas for the Arctic Ocean with CryoSat altimeter data. Through its high inclination orbit, the CryoSat mission provides the most complete altimeter data set ever used in this region, and so should enable the production of a highly accurate Arctic tidal model. This in turn will improve the quality of CryoSat Sea Surface Height measurements and all derived products (e.g. mean sea surface, mean dynamic topography).

Together these studies provide an important foundation for exploiting data from the Sentinel-3 and Sentinel-6/Jason-CS missions.

The work described in this presentation was supported by ESA through the STSE programme. We also acknowledge the support of CNES who provided the CNES-CPP CryoSat Products used in these studies. CNES-CPP products were developed by CNES and CLS in the frame of the "Sentinel-3 SRAL SAR mode performance assessment" study.

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### **Validation of CryoSat-2 Performance Over Arctic Sea Ice**

*Alessandro Di Bella<sup>1</sup>, Henriette Skourup<sup>1</sup>, Jerome Bouffard<sup>2</sup>, Tommaso Parrinello<sup>2</sup>*

*<sup>1</sup>Technical University of Denmark / National Space Institute, Denmark; <sup>2</sup>ESA/ESRIN*

The main objective of this work is to validate CryoSat-2 (CS2) SARin performance over sea ice by use of airborne laser altimetry data obtained during the CryoVEx 2012 campaign. A study by [1] has shown that the extra information from the CS2 SARin mode increases the number of valid sea surface height estimates which are usually discarded in the SAR mode due to snagging of the radar signal. As the number of valid detected leads increases, the uncertainty of the freeboard heights decreases.

In this study, the snow freeboard heights estimated using data from the airborne laser scanner are used to validate the sea ice freeboard obtained by processing CS2 SARin level 1b waveforms. The possible reduction in the random freeboard uncertainty is investigated comparing two scenarios, i.e. a SAR-like and a SARin acquisition.

It is observed that using the extra phase information, CS2 is able to detect leads up to 2370 m off-nadir. A reduction in the the total random freeboard uncertainty of ~40% is observed by taking advantage of the CS2 interferometric capabilities, which enable to include ~35% of the waveforms discarded in the SAR-like scenario.

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### **Cryosat2 Assessment of Inland Water Height Retrieval over River Networks**

*Philippa A. M. Berry<sup>1</sup>, Robert Balmbra<sup>2</sup>, Richard G. Smith<sup>3</sup>*

*<sup>1</sup>Roch Remote Sensing, United Kingdom; <sup>2</sup>Cyber Security Centre Warwick University; <sup>3</sup>STRL/CSC De Montfort University*

The Cryosat2 mission presents challenges for measurement of inland water heights as the long repeat period complicates generation of useful time series. Modelling techniques can be used to propagate the measurements to common virtual ground stations; in-situ gauge data may be interpolated to the Cryosat2 track locations [e.g. 1] for validation purposes. However, the Cryosat2 mission offers a unique perspective on observing river networks. The dense spatial sampling allows detailed analysis of river waveforms in both SAR and LRM modes, allowing characterisation of river systems in terms of the successful retrieval of 'clean' waveforms. Combining these results with assessment of river height time series from prior missions, including time series successfully retrieved from Envisat, ERS2, Topex and Jason1/2 [e.g. 2], and, crucially, analysis of locations where useable time series were not retrieved, enables an assessment of the extent to which river network heights may be accessible from Sentinel3 and future missions.

This paper presents series of analyses across multiple river networks in varying terrain and climate conditions, including the Amazon basin, Ganges, Brahmaputra, Orinoco, Syr Darya and Nile, using Cryosat2 SAR and LRM mode waveforms. Multiple cycles of data are utilised. The results show that there is successful retrieval of small numbers of 'clean' waveforms from all river systems examined in both SAR and LRM modes at 20Hz. Time series analysis from prior missions over these river networks confirms the successful retrieval of heights even when only one or two 'clean' waveforms are present. Combining these results enables classification of these river networks in terms of their accessibility for altimeter monitoring. The availability of Cryosat2 FBR data in SAR mode increases the time series generation capability to 80Hz (due to the discontinuous sampling); together with an assessment of the 1800Hz Envisat burst echoes over river networks [3] this is shown to allow retrieval over smaller tributaries and also demonstrates enhanced measurement capability where islands and sandbars

interrupt the river course towards the minimum of the hydrological cycle. Over all river systems presented, monitoring of river networks using satellite altimetry is concluded to be an effective strategy. The availability of waveforms at a higher sampling frequency is demonstrated to increase this monitoring capability, allowing monitoring of smaller tributaries and also enabling recovery of river heights towards the minimum of the hydrological cycle.

1 R. Schneider, P.N.Godiksen, M.-E. Ridler et al., 2016. Combining Envisat and CryoSat-2 Altimetry to Inform Hydrodynamic Models. Proc. 'Living Planet Symposium 2016', Prague, Czech Republic, 9–13 May 2016 (ESA SP-740, August 2016)

2 Berry, P.A.M., Smith,R.G. & Benveniste, J., 2012. Envisat Altimetry For River And Lakes Monitoring. Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International pp 1844-1848.

3 Berry, P. A. M., Smith, R. G., Salloway, M. K., Benveniste, J., 2011. "Global Analysis of EnviSat Burst Echoes Over Inland Water," IEEE Trans. Geoscience and Remote Sensing, Issue 99, pp.1-6. doi: 10.1109/TGRS.2011.2170695

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### **Sensitivity of NEMO-LIM3 Coupled Ice-Ocean Model to Initial Sea Ice Thickness States from CryoSat-2**

*Heidi Sallila, Eero Rinne, Petteri Uotila  
Finnish Meteorological Institute, Finland*

We present the sensitivity of a coupled sea-ice-atmosphere model NEMO-LIM3 to the initial sea ice thickness. To study the sensitivity we built a scheme where the sea ice thickness of the model is nudged with CryoSat-2 measured ice thickness with different relaxation parameters in the spring 2012. We then run the model with atmospheric forcing till fall 2012 and compare the sea ice extent and volume to different independent estimates of the sea ice in the Arctic. In other words we want to see how well our model is able to reproduce the record sea ice minimum of 2012 and will the nudging improve the modelled sea ice estimates.

All simulations presented here are based on the version 3.6\_STABLE of the NEMO-LIM ocean-ice modelling system, in the ORCA025 horizontal grid configuration with 75 vertical ocean levels. In NEMO, the OPA ocean component is coupled with the LIM3.6 sea-ice model. LIM3.6 is a sea-ice model in the line of the AIDJEX model, with multiple sea-ice categories. Multiple categories allow to resolve the intense growth and melt of thin ice, as well as the redistribution of thinner ice onto thicker ice due to ridging and rafting. Thermodynamics are multi-layer and include an explicit description of the effect of brine on the storage and conduction of heat, and a parameterization of brine drainage that affects ocean-ice salt exchanges. The default NEMO3.6 configuration uses five ice thickness categories and two vertical layers for thermodynamics.

Simulations were forced by the DFS5.2 atmospheric data set, developed through the DRAKKAR consortium. Prescribed ocean-atmosphere surface boundary conditions were calculated by using the CORE bulk formulae.

We show that nudging the NEMO-LIM3 towards CryoSat-2 thickness estimates at the start of melt season has a significant impact on the sea ice volume estimates for end of melt season. Varying the relaxation parameter influences both sea ice volume and extent estimates. Furthermore, we speculate that the winter-to-summer sea-ice extent and volume predictions are improved if more realistic sea-ice volume initial conditions are used.

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### **Optimizing Spectral Windows For Processing CryoSat SAR Mode Data Over Sea Ice**

*Walter H F Smith<sup>1</sup>, Alejandro E Egado<sup>1,2</sup>*

*<sup>1</sup>NOAA Lab for Satellite Altimetry, United States of America; <sup>2</sup>University of Maryland, College Park, Maryland, USA*

In satellite radar altimetry, the elevation, roughness, and radar cross section of Earth surfaces are estimated by fitting models to power spectral density (PSD) estimates known as "waveforms". In conventional altimetry the PSD is one-dimensional and maps backscattered power to range (distance). In the "Delay/Doppler" or "multi-looked SAR" process (hereafter, "D/D-SAR") the PSD is two-dimensional, mapping power to range and along-track position on the ground. In each dimension the PSD estimate suffers from "leakage" because the Earth returns power at a continuum of ranges and along-track positions, and not merely those corresponding to the frequencies correctly sampled by the discrete Fourier transform (DFT).

Leakage may be mitigated, and the PSD resolution function shaped, by use of a spectral window. To date, altimetry has used either no window, or a Hamming window. No window achieves the highest possible resolution (desirable) but allows the most leakage (undesirable). The Hamming window suppresses the leakage but at the expense of about a 30% degradation of resolution; for example, the along-track resolution of Cryosat and Sentinel-3 D/D-SAR is increased from about 300 m to about 400 m.

The signal-to-noise ratio (SNR, noise being due to quantization, random thermal and also image clutter sources) in altimetry is usually not more than 25 dB, and so there is no point in choosing a window with (mainlobe integral)/(sidelobe integral) ratio, MSR, much larger than about 30 dB. The Hamming window has too much MSR (38 dB), and too much widening of the mainlobe (degrading resolution). Better resolution can be achieved by designing a window to have only as much MSR as the application needs or the data SNR permits.

This paper suggests better windows. Here, “better” means that the PSD resolution function (known in the radar literature as the “point target response”, PTR) is as Gaussian as possible, and as narrow in its main lobe as possible, while achieving only as much leakage suppression as the data signal-to-noise ratio allows.

The estimated PSD is (to a good approximation) the true PSD convolved with the PTR. Since convolution is an integral, one should characterize the PTR’s performance using integral measures of bandwidth, side lobe energy, etc., as opposed to point values (bandwidth at half power or at zero crossings, peak side lobe levels). These integrals can be evaluated in terms of matrix-vector quadratic forms, the eigenvectors of which can build good windows.

The (mainlobe integral)/(sidelobe integral) ratio, MSR, has a maximizing eigenvector, the (first) DPSS (or multi-taper or Slepian) window. The root-mean-square window bandwidth (PTR  $\sigma$ ), called here RMS, has a minimizing eigenvector known as the Sine Window and used in MPEG compression. Windows having the most Gaussian performance under convolution can be built from linear combinations of eigenvectors associated with the RMS bandwidth measure.

We will present CryoSat SAR mode data obtained over areas of sea ice with leads, and will process the FBR data using no window, the Hamming window, and “better” windows, in order to show the value obtained by optimizing the window’s performance.

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### **The Norwegian Coastal Current Observed by CryoSat2 SARIn Altimetry**

*Martina Idzanovic<sup>1</sup>, Vegard Ophaug<sup>1</sup>, Ole Baltazar Andersen<sup>2</sup>*

<sup>1</sup>MNBU, Aas, Norway; <sup>2</sup>DTU space, Denmark

The Norwegian Coastal Current (NCC) transports warm and relatively fresh water along the Norwegian coast and into the Barents Sea, with its origin in Baltic water entering Skagerrak. Along its way northward it is fed by additional freshwater discharge. The NCC is important for the regional marine ecosystem and contributes to the poleward transport of warm Atlantic Water, maintaining the relatively mild climate in northwest Europe.

Although satellite altimetry is a mature technique, globally observing the sea surface height with an accuracy of a few centimeters, numerous effects degrade the observations in the coastal zone. For example, the radar footprint is contaminated by land and bright targets, and the range and geophysical corrections become difficult to model.

The rugged Norwegian coast presents a further challenge, and the NCC, at times only a few tens of kilometers wide, typically falls into a zone where conventional altimeters do not deliver reliable observations. The European Space Agency’s CryoSat2

(CS2) satellite is the first to carry a SAR altimeter instead of the conventional pulselimited system, resulting in higher range precision and alongtrack resolution. This allows for tracking finer structures of the sea surface and get closer to the coast. We use CS2 low resolution and SARIn observations, for the period 2012-2015, along the Norwegian coast and determine a mean dynamic topography (CS2MDT) that is validated using tide gauges. In turn, geostrophic surface currents are derived from both the CS2MDT and the operational coastal numerical ocean model of MET Norway and compared. For the first time, the NCC is revealed by spacegeodetic techniques, giving confidence in the new generation SAR altimeters for coastal sealevel recovery.

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### **A Synthesis of Snow Depth Observations in the Arctic: Towards a Seasonal Snow Depth Product for CryoSat-2**

*Melinda Webster<sup>1</sup>, Alek Petty<sup>1,2</sup>, Linette Boisvert<sup>1,2</sup>, Thorsten Markus<sup>1</sup>*

<sup>1</sup>NASA Goddard Space Flight Center, USA; <sup>2</sup>Earth System Science Interdisciplinary Center (ESSIC), University of Maryland, USA

Knowledge of snow depth on sea ice is critical for accurate retrievals of sea ice thickness from current (CryoSat-2) and next-generation altimetry data (e.g. ICESat-2, CryoSat-3). In 1937 and 1954-1991, efforts led by the former Soviet Union established the first time-series of snow depth measurements in the central Arctic, a record which has become the most widely-used snow climatology for snow depth on Arctic sea ice to date. Since then, limited efforts have been made towards continued monitoring of Pan-Arctic snow conditions, forming an acute gap in our understanding of the Arctic system as it evolves in a changing climate.

In recognition of this knowledge gap, we present initial results from the Precipitation, Accumulation and Snow Thickness in the Arctic (PASTA) project; a new initiative aimed at improving seasonal estimates of Pan-Arctic snow depth for use by the modeling and remote sensing communities. Here we present an overview of the different sources of data (and additional data we hope to obtain) in this Arctic snow depth synthesis, including *in-situ*, buoy, airborne and satellite datasets. We describe our initial efforts to optimally interpolate datasets that span different spatial scales, and discuss planned efforts to assimilate these data with dynamic snowfall estimates from reanalysis products. We also present preliminary efforts to initiate a community snow data repository for the continued production of an up-to-date, synthesized, Arctic snow depth dataset.

We anticipate that this new snow depth dataset will provide information that is more representative of the current state of the Arctic, improving altimeter-derived retrievals of sea ice thickness and assessments of polar climate variability in global climate models.

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### **Arctic Lead Detection using a Waveform Unmixing Algorithm from CryoSat-2 Data**

*Sanggyun Lee, Junggho Im, Daehyeon Han  
Ulsan National Institute of Science of Technology,  
Korea, Republic of (South Korea)*

Arctic areas consist of ice floes, leads, and polynyas. While leads and polynyas account for small parts in the Arctic Ocean, they play a key role in exchanging heat flux, moisture, and momentum between the atmosphere and ocean in wintertime because of their huge temperature difference. In this study, a linear waveform unmixing approach was proposed to detect lead fraction. CryoSat-2 waveforms for pure leads, sea ice, and ocean were used as end-members based on visual interpretation of MODIS images coincident with CryoSat-2 data. The unmixing model produced lead, sea ice, and ocean abundances and a threshold ( $> 0.7$ ) was applied to make a binary classification between lead and sea ice. The unmixing model produced better results than the existing models in the literature, which are based on simple thresholding approaches. The results were also comparable with our previous research using machine learning based models (i.e., decision trees and random forest). A monthly lead fraction was calculated, dividing the number of detected leads by the total number of measurements. The lead fraction around Beaufort Sea and Fram strait was high due to the anti-cyclonic rotation of Beaufort Gyre and the outflows of sea ice to the Atlantic. The lead fraction maps produced in this study were matched well with monthly lead fraction maps in the literature. The areas with thin sea ice identified from our previous research correspond to the high lead fraction areas in the present study.

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### **Global Evaluation Of The New CryoSat Geophysical Ocean Products**

*Francisco Calafat<sup>1</sup>, Chris Banks<sup>1</sup>, Paolo Cipollini<sup>1</sup>, Helen Snaith<sup>2</sup>, Jérôme Bouffard<sup>3</sup>, Pierre Féménias<sup>4</sup>*

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Marine products from CryoSat-2 generated by a dedicated processor (CryoSat Ocean Processor or COP) have been available since April 2014. Here we present the results of a verification and scientific validation of the Geophysical Ocean Products (GOP), which have consolidated orbits and are available 30 days after acquisition. This assessment, carried out within the ESA-funded Cryocean-QCV project, is performed for the sea surface height (SSH), the significant wave height (SWH), and the wind speed. The mean value of the 20 Hz SSH anomaly (SSHA) noise corresponding to a SWH of 2 m is 6.3 cm for LRM (Low Resolution Mode) data and 10.2 cm for pseudo-LRM data. The standard deviation of the crossovers is 5.4 cm. The SSH is validated at the coast against the sea level measured

by a set of carefully selected and quality controlled tide gauges, and compared with Jason-2 observations. Correlations between satellite SSH and tide gauge records are statistically significant at nearly all stations, with a median value of 0.78 and 0.76 for CryoSat-2 and Jason-2, respectively. The Global Mean Sea Level (GMSL) curve from the GOP matches well the same curve from other altimetry missions, suggesting that CryoSat-2 is suitable for GMSL monitoring. In the open ocean the SSH is compared globally with the steric heights derived from temperature and salinity profiles as measured by Argo floats. The median correlation between SSH and steric heights is 0.68. The correlation, however, shows a strong latitudinal dependence, with higher values at low latitudes (median  $> 0.8$  in the  $10^{\circ}\text{S}$ – $10^{\circ}\text{N}$  band). Regarding SWH and wind speed, they are both validated against buoy observations. The SWH shows an RMS of 15 cm whereas wind speed exhibits a bias of about 2 m/s relative to both Jason-2 and to buoy data. In addition, the SWH is also compared with the values provided by the Wavewatch III model. Differences between CryoSat-2 and the WW3 are less than 20% of the SWH over most areas of the ocean.

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### **Improving the Short Wavelengths of Mean Sea Surface using CryoSat Data**

*Philippe Schaeffer<sup>1</sup>, Yannice Faugère<sup>1</sup>, Isabelle Pujol<sup>1</sup>,  
Nicolas Picot<sup>2</sup>*

*<sup>1</sup>CLS, France; <sup>2</sup>CNES*

The CNES\_CLS 2015 Mean Sea Surface, as well as its former versions, was determined from altimetric data which are sampled at a frequency of 1 Hz (7 km along tracks). Theoretically, this introduces limits concerning the mapping of wavelengths less than 20-30 km.

Until now, this sampling represented a good compromise between signal and instrumental noises. Thanks to the implementation of more efficient altimeters and also considering the improvement of the processing methods (e.g. retracking), the CryoSat LRM-mode and more especially the SAR-mode allow us today to access to less noisy observations at higher frequencies.

It is therefore particularly interesting to use this new kind of observations in order to analyze their contribution for mapping topographic structures at wavelengths less than 30 km. We propose to present results obtained from analyzes carried out with Cryosat data sampled at 20 Hz. Goal is here to prepare these data for the determination of the next reference fields, and in particular to improve the finest topographic structures of the MSS which is used as support for ongoing and future missions such as SWOT.

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## Squeezing SARIn Capabilities for Complex Scenarios: L1 & L2 Processing Improvements

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<sup>1</sup>isardSAT Ltd., United Kingdom; <sup>2</sup>isardSAT S.L., Spain

The CryoSat mission is designed to determine fluctuations in the mass of the Earth's land and the marine ice fields. Its primary payload is a radar altimeter that operates in different modes optimised depending on the kind of surface: Low resolution mode (LRM), SAR mode (SAR) and SAR interferometric mode (SARIn). This radar is named SIRAL: Synthetic aperture interferometer radar altimeter [1]. The SARIn mode uses two antennas allowing to compute cross-track angles at which signals arrives.

For scenarios with large topographical variations over short distances, a received SARIn waveform can sometimes have more than one peaks, so different elevations can be retrieved from a single waveform. Over certain regions with certain x-track slope conditions, the elevation profile x-track can be retrieved using the phase difference information.

Firstly with data from ASIRAS [2] and secondly with CryoSat-2 [3] data, the computation of surface elevation profiles over ice caps and glaciers using the so called "swath processing" proved the powerful capabilities of the SARIn mode, improving the spatial resolution of the elevation measurements.

Improvements to the L2-swath processing approach have been investigated and implemented within the ESA founded projects CryoSat+ for Topography and CryoSat+ for Mountain Glaciers. The processing improvements are not only focused in the retracking algorithms but also on the algorithms that are applied in the early stages of the processing chain in order to clean the stack data, multi-looked waveforms and phase difference information as much as possible.

These new algorithm and improvements, initially designed for glaciers, have now been evaluated over other areas such as Coastal and Inland Waters.

[1] C.R. Francis, "CryoSat Mission and Data Description", CS-RP-ESA-SY-0059.

[2] Hawley R.L., et.al.: Ice-sheet elevations from across-track processing of airborne interferometric radar altimetry, *Geophys. Res. Lett.*, 36, L25501, doi:10.1029/2009GL040416, 2009.

[3] Laurence Gray et.al., Interferometric swath processing of Cryosat data for glacial ice topography, *The Cryosphere*, 7, 1857-1867, doi:10.5194/tc-7-1857-2013

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## Transponder Calibration in SAR/SARIN Altimetry: from CryoSat-2 to Sentinel-3

Albert Garcia-Mondejar<sup>1</sup>, Marco Fornari<sup>2</sup>, Jérôme Bouffard<sup>3</sup>, Pierre Féménias<sup>4</sup>, Mònica Roca<sup>1</sup>

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Transponders are commonly used to calibrate absolute range from conventional altimeter waveforms because of its characteristic point target radar reflection. The waveforms corresponding to the transponder distinguish themselves from the other waveforms resulting from natural targets, in power and shape.

ESA has deployed a transponder available for the CryoSat project (a refurbished ESA transponder developed for the ERS-1 altimeter calibration). It is deployed at the KSAT Svalbard station: SvalSAT. Another transponder has been deployed by Technical University of Crete for the Sentinel 3 calibration in the island of Crete.

For CryoSat-2 [1], we are using the transponder to calibrate SIRAL's range, datation, and interferometric baseline (or angle of arrival) to meet the missions requirements [2].

For Sentinel-3 we are using the transponder to calibrate SRAL's range, datation to meet the missions requirements [3].

In these calibrations, we are using 3 different type of data: the raw L1A data, the stack beams before they are multi-looked (L1BS), and the multi-looked waveform products (L1B) [4].

Ideally 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 performing its measurement [5]. When this error can be assumed to be constant regardless the conditions, it will provide the bias of the instrument. And if the measurements can be repeated after a certain period of time, it can also provide an indication of the instrument drift.

The performances of the CryoSat-2 altimeter, the SIRAL (Synthetic aperture interferometer radar altimeter), have been monitored since 2010 with the Transponder measurements. The range and datation biases from the processor have been corrected in the initial Baselines and now with the Baseline C the long-term trends can be performed in order to evaluate the aging of the instrument.

For Sentinel-3 altimeter, the first data with the Crete TRP have been analysed and the first performances assessment will be made before the end of the Commissioning Phase.

On this presentation the main results with the CryoSat-2 and Sentinel-3 altimeters will be shown.

[1] C.R. Francis, "CryoSat Mission and Data Description", CS-RP-ESA-SY-0059.

[2] CryoSat Science and Mission Requirements Document, CS-RS-UCL-SY-001.

[3] D.J.Wingham, et al.: "CryoSat: A mission to

determine the fluctuations in Earth's land and marine ice fields", *Advances in Space Research* 37 (2006) 841–871.

[4] Sentinel-3 Mission Requirements Document, EOP-SMO/1151/MD-md.

[5] SIRAL2 Calibration using TRP: Detail Processing Model – DPM; ISARD\_ESA\_CR2\_TRP\_CAL\_DPM\_030.

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### Tuning SAR Processing to Measure Sea Ice Freeboard

*Sara Fleury<sup>1</sup>, Jonas Verley<sup>1</sup>, Kévin Guerreiro<sup>1</sup>, Antoine Laforge<sup>1</sup>, Denis Blumstein<sup>2</sup>, Salvatore Dinardo<sup>3</sup>, Jérôme Benveniste<sup>4</sup>*

<sup>1</sup>CNRS, France; <sup>2</sup>CNES; <sup>3</sup>EUMETSAT; <sup>4</sup>ESA-ESRIN

SAR altimetry has demonstrated its capabilities to measure the sea level with better performances than the LRM mode, as shown by sea surface height spectrum. Over sea-ice, several freeboard products computed from CryoSat-2 altimeter are already available, including within the official ESA Baseline-C GDR.

While these products provide relatively accurate estimates of seasonal and inter-annual sea-ice freeboard height, they are still too much imprecise to be integrated within climate models. Several studies have shown that the main uncertainty still comes from the freeboard measurement (for about 50%, the next one being related to the snow cover, followed by the barometer effect, the tides, the mean sea level, ...).

Until now the studies to improve the heights measurements mainly concerned the level 2 processing related to the conversion of the waveforms to ranges over leads and floes:

- the waveform classification, with the objective to distinguish echoes originating from leads and from ice floes and to remove echoes that mixed-up both surfaces ;
- the waveform retracers, with the objective to handle both the highly specular echoes over leads, and diffuse echoes over floes possibly cover by snow.

In this study we show that the previous L1 step, that consists in producing the synthetic Doppler echoes, may have a non-negligible impact on the freeboard retrieval depending on the chosen processing strategy.

Indeed, unlike for LRM altimetry, in SAR mode the raw echoes are downloaded and processed off-line, which offers a unique opportunity to master the chain process and to adapt it according to the type of the observed surfaces.

Several theoretical studies have proposed methodologies to improved the SAR focalization (exact-beam), to reduced the SAR side-lobe effects over specular surfaces (hamming), to interpolate waveforms to better handle very peaky waveforms (zero-padding), to account for the antenna pattern, to increase the

along-track sampling (eg, at 80hz) or even increase the along-track resolution (full-focused SAR).

The ESA GPOD service offers a web interface to configure and compute SAR data "à la carte" using the SARvatore processing chain (<http://wiki.services.eoportal.org/tiki-index.php?page=GPOD+CryoSat-2+SARvatore+Software+Prototype+User+Manual>). This interface allows to select a large set of SAR processing options: hamming filter, zero-padding, antenna compensation, exact-beam forming, single-look, 80hz.

Using this service, we have computed several datasets covering most of these configuration combinations. Each dataset is composed of all the tracks flying over the west part of the Arctic Ocean (Beaufort to Svalbard) from mid-March to mi-April 2015, i.e. during the 2015 Operation Ice Bridge (OIB) campaign.

These datasets have been converted into along-track freeboard using a same chain, and then gridded in stereo-polar projection maps of 10km resolution and compared with the OIB freeboard measurements. We present the various solutions and analyze the impact of each SAR processing option on the retrieved freeboard distribution compared with OIB.

We also show how some new parameters issued from the stacks and RIPs intermediate SAR product allow to better identify leads and floes, and could even help for the retracking step, avoiding side lobe and off-nadir effects.

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### Coastal Altimetry from CryoSat-2

*Luciana Fenoglio<sup>1</sup>, Salvatore Dinardo<sup>2</sup>, Christopher Buchhaupt<sup>3</sup>, Bernd Übbing<sup>1</sup>, Remko Scharroo<sup>4</sup>, Matthias Becker<sup>3</sup>, Jürgen Kusche<sup>1</sup>, Jerome Benveniste<sup>5</sup>*

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CryoSat-2 SAR altimetry provides in coastal zone improved measurements of height, wave height and wind speed compared to conventional altimetry. We investigate the North-Eastern Atlantic shelf from Lisbon to Bergen and river estuaries in the German Bight.

We consider SAR CryoSat-2 altimetry products from the GPOD and SCOOP projects. The reduced SAR altimetry (RDSAR) are in-house products. The conventional altimetry data are Jason-2 and Envisat data from the Climate Change Initiative CCI project and standard ESA products.

Improved processing include application of sub-waveform re-trackers for RDSAR and various approaches in SAR altimetry, as Hamming weighting window on the burst data prior to the azimuth FFT, zero-padding prior to the range FFT, doubling of the extension for the radar range swath.

We cross-validate the various products with different options and validate them with in-situ data to assess the improved accuracy and precision and their performance for long-term water level change studies.

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### **Determining Arctic Freshwater Fluxes with Cryosat-2**

*Ole Baltazar Andersen<sup>1</sup>, Karina Nielsen<sup>1</sup>, Louise Sandberg Sørensen<sup>1</sup>, Henriette Skourup<sup>1</sup>, Natalia Havelund Andersen<sup>1</sup>, Thomas Nagler<sup>2</sup>, Alexei Kouraev<sup>3</sup>, Diego Fernandez<sup>4</sup>, Christina Surduu<sup>4</sup>*

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In support to Science Elementes ESA has initiated a new CLIC initiative for the Arctic Ocean (Arctic +) on determining the Arctic Freshwater fluxes using Earth Observation data.

One of the project supported by this initiative is the ArcFlux works which started in September 2016 will be introduced in this presentation. This project aims to determine the largest component to the Arctic Freshwater budget, namely the contribution from large rivers, glaciers as well as in-out flow of freshwater through the ocean pathways. Here the importance of Cryosat-2 SAR altimetry for determining the Arctic Freshwater fluxes will be presented and the first results will be shown

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### **The CryoSat SciEnce-oriented Data ANalysis Over Sea-ICE Areas Project**

*Pierre Laurent Fabry<sup>1</sup>, Nicolas Bercher<sup>1</sup>, Stefan Hendricks<sup>2</sup>, Robert Ricker<sup>2</sup>, Sara Fleury<sup>3</sup>, Frédérique Rémy<sup>3</sup>, Jean-Christophe Poisson<sup>4</sup>, Pierre Thibaut<sup>4</sup>, Jérôme Bouffard<sup>5</sup>, Pierre Féménias<sup>5</sup>*

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This communication presents the many aspects and some preliminary results of the ESA funded Cryo-seaNice project that just started (November 2016). The acronym stands for CryoSat SciEnce-oriented data ANalysis over sea-ICE areas. The high level objectives of the project are

- to provide an independent evaluation of Baseline-C operational IPF2 freeboard products,
- to support ESA in the definition of future CryoSat IPF evolutions based on the outcomes of targeted R&D activities focusing on CryoSat data analysis over sea-ice areas,
- to study, prototype, test new or optimized algorithms that may impact IPF-1 and/or IPF-2,
- to study, prototype, test new freeboard products.

A team with very complementary expertises has been set to address the complex subject of sea-ice remote sensing from both the high spatial diversity and the

strong temporal variability aspects due to the sea-ice physics, meteorological events as well as local surface currents.

Dedicated science oriented tools therefore need to be put in place to make best profit of both in situ data and imagery to thoroughly understand the signatures within the altimeter signals.

It is expected that some of the CryoSat Ice Processor limitations be detected/analysed through a refined analysis of the physics behind the Ku band SAR/SARin altimeter products and Ka band products over the Sea-Ice domain.

The team will also implement and assess the outputs of new/recent geophysical retracers.

The various aspects and steps of the projects will be presented : Refine the surface type detection; Improve retracking using physical based retracers instead of threshold based retracers ; Tackle continuity issues (proper retracking of specular and brownian WF in sequence, off-nadir hookings, side lobe contamination effects, freeboard continuity especially

at the pack ice - fast ice transitions and between SAR and SARIN modes), assess snow cover impact onto freeboard and ice-thickness measurements, Analyse and Improve the existing freeboard SNR, Study, Prototype and Assess new freeboard measurement techniques, Exploit SARIN mode for freeboard measurement, test SARIN swath-altimetry over sea-ice.

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### **Greenland Surface Elevation Validation and DEM/Retracker Accuracy Assessment from in-situ GPS measurements**

*Thomas B. Overly<sup>1</sup>, Robert L. Hawley<sup>1</sup>, Eric Lutz<sup>1</sup>, Erich C. Osterberg<sup>1</sup>, Veit Helm<sup>2</sup>, Sebastian B. Simonsen<sup>3</sup>, Zoe Courville<sup>4</sup>, Gifford J Wong<sup>1</sup>*

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Observation of variations in surface elevation of the continental ice sheets improves understanding of the short-term response of the cryosphere to climate change. CryoSat-2's synthetic aperture interferometric radar altimeter (SIRAL) seeks to observe ice sheet surface elevation within a few centimeters accuracy. CryoSat-2 elevation products must be validated against independent ground based observations. Kinematic GPS collected during the 2011 Greenland Inland Traverse (GrIT) from Thule to Summit Station provides surface elevation measurements across 1120km of the Greenland Ice Sheet. We compare GrIT GPS elevations to published and custom Digital Elevation Models (DEMs) generated from CryoSat-2 Level 1B and Level 2



products (Baseline C). The ground-based GPS measurements validate regional surface-height changes observed by CryoSat-2. We examine L1B elevation accuracy using three re-tracker algorithms: a threshold first maximum re-tracker (TFMRA), a midpoint threshold re-tracker (a variation of NASA's Goddard Space Flight Center re-tracker), and an offset center of gravity re-tracker (OCOG). Results of the re-tracker assessment indicate optimal methods for surface re-tracking and DEM generation, reducing uncertainty of Surface Elevation Change estimates.

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### **Comparing Coincident IceBridge and CryoSat-2 Observations Over Sea Ice**

*Donghui Yi<sup>1</sup>, Nathan Kurtz<sup>1</sup>, Jeremy Harbeck<sup>1</sup>, Michelle Hofton<sup>2</sup>, Serdar Manizade<sup>3</sup>, Helen Cornego<sup>1</sup>*

*<sup>1</sup>NASA/GSFC, USA; <sup>2</sup>University of Maryland, USA; <sup>3</sup>NASA/WFF, USA*

In this study, we will compare sea surface elevation, sea ice surface elevation, and sea ice freeboard using 10 coincident CryoSat-2, ATM, and LVIS observations. We will apply identical ellipsoid, geoid model, tide models, and atmospheric corrections to CryoSat-2, ATM, and LVIS data. For CryoSat-2, we will use surface elevation generated based on the methods from four different groups (UCL, NASA/Goddard, AWI, and NASA/JPL). We will use surface elevation and sea ice freeboard in the OIB data product for ATM and the elevation and sea ice freeboard calculated through a Gaussian waveform fitting method for LVIS. The ATM and LVIS elevations and freeboards will be averaged at each CryoSat-2 footprint for comparison. The four different CryoSat-2 retrackerers show quite significant mean differences in elevation. The mean elevations of ATM, LVIS, and Cryosat-2 are also quite different. We will investigate how these elevation differences propagate into the retrieval of sea ice freeboard. The results of this study are important for the mutual calibration/validation of the ATM, LVIS, and CryoSat-2 data products. The better understanding of ATM, LVIS, and Cryosat-2 results will also help to bridge the data gap between ICESat and ICESat-2.

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### **An Assessment of Arctic Radiative Feedbacks in Coupled Ocean-Atmosphere Models**

*Brian Soden, Eui-Seok Chung*

*University of Miami, United States of America*

Climate models project that in response to increases in anthropogenic greenhouse gases Arctic surface air temperatures increase 2-3 times faster than the global average. Although the amplified warming of the Arctic region has been attributed in large part to the lapse rate and surface albedo feedbacks, the radiative feedback processes have been less comprehensively analyzed from the surface perspective. To enhance

understanding of the contribution of radiative feedback processes to Arctic warming amplification, we apply a radiative kernel method to coupled model simulations forced by an abrupt increase in atmospheric CO<sub>2</sub> to determine the strength of radiative feedbacks at the surface as well as at the top of the atmosphere (TOA). Consistent with previous studies, our analysis indicates that from the TOA perspective the lapse rate and surface albedo feedbacks play a more important role in Arctic warming amplification than the water vapor and cloud feedbacks. When quantified at the surface, however, the lapse rate feedback is shown to oppose the surface warming because the temperatures in the troposphere increase less than the surface air temperature over the Arctic region. In addition, the surface-based cloud feedback is found to exhibit a positive contribution to the surface warming relative to the TOA perspective, whereas the opposite is noted for the water vapor feedback.

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### **CryoTop Evolution - CryoSat-2 Swath Elevation, Digital Elevation Models, Rates of Elevation Change Products**

*Noel Gourmelen<sup>1</sup>, Maria Jose Escorihuela<sup>2</sup>, Anna Hogg<sup>3</sup>, Jan Wuite<sup>4</sup>, Flora Weissgerber<sup>1</sup>, Monica Roca<sup>2</sup>, Thomas Nagler<sup>4</sup>*

*<sup>1</sup>University of Edinburgh, United Kingdom; <sup>2</sup>isardSAT, Spain; <sup>3</sup>Center for Polar Observation and Modeling, University of Leeds, UK; <sup>4</sup>ENVEO, Austria*

Reference and repeat-observations of ice sheet margin topography is critical to identify changes in ice thickness, provide estimates of mass gain or loss and thus quantify the contribution of the cryosphere to sea level change. The ESA Altimetry mission CryoSat-2 aims at gaining better insight into the evolution of the cryosphere, in particular over the steep slopes typically found along ice sheet margins where the majority of the mass loss is taking place. CryoSat's revolutionary design features a Synthetic Interferometric Radar Altimeter (SIRAL), with two antennas for interferometry, the corresponding SAR Interferometer (SARIn) mode of operation increases spatial resolution while resolving the angular origin of off-nadir echoes occurring over sloping terrain. The SARIn mode is activated over ice sheet margins and the elevation for the Point Of Closest Approach (POCA), or level-2, is a standard product of the CryoSat-2 mission.

CryoSat-2 SARIn mode allows a new approach for more comprehensively exploiting the CryoSat-2 record and produce ice elevation and elevation change with enhanced spatial resolution compared to standard CryoSat-2 level-2 products. In this so-called CryoSat-2 Swath SARIn (CSSARIn) approach, the entire waveform is analysed providing elevation beyond the POCA, leading to between 1 and 2 orders of magnitude more elevation measurements than conventional level-2 product. As part of the European Space Agency project CryoTop Evolution we are generating CSSARIn elevation, Digital Elevation Models and maps of rates of

surface elevation change over the Greenland and Antarctic Ice Sheets. These products will be generated and distributed to the community. Here we will present the methods and quality assessment of the products as well as showcase examples of the added value of the products.

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### **Tropical Cyclones Above Australia During Last 12 Years**

*Liudmila Vanina-Dart<sup>1,2</sup>, Evgenij Sharkov<sup>1</sup>*

<sup>1</sup>Space Research Institute, Moscow, Russian Federation; <sup>2</sup>The "Seeingear"elibrary, Chain Lane, Battle, UK

A tropical cyclone (TC) is the global generic term for an intense circulating weather system over tropical seas and oceans. It is accompanied with very strong winds, heavy rains & large ocean waves.

It is well known that the tropical zone of the global ocean-atmosphere system plays a key role in the dynamics and evolution of synoptic and climatic meteorological processes on Earth. The ocean-atmosphere system of the Earth's tropical zone has a unique

property. It can generate sufficiently organized and stable mesoscale vortex structures, TCs, from the atmospheric turbulent chaos in the global circulation system. For a long time the process of generation of these vortex systems in the Earth's atmosphere was considered a purely meteorological phenomenon when it was investigated based on standard meteorological approaches(1).

Depending on the influence source position, the atmospheric layers can interact both from below and from above. Upward-propagating planetary, tidal, and gravity waves that penetrate through the systems of zonal winds and are reflected by them are considered the

physical basis of the influence from below. These waves are caused by intense dynamic processes in the troposphere, and the transfer characteristics are determined by the thermodynamic regime of the middle atmosphere.

Based on the results obtained in these investigations, it was concluded that the gravity waves (GW) are the main possible influence factors on the ionosphere by the active underlying cyclones. In turn, TCs are not only long-living area sources of disturbances, but also moving in a wide area. Thus, we will have to deal with addition of waves and anisotropic pattern of the ionospheric excitation. Simultaneously, it should be borne in mind that not all of the GWs from the TC will reach ionospheric heights because of filtering by strong tropospheric winds. The IGW occurrence mechanism is most likely based on the hypothesis of the growth and decay of convective towers with a spatial scale of about 100 km and time scales of a few hours.

In this presentation the author analyzes the dynamic ocean parameters and ionosphere parameters,

received in the process of satellite remote sensing above TC (above Australia) in the last 12 years in the south-eastern area of the East hemisphere.

1. L. B. Vanina-Dart and E. A. Sharkov, Main Results of Recent Investigations into the Physical Mechanisms of the Interaction of Tropical Cyclones and the Ionosphere//ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2016, Vol. 52, No. 9, pp. 1119–1126. © Pleiades Publishing, Ltd., 2016.

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### **Multi-Sensor Radar Measurements of Snow on Sea Ice near Eureka, Nunavut, Canada**

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The influence of heterogeneous snow properties on wideband radar is evaluated for data collected over first year sea ice (FYI) near Eureka, Nunavut, Canada (79°59'20"N, 85°56'27"W) on March 25<sup>th</sup>, 2014. As part a collaborative CryoVex and Operation IceBridge (OIB) mission, the Airborne Synthetic Aperture and Interferometric Radar Altimeter System (ASIRAS; 12.5-14.5 GHz), the Center for Remote Sensing of Ice Sheets (CRENIS) Ku-Band Radar Altimeter (13-17 GHz), and CRENIS Snow Radar (2-8 GHz) were flown over a 60 km FYI transect within Eureka Sound, coincident with an Environment and Climate Change Canada (ECCC) field campaign. *In situ* snow and ice measurements within the footprints of the CryoVex and OIB radars were completed over a 6-day period immediately following the overflights. Distributed measurements of snow depth, snow density, and snow salinity were collected along the flight lines with 95% falling within the OIB and CryoVex radar footprints. In addition to the along-track sampling, three intensive measurement grids (250 m x 500 m) were completed to evaluate spatial variability in the radar across-track dimension and at finer spatial scales relative to potential radar products. An extended sampling protocol at these sites included multiple snow pits to characterize local-scale variations in snow stratigraphy and grain size. Strong spatial and temporal coincidence amongst the CryoVex, OIB, and ECCC datasets provides a unique opportunity to evaluate the multi-sensor radar response of snow on land fast FYI with direct applicability to altimetry-based snow and sea ice property retrievals. Synergistic retrieval potential is discussed along with a set of recommendations for future campaign design.

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## Comparison of Cryosat-2 Altimeter Data with ICESat-2 Simulator (SIMPL) Data over Western Greenland Outlet Glaciers

Gavin Christopher Medley<sup>1,2</sup>, Ute Christina Herzfeld<sup>1,2,3</sup>, Thomas Trantow<sup>1,2</sup>, Stephen Palm<sup>4</sup>, Harding David<sup>5</sup>, Dabney Philip<sup>5</sup>

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In altimetry, different instruments exhibit varying data characteristics and spatial resolutions. We aim to compare these aspects between CryoSat-2 data and data generated by a simulator instrument for NASA's Ice, Cloud and Land Elevation Satellite (ICESat-2). Recently, a new form of altimeter -- micropulse photon-counting LiDAR, has been developed in preparation for the ICESat-2 mission which will carry the Advanced Topographic Laser Altimeter System (ATLAS) aboard. Simulator instruments have been developed to facilitate algorithm development and to evaluate the instrument concept prior to launch (now planned for 2018). One such simulator instrument is the Slope Imaging Multi-polarization Photon-counting LiDAR (SIMPL). A primary objective for the ICESat-2 mission is the precise measurement of global land and sea ice elevation change so to create realistic simulated ATLAS data, a campaign was launched in 2015 to fly SIMPL over locations in western Greenland.

As a general objective, we set out to study elevation change using CryoSat-2 data alongside SIMPL data. We use the elevation estimate derived from SIMPL flight data via the Density Dimension Algorithm (DDA) to analyze elevation and elevation change signal from CryoSat-2 data over northwest Greenland outlet glaciers Sverdrup Gletsjer and Gieseckebraer. We examine complex surface topography over crevassed areas in outlet glaciers using the DDA to evaluate the SIMPL instrument and compare the elevation estimate to CryoSat-2 data. In particular, we attend to the differences in spatial resolution between CryoSat-2 and SIMPL to evaluate the potential precision of ATLAS for the ICESat-2 mission. In the interest of maximizing useful data, we present a cloud segmentation algorithm that allows utilization of SIMPL data in the presence of modest cloud cover to create a more thorough comparison. Lastly, we validate the SIMPL instrument data by creating a difference map from CryoSat-2 elevation estimates and by analysis of surface roughness with comparison LandSat 8 images.

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## Retrieving Surface Soil Moisture from Cryosat2 Data in Arid and Semi-Arid Terrain

Philippa A. M. Berry<sup>1</sup>, Robert Balmbra<sup>2</sup>

<sup>1</sup>Roch Remote Sensing; <sup>2</sup>Cyber Security Centre Warwick University

Measuring soil surface moisture using satellite radar altimeter backscatter is a comparatively new application. The basis of the technique is to construct very detailed DRy EArth ModelS (DREAMS) [1], using multi-mission recalculated and cross-calibrated altimeter backscatter fused with ground truth, with repeat arc analysis used to identify and mask out remaining areas of model instability [2]. For the current generation of DREAMS, there is a requirement that the surface be dry for at least one month of the year, so this technique was tested over desert and semi-arid terrain.

For the Cryosat2 mission, both the technique and the DREAMS had to be re-engineered to compensate for the mission long repeat period. This severely curtailed repeat arc analysis and required the DREAMS to be consistent and accurate over the entire model, due to the dense track sampling. To meet this standard, the models were completely re-engineered, incorporating detailed ground truth and enhanced modelling techniques. DREAMS were initially crafted for three desert regions to test the derivation of soil moisture. The Simpson desert was chosen despite the complex dune structure because detailed campaign data were available from collaborative research with the BNR (now QLCCC). The Tenere desert was selected as a small annual signal had been observed in soil moisture data derived from ERS2. The Kalahari desert was included because this is a region where significant moisture is present for several months each year so this offered the greatest likelihood for signal detection.

After initial work as part of the EU LOTUS project [3], several years of Cryosat2 data were processed and analysed. Over the Kalahari, Cryosat2 soil moisture estimates have now been successfully validated with other remote sensed soil moisture estimates [4] and sample results are presented here.

New DREAMS have now been created for the Gibson and Victoria deserts in Australia, and the whole of the Arabian desert. Each new area is tested with Cryosat2 data, which provides a stringent test of the remodelled DREAMS. Results are extremely promising, and it is concluded that all arid and semi-arid regions modelled with this enhanced technique will allow soil moisture estimates to be derived from Sentinel3.

1 Berry, P.A.M., Carter, J.O., 2011. Altimeter derived Soil Moisture Determination – Global Scope and Validation. IAHS 'red book' for IUGG 2011.

2 Berry, P.A.M., Dowson, M., Smith, R.G., Benveniste, J., 2012. Soil Moisture From Satellite Radar Altimetry (SMALT). Proceedings of the ESA Living Planet Symposium 2012.

3 Berry, P.A.M. & Balmbra, R., 2016. Soil Surface Moisture from Cryosat2 and Sentinel-3 Satellite Radar Altimetry. Proc. 'Living Planet Symposium 2016', Prague, Czech Republic, 9–13 May 2016 (ESA SP-740, August 2016).

4 Wagner, W., W. Dorigo, R. de Jeu, D. Fernandez, J. Benveniste, E. Haas, M. Ertl (2012) Fusion of active and passive microwave observations to create an Essential Climate Variable data record on soil moisture, ISPRS Annals. Volume I-7, XXII ISPRS Congress, Melbourne, Australia, 25 August-1 September 2012, 315-321

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#### **Elevation change of Antarctic ice shelves from 2011 to 2016 using CryoSat-2**

*Daehyeon Han<sup>1</sup>, Jungho Im<sup>1</sup>, Hyangsun Han<sup>2</sup>*

*<sup>1</sup>UNIST, Korea, Republic of (South Korea); <sup>2</sup>Korea Polar Research Institute*

The elevation change of ice shelves in Antarctic area is the one of the key factors to identify the current melting processes associated with ice thickness change and ice mass balance. The acceleration of ice elevation change is also crucial to understand the trend of thinning ice shelves. Cryosat-2 has provided the recent surface elevation data over the Antarctica with high spatial resolution since 2010. In this study, the elevation change and its acceleration of Ross, Filchner-Ronne, and Amery ice shelves in Antarctic are derived using CryoSat-2 SARIn L2 surface elevation data from 2011 to 2016. The mean ice elevation change between 2011 and 2016 was negative, indicating the declination of ice elevation. The acceleration of annual ice elevation change was derived by coupling the elevation changes for two years from 2011-2012 to 2015-2016, which showed the faster thinning trend of study area over the years. The results provide the ice elevation change and its acceleration patterns over three major ice shelves in recent years, producing high resolution (2.5 km) grids of mean elevation change and acceleration. This study suggests that the declination rate of the mean ice elevation became higher over the study area when compared with the previous studies using other satellite measurements such as ICESat.

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#### **Analysis of the Complete Bouguer Gravity Anomaly and the Parker-Oldenburg Inversion for the Three-Dimensional Moho depth Model in the Central Alborz Structural Zone, Northern Iran**

*Soran Parang<sup>1</sup>, Abdolreza Safari<sup>1</sup>, Mohammad Ali Sharifi<sup>1</sup>, Abbas Bahrodi<sup>2</sup>*

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The separative boundary between crustal and mantle rocks is called the Moho discontinuity. This boundary explains massive variations in the velocity of seismic waves, chemical structure, and lithology. The Moho depth, the depth of the boundary, is used in the identification of the general structure of the Earth's crust, geology and regional tectonics. The aim of this

study is to develop a Moho depth model for the central part of the Alborz Mountains, which is located in northern Iran, parallel to the southern margin of the Caspian Sea, using the complete Bouguer gravity anomaly data and the Parker-Oldenburg approach, which is utilized to determine the geometry of the density interface from the gravity anomaly. The free-air gravity anomaly data calculated from the EGM2008 geopotential model and spherical harmonics, terrain correction and elevation data from ETOPO1 are deployed to compute the complete Bouguer gravity anomaly in the studied region. For the estimation of the Moho depth, the complete Bouguer anomaly data is used in the Parker-Oldenburg inversion algorithm. According to this algorithm, the depth of the Moho discontinuity can be obtained through an iterative inversion procedure and a series of Fourier transforms of the gravitational anomaly. The results show that the Moho depth is ~46 km beneath the northern part of the Central Iranian Plateau, 53–56 km in the central part of the Alborz Mountains and ~48 km in the Southern Caspian Basin.

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#### **Benefits of the Cryosat-2 Altimeter Mission for the Observation of Inland Waters**

*Pierre Thibaut<sup>1</sup>, Lionel Zawadzki<sup>1</sup>, Nicolas Taburet<sup>1</sup>, Clément Lacrousts<sup>1</sup>, Thomas Moreau<sup>1</sup>, François Boy<sup>2</sup>, Nicolas Picot<sup>2</sup>*

*<sup>1</sup>Collecte Localisation Satellite, France; <sup>2</sup>Centre National d'Etudes Spatial, France*

The key drivers for improving the inland water height monitoring capability from space observations are two-fold. The first one consists in increasing the temporal and spatial coverage of the radar altimeter measurements by enlargement of the altimeter constellation or densification of the observation points (between virtual stations over rivers for missions on repetitive tracks). The second one requires improvements in the water level estimation availability and precision.

The new generation of radar altimeters featuring a delay/doppler mode (Cryosat-2 and Sentinel-3A, and in a near future Sentinel-3B and Jason-CS missions) clearly fulfills this second point offering improved performances with respect to conventional altimeters. The improved along-track spatial resolution of the delay/doppler altimeter may enable the measurement of high-resolution water level transects across rivers and other water basins where conventional altimeters echoes are impacted by off-nadir reflections or land returns because of their larger footprint size.

While most of the altimeter missions have a repetitive orbit crossing the inland water patterns at stable positions (concept of virtual station), Cryosat-2 has the particularity to slightly drift along the orbit giving access to a very dense geographical sampling of each river basin. With the view to producing high level hydrological products merging all altimeter missions

and providing water level and slopes at any time and any point of a river, this particularity becomes an advantage that can/must be exploited. The precise knowledge of topography and its dynamic is also of special importance for the preparation and the validation of the SWOT mission (launch around 2020).

In this context, we propose to give an illustrated overview of the Cryosat-2 specificities and performances over hydrological conditions and to show how beneficial its measurements are for the global altimetry constellation.

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### **Analysis of CryoSat-2 SAR data over ice sheets and algorithm development in preparation for Sentinel-3**

*Malcolm McMillan<sup>1</sup>, Roger Escola<sup>2</sup>, Monica Roca<sup>2</sup>, Maria Jose Escorihuela<sup>2</sup>, Pierre Thibaut<sup>3</sup>, Andrew Shepherd<sup>1</sup>, Frederique Remy<sup>4</sup>, Jerome Benveniste<sup>5</sup>, Americo Ambrozio<sup>5</sup>, Marco Restano<sup>5</sup>*

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In late 2014, CryoSat-2 was switched from LRM to SAR mode over 3 Antarctic study sites to provide an exploratory SAR dataset in advance of the Sentinel-3 launch in 2016. Here we present analysis of these SAR acquisitions and describe ongoing work to use these CryoSat-2 data to improve SAR altimetry processing methods for ice sheets. This work has been undertaken as part of the SPICE (Sentinel-3 Performance Improvement for Ice Sheets) study, funded by ESA's SEOM (Scientific Exploitation of Operational Missions) programme.

More specifically, we will (1) compare the CryoSat-2 SAR elevation measurements to LRM observations acquired during the subsequent orbit cycle, (2) evaluate SAR elevation retrievals using different retracers, and (3) develop pseudo-LRM measurements from the SAR FBR data, to investigate the ability to generate a low resolution product from a closed burst SAR system. For all processing scenarios, we will evaluate the ice sheet elevation measurement using reference airborne and satellite datasets. Finally, we will describe future SPICE activities, which will focus on algorithm developments to existing Delay-Doppler processing schemes, implementation of new SAR retracers designed for ice sheets, and comparison to AltiKa Ka-band altimetry to study radar wave penetration into the snowpack.

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