


SPACE AGENCIES INVOLVED
IN THE SAR COORDINATION
WORKING GROUP OF PSTG



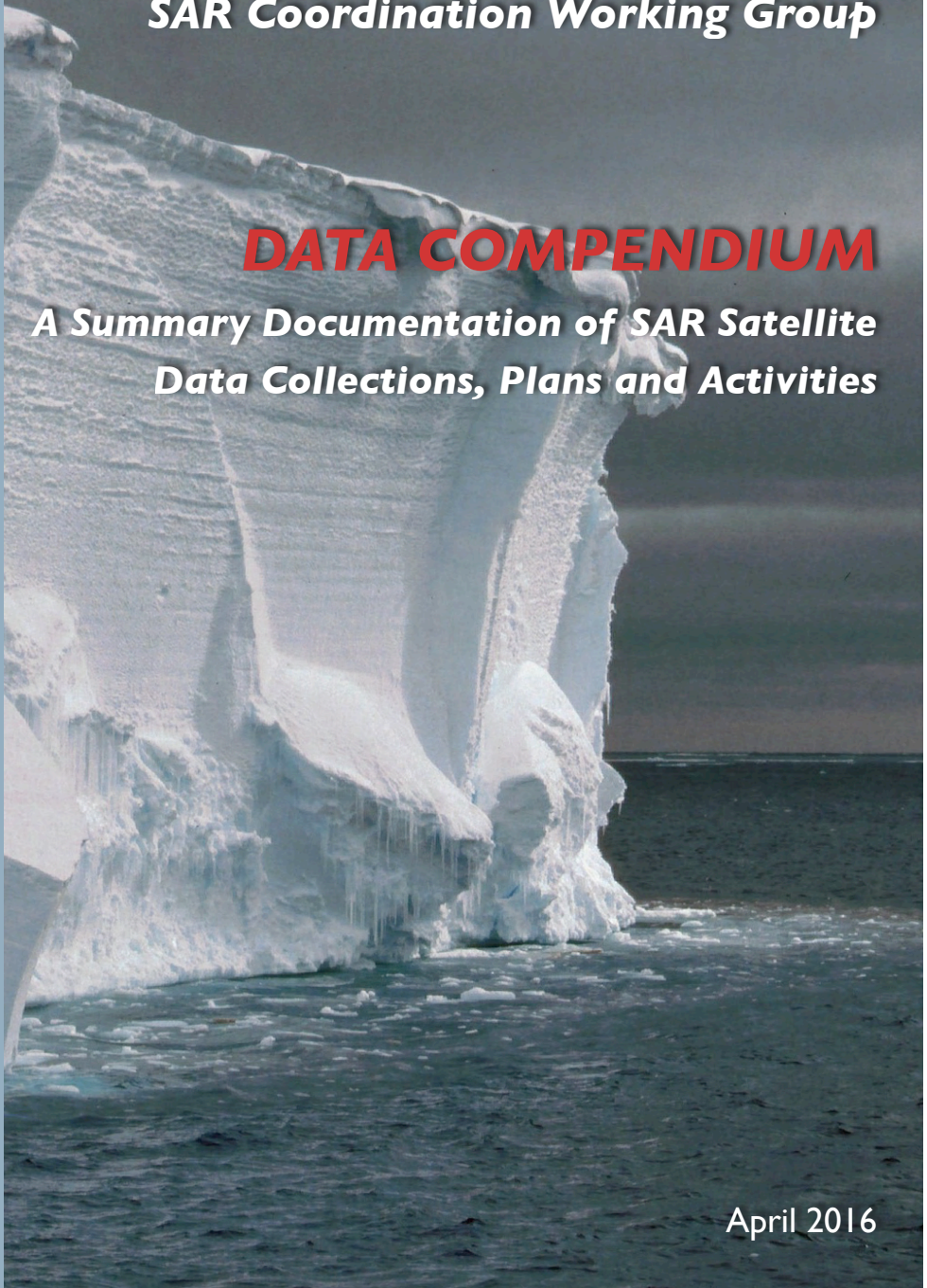
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Polar Space Task Group SAR Coordination Working Group

DATA COMPENDIUM

*A Summary Documentation of SAR Satellite
Data Collections, Plans and Activities*



April 2016

Title Page Illustrations:

Edge of an ice shelf, near Halley Station, Antarctica *[large photo]*

Credit: Ralph Timmermann, AWI

Snow backscatter map of the European Alps *[top left]*

Credit: University of Zurich; map contains modified Copernicus Sentinel data

Sentinel-1A satellite *[top center]*

Credit: ESA

Antarctica, preliminary velocity map product *[top center-right]*

Credit: MDA and Bernd Scheuchl / UCI

Map of Greenland with location of outlet glaciers selected for satellite SAR data collection *[top right]*

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Executive Summary

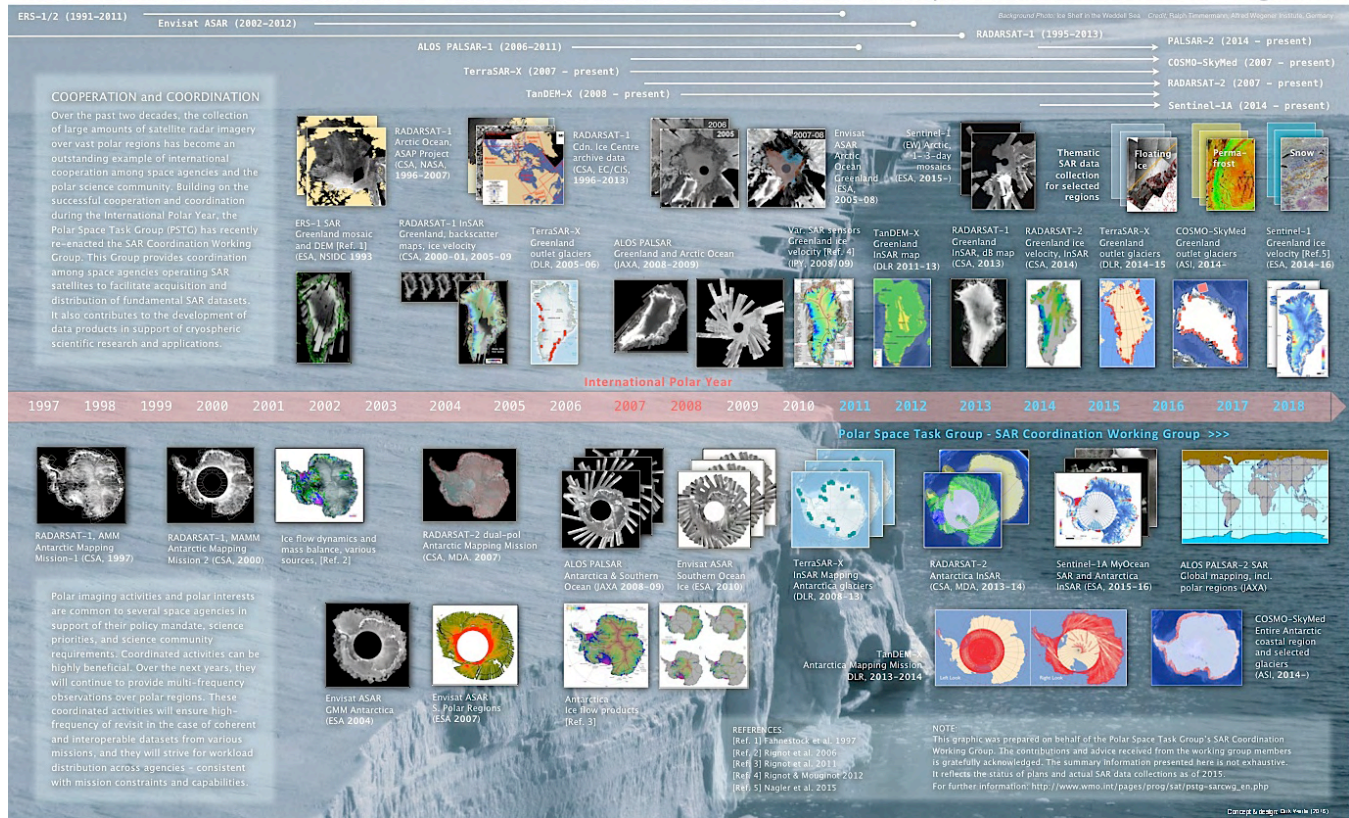
During the past two decades, the collection and utilization of large amounts of satellite radar imagery over vast polar regions has become an outstanding example of international cooperation among space agencies and the polar science community. Building on the successful cooperation and coordination during the International Polar Year (2007/08), the Polar Space Task Group (PSTG) has recently re-enacted the Synthetic Aperture Radar (SAR) Coordination Working Group (CWG). The Group provides coordination among space agencies operating SAR satellites to facilitate collection of fundamental SAR datasets and contributes to the development of science products in support of cryospheric research and applications.

This compendium contains summary descriptions and illustrations of comprehensive satellite radar data of polar regions as a result of well-planned and coordinated efforts of representatives from space agencies, international organizations, and the science community. The document describes SAR data

sets that have been acquired, both prior to and during the mandate of PSTG SAR CWG, and those data sets that are planned for the coming years. The plans address imaging requirements articulated by the scientific community with regard to four themes: ice sheets, floating ice, permafrost, and snow. The data collection is based on science priorities and exploits the particular strengths of each sensor and share the load.

The information contained in this document represents a snapshot in time. It is expected that its content will evolve in relation to the PSTG strategic plans and priorities, reflect the growing demand for the unique and reliable imaging capabilities of SAR instruments, and take into account the near future addition of new SAR missions. The datasets described in the Compendium are intended to be available for scientific purpose, and their wide-spread use should lead to a wealth of new observations, analyses and conclusions.

Overview of Two Decades of Coordinated Satellite SAR Data Acquisitions over Polar Regions



A larger version of this poster is available on the WMO - PSTG web page under "Information Resources" at http://www.wmo.int/pages/prog/sat/pstg_en.php

Foreword

The 4th International Polar Year (IPY-4), from 2007– 2009, was a major international programme initiated by the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU). The results were remarkable, achieved through a combination of internationally federated, interdisciplinary research which yielded new scientific discoveries, development of new methods and tools to better understand the cryosphere. IPY-4 has delivered an array of data which led to new understanding of the role of the Polar Regions in the Earth system.

During the International Polar Year (IPY) the Joint Committee (JCOMM) of WMO and ICSU mandated the IPY-Space Task Group (IPY-STG) to plan and coordinate the satellite data acquisition to fulfill the satellite data needs of approved IPY projects, thereby enabling their scientific objectives to be achieved. The IPY- STG comprised invited representatives of the major space agencies, thereby representing the interests of both Research and Development and Operational agencies.

In 2011, the Polar Space Task Group (PSTG) was established as an Advisory Group to the WMO Executive Council Panel of Experts on Polar Observations Research and Services (EC-PORS) and comprises Space Agency experts. PSTG established the SAR Coordination Working Group (SAR CWG) as a sub-group to focus on the particular scientific requirements that could be

satisfied by SAR sensors, and to coordinate acquisitions of SAR data to respond to those requirements. The member agencies and commercial data suppliers possess SAR sensors with polarimetric capabilities at various wavelengths. The potential data is rich in information content, particularly with regard to cryospheric applications, such as discrimination of floating ice from ocean, velocity mapping of glaciers, and elevation estimation. These data can lead to such important information as ice sheet mass balances.

Cooperation and coordination are essential in this process, so that the data collection can be shared between like sensors (e.g. the C-band radars or the X-band radars), and so that data from different sensors (e.g. C-band data with X-band data) can be combined to enrich the information content.

This document describes the SAR data sets that have been acquired, both prior to and during the PSTG SAR CWG, and those data sets which are planned for the coming years. The data is intended to be available for scientific purposes, and should lead to a wealth of new observations, scientific analyses, and new applications.

We would like to sincerely thank the scientist partners and the SAR data providers, both public space agencies and commercial providers, for their invaluable contributions.

Mark Drinkwater and Yves Crevier



PSTG SAR Coordination Working Group members meeting at DLR, Germany, October 8-9, 2015.
(Photo courtesy of DLR)

Content

Executive Summary	i
Foreword	ii
Content	iii
SECTION I - INTRODUCTION	
Background Information	1
Value of Coordinating Satellite SAR Data Collection	1
Building on Past Achievements	2
Science Community Engagement	3
Existing SAR Data Sets of Polar Regions	3
PSTG Strategic Priorities	3
Document Overview	4
SECTION 2 - ICE SHEETS	
Thematic Area: Ice Sheets	5
Previous SAR Data Collections	7
SAR Data Collection Coordinated through PSTG	14
Examples of Systematic, Wide-area Science Products	23
Planned SAR Data Collection Coordinated through PSTG	25
SECTION 3 - FLOATING ICE	
Thematic Area: Floating Ice	26
Previous SAR Data Collections	27
SAR Data Collection Coordinated through PSTG	30
Planned SAR Data Collection Coordinated through PSTG	33
SECTION 4 - PERMAFROST	
Thematic Area: Permafrost	34
Previous SAR Data Collections	35
Planned SAR Data Collection Coordinated through PSTG	39
SECTION 5 - SNOW	
Thematic Area: Snow	40
Previous SAR Data Collections	41
SAR Data Collected through PSTG Coordination	42
Planned SAR Data Collection Coordinated through PSTG	43
ANNEX	
List of Acronyms	44
Acknowledgments	45

SECTION I - INTRODUCTION

Background Information

One of the major successes of the International Polar Year (IPY) in 2007-2008 was the unprecedented amount of high-resolution synthetic aperture radar (SAR) satellite imagery collected over the polar regions and the high quality data products that have since been generated. This outstanding accomplishment relied on a well-coordinated effort on the part of several space agencies, satellite operators and the science community.

The current endeavour builds on the legacy of the successful International Polar Year Space Task Group (IPY-STG) SAR Coordination Working Group's effort to fulfill the need for inter-Agency mission acquisition planning and to carry out implementation actions at agency level. The Polar Space Task Group (PSTG) re-enacted the SAR Coordination Working Group with the aim to provide coordination across space agencies with SAR missions, to facilitate acquisition and distribution of fundamental SAR satellite datasets, and to contribute to or support development of specific derived products in support of cryospheric scientific research and applications. Detailed documentation on the activities of the PSTG and its Terms of Reference can be accessed here: http://www.wmo.int/pages/prog/sat/pstg_en.php and http://www.wmo.int/pages/prog/sat/documents/PSTG-SARCWG_ToR_Nov2014.pdf. The site also contains background and meeting documents of the PSTG predecessor, the International Polar Year Space Task Group.

The PSTG has been established under the auspices of the World Meteorological Organization's (WMO) Executive Council Panel of Experts on Polar Observations Research and Services (ECPORS). The group's mandate is to provide coordination across Space Agencies to facilitate acquisition and distribution of fundamental satellite datasets, and to contribute to or support development of specific derived products in support of cryospheric and polar scientific research and applications.

The SAR Coordination Working Group (SAR CWG) is a subsidiary group to PSTG. It is tasked with requests for coordinated acquisition, dissemination, processing and analysis of satellite-based SAR data in response to requests by the user community, and on behalf of PSTG. PSTG recommended establishment of the SAR CWG at its second session in June 2012 (PSTG-2 Final Report). The SAR CWG coordinates its activities and membership with the PSTG. The Group has a mandate to:

- ◆ *Identify and prioritize the acquisition of multi-frequency SAR data of polar regions based on the needs expressed by the scientific and related applications communities.*
- ◆ *Maintain constant dialogue with these communities*
- ◆ *Maintain constant dialogue with private sector data provider partners*
- ◆ *Share information on the current status of the various international SAR missions and specific activities relevant to polar regions*
- ◆ *Ensure that data are being made available to qualified end-users*

Membership of the SAR CWG is open to include several stakeholder groups and their representatives:

- ◆ *All SAR Operating Agencies (thematic experts and mission managers)*
- ◆ *Other agencies to ensure availability of complementary datasets (i.e. providers of optical sensor data)*
- ◆ *Members of the science community representing thematic sectors of priority*
- ◆ *Members of the "commercial arm" of SAR missions*

The SAR CWG is chaired by a representative of one of the participating space agencies and meets regularly to report and review on its activities. Further documentation regarding mandate and activities of the Group can be found here: http://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-SARCWG-2_Doc_03_ToR02.pdf and http://www.wmo.int/pages/prog/sat/pstg-sarcwg_en.php.

Value of Coordination

Polar imaging activities and Polar interests are common to several space agencies in support of their policy mandate, science priorities, and science community requirements. Coordinated activities among the agencies can be highly beneficial in that they:

- ◆ *Provide multi-frequency observation over polar regions (complementary observation and information depth)*
- ◆ *Ensure high-frequency of revisit in the case of "coherent and inter-operable" datasets from various missions*
- ◆ *Ensure workload distribution across agencies – justified by mission constraints and capabilities*

International collaboration is an essential element in the process of coordinating polar imaging activities. Several *ad hoc* activities and tasks have been initiated, highlighting the collaborative spirit of PSTG. The approach to each new task requires open minds on the part of all participants, as established processes need to be adjusted to accommodate the collaboration and achievement of common goals. Some efforts work flawlessly; others still require improvement, yet they are still expected to result in success and a valuable set of “lessons learned.”

From a strategic perspective, the PSTG is focused on various theme areas and associated issues. These cryospheric science issues are outlined in the Strategic Plan 2015-2018, as follows:

- ◆ *Sea ice mass balance and mass variability*
- ◆ *Ice sheet mass balance contribution to sea level*
- ◆ *Atmospheric products to facilitate improved polar numerical weather prediction*
- ◆ *Freshwater budget closure at high latitudes (snow and permafrost impact on polar hydrological cycle)*
- ◆ *Circumpolar changes in permafrost and terrestrial biosphere (consequences for carbon and hydrological cycles)*
- ◆ *Physical forcing of atmospheric chemistry in polar atmosphere (surface/troposphere, and troposphere/stratosphere coupling in the upper-tropospheric/lower-stratosphere)*

A Strategic Plan has since been under development by the PSTG during the 2014 to 2015 time frame. The themes and objectives of the plan also serve as guidance for the SAR CWG and the thrust of its activities (http://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-4_Doc_10-01_StrategicPlan-MD.pdf). In cooperation with the science community, the working group has since directed its SAR data acquisition efforts toward four thematic areas: permafrost, wet snow, floating sea ice, and ice sheets.

Building on Past Achievements

Working group activities similar to the ones of the current PSTG and its SAR CWG can be traced back to the *Global Interagency IPY Polar Snapshot Year* a decade ago. The GIIPSY project had two main goals: to develop consensus requirements on polar science objectives that could be met with Earth observation satellites, and to capture multi-mission polar snapshots.

Further coordination was achieved through the IPY Space Task Group in 2007 and 2008. The IPY-STG managed to optimize space agency contributions in order to attain major IPY science objectives. Overall, the IPY represented an international framework for understanding polar processes and high-latitude climate. Within that framework, Earth observation offered unique capabilities for obtaining essential data for predictive models.

The accomplishments of the IPY-STG and its SAR Working Group are examples of the successful work and outcomes of the coordination activities. Initially convened under WMO/ICSU, the STG comprised of nominated representatives from space agencies who coordinated SAR data acquisitions across CEOS and CGMS agencies. They achieved their goals by focussing on projects compatible with operational mandates of individual agencies and commercial partners and by encouraging participation from other nations.

The STG accomplished its work by identifying a limited number of the very important scientific objectives that were achievable within its mandate and the IPY framework. The objectives included Pole-to-coast InSAR data acquisitions for ice velocity measurements of Antarctica as well as repeat fine-resolutions SAR data collection for mapping sea ice motion within the entire Southern Ocean. Using optical sensors, the objectives in northern latitudes included high-resolution visible and infra-red snapshots of circumpolar permafrost regions and pan-Arctic high and moderate resolution visible and infra-red snapshots of lake and river freeze-up and break-up conditions. Polar meteorology and atmospheric chemistry goals were added later. Outstanding examples of multi-sensor SAR views of polar ice sheets pre-dating PSTG and SAR CWG activities include:

- ◆ *Canadian Antarctica mapping missions (RADARSAT-1); Greenland InSAR mapping project 2000-08*
- ◆ *ESA Antarctic mapping with ASAR, monthly sea ice extent (2007-09), Arctic sea ice extent 2007-08)*
- ◆ *JAXA Antarctic mapping with ALOS PALSAR (2007-08); Greenland ice stream mapping*
- ◆ *ASI mapping with COSMO SkyMed (Wilkins Ice Shelf disintegration, 2009)*

Ice Sheet products resulting from IPY data collection are located at NASA's Distributed Active Archive Center at the National Snow & Ice Data Center (NSIDC) in the United States (http://nsidc.org/data/measures/data_summaries.html). Examples include:

- ◆ *NSIDC-0525. PI: E. J. Rignot / MEaSURES InSAR-Based Ice Velocity Maps of Central Antarctica: 1997 and 2009*
- ◆ *NSIDC-0498. PI: E. J. Rignot / MEaSURES Antarctic Grounding Line from Differential Satellite Radar Interferometry*
- ◆ *NSIDC-0484. PI: E. J. Rignot / MEaSURES InSAR-Based Antarctica Ice Velocity Map*
- ◆ *NSIDC-0481. PI: I. Joughin / MEaSURES Greenland Ice Velocity: Selected Glacier Site Velocity Maps from InSAR*
- ◆ *NSIDC-0478. PI: I. Joughin / MEaSURES Greenland Ice Velocity Map from InSAR Data*

Science Community Engagement

The Polar Space Task Group and its SAR CWG have reached out to the international science community who has identified and documented the SAR satellite data required to support their scientific endeavours. These concentrate on four thematic areas:

- ◆ *Ice Sheets*
- ◆ *Floating Ice*
- ◆ *Permafrost*
- ◆ *Snow*

The SAR CWG is pursuing a dialogue with representatives of the science community to ensure that the understanding of common objectives is clear, that both scientists and data providers are responsive in the dialogue, and that the data requirement documents are updated, as necessary.

The working group received several key agency contributions that responded to the initially established ice sheet community requirements. Two leaflets were produced to document these activities. They include *Continued and Coordinated Ice Sheet Observations from Space* and an article that was published in the *WMO Bulletin* 63(1) 2014.

At the outset, a consolidated ice sheet user requirements document was presented to PSTG and initiated the development of a response plan for the years 2013 to 2015. The European Space Agency launched a Climate Change Initiative (CCI) Ice Sheet user survey for Antarctica, and its results are considered in further PSTG responses to ice sheet requirements. Similarly, NASA launched ice sheet activities in its MEASUREs program to support the production of geophysical products from the SAR data.

More recently, a series of user requirements related to the floating ice, permafrost, and snow science themes have been completed. Summaries are included in the following theme-related sections. Leading scientists in the aforementioned theme areas have contributed to important documentation for the definition of science and SAR data requirements and provided essential information for the space agencies to consider when planning and coordinating their satellite SAR data acquisition campaigns.

Existing SAR Data Sets of Polar Regions

Modelled on the RADARSAT-1 Antarctic Mapping Mission in 1997, which was a cooperative effort between Canada and the United States, several space agencies have since acquired a series of SAR data sets over polar regions. A Space Task Group was formed in 2006 in preparation of the International Polar Year. Data sets were collected in a systematic and coordinated way by Canadian, European, Japanese, Italian and German satellite SAR

systems. The data sets are also included here because of their relevance and value to the science community and current research endeavours. There are several data repositories that contain these polar SAR data products and metadata. Examples include the Byrd Polar and Climate Research Center (<http://research.bpcrc.osu.edu/rs1/radarsat/data/>) and the National Snow and Ice Data Center (<http://nsidc.org/data/measures>) in the United States; Japanese IPY data sets are archived by the Japanese Space Agency Jaxa (http://www.eorc.jaxa.jp/ALOS/en/ipy/ipy_index.htm); and the Canadian Polar Data Catalog (<http://www.polardata.ca/>).

PSTG Strategic Priorities

The Polar Space Task Group has a mandate that allows the Group to pursue several strategic priorities for both optical and radar data acquisitions over polar regions (http://www.wmo.int/pages/prog/sat/documents/SAT-GEN_PSTG-StratPlan2015-2018.pdf). It places priority on achieving coordinated space-based observations of the elements of the polar regions and cryosphere at the appropriate time and space scales, and where feasible collocated with airborne and/or ground-based measurements. Priority needs in the four theme areas will be addressed by exploiting microwave imaging radar, microwave radiometer, altimeter, scatterometer, optical imagery, lidar, gravimeter and other relevant data sources, as relevant.

Ice Sheets, Ice Shelves, Ice Caps and Glaciers

The PSTG is addressing the scientific requirements for ice sheets and ice caps (*Scheuchl and others, 2013*) in the following ways:

- ◆ *Follow through the coordinated acquisition plan of SAR/InSAR imagery over Antarctica and Greenland, initiated in 2013 (SAR_CWG, 2013)*
- ◆ *To extend Ice Sheet Mass Balance Intercomparison Exercise. (IMBIE) beyond 2009, to reduce uncertainties in ice sheet mass balance and to reconcile altimetry, SAR and gravimetric ice sheet mass balance estimates*
- ◆ *To provide complementary data on ice sheet surface accumulation and albedo*
- ◆ *To secure continuity in gravimetry data for mass change estimates*
- ◆ *To develop SAR altimeter swath mapping capability and products*

For addressing the scientific requirements for glaciers and ice caps, the PSTG will strive:

- ◆ *To extend optical imaging and stereo image data for generation of digital elevation models, glacier and ice cap outlines and hypsometry*
- ◆ *To investigate capabilities of SAR altimetry over mountain glaciers and ice caps*

Floating Ice

The PSTG is addressing the scientific requirements for studying floating ice and related parameters (*Falkingham and others, 2014*) in the following ways:

- ◆ *Establish a multi-agency plan for acquiring contiguous (seamless) six days repeat pan-Arctic SAR imaging at consistent polarization combination (with view to expanding to an intermediate goal of less than three days repeat in future with right-looking Sentinel-1 (S-1), RADARSAT Constellation Mission (RCM), etc.; and subsequently sub-daily data with C-, X-, S-, L-band SAR combined data sources)*
- ◆ *Establish Arctic Tundra lakes and river monitoring sites, as extension of sea ice coverage*
- ◆ *Assure continuity in all-weather ice concentration, extent, motion and thickness data in support of the sea ice climate data time to secure the sea ice Essential Climate Variable (GCOS, 2010)*
- ◆ *Coordinate with field campaigns, ice camps and drifting buoys to maximise synergies and product validation possibilities (and uncertainty estimates)*

Permafrost

The PSTG is addressing the scientific requirements for studying permafrost and related parameters (*Bartsch and others, 2014*) in the following ways:

- ◆ *Establish coordination and acquisition planning needed to achieve routine high-resolution circumpolar coverage for monitoring variability in carbon pools*
- ◆ *Establish multi-sensor monitoring around key research locations where Global Terrestrial Network for Permafrost (GTN-P) and in-situ measurements are made ("cold spots") (supplement existing Terra-SAR-X acquisitions; bi-weekly InSAR for modeling)*
- ◆ *Obtain <1 m summer (July-Aug) optical images around each Arctic Cold Spot for upscaling/downscaling of local periglacial processes*
- ◆ *Quantify rates of pan Arctic coastal erosion (Annual circumpolar Arctic coastline mapping at <10m optical resolution; InSAR estimates of erosion/degradation)*
- ◆ *Establish SAR monitoring of Arctic permafrost transects on routine basis to supplement existing 30-300 m pan-Arctic multispectral imaging (Antarctic Peninsula covered by sea ice requirements)*
- ◆ *Derive SAR DEM and custom land use classification map suitable for permafrost community needs*
- ◆ *Use snow extent/snow-water equivalent (SWE), frost depth, soil moisture, and Land Surface Temperature (LST), products developed elsewhere*

Snow

The PSTG is addressing the scientific requirements for studying terrestrial snow, snow melt and related parameters (*Luojus and others, 2014*, and *Small and others, 2014*), in the following ways:

- ◆ *Assure continuity in routine continental scale monitoring of snow areal extent and SWE data in support of GCW Snow Watch and snow applications and service development*
- ◆ *Plan SAR data as complement to passive microwave and 300m optical data for continental scale snow extent/ SWE - and in Alpine regions and rugged topography where other methods fail*
- ◆ *Establish less than three day repeat SAR monitoring (ascending/descending combinations) of European Alpine region and other selected mountain regions (Scandinavia, Canadian Pacific mountains) during seasonally-limited snow melt time window*
- ◆ *Establish common polarization/mode observation strategy between SAR missions*
- ◆ *Demonstrate routine snow melt data processing*
- ◆ *Pilot a snow melt service (seasonal snow melt/runoff/ hydropower/water resource availability)*
- ◆ *Expand temporal/spatial revisit to operationalize services*

Regarding the scientific requirements for freshwater budget and reducing uncertainties in solid precipitation and mass balance in the polar regions, the PSTG will rely on the following:

- ◆ *Development of new methods for snow depth retrievals on sea ice (e.g. Operation Ice Bridge)*
- ◆ *Development of snow product intercomparison exercise in connection with GCW CryoNet to assure product validation, and quality assurance (via member engagement in activities such as SnowPEX)*

Using the PSTG priorities and science requirements for the theme areas as a guide, the SAR Coordination Working Group proceeded with their SAR data acquisition planning activities to address the priorities and to fulfill the requirements.

Document Overview

Section 2 to Section 5 focus on the four theme areas, containing a brief outline of user requirements and detail past, present and planned satellite SAR data acquisitions over polar regions in an effort to facilitate their utilization and point to their archive locations. The recent SAR data collections coordinated by the PSTG are summarized in the same fashion. SAR data coordination activities and previous SAR data collections over polar regions during the past 25 years have been summarized in the form of a poster, as illustrated on page i. Section 2 to Section 5 conclude with a tabulated list of current activities and plans.

SECTION 2 - ICE SHEETS

Section Overview

This section is subdivided into five parts. The ice sheet theme area is introduced first, outlining science issues and requirements related to satellite SAR data acquisitions. This is followed by compilation of SAR data set that were acquired over polar regions prior to the PSTG, as well as those data collections that are currently coordinated through the PSTG's SAR CWG. A set of science products and a listing of ice sheet related SAR data sets currently under consideration by SAR CWG concludes the section.

Thematic Area: Ice Sheets

In May 2013, the ice sheets science community provided PSTG a comprehensive description of the key science issues and SAR data requirements based on a survey of 67 scientists. The document outlines general requirements and defines super sites for specific observations. The document may be accessed at http://www.wmo.int/pages/prog/sat/pstg_en.php.

The requirements specification addresses both Greenland and Antarctica ice sheets.

Key ice sheet science issues include:

- ◆ *Surface elevation change*
- ◆ *Ice velocity*
- ◆ *Grounding line location*
- ◆ *Calving front location*

With these in mind, the community specified areas of data acquisition, observation frequency, preferred imaging characteristics (resolution, swath, polarization, incidence angle), and data accuracy. Additional sensor specific recommendations were provided. A general set of preferences include the following:

- ◆ *Polarization: HH preferred*
- ◆ *Acquisition mode: Stripmap preferred, (a notable exception is Sentinel-1 IWS, a TOPS mode. See Sentinel-1 specific sections for details)*
- ◆ *Incidence angle range: Based on experience, 23 to 45 degrees worked fine (even 57 deg. to cover South Pole). Where possible, the same range of incidence angles should be used over individual glaciers and super sites to simplify result comparisons. Regional requirements may lead to specific preferences, specifically on smaller outlet glaciers in mountainous terrain*

- ◆ *Acquisition strategy: Acquire at least some long tracks (i.e. coast to coast, rock to rock) to aid processing and calibration*

Ice sheet research concentrates on Greenland and Antarctica. For Greenland, particular SAR-based observation requirements include the following general observation requirements:

- ◆ *Annual coverage of all of Greenland with at least four consecutive cycles – Arctic winter observations (December to March)*
- ◆ *A secondary full coverage each year would be an asset (3 cycles), preferably in July-September in order to capture seasonal variability*
- ◆ *Additional coverages in Arctic winter would also be an important science contribution as a means of reducing observational errors*
- ◆ *Plan acquisitions to include both ascending and descending coverages, while allowing for use of the interferometric phase data*

In the event of reduced data acquisition capacity, the community recommended the following observation priorities:

- ◆ *Annual coverage of all of coastal Greenland with at least four consecutive cycles (Arctic winter acquisitions preferable)*
- ◆ *Full coverage every second year*
- ◆ *Provide additional coverages of coastal regions*

Specific sensor considerations for Greenland acquisitions include:

- ◆ *L-band: Most critical in southern Greenland, specifically the southeast area where C-band decorrelation has been encountered when using 35-day repeat orbit data. Full coverage desired and long tracks (coast to coast) aid data processing and calibration*
- ◆ *C-band: Full coverage is desired with long tracks (coast to coast) to aid in data processing and calibration*
- ◆ *X-band: Continuation of the current approach (with reference to super sites) is recommended, including more frequent coverage of smaller, high impact regions*

In response to a PSTG request, the science community also identified specific super sites that would benefit from high-resolution X-band data acquisition. The response focuses on 53 Greenland glaciers, based on existing research super sites or individual principal investigator areas of interest. Site specifics

are provided in the science requirements document and include sensor-specific configuration preferences.

General observation requirements for Antarctica include:

- ◆ **Annual coverage of all of Antarctica with at least four consecutive cycles – winter observations. More cycles are considered an asset**
- ◆ **More frequent (monthly) observations of critical areas with every possible acquisition of selected tracks (Pine Island/Thwaites Glacier region; Antarctic Peninsula; Totten Glacier)**

Considering that imaging resources may be limited, the science community recommended the following reduced observation priorities should such a scenario arise:

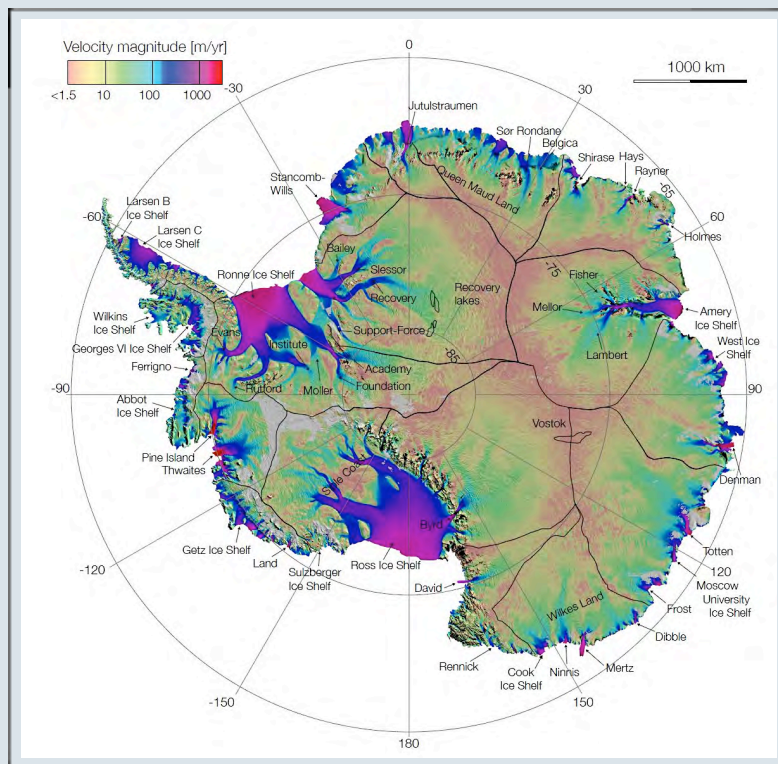
- ◆ **Plan for a full Antarctic coverage at least every 3 years**
- ◆ **Provide annual coverage of Antarctic continent outline (right looking: all coastal areas; left looking: Transantarctic Mountains and Ross and Ronne/Filchner ice shelves)**
- ◆ **More frequent (monthly) observations of critical areas with every possible acquisition of selected tracks**

While left looking data acquisitions are desirable, the change from right- to left-looking can strain satellite resources and requires

careful planning and execution. With this in mind the science community recommendations call for one full coverage per year (four consecutive cycles). Sensor specific recommendations for Antarctica data acquisitions include:

- ◆ **L-band: Most critical in coastal zones and WAIS (C-band decorrelation is present for 24 and 35-day repeat orbit, however, 6 and 12-day repeat period of S-1 should reduce this problem in the future)**
- ◆ **C-band: Historically most impact in the interior, coastal coverage is also recommended, particularly for missions with shorter repeat orbits.**
- ◆ **X-band: Recommend continuation of current approach using COSMO-SkyMed and TerraSAR-X with more frequent coverage of smaller, high impact regions and some limited basin wide coverage of selected regions**

Other X-band high-resolution recommendations were made for Antarctic super sites including 39 glaciers. These recommendations included desired sensor configuration requirements and are fully documented in the ice sheets science requirements document noted above.



First complete map of the speed and direction of ice flow in Antarctica, derived from satellite radar interferometric data.

Credit: NASA/JPL, UCI, ESA, CSA, JAXA

Source: Rignot, Mouginot & Scheuchl 2011, Science 333 (6048)

Science products are available through NASA's MEaSUREs Program at <http://nsidc.org/data/measures/> and <http://nsidc.org/data/nsidc-0484/>

Previous SAR Data Collections

Prior to the re-encantment of the Polar Space Task Group in 2013, several comprehensive SAR data sets of the Greenland and Antarctica ice sheets were collected. Their main characteristics are listed below.

Greenland Ice Sheet ERS-1 SAR and ERS-2 SAR

AGENCY: ESA

SATELLITE: ERS-1 and ERS-2

TIME FRAME: 1991 to 2011 (mission lifetime)

ERS -1 ice-phase I : Dec. 28, 1991 – Mar. 30, 1992 (3-day revisit)

ERS -1 ice-phase II: Dec. 23, 1993 – Apr. 10, 1994 (3-day revisit)

ERS -2 ice-phase I : Mar. 10, 2011 – Jul. 4, 2011 (3-day revisit)

SCIENCE THEME: Ice sheet

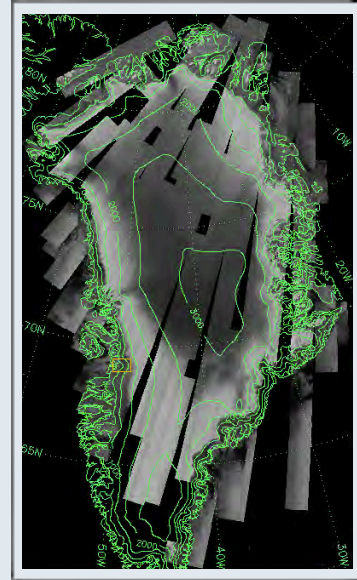
OBJECTIVE: Mapping and monitoring of the Greenland ice sheet, including provision of integrated SAR mosaic and DEM dataset

APPROACH:

- ◆ ERS-1 SAR and predominantly ERS-2 SAR image swaths digitally mosaicked and geolocated
- ◆ In case of DEM, modeled elevation every 0.02 degrees latitude and every 0.05 degrees longitude, roughly equal to a 2 km by 2 km grid spacing
- ◆ ERS-1 SAR and predominantly ERS-2 SAR image swath all through the period 1991-2011, digitally mosaicked and geolocated

METRIC ESTIMATE:

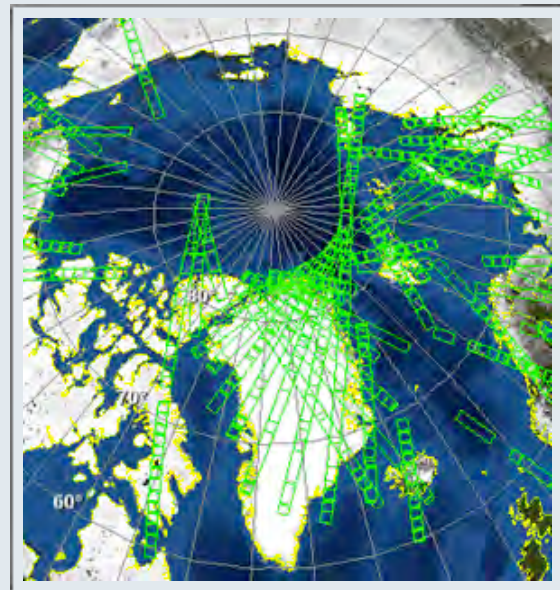
- ◆ Example of ERS-1 mosaic of 1992: 411 MB, covering approximately 80% of Greenland ice sheet
- ◆ Generally, ERS-1 and ERS-2 SAR data are available through the ESA data access portal at <http://earth.esa.int>



ERS-I SAR data collection over Greenland in 1992, superimposed on a contour map of the island (in green outlines).

Credit: ESA

Science products are available through NSIDC at <https://nsidc.org/data/docs/daac/> and [nsidc0052_greenland_sar_dem.gd.html](https://nsidc.org/data/docs/daac/nsidc0052_greenland_sar_dem.gd.html)



ERS-2 SAR data coverage (in green) acquired over the Arctic during the ice phase in 2011.

Credit: ESA

Science products are available through NASA's MEaSUREs program at <https://nsidc.org/data/measures> and http://nsidc.org/data/measures/data_summaries

Greenland Ice Sheet Various SAR Sensors

AGENCIES: CSA, ESA, JAXA
(during International Polar Year (IPY))

SATELLITES: Various SAR satellites

TIME FRAME: 2008 to 2009 (IPY)

SCIENCE THEME: Ice sheets

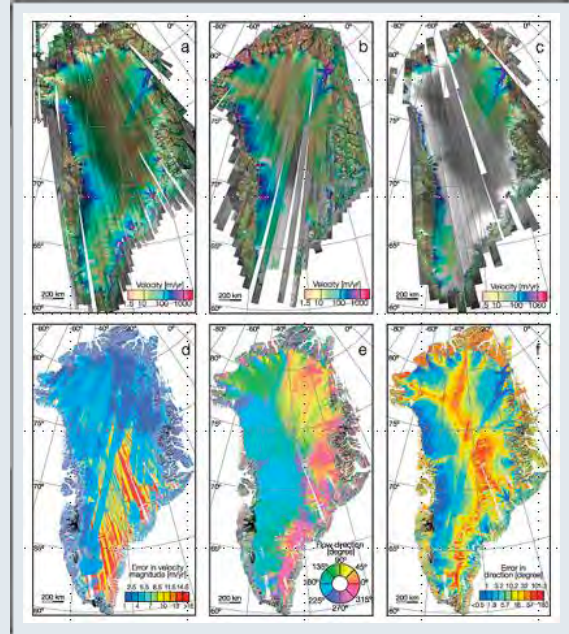
OBJECTIVE: Greenland ice velocity

APPROACH:

- ◆ Coordinated data acquisition by three SAR sensors, including Envisat ASAR, ALOS PALSAR and RADARSAT-1
- ◆ All SAR data collected with HH polarization

METRIC ESTIMATE:

- ◆ RADARSAT-1: 2007 to 2008 mosaic, 2008 to 2009 mosaic
 - ◆ ALOS: 2009 to 2010 mosaic, 20 m and 100 m resolution
- Data Format: GeoTiff, Shapefile
- Data Volume:
- 100m – 236-274 MB (uncalibrated), 419-477 MB (calibrated)
- 20m – 8.5-9.4 GB (uncalibrated), 13-15 GB (calibrated)



Examples of SAR data collections over Greenland during IPY (top) and related ice velocity products.

Credit: E. Rignot and J. Mouginot, University of California / Irvine
Science products are available through NASA's MEASUREs program at <http://nsidc.org/data/docs/measures/nsidc-0633/>

Greenland Ice Sheet TerraSAR-X

AGENCY: DLR (in cooperation with U. Washington)

SATELLITE: TerraSAR-X

TIME FRAME: Jan.-Dec. 2009 and 2010-2011 (Greenland Ice Mapping Project)

SCIENCE THEME: Ice sheets, Greenland outlet glaciers

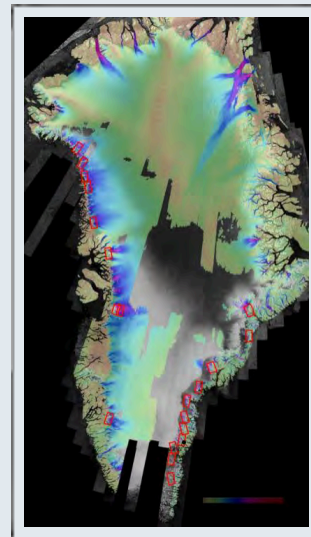
OBJECTIVE: Monitoring outlet glaciers

APPROACH:

- ◆ Acquisition of repeat-pass InSAR pairs

METRIC ESTIMATE:

- ◆ 2009: 245 high-resolution TerraSAR-X stripmap scenes
- ◆ 2010 to 2011: n/a
- ◆ InSAR data products are available in the TerraSAR-X data archive at www.eoweb.de



Location of TerraSAR-X data acquisitions (red outlines) over Greenland glaciers in 2009, overlaid on an ice velocity map derived from processing RADARSAT-1 InSAR data acquired during an earlier campaign in 2005/06).

Credit: DLR and I. Joughin / U. Washington (ice velocity map)

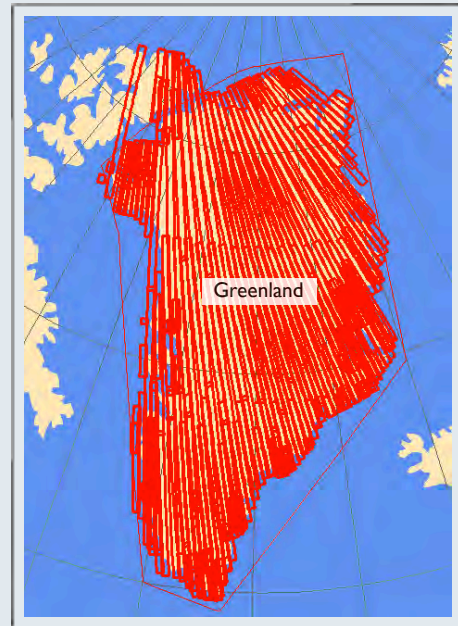
Greenland Ice Sheet TanDEM-X

AGENCY: DLR
 SATELLITE: TanDEM-X
 TIME FRAME: 2011 to 2012
 SCIENCE THEME: Ice sheets
 OBJECTIVE: High resolution InSAR DEM of Greenland
 APPROACH:

- ◆ First coverage 2011; second coverage 2012
- ◆ Additional acquisitions (outlet glaciers, complex topography) for multiple baseline processing
- ◆ Crossing (descending) orbits (1st and 2nd coverage) in the period of August 2013 to April 2014
- ◆ The bistatic acquisitions will be combined in a single DEM

METRIC ESTIMATE:

- ◆ 90 m pixel spacing DEM planned to be available in 2016
- ◆ Includes ~10 km margins
- ◆ Size estimates at <100 GB including various layers (backscattering amplitude, phase unwrapping flag, error and water masks)



TanDEM-X SAR data collection over Greenland in 2011 and 2012, including two complete operational coverages obtained during ascending orbits.

Credit: DLR

Greenland Ice Sheet COSMO-SkyMed

AGENCY: ASI
 SATELLITE: COSMO-SkyMed constellation (4 satellites)
 TIME FRAME: 2008 to 2010
 SCIENCE THEME: Ice sheets
 OBJECTIVE:

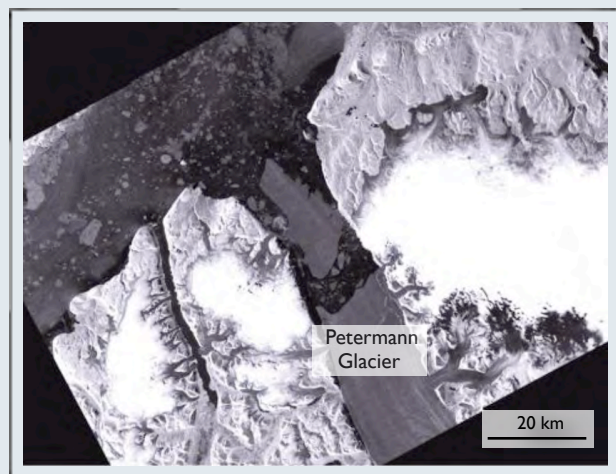
- ◆ Bi-daily acquisitions of the Petermann Glacier from 2010
- ◆ Monitoring of main glaciers and ice sheets

APPROACH:

- ◆ Stripmap mode (3 to 5 m resolution, 40 km swath)
- ◆ ScanSAR wide region mode (30 m resolution, 100 km swath)
- ◆ ScanSAR huge region mode (100 m resolution, 200 km swath)
- ◆ CSK pairs (18 minute gap)

METRIC ESTIMATE:

- ◆ Data sets available in CSK archive
- ◆ Large dataset from 2008 onwards
- ◆ Glaciers and ice sheets – daily monitoring from 2008



Example of COSMO-SkyMed SAR data collection over the Petermann Glacier, Greenland.

Credit: ASI

Greenland Ice Sheet RADARSAT-1

AGENCY: CSA
 SATELLITE: RADARSAT-1
 TIME FRAME: 2001 to 2002 and 2005 to 2008
 SCIENCE THEME: Ice Sheets
 OBJECTIVE:

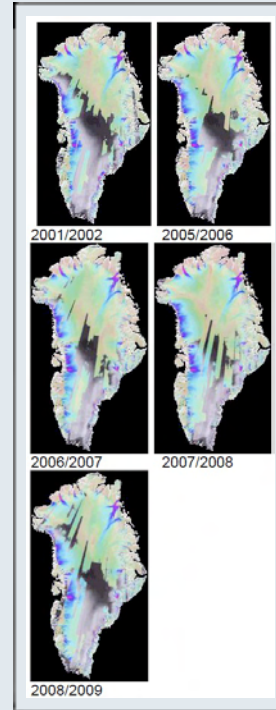
- ◆ InSAR coverage of Greenland ice sheet with four repeats
- ◆ SAR data used for the generation of ice sheet velocity maps
- ◆ 2005-2008 data ordered through ASF by NASA (NASA/CSA MOU), processed by ASF

APPROACH:

- ◆ Fine mode descending acquisitions mostly
- ◆ Winter acquisitions for best chance of data correlation
- ◆ Jacobshavn Glacier continuously monitored (2005-2008)

METRIC ESTIMATE:

- ◆ Science products are available through NASA's MEaSUREs program at <http://nsidc.org/data/docs/measures/nsidc-0633/>
- ◆ 2001/2002: MAMM add on (pre-IPY)
- ◆ 2005/2006: ~612 GB, ~43 tracks (x4)
- ◆ 2006/2007: ~620 GB, ~43 tracks (x4)
- ◆ 2007/2008: ~674 GB, ~43 tracks (x4)
- ◆ 2008/2009: ~730 GB, ~43 tracks (x4) CSA IPY contribution
- ◆ Monitoring Jacobshavn: 3 tracks centered on the Glacier – every possible track acquired: 195 GB



RADARSAT-1 InSAR data collection over Greenland during the years 2001 and 2002, and 2006 to 2009 and ice velocity products derived from the SAR data.

Credit: CSA (SAR data) and Joughin / U.Washington (velocity maps)

Antarctica Ice Sheet COSMO-SkyMed

AGENCY: ASI
 SATELLITE: COSMO-SkyMed constellation (4 satellites)
 TIME FRAME: 2008 to 2012
 SCIENCE THEME: Ice Sheets
 OBJECTIVE:

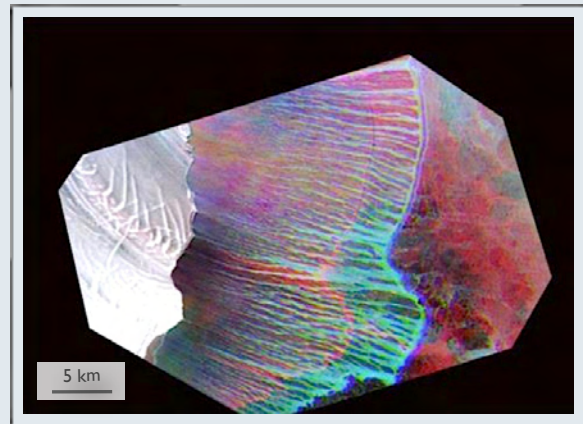
- ◆ Monitoring of main glaciers (i.e., Drygalsky) and ice sheets
- ◆ Monitoring of polynya in Ross Bay
- ◆ Monitoring of Antarctic Peninsula (Wilkins ice shelf)
- ◆ Continuous monitoring of the French-Italian Concordia Station (Dome-C) and M, Zucchelli Station, from 2012

APPROACH:

- ◆ Stripmap mode (3-5 m resolution, 40 km swath)
- ◆ InSAR acquisitions
- ◆ ScanSAR wide region mode (30 m resolution, 100 km swath)
- ◆ ScanSAR huge region mode (100 m resolution, 200 km swath)
- ◆ Multiple acquisitions over short time intervals

METRIC ESTIMATE:

- ◆ Data sets available in CSK archive
- ◆ Acquisitions in 1-day/8-day intervals are also available



Example of a COSMO-SkyMed multi-temporal SAR image product illustrating the expansion of the Ross Sea polynya over a three hour period.

Credit: ASI

Antarctica Ice Sheet ERS-1 and ERS-2 (Ice Phases)

AGENCY: ESA
 SATELLITE: ERS-1 SAR
 TIME FRAME: 1991 to 2011 (mission lifetime)
 ERS -1 ice-phase I: Dec. 28, 1991 – Mar. 30, 1992 (3-day revisit)
 ERS -1 ice-phase II: Dec. 23, 1993 – Apr. 10, 1994 (3-day revisit)
 ERS -2 ice-phase I: Mar. 10, 2011 – Jul. 4, 2011 (3-day revisit)
 SCIENCE THEME: Ice sheets, selected areas, Antarctica
 OBJECTIVE:

- ◆ Frequent revisit, InSAR data collection

APPROACH:

- ◆ 3-day repeat cycle (1992: 1359 orbits, 1994: 1547 orbits)

METRIC ESTIMATE

- ◆ Alaska SAR Facility, Level 0 (unprocessed/raw data)
 Level 1 (amplitude – processed images)
<https://www.asf.alaska.edu/sar-data/ers-1/>
- ◆ ERS-1 and ERS-2 SAR data are available through the ESA data access portal at <http://earth.esa.int>

ERS-1/ERS-2 Tandem Phase

AGENCY: ESA
 SATELLITE: ERS-1 and ERS-2 SAR
 TIME FRAME: August 1995 to July 2011
 SCIENCE THEME: Ice sheets, selected areas, Antarctica
 OBJECTIVE:

- ◆ Improved revisit time, InSAR data collection in support of monitoring dynamic ice conditions

APPROACH:

- ◆ ERS-1 and ERS-2 SAR imaging intervals of 1 to 8 days

METRIC ESTIMATE:

- ◆ ERS-1 and ERS-2 SAR data are available through the ESA data access portal at <http://earth.esa.int>

Envisat ASAR

AGENCY: ESA
 SATELLITE: Envisat ASAR
 TIME FRAME: Global Mapping mode acquisitions all throughout mission lifetime (March 2002 to April 2012)
 SCIENCE THEME: Ice sheets
 OBJECTIVE:

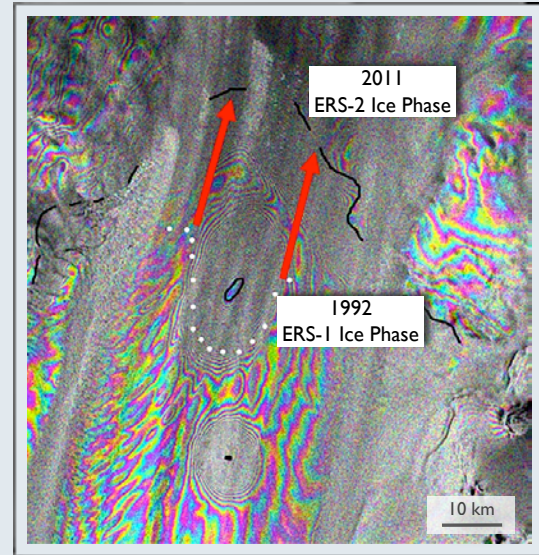
- ◆ Complete yearly mapping of ice sheet within sensor visibility

APPROACH:

- ◆ IM, AP mode acquisitions

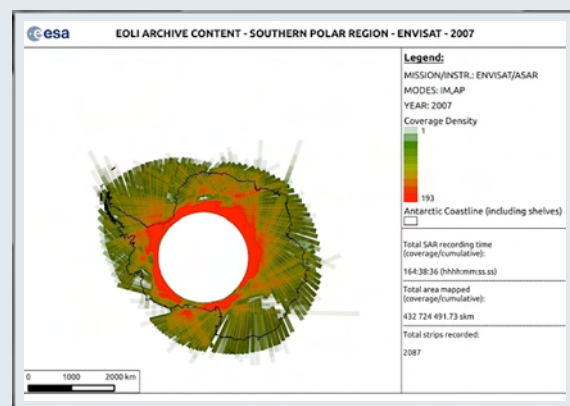
METRIC ESTIMATE:

- ◆ > 1700 image swaths per year (2006 to 2010)
- ◆ Envisat ASAR data are available through the ESA data access portal at <http://earth.esa.int>



Grounding line retreat (red arrows) of the Pine Island Glacier in Antarctica, generated using ERS-1 (1992) and ERS-2 SAR (2011) Ice Phase InSAR data.

Credit: SAR data courtesy ESA; image product courtesy of Jeremie Mougnot, University of California, Irvine



Envisat ASAR coverage density map of Antarctica, based on 2087 SAR image strips collected in 2007, red colour indicating high density (up to 190 scenes) and light green colour indicating very low density.

Credit: ESA

Antarctica Ice Sheet RADARSAT-I AMM

AGENCY: CSA
 SATELLITE: RADARSAT-1
 TIME FRAME: 1997
 SCIENCE THEME: Antarctic Mapping Mission (AMM)
 OBJECTIVE:

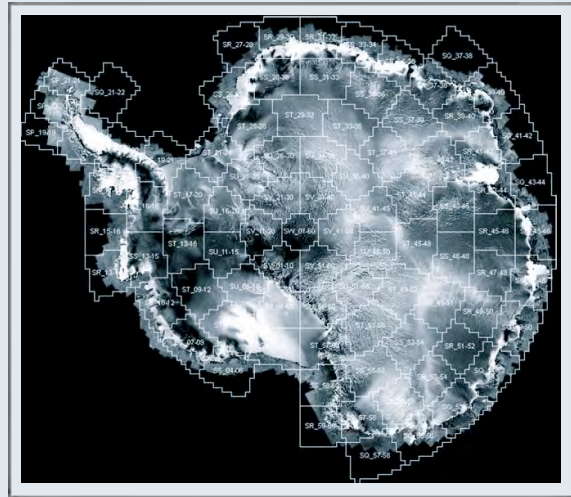
- ◆ Acquire first seamless SAR mosaic of Antarctica

APPROACH:

- ◆ Standard and extended beam mode data collection

METRIC ESTIMATE:

- ◆ 90 SAR image tiles at 25 m resolution
- ◆ Various mosaic products (125 m to 1 km resolution)
- ◆ Data are available at <https://www.asf.alaska.edu/other-data/ramp/amm1/ramp-data/>



RADARSAT-I mosaic of the 1997 Antarctic Mapping Mission, with 90 SAR image tiles superimposed.

Credit: CSA and Ohio State University;ASF (tile map)

RADARSAT-I MAMM

AGENCY: CSA
 SATELLITE: RADARSAT-1
 TIME FRAME: 2000
 SCIENCE THEME: Modified Antarctic Mapping Mission (MAMM)

OBJECTIVE:

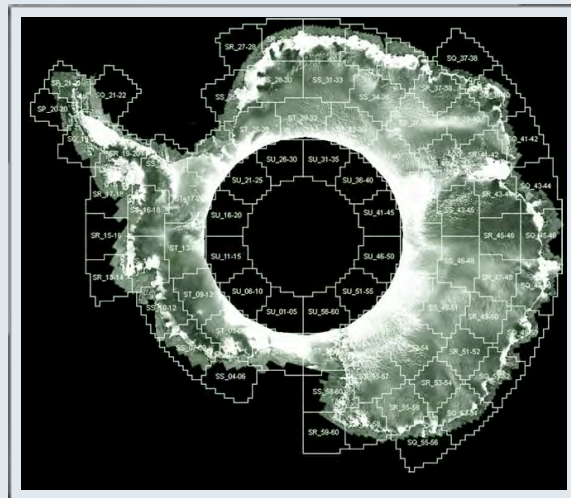
- ◆ Acquire InSAR mosaic of parts of Antarctica

APPROACH:

- ◆ Standard and Fine mode InSAR data collection

METRIC ESTIMATE:

- ◆ 90 SAR image tiles at 25 m resolution
- ◆ Various mosaic products (125 m to 1 km resolution)
- ◆ Data are available at <https://www.asf.alaska.edu/other-data/ramp/antarctic-mapping-mission-2/>



RADARSAT-I mosaic of the 2000 Modified Antarctic Mapping Mission, with SAR image tiles superimposed.

Credit: CSA and ASF (data coverage map)

Antarctica Ice Sheet RADARSAT-2

AGENCY: CSA / MacDonald Dettwiler Assoc. Ltd.

SATELLITE: RADARSAT-2

TIME FRAME: 2007

SCIENCE THEME: Ice sheets, SAR mosaic of Antarctica

OBJECTIVE:

- ◆ Acquire first dual-pol SAR mosaic of Antarctica

APPROACH:

- ◆ Mosaic: left-looking Wide mode W2 (HH/HV) and Extended High EH4 beam mode
- ◆ Velocity map: data collection 78 degrees S to pole (summer)

METRIC ESTIMATE:

- ◆ Antarctica mosaic
- ◆ Various ice velocity maps
- ◆ Data available through the Polar Data Catalogue at <https://www.polardata.ca/>

Antarctica Ice Sheet RADARSAT-2

AGENCY: CSA

SATELLITE: RADARSAT-2

TIME FRAME: 2009, 2011

SCIENCE THEME: Ice Sheets

OBJECTIVE:

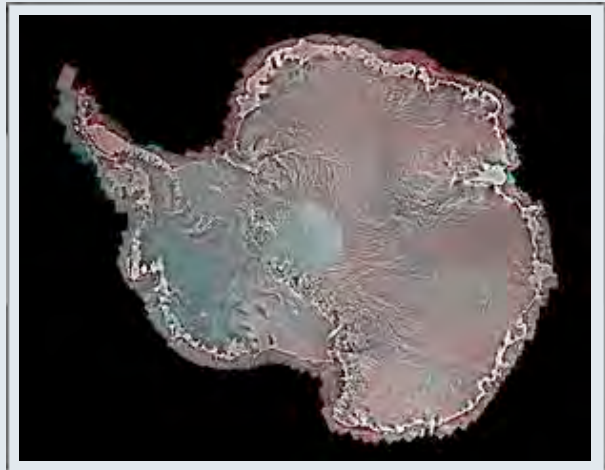
- ◆ Coverage of Central Antarctica (~78 degrees South to Pole) with interferometric SAR data (three repeats)
- ◆ CSA contribution to IPY
- ◆ RADARSAT-2 is the only sensor to provide operational left looking coverage
- ◆ Coastal coverage provided by ESA and JAXA

APPROACH:

- ◆ 2009: full scale acquisition campaign (Standard S5 mode, left looking, descending orbit; Extended High EH4 mode, left looking to cover South Pole), variable track lengths
- ◆ 2011: Gap filler campaign to close gaps resulting from conflicts and to try again in areas with very low correlation

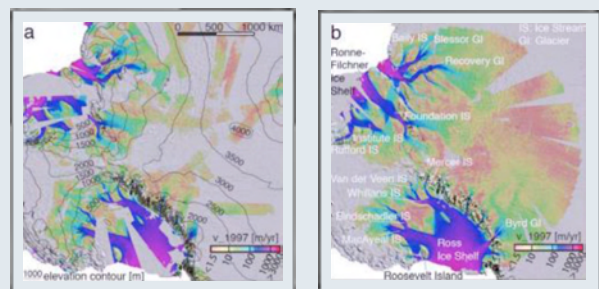
METRIC ESTIMATE:

- ◆ 2009 data volume ~2.75 TB
- ◆ Standard S5 mode: 85 tracks, 3 consecutive orbits (2619 frames in 85 swaths)
- ◆ Extended High EH4 mode: 43 tracks, three consecutive orbits (456 frames in 43 swaths) 2011 (data volume: ~520 GB):
- ◆ Standard S5: 23 tracks, 3 orbits (342 frames in 23 swaths)
Total data volume: ~3.3 TB (SLC data)



RADARSAT-2 mosaic of the 2007 dual-pol Antarctic mapping project, comprised of 3000 SAR images.

Credit: RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2008) All Rights Reserved. RADARSAT is an official mark of the Canadian Space Agency.



Ice velocity products derived from RADARSAT-2 coverage of Central Antarctica, collected between 2009 and 2011. The data sets provided the only large scale coverage of the region so far. The only other (partial) coverage of the area was provided by RADARSAT-1 in 1997.

Source: Scheuchl, B., Mougnot, J., and Rignot, E. 2012. Ice velocity changes in the Ross and Ronne sectors observed using satellite radar data from 1997 and 2009, *The Cryosphere* 6, 1019-1030, doi: 10.5194/tc-6-1019-2012.

Science products are available through NASA's MEaSUREs program at <https://nsidc.org/data/measures> and http://nsidc.org/data/measures/data_summaries

SAR Data Collection Coordinated through PSTG

PSTG SAR CWG data acquisitions are driven by science community data requirements. The following describes the data sets acquired to date. The data set descriptions have been organized by science theme and region. In some cases the data collection may have begun prior to the formation of PSTG SAR CWG. The data acquisitions concentrated initially on the ice sheet thematic.

PSTG coordinated SAR data sets have been acquired by the Italian Space Agency (ASI), the Canadian Space Agency (CSA), the German Aerospace Center (DLR), and the European Space Agency (ESA). The data sets were planned and acquired during the 2008 to 2015 time frame over Greenland and the Antarctic continent by the COSMO-SkyMed, RADARSAT-1 and RADARSAT-2, the TerraSAR-X and TanDEM-X, and the Sentinel-1A radar satellites.

Acquired SAR Data: Greenland Ice Sheet - TerraSAR-X

AGENCY: DLR

SATELLITE: TerraSAR-X

TIME FRAME: 2010. ongoing (as of 2016)

SCIENCE THEME: Ice Sheets

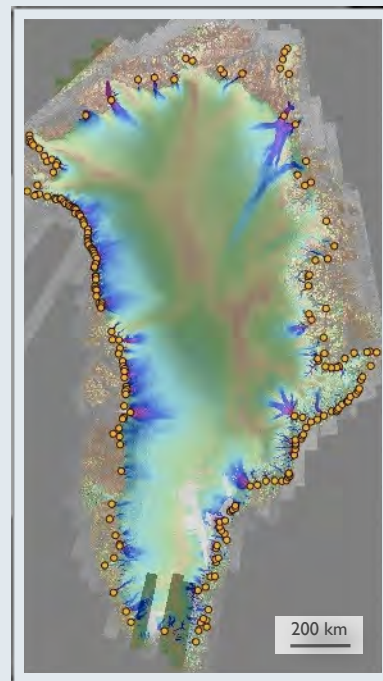
OBJECTIVE: Ice velocity measurements of outlet glaciers; monitoring of ~25 major, rapidly changing glaciers

APPROACH:

- ◆ TerraSAR-X strip map mode (30 km swath width, <3 m resolution)
- ◆ InSAR pairs covering the glacier termini several times per year

METRIC ESTIMATE:

- ◆ 1 scene with 30 km x 50 km dimension as SLC (SSC) product is about 1.5 GB
- ◆ About 2000 scenes acquired between 2010 and 2014/15 amounting to approximately 3 TB of disk space
- ◆ InSAR data products available in the TerraSAR-X data archive at www.esoweb.de



Location of Greenland outlet glaciers monitored since 2010 by TerraSAR-X (yellow dots) superimposed on the ice velocity map derived from RADARSAT-1 SAR data.

Credit: DLR and I. Joughin / U. Washington (ice velocity map)

Greenland Ice Sheet RADARSAT-1

AGENCY: CSA

SATELLITE: RADARSAT-1

TIME FRAME: 2013

SCIENCE THEME: Ice Sheets

OBJECTIVE: Post-IPY coverage of the Greenland ice sheet; full interferometric (InSAR) coverage of the ice sheets with multiple repeat acquisitions (minimum of three).

APPROACH:

- ◆ Similar to previous efforts
- ◆ January to March 2013 acquisitions
- ◆ Descending fine mode data
- ◆ Ascending standard mode data (limited coverage)
- ◆ Data processing at Alaska SAR Facility
- ◆ International collaboration between CSA/MDA, ESA/KSAT and NASA/ASF

METRIC ESTIMATE:

Fine mode descending:

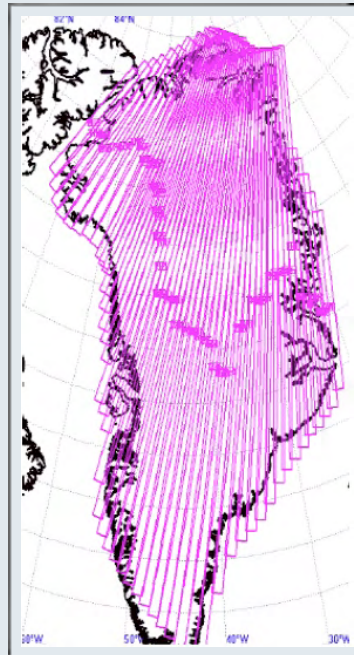
- ◆ 49 tracks (33 triplets, 16 pairs)

Standard mode ascending:

- ◆ 17 tracks
- ◆ five triplets (PAL)
- ◆ three triplets, four pairs, five single

Data volume:

- ◆ ~700 GB (similar to the 2008/09 campaign)



RADARSAT-1 InSAR data acquisition plan (partial) and example of data product for the Greenland ice sheet campaign, 2013.

Credit: CSA, MDA

Greenland Ice Sheet RADARSAT-2

AGENCY: CSA

SATELLITE: RADARSAT-2

TIME FRAME: 2013

SCIENCE THEME: Ice Sheets

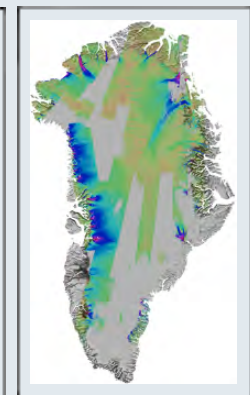
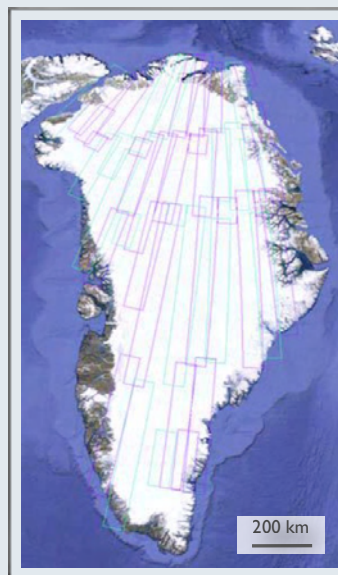
OBJECTIVE: Post-IPY coverage of the Greenland ice sheet; Full interferometric coverage of the ice sheets with multiple (minimum 3) repeats.

APPROACH:

- ◆ Standard mode coverage to reduce sensor load and probability for conflict
- ◆ Shorter tracks to increase chance of downlink success
- ◆ Descending coverage plus ascending augmentation in key areas (*i.e.*, NW and SE coast)

METRIC ESTIMATE:

- ◆ Data volume ~394 Gb (as of 2014)



RADARSAT-2 InSAR data acquisition plan for Greenland ice sheet 2013 campaign, and example of a velocity map derived from the data collected.

Credit: CSA, MDA, UCI

Greenland Ice Sheet - Sentinel-1A

AGENCY: ESA
 SATELLITE: Sentinel-1A
 TIME FRAME: 2014 to 2016
 SCIENCE THEME: Ice Sheets - Greenland

OBJECTIVE

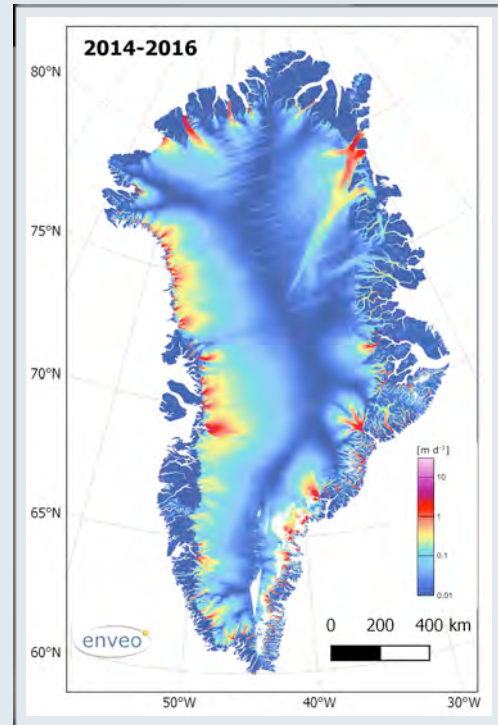
- ◆ ESA Sentinel-1 contribution to PSTG / ESA-CCI
- ◆ Full coverage of Greenland ice sheet / Canadian Arctic ice caps in 3-4 consecutive 12-day repeat cycles, both ascending and descending, one campaign per year (December to March)
- ◆ All year consecutive monitoring of Greenland coastal outlet glaciers

APPROACH:

- ◆ Interferometric Wide Swath mode (250 km swath)
- ◆ HH polarization
- ◆ Campaign planning respecting CMEMS sea ice monitoring needs

METRIC ESTIMATE:

- ◆ All Sentinel-1 data upon self-registration freely available at <https://scihub.copernicus.eu/dhus/#/home>



Ice velocity map of Greenland, 2014 to 2016, derived from Sentinel-1A SAR data collected in InSAR Wide Swath Mode.

Credit: ESA / ENVEO. Map contains modified Copernicus Sentinel data (2014-2016). See also Nagler et al. 2015 <http://www.mdpi.com/2072-4292/7/7/9371>

Antarctica Ice Sheet - PALSAR

AGENCY: JAXA
 SATELLITE: ALOS - PALSAR
 TIME FRAME: 2006 to 2008
 SCIENCE THEME: Ice Sheets

OBJECTIVE:

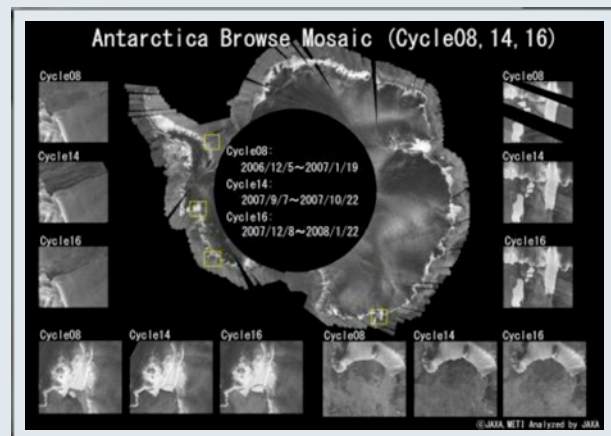
- ◆ L-band SAR and InSAR coverage of Antarctica

APPROACH: Browse mosaic at 500 m resolution

- ◆ Mosaic data from Cycles 8, 14, and 16
 - Cycle 8 – Dec. 5, 2006 ~ Jan. 19, 2007
 - Cycle 14 – Sep. 7, 2006 ~ Oct. 22, 2007
 - Cycle 16 – Dec. 8, 2007 ~ Jan. 22, 2008

METRIC ESTIMATE:

- ◆ Archive information is available at http://www.eorc.jaxa.jp/ALOS/en/kc_mosaic/kc_500_antarctic.htm

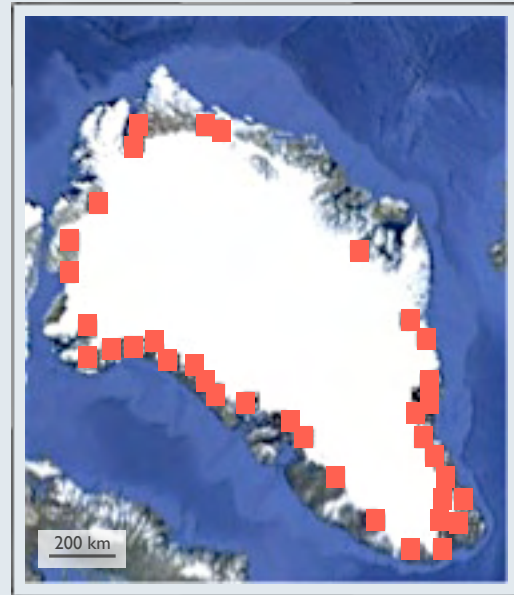


Example of ALOS PALSAR coverage of Antarctica during 2006 to 2008.

Credit: JAXA, Japan

Greenland Ice Sheet and Arctic - COSMO-SkyMed

- AGENCY: ASI
 SATELLITE: COSMO-SkyMed constellation (4 satellites)
 TIME FRAME: 2014 onwards
 SCIENCE THEME: Ice sheets
 OBJECTIVE: InSAR time series of main glaciers and ice sheets in Greenland and in the Arctic region.
 APPROACH:
- ◆ Stripmap mode (3-5 m resolution, 40 km swath)
 - ◆ ScanSAR wide region mode (30 m resolution, 100 km swath)
 - ◆ ScanSAR huge region mode (100 m resolution, 200 km swath)
- METRIC ESTIMATE:
- ◆ Monitoring of main glaciers and ice sheets is ongoing, with updates in September 2014 and December 2014
 - ◆ Collection of InSAR data (4 day/16 day intervals)
 - ◆ ~4000 scenes acquired (Status: December 2015)
 - ◆ Archive information is available at the COSMO-SkyMed data catalog <http://87.241.31.78/index.php>

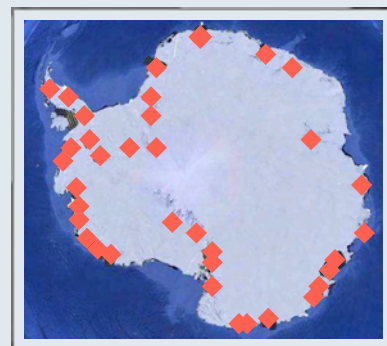
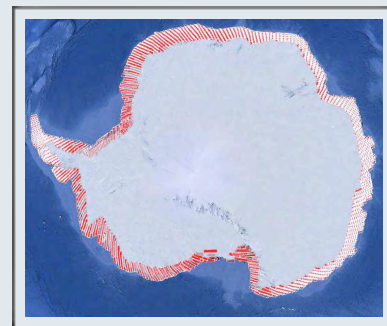


COSMO-SkyMed Ice Sheet Campaign, with a focus on 53 Greenland outlet glaciers.

Credit: ASI, Italy

Antarctica Ice Sheet - COSMO-SkyMed

- AGENCY: ASI
 SATELLITE: COSMO-SkyMed constellation (4 satellites)
 TIME FRAME: 2014 and onwards
 SCIENCE THEME: Ice sheets
 OBJECTIVE:
- ◆ InSAR time series of Antarctic glaciers and ice sheets
 - ◆ Complete InSAR mapping of the entire Antarctic coast
- APPROACH:
- ◆ Stripmap mode (3 to 5 m resolution, 40 km swath)
 - ◆ ScanSAR wide region mode (30 m resolution, 100 km swath)
 - ◆ ScanSAR huge region mode (100 m resolution, 200 km swath)
- METRIC ESTIMATE:
- ◆ Data sets available in CSK archive
 - ◆ Glaciers and ice sheets: acquisition increasing from September 2014, with further updates in January 2015
 - ◆ Acquisitions in 4 day/16 day intervals
 - ◆ Coastline monitoring from January 2015, 16 day interval
 - ◆ Archive information is available at the COSMO-SkyMed data catalog <http://87.241.31.78/index.php>



Coverage map of COSMO-SkyMed SAR data acquisition along the entire coast of Antarctica (top) and 39 selected glaciers (bottom).

Credit: ASI, Italy

Antarctica TanDEM-X

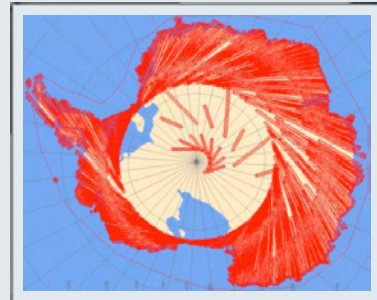
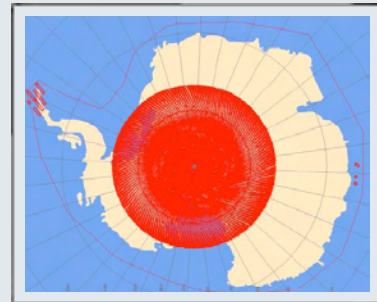
AGENCY: DLR
 SATELLITE: TanDEM-X
 TIME FRAME: 2013 to 2014
 SCIENCE THEME: Ice Sheets
 OBJECTIVE: High resolution InSAR DEM of selected areas of the Antarctic ice sheet.

APPROACH:

- ◆ First coverage 2013 (left and right looking)
- ◆ Second coverage 2014 (left and right looking)
- ◆ Acquisitions will be combined into a single DEM

METRIC ESTIMATE:

- ◆ 90m pixel spacing DEM planned to be available in 2016
- ◆ Includes ice shelves and ~10 km margins
- ◆ Size estimates at <100 GB including various layers (backscattering amplitude, phase unwrapping flag, error and water masks insert)



TanDEM-X InSAR data acquisition over Antarctica in 2013, including areas covered between April 29, 2013 and June 1, 2013 in left looking imaging mode (top) and areas covered between June 2, 2013 and July 4, 2013 in mainly right looking mode.

Credit: DLR, Germany

Antarctica TerraSAR-X

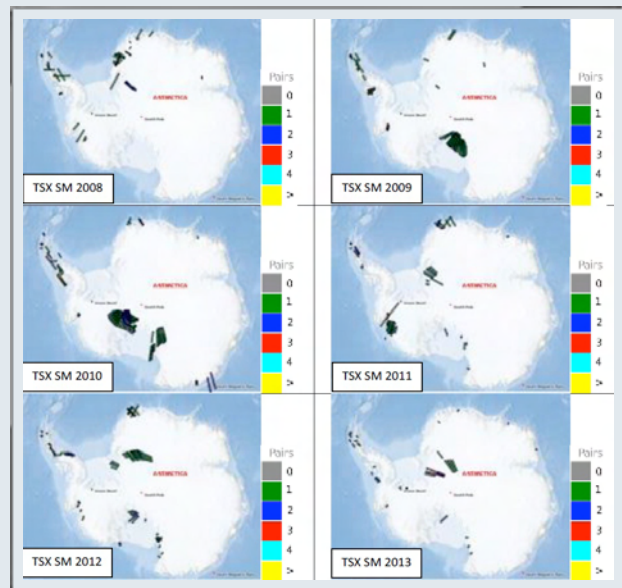
AGENCY: DLR
 SATELLITE: TerraSAR-X
 TIME FRAME: 2008 to 2013
 SCIENCE THEME: Ice Sheets
 OBJECTIVE: Provide InSAR data pairs for high resolution velocity measurements.

APPROACH

- ◆ TerraSAR-X strip map mode (30 km swath width, <3 m resolution)
- ◆ Data pairs with 11 (or 22) day repeat cycle

METRIC ESTIMATE

- ◆ 1 scene (30 km x 50 km) as SLC (SSC) product is 1.5 GB
- ◆ Upper limit of disk space (for data acquired between 2008 and 2013) is ~10 TB



Map of TerraSAR-X InSAR data acquisitions for the detailed Antarctica ice sheet campaign, 2008 to 2013.

Credit: DLR, Germany

Antarctica RADARSAT-2

AGENCY: CSA

SATELLITE: RADARSAT-2

TIME FRAME: 2013

SCIENCE THEME: Ice Sheets

OBJECTIVE: Post-IPY coverage of coastal Antarctica with interferometric SAR data (minimum three repeats);

RADARSAT-2 is the only sensor capable of providing large area data coverage following the end of multiple missions post-IPY.

APPROACH:

- ◆ Background mission right looking
- ◆ S1 mode acquisitions (reach far South)
- ◆ Shorter tracks to increase chance of successful downlink
- ◆ Limited left looking acquisitions for key areas
- ◆ Pine Island Glacier (additional repeats)
- ◆ Pre-eclipse campaign (January to May 2013)
- ◆ Post-eclipse campaign (September to December 2013)

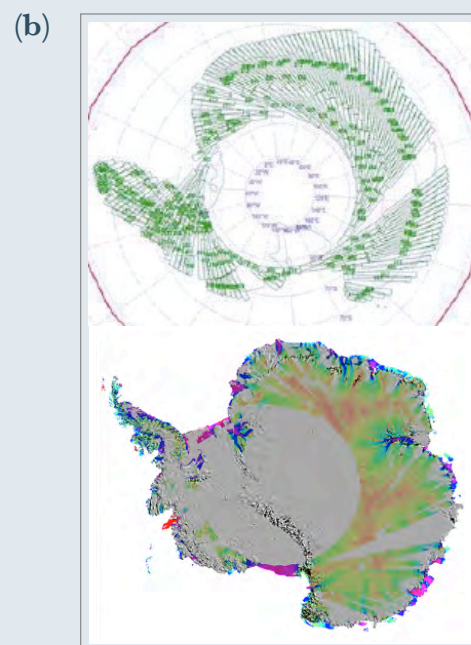
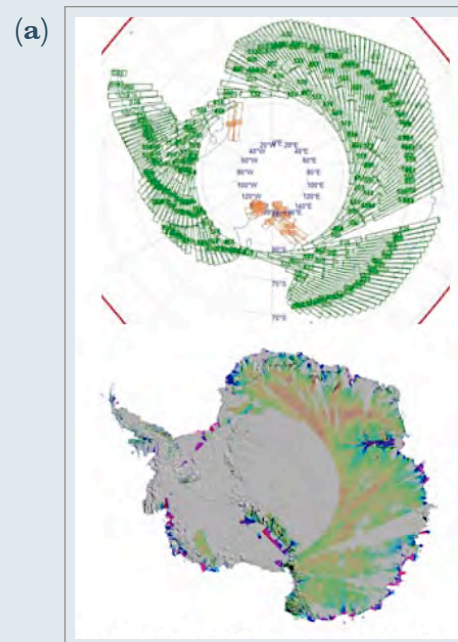
METRIC ESTIMATE:

Pre-eclipse campaign:

- ◆ Number of Frames: 6248
- ◆ Disk space: ~ 3 TB (SLC data)

Post-eclipse campaign:

- ◆ Number of Frames: 6326
- ◆ Disk space: ~ 3 TB (SLC data)



RADARSAT-2 SAR coverage of Antarctica in 2013, showing (a) pre-eclipse acquisition plans and preliminary velocity map product and (b) post-eclipse coverage and preliminary velocity map product.

Credit: MDA and B. Scheuchl / UCI

Antarctica RADARSAT-2

AGENCY: CSA
 SATELLITE: RADARSAT-2
 TIME FRAME: 2014-2017
 SCIENCE THEME: Ice Sheets

OBJECTIVE:

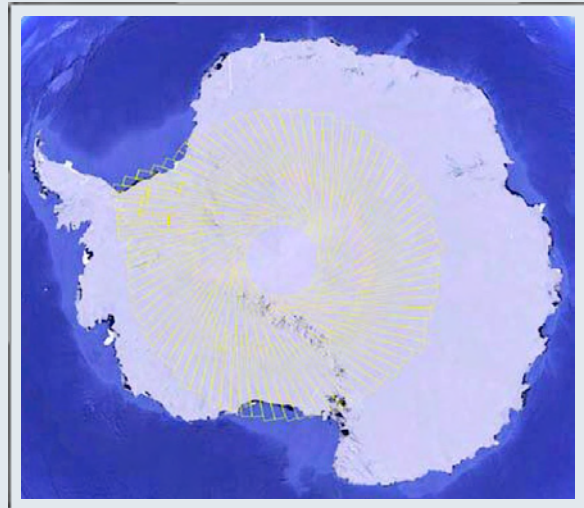
- ◆ Post-IPY coverage of central Antarctica with interferometric SAR data (three repeats)
- ◆ CSA contribution to PSTG
- ◆ RADARSAT-2 is the only sensor to provide operational left looking coverage

APPROACH:

- ◆ Background mission: left looking, similar to 2009 campaign
- ◆ EH4 mode acquisitions for South Pole (campaign started December 2013 and completed with some gaps)
- ◆ S-5 mode acquisitions (e.g. Ross and Ronne Ice Shelves and other areas south of ~78 South; first part of S5 campaign in January to March 2015; gap filler campaign September to December 2015)

METRIC ESTIMATE:

- ◆ Once completed, the disk space requirement is estimated at around 3 TB (SLC), similar to the 2009 campaign



RADARSAT-2 SAR S5 coverage plan for parts of Antarctica, the plan is currently under consideration and may be spread over multiple years.

Credit: MDA and B. Scheuchl / UCI

Antarctica RADARSAT-2

AGENCY: CSA
 SATELLITE: RADARSAT-2
 TIME FRAME: 2014 to 2017
 SCIENCE THEME: Ice Sheets

OBJECTIVE:

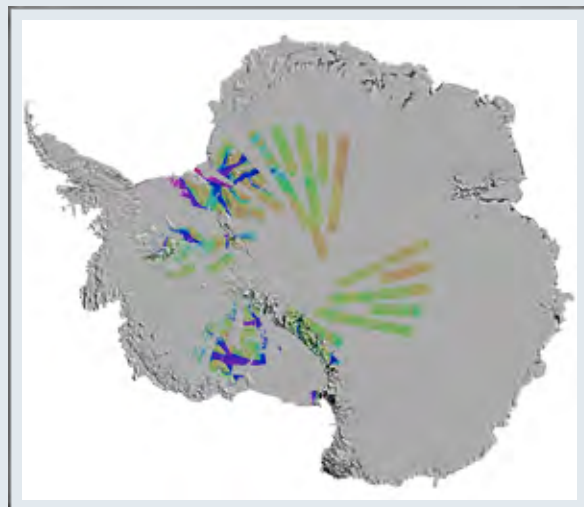
- ◆ Augment Sentinel-1A C-band data acquisition scenarios with ongoing right looking acquisitions in key coastal areas (Fine wide Stripmap mode)
- ◆ Provide coverage of key regions in Central Antarctica using select left looking acquisitions
- ◆ CSA contribution to PSTG

APPROACH:

- ◆ Background mission: right looking
- ◆ Ongoing for Pine Island Glacier / Thwaites Glacier
- ◆ Under consideration for API, Totten, Denman
- ◆ Fine wide stripmap mode, higher resolution (right looking only)
- ◆ Standard mode left looking acquisitions

METRIC ESTIMATE:

- ◆ This is a background campaign only and may vary depending on resource availability



Example of preliminary ice velocity map derived from RADARSAT-2 SAR EH4 coverage of parts of Antarctica.

Credit: MDA and B. Scheuchl / UCI

Antarctica Sentinel - IA

AGENCY: ESA

SATELLITE: Sentinel-1A

TIME FRAME: 2014 to 2015

SCIENCE THEME: Ice Sheets - Antarctica

OBJECTIVE:

- ◆ ESA Sentinel-1 contribution to PSTG / ESA-CCI
- ◆ At least biannual extended winter campaign over the whole ice sheet up to S1 visibility boundary; reduced campaign in other years, focusing on selected fast moving margin areas
- ◆ Three or more consecutive repeats during austral winter (May to September)
- ◆ All year continuous Sentinel-1A coverage of key fast changing sub-regions, e.g. Antarctic Peninsula and Amundsen Sea embayment

APPROACH:

- ◆ Interferometric Wide Swath mode (250 km swath)
- ◆ HH polarisation
- ◆ Campaign planning respecting CMEMS sea ice monitoring needs
- ◆ No Sentinel-1A visibility South of 78.5 degrees; coordinated contribution of RADARSAT-2/RCM expected

METRIC ESTIMATE:

- ◆ Avg. campaign volume ~ 3000 SLC products (~ 10-12 TB)
- ◆ All Sentinel-1A data freely available (upon self-registration) at <https://scihub.copernicus.eu/dhus/#/home>

Antarctica & Greenland - ALOS 2

AGENCY: JAXA

SATELLITE: ALOS-2

TIME FRAME: 2014 to 2016

SCIENCE THEME: Glaciers – Greenland and Antarctica

OBJECTIVE:

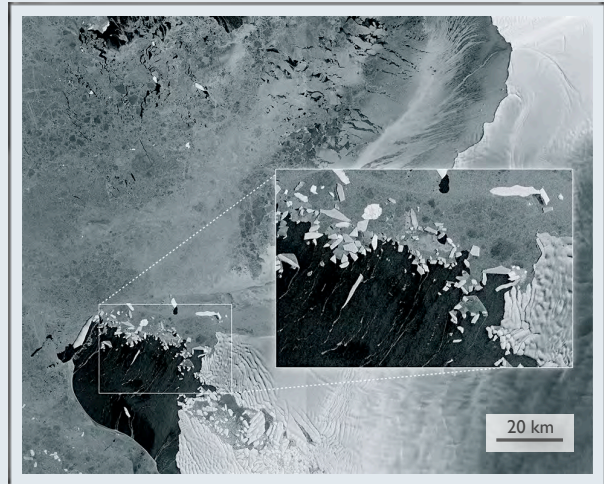
- ◆ Data acquisitions as part of the Basic Observation Scenario for PALSAR-2 instrument
- ◆ Repetition of observations according to seasonality and location

APPROACH:

- ◆ Stripmap mode (10 m DP, off-nadir 32.5 degrees)
- ◆ Dual polarization
- ◆ Right looking – northern hemisphere
- ◆ Left looking – southern hemisphere

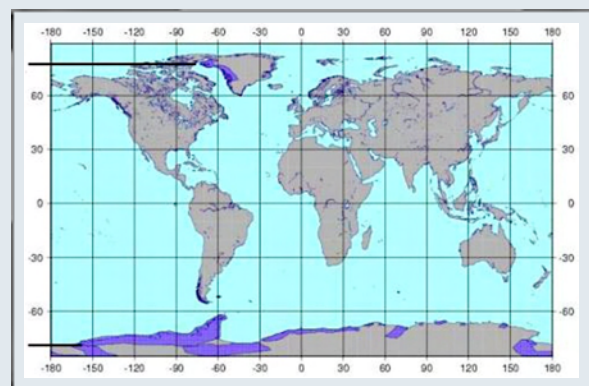
METRIC ESTIMATE:

- ◆ Three coverages per year



Example of Sentinel-1A Interferometric Wide Swath SAR data acquisition of April 13, 2014 over parts of Pine Island and Thwaites Glacier, West Antarctica.

Credit: ESA



JAXA's basis observation strategy coverage map of Greenland and Antarctica ice sheets for ALOS-2 SAR data acquisition.

Credit: JAXA, Japan

Examples of Systematic, Wide-area Science Products

NASA MEaSUREs - Greenland

PROGRAM: Making Earth System Data Records for
Use in Research Environments
(MEaSUREs)

TIME FRAME: 2001 to 2010

SCIENCE THEME: Ice Sheets - Greenland

OBJECTIVE(S) FOR PRODUCT DEVELOPMENT:

- ◆ Provide a comprehensive, high-resolution, digital mosaic of ice motion in Greenland generated from InSAR data
- ◆ Provide annual, high-resolution, digital mosaics of ice motion in Greenland
- ◆ Provide ice velocity time series products for selected outlet glaciers

LINK(S) FOR PRODUCT AND ARCHIVE INFORMATION:

<http://nsidc.org/data/measures/>

<http://nsidc.org/data/NSIDC-0478/>

<http://nsidc.org/data/NSIDC-0481/>

NASA MEaSUREs - Antarctica

PROGRAM: Making Earth System Data Records for
Use in Research Environments (MEaSUREs)

TIME FRAME: 1996 to 2012

SCIENCE THEME: Ice Sheets - Antarctica

OBJECTIVE(S) FOR PRODUCT DEVELOPMENT:

- ◆ Provide a comprehensive, high-resolution, digital mosaics of ice motion in Antarctica generated from InSAR data (450 m and 900 m pixel spacing)
- ◆ Provide ice velocity time series products for selected regions (Amundsen Sea Embayment, Central Antarctica)
- ◆ Provide a InSAR based grounding line product for Antarctica
- ◆ Primary focus of the products was on using data acquired during IPY. Where necessary, pre-IPY data as described in this document were used to provide better coverage or temporal information

LINK(S) FOR PRODUCT AND ARCHIVE INFORMATION:

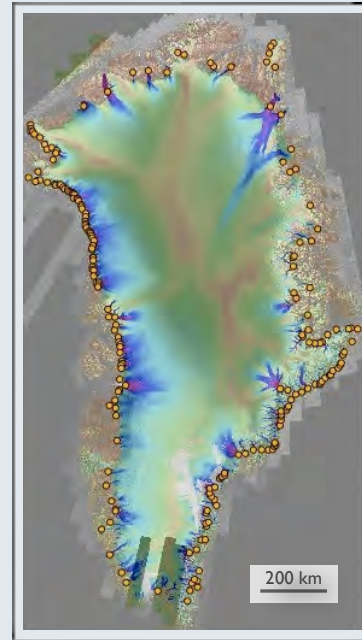
<http://nsidc.org/data/measures/>

<http://nsidc.org/data/NSIDC-0484/>

<http://nsidc.org/data/NSIDC-0498/>

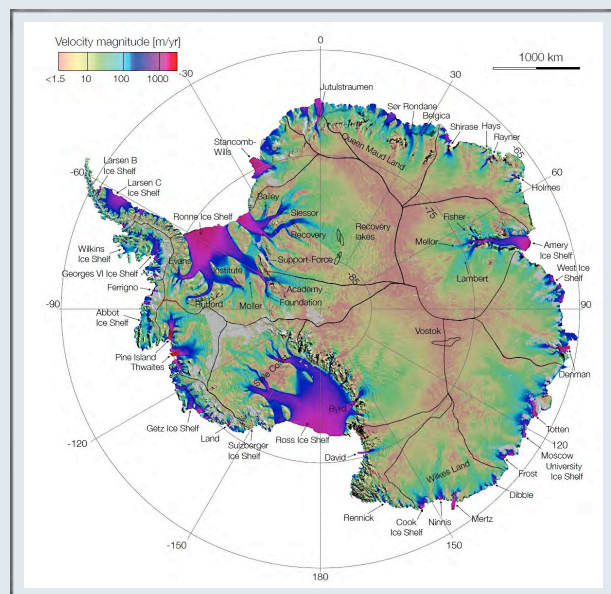
<http://nsidc.org/data/NSIDC-0525/>

<http://nsidc.org/data/NSIDC-0545/>



Ice velocity map product of Greenland generated with RADARSAT-I SAR data: main outlet glacier locations along the coast are indicated in yellow.

Credit: DLR and I. Joughin / U. Washington (ice velocity map)



First complete map of the speed and direction of ice flow in Antarctica, derived from satellite radar interferometric data.

Credit: NASA/JPL, UCI, CSA, ESA, JAXA

ESA Climate Change Initiative - Greenland

AGENCY: ESA / Copernicus
 SATELLITE: Sentinel-1A
 TIME FRAME: October 2014 to March 2016
 (for ice velocity maps 2015 and 2016)
 SCIENCE THEME: Ice sheets – Greenland
 OBJECTIVE: Monitoring of ice dynamics of the Greenland ice sheet

APPROACH:

- ◆ Interferometric Wide Swath mode (250 km swath); single polarisation; ascending and descending orbits
- ◆ Campaigns: Nov. 2014 – Dec. 2015; Dec. 2015 – Mar. 2016
- ◆ Method: coherent / incoherent image cross correlation

DATA SET:

- ◆ Overall: 2876 S1 SLC slices, 7.5 TB (zipped), 148958 burst pairs analysed (12, 24 and 36 repeat pass)

OUTPUT:

- ◆ Raster file of velocity components (m/day), 250 m pixel spacing

LINKS FOR PRODUCT AND ARCHIVE INFORMATION:

<http://esa-icesheets-cci.org/>

<http://products.esa-icesheets-cci.org/>

<https://cryoportals.enveo.at>

ESA Climate Change Initiative - Antarctica

AGENCY: ESA / Copernicus
 SATELLITE: Sentinel-1A
 TIME FRAME: October 2014 to March 2016
 (for ice velocity maps 2015 and 2016)
 SCIENCE THEME: Ice sheets – Antarctica
 OBJECTIVE: Monitoring of ice sheet dynamics

APPROACH:

- ◆ Interferometric Wide Swath mode (250 km swath); single polarisation; ascending and descending orbits
- ◆ Acquisition campaign: Oct. 2014 to March 2016
- ◆ Method: coherent / incoherent image cross correlation

DATA SET:

- ◆ Overall: 3706 S1 SLC slices, 8.3 TB (zipped), 78364 burst pairs analysed (12, 24 and 36 repeat pass)

OUTPUT:

- ◆ Raster file, velocity components (m/day), 250 m pixel spacing

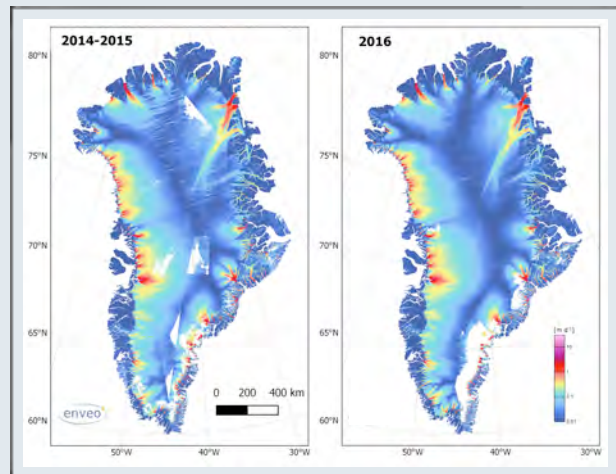
LINKS FOR PRODUCT AND ARCHIVE INFORMATION:

<http://www.esa-icesheets-antarctica-cci.org/>

<http://esa-icesheets-cci.org/>

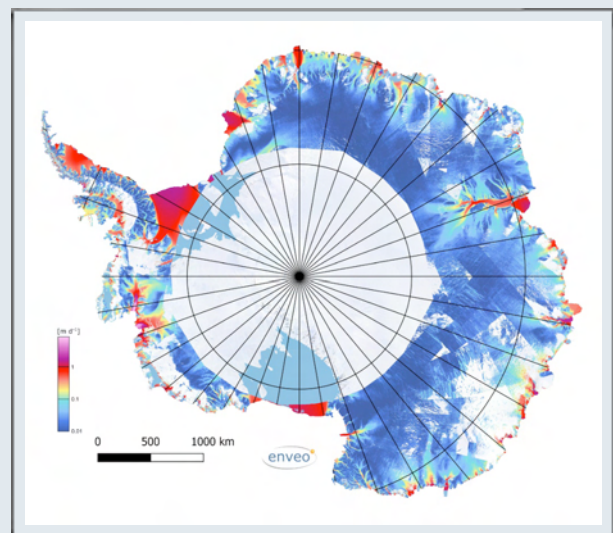
<http://www.esa-icesheets-antarctica-cci.org/index.php?q=products>

<http://products.esa-icesheets-cci.org/>



Ice velocity map products generated with Sentinel-1A SAR data collected over Greenland during 2014-2016.

Credit: ESA, ENVEO, map contains modified Copernicus Sentinel data (2014-2016); Nagler, Rott, Hetzenecker, Wuite, Potin (2015)



Ice velocity map product generated with Sentinel-1A SAR data collected over Antarctica during 2015.

Credit: ESA, ENVEO, map contains modified Copernicus Sentinel data (2015); Nagler, Hetzenecker, Wuite, Rott, ENVEO IT GmbH (2015)

Planned SAR Data Collection Coordinated through PSTG for Ice Sheets

The following table shows the acquisition plans discussed at recent meetings of the SAR CWG. This refers to a commitment to investigate acquisitions, and if possible, execute them. It is recognized that individual representatives cannot commit their

agency without management approval. These acquisitions are limited by availability of satellite resources. The table is being modified and updated two to four times per year.

Table S2: PSTG SAR CWG activities related to Ice Sheets

Strategic Priority	Agency	Location	Plan 2015-16 / Status / Gaps
Follow the Coordinated Ice Sheet Observation Plan	CSA		<p><i>General statement:</i> Update to user requirements needed to refresh the requirements document based on user survey for Antarctic and based on currently implemented acquisition plans. L-band SAR summer InSAR pairs/coherence needed for debris glacier mapping. L-band SAR ice sheet coverage needed over the margins of Greenland and Antarctica in JAXA's Basic Observation Scenario is presently insufficient to meet user requirements.</p> <p><i>Plan:</i> RADARSAT-2 left looking acquisition plan for Central Antarctica created; three-year scenario that would provide a full coverage and focus annually on critical regions (i.e. grounding line regions of Ross and Ronne Ice shelves); The first two years have been acquired, year three acquisitions will be shifted forward to the second half or 2016 to attempt an early completion. Selected coastal areas are monitored using Fine Wide mode. A modified 2017 data plan is under consideration. It will include a gap filler campaign to ensure a second full data coverage of Central Antarctica following the IPY campaign (2009, 2011) as well as some ongoing coastal acquisitions. Some background acquisitions in Greenland are planned, due to high potential for resource conflict (acquisition and downlink) and ongoing acquisitions by other sensors, this is deemed lower priority.</p>
	DLR		<p><i>Plan:</i> In April 2015 DLR joined Antarctic Climate Change Initiative with TerraSAR-X; SAR data will support the GLL and IV. TerraSAR-X coverage of 27 outlet glaciers of Greenland ongoing. Regular TanDEM-X SAR coverage of supersites, incl. Greenland and Antarctica; TanDEM-X – 90 m pixel spacing DEM planned to be available by 2016; a call for data will be established.</p>
	ESA	Greenland Antarctica	<p><i>Plan:</i> Annual winter campaign with 3-4 consecutive acquisitions, each ascending and descending.</p> <p><i>Plan:</i> At least bi-annual extended winter campaign over the whole ice sheet up to Sentinel-1 visibility boundary at 78.5 degrees South. Reduced campaign in other years focusing on selected fast moving margin areas. Four consecutive acquisitions as a goal. Complementary and cooperative regular left looking campaigns south of 78 degree assumed to be conducted by Radarsat-2/RCM. In addition continuous all year Sentinel-1 coverage of key fast changing sub-regions, e.g. Antarctic Peninsula and Amundsen Sea embayment.</p>
	ASI	Arctic ice caps Greenland and Antarctica	<p><i>Plan:</i> Canadian icecaps associated with the Greenland Campaign. Iceland and Svalbard covered continuously within the Sentinel-1 routine European coverage. Zonal mapping (repeat pairs several times per year).</p> <p><i>Plan:</i> COSMO-SkyMed regular coverage of around 90 glaciers of Greenland and Antarctica including supersites in Greenland and Antarctica. Continuous coverage of the entire coast of Antarctica.</p>

SECTION 3 - FLOATING ICE

Section Overview

This section is subdivided into four parts. The floating ice theme area is introduced first, outlining science issues and requirements related to satellite SAR data acquisitions. This is followed by compilation of SAR data set that were acquired over polar regions prior to the PSTG as well as those data collections that are currently coordinated through the PSTG's SAR CWG. A listing of floating ice related SAR data sets currently under consideration by the SAR CWG concludes this section.

Thematic Area: Floating Ice

The requirements for satellite observations of floating ice, i.e. sea ice, icebergs and freshwater ice on inland water bodies (lakes, rivers), were laid out in a comprehensive white paper (PSTG-4/doc.08-04 http://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-4_Doc_08-04_GlobSatObsReq-FloatingIce.pdf). The paper was reviewed by more than 150 scientists; input was accepted also from operational communities. The document identified the properties of sea ice, icebergs and freshwater ice that are of greatest scientific interest with respect to the impacts of climate change, and recommended strategies to monitor and measure these properties with SAR from space. The objective was to identify the required set of satellite measurements to address key science questions relevant to the assessment of the impacts of climate change in the polar regions. The white paper identified and summarized in tabular form, the most important sea ice parameters, in order of priority:

- ◆ *Ice thickness and thickness distribution*
- ◆ *Snow depth on sea ice*
- ◆ *Ice deformation*
- ◆ *Other characteristics*

SAR-related observation requirements include the following:

- ◆ *Multi-frequency observations:*
L-band with either C- or X-band; little demand for C- and X-band together except to increase temporal resolution; all SAR frequencies available, ideally simultaneously.
- ◆ *Keep differences in time and incidence angles as small as possible between different satellites providing multi-frequency observation*
- ◆ *Finer temporal resolution:*
Diurnal and tidal effects have an impact on the choice of SAR data acquisitions regarding the observation of floating ice properties; approximately 6-hourly intervals are needed to resolve these effects.

- ◆ *Spatial resolution needed for scientific investigation of processes is typically an order of magnitude finer than for operational use:*

50 to 100 metres is common for operational ice charting and NWP; 5 to 10 metres is a more typical requirement for research.

Regarding SAR data acquisition modes:

- ◆ *The minimum polarization requirement is HH+HV and HH+VV*
- ◆ *Quad-polarization and full polarimetry needed to advance understanding and algorithm and model development*
- ◆ *Further research is required with compact polarimetry to validate its information content*
- ◆ *A broad range of incidence angles is required*
- ◆ *Increased interest in assessing steeper angles than have historically been used (<20°)*
- ◆ *Swath width should be as large as possible while meeting the requirements for resolution, polarization and interferometry*
- ◆ *Keep effective noise floor as low as possible (<-35dB) particularly at steep incidence angles and with cross-polarization*

Geographic areas of interest include:

- ◆ *Arctic Ocean, from the Beaufort Sea to Fram Strait*
- ◆ *Canadian Arctic Archipelago*
- ◆ *Entire marine area around Antarctica and extending to the limit of iceberg drift*
- ◆ *Comprehensive coverage of fast ice around the Antarctic ice sheet margins*
- ◆ *Marginal ice zones globally*
- ◆ *The Great Lakes–St Lawrence River system*
- ◆ *Lakes and large rivers of northern North America and Eurasia*
- ◆ *Barents Sea, Baffin Bay, Labrador Sea and around the Antarctic bases*

Other important considerations include the following:

- ◆ *Seeking partnerships with commercial sector to overcome potential conflicts in data acquisition*
- ◆ *Recognizing the impact of SAR data highest for regional modelling*
- ◆ *Field data acquisitions*
- ◆ *Making data access easier especially for historical SAR data.*

Previous SAR Data Collections

Prior to the re-enactment of the Polar Space Task Group in 2013, comprehensive SAR data sets of sea ice were collected over polar regions by various satellite SAR missions, as follows.

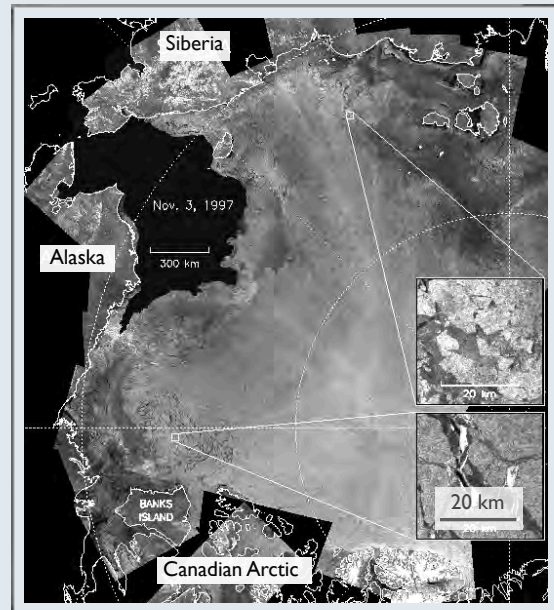
Floating Ice - RADARSAT-1

AGENCY: CSA and NASA
 SATELLITE: RADARSAT-1 SAR
 TIME FRAME: 1996 to 2007
 SCIENCE THEME: Floating Ice – Arctic Ocean
 OBJECTIVE: Annual SAR snapshots of sea ice minimum and maximum extent in the Arctic Ocean
 APPROACH:

- ◆ Systematic seasonal data collection (May to November)
- ◆ Selective winter data collection (December to April)

METRIC ESTIMATE:

- ◆ Approximately 7,000 images collected
- ◆ Data collection every one to five days
- ◆ Data available through Polar Data Catalogue at www.polardata.ca



Mosaic of RADARSAT-1 SAR (C-HH) imagery acquired over the Arctic Ocean, November 3, 1997.

Credit: CSA and NASA

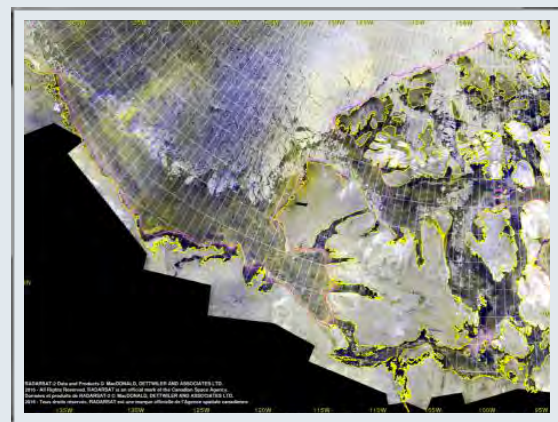
Floating Ice - RADARSAT-1 and RADARSAT-2

AGENCY: CSA and Environment Canada
 SATELLITE: RADARSAT-1 SAR
 TIME FRAME: 1996 to present
 SCIENCE THEME: Floating Ice – Canadian Ice Centre Archived Data
 OBJECTIVE: RADARSAT SAR data collection in support of operational ice monitoring in Canadian waters
 APPROACH:

- ◆ ScanSAR Wide mode mosaics
- ◆ Block-averaged and full-resolution SAR images
- ◆ Ongoing acquisitions

METRIC ESTIMATE:

- ◆ 35,000+ RADARSAT SAR scenes
- ◆ Data source <https://www.polardata.ca/pdcsearch/>



Mosaic of RADARSAT-2 SAR (C-HH/HV) imagery acquired over the western Arctic region of Canada, January 22, 2016.

Credit: RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2008) All Rights Reserved. RADARSAT is an official mark of CSA. Mosaic by CIS, Environment Canada

Floating Ice - Envisat ASAR

AGENCY: ESA
 SATELLITE: Envisat ASAR
 TIME FRAME: 2002 to 2011
 SCIENCE THEME: Floating Ice – northern hemisphere and southern hemisphere

OBJECTIVE:

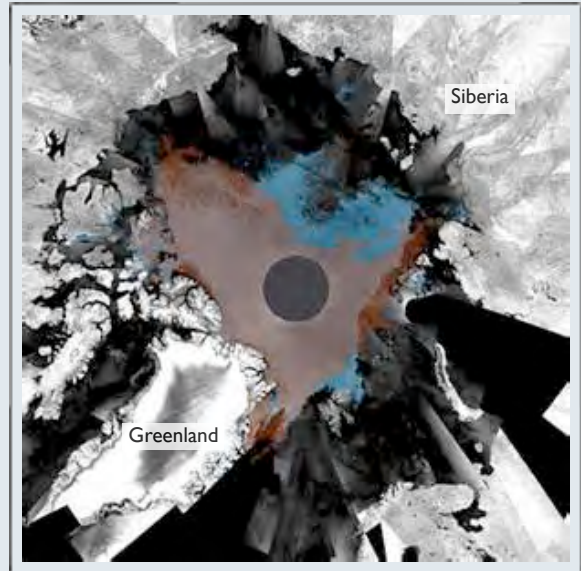
Systematic coverage to monitor sea ice dynamics

APPROACH

- ◆ Systematic coverage of Antarctica, Antarctica seas and Arctic seas, using ASAR Wide Swath Mode, HH Pol. (150 m resolution) and Image Mode, HH Pol. (25 m res.)
- ◆ Supplementary coverage of all polar areas using ASAR Global Monitoring Mode, Polarisation HH (1000 m resolution) when ASAR not operated in Wide Swath Mode or Image Mode

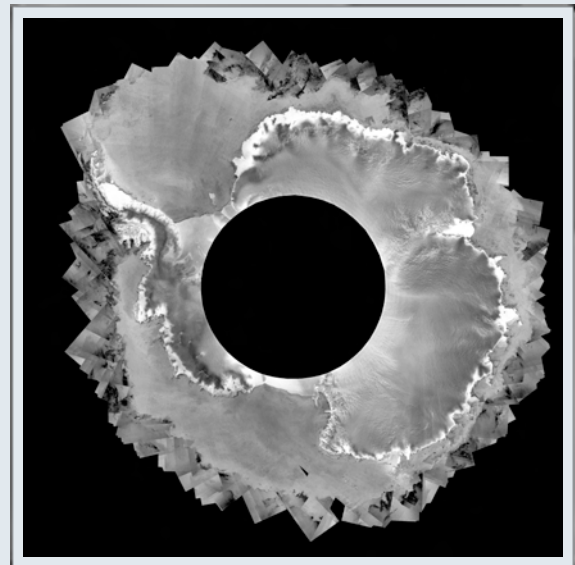
METRIC ESTIMATE:

- ◆ Data access through ESA, PolarView and the Alaska Satellite Facility at <https://www.asf.alaska.edu/>



Coverage of Envisat-ASAR data collected to record the minimum extent of Arctic sea ice during 2007 (red) and 2008 (blue).

Credit: ESA



Example of an Envisat ASAR mosaic of Antarctica and the southern Polar Ocean collected during April of 2004.

Credit: ESA

Floating Ice - ALOS PALSAR

AGENCY: JAXA
 SATELLITE: ALOS PALSAR
 TIME FRAME: 2008 to 2009
 SCIENCE THEME: Floating Ice and Ice Sheets

OBJECTIVES:

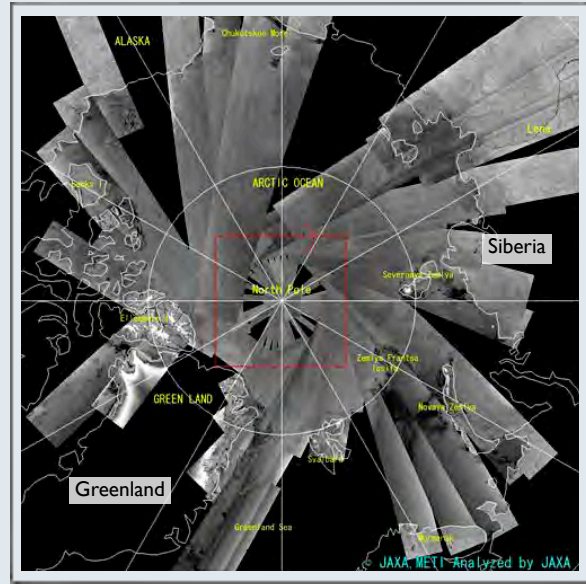
- ◆ Multi-temporal coverage of Arctic Ocean and Greenland using ScanSAR and FDB49 modes

APPROACH:

- ◆ Data collection for seasonal mosaics (45 day period) at 500 m resolution

METRIC ESTIMATE:

- ◆ Jul. 25, 2008~Sep. 08, 2008 – Ascending WB1 mode (cycle 21) – approx. 358 MB
- ◆ Sep. 9, 2008~Oct. 24, 2008 – Ascending FBD mode (cycle 22) – approx. 282 MB
- ◆ Oct. 25, 2008~Dec. 09, 2008 – Ascending FBS mode (cycle 23) – approx. 3.5 GB
- ◆ IPY ALOS PALSAR data may be accessed through http://www.eorc.jaxa.jp/ALOS/en/ipy/ipy_index.htm



Mosaic of ALOS PALSAR coverage of the Arctic Ocean, June 9, 2008, with North Pole at centre of map.

Credit: JAXA, Japan

Floating Ice - COSMO-SkyMed

AGENCY: ASI
 SATELLITE: COSMO-SkyMed constellation (4 satellites)
 TIME FRAME: 2011 onward
 SCIENCE THEME: Floating Ice

OBJECTIVES:

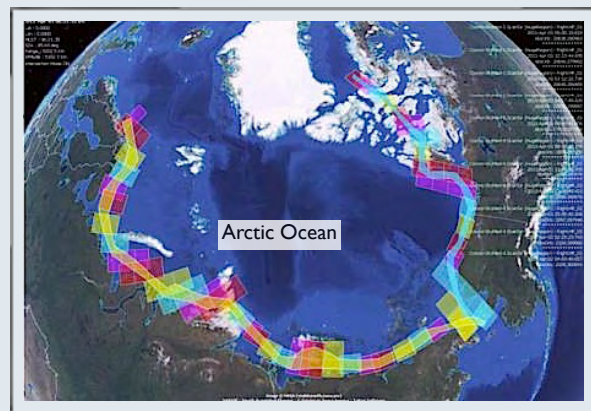
- ◆ Post-IPY: monitoring the polar routes within one day
- ◆ COSMO-SkyMed constellation is able to monitor wide areas in relatively short time
- ◆ COSMO-SkyMed agility allows it to monitor the North Pole

APPROACH:

- ◆ Stripmap mode (3 to 5 m resolution, 40 km swath)
- ◆ ScanSAR wide region mode (30 m resolution, 100 km swath)
- ◆ ScanSAR huge region mode (100 m resolution, 200 km swath)

METRIC ESTIMATE:

- ◆ Data sets available in CSK archive
- ◆ Polar routes monitoring scenario within one day using ScanSAR huge mode
- ◆ ScanSAR and stripmap acquisitions are performed within one to eight day intervals for specific cases



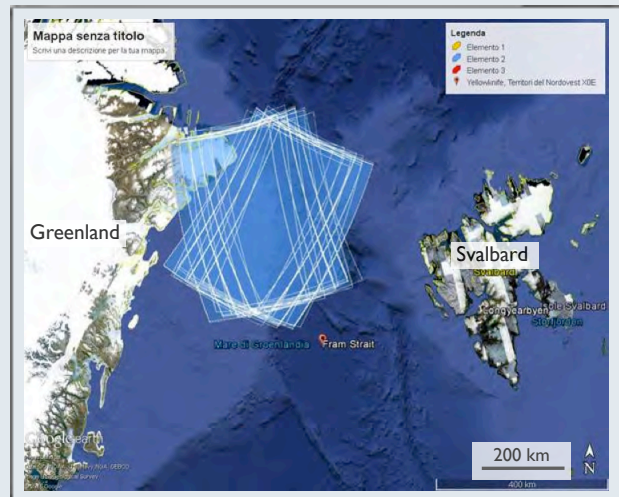
COSMO-SkyMed SAR coverage map of coastal areas within the North circumpolar regions.

Credit: ASI, Italy

SAR Data Collection Coordinated through PSTG

Eastern Greenland - COSMO-SkyMed

- AGENCY: ASI
- SATELLITE: COSMO-SkyMed constellation (4 satellites)
- TIME FRAME: 2013 onward
- SCIENCE THEME: Floating Ice
- OBJECTIVE: Monitoring of specific areas to provide information on East Greenland current and sea ice drift.
- APPROACH:
- ◆ Stripmap mode (3 to 5 m resolution, 40 km swath)
 - ◆ ScanSAR wide region mode (30 m resolution, 100 km swath)
 - ◆ ScanSAR huge region mode (100 m resolution, 200 km swath)
- METRIC ESTIMATE:
- ◆ Data sets available in CSK archive
 - ◆ Fram Strait data from April 2013 and onward

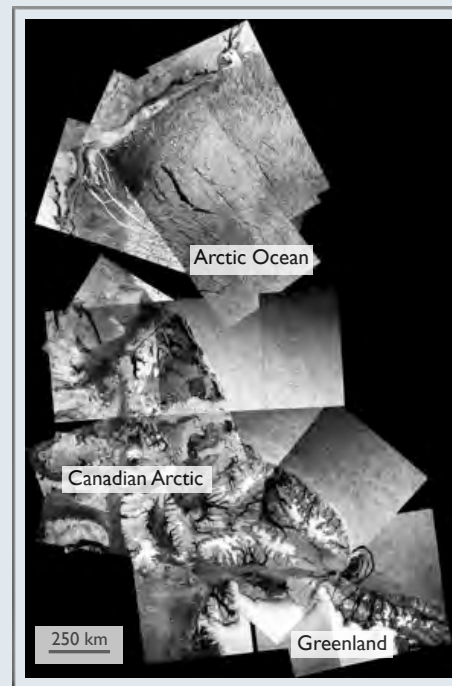


COSMO-SkyMed repeat coverage area with regard to floating ice in Fram Strait.

Credit: ASI, Italy

Western Arctic - RADARSAT-2

- AGENCY: CSA and Environment Canada
- SATELLITE: RADARSAT-2
- TIME FRAME: 2014-2015
- SCIENCE THEME: Western Arctic sea ice and snow cover
- OBJECTIVE: Support for NASA Operation Ice Bridge (OIB)
- APPROACH:
- ◆ RADARSAT-2 SAR data collection covering the OIB sea ice domain for validation and contextual information prior to and during airborne flights
- METRIC ESTIMATE:
- ◆ 2013 – 352 images collected
 - ◆ 2014 – 531 images collected
 - ◆ 2015 – 762 images collected



Example of RADARSAT-2 coverage (mosaic) in support of NASA's Operation Ice Bridge airborne data acquisitions.

Credit: Environment Canada; RADARSAT-2 data copyright MDA

Arctic Ocean - Sentinel-1A

AGENCY: European Commission (EU), ESA

SATELLITE: Sentinel-1A

TIME FRAME: September 2014 onwards

SCIENCE THEME: Floating ice

OBJECTIVE:

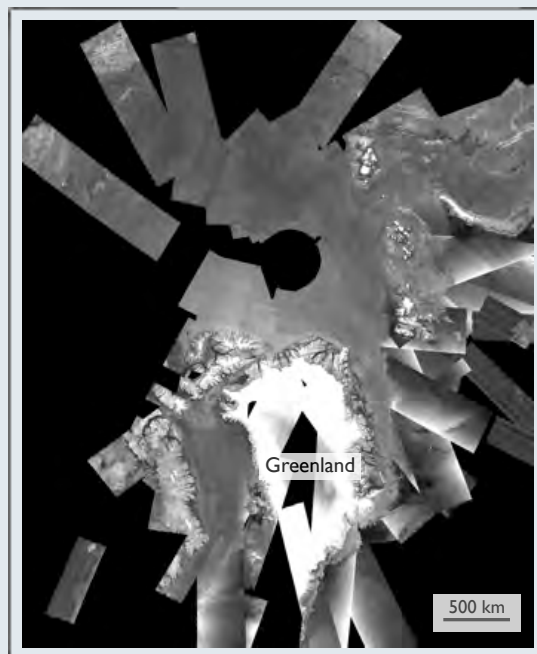
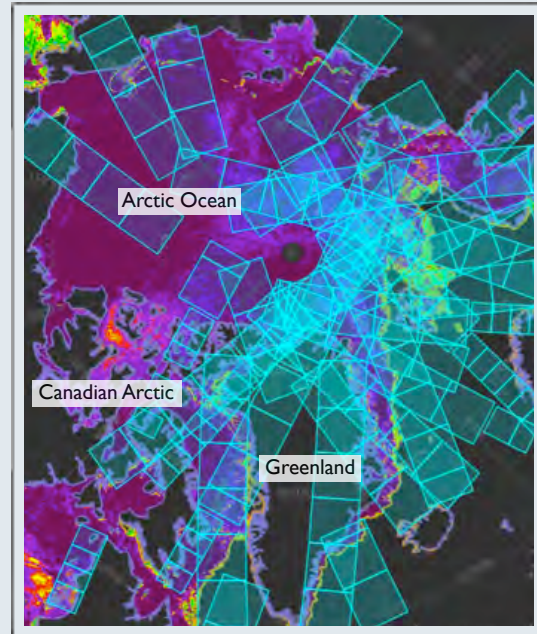
- ◆ Routine high temporal sampling coverage of European Arctic in support of Copernicus Marine Environment Monitoring Service
- ◆ Provision of routine Sentinel-1A acquisitions in standard modes according to predefined acquisition plan

APPROACH:

- ◆ Extra Wide swath mode (20 m x 40 m mode resolution; 90 m GRD product resolution (12 looks) or 50 m GRD product resolution (3 looks); 400 km swath; Dual HH+HV, Single HH polarisation)
- ◆ Interferometric Wide swath Mode (5 x 20 m mode resolution; 20 m GRD product resolution (5 looks) or 90 m GRD product resolution (105 looks); 250 km swath; Dual HH+HV, Single HH polarisation)
- ◆ Dense sampling (3-4 day coverage, act 2015/2016; 1-2 day coverage with constellation planned 2017 onwards) in the central Arctic (~-90 W to 110E); background coverage (10-12 day coverage) outside the CMEMS core areas (~110E to -90 W)
- ◆ 80-90 % of acquisitions in EW mode HH-HV polarisation, 10-20 % of acquisitions in the extreme North in EW mode HH polarisation

METRIC ESTIMATE:

- ◆ 2015: ~ 30 000 EW GRDM products/ ~ 11 TB from Sentinel-1A
- ◆ Double volume to be expected with Sentinel-1 constellation in full operations 2017 onwards
- ◆ All Sentinel-1 data freely available (upon self-registration) at <https://scihub.copernicus.eu/dhus/#/home>
Image Mosaics available via Polarview <http://www.polarview.aq/arctic>, or <http://www.seaice.dk/>
Images from Greenlandic coastal waters data available via <http://ocean.dmi.dk/arctic/satimg.uk.php>



Example of a three-day Sentinel-1A coverage map of the European Arctic (top) and SAR image mosaic (bottom), March 16 to 19, 2016.

Credit: ESA, Polar View Consortium, and DMI.

Southern Ocean - Sentinel-1A

AGENCY: European Commission (EU), ESA

SATELLITE: Sentinel-1A

TIME FRAME: 2015 onwards

SCIENCE THEME: Floating ice

OBJECTIVE:

- ◆ Coverage of complete sea ice zone on the Southern Ocean 2-3 times per month (act. 2015/2016) a.o. for monthly ice edge description, iceberg monitoring
- ◆ Increased coverage over Ross- and Weddell Sea, suitable to measure ice drift

APPROACH:

- ◆ Extra Wide swath mode (20 m x 40 m mode resolution; 90 m GRD product resolution (12 looks); 400 km swath; single HH polarisation)

METRIC ESTIMATE:

- ◆ 2015: ~ 8 000 EW GRDM products/ ~ 1.6 TB from Sentinel-1A; increased volume expected with Sentinel-1 constellation from 2017 onwards
- ◆ All Sentinel-1 data freely available (upon self-registration) at <https://scihub.copernicus.eu/dhus/#/home>

Floating Ice (Northern and Southern Hemispheres) - ALOS 2

AGENCY: JAXA

SATELLITE: ALOS-2

TIME FRAME: 2014-2016

SCIENCE THEME: Floating ice

OBJECTIVE:

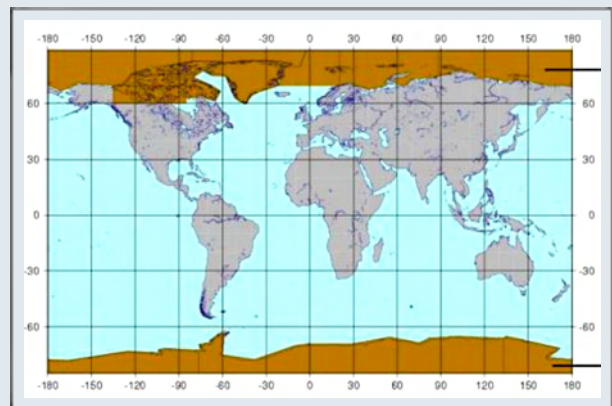
- ◆ Data acquisitions as part of the Basic Observation Scenario for PALSAR-2 instrument
- ◆ Repetition of observations according to seasonality and location

APPROACH:

- ◆ ScanSAR 350 km (100 m res., off-nadir 26.2-41.8 degrees)
- ◆ Polarization – HH+HV
- ◆ Right looking – northern hemisphere
- ◆ Left looking – southern hemisphere

METRIC ESTIMATE:

- ◆ Three coverages per year



JAXA's basis observation strategy coverage map of northern hemisphere and southern hemisphere floating ice for ALOS-2 SAR data acquisition.

Credit: JAXA, Japan

Planned SAR Data Collection Coordinated through PSTG for Floating Ice

The following table shows the acquisition plans discussed at recent meetings of the SAR CWG. This refers to a commitment to investigate acquisitions, and if possible, execute them. It is recognized that individual representatives cannot commit their

agency without management approval. These acquisitions are limited by availability of satellite resources. The table is being modified and updated two to four times per year.

Table S3: PSTG SAR CWG activities related to Floating Ice

Strategic Priority	Agency	Location	Plan 2015-16 / Status / Gaps
Acquire contiguous (seamless) six days repeat pan-Arctic and Southern Ocean SAR imaging at consistent polarization combination (with view to expanding to an intermediate goal of less than three days repeat in future with right-looking Sentinel-1 (S-1), RCM, etc.; and subsequently sub-daily data with C-, X-, S-, L-band SAR combined data sources)	CSA	Three-quarters of Arctic Basin with high frequency, plus background coverage of Western Arctic; Southern Ocean	<i>Plan:</i> Canadian Ice Service can provide RADARSAT-2 ScanSAR imagery (8-bit only) over Canadian Arctic waters during the operational monitoring period (July to late October). During the non-operational period (November to June), Stephen Howell of Environment Canada, Climate Research will program one to three coverages of the western Canadian Arctic from RADARSAT-2 (ScanSAR only) to complement Sentinel-1 (i.e. fill the western Canadian Arctic gap). Distribution will be via a MURF sponsored by Environment Canada, backdated to March 2015. This will be separate from RADARSAT-2 imagery used to support ice thickness and snow surveys during OIB (NASA). Aspects of the plan may require consent of MDA.
	DLR		<i>Plan:</i> Ice support in NRT for ships operating in ice (demonstration) <ul style="list-style-type: none"> • Combination of sea ice parameters and meteo (concentration/winds) from Terra-SAR-X • Unique HH/VV combination for floe-size distribution • Wind/wave interaction in marginal ice zone (SWH and peak wavelength) • Iceberg tracking for IIP; insufficient repeat to track icebergs
	NOAA		<i>Plan:</i> NOAA is operationally processing any available SAR dataset for met-ocean and sea ice analyses; demonstration of capability to fill pole hole with COSMO-SkyMed (CSK) background data for sea ice analysis; pilot project to test CSK multi sat data to support IIP flights. NOAA request to test data from TanDEM-X, CSK and other SAR acquisitions in support of resupply/science cruise to McMurdo. Need routine sea ice information over the North Pole.
	ASI		<i>Plan:</i> COSMO-SkyMed coverage for providing information on eastern Greenland current and sea ice drift and northern circumpolar routes (also available in 1 day). CSK contribution to this priority is provided also through CSK AO specific projects and further contributions are under evaluation.
Establish tundra lakes and river monitoring sites.	CSA	Canadian lakes	<i>Plan:</i> CSA will provide info on winter lake monitoring program to permafrost and floating ice communities and assess the value.
	DLR	10 DLR Cold Spots	<i>Plan:</i> TerraSAR-X classification of river and lake ice – in tundra regions. Water; frozen to ground; consolidated ice; frazil ice. Classification of Sentinel-1 data using Kenneough elements. All of the above are demonstrations.
	ESA	Great Lakes and major Canadian lakes	All year EW mode HH-HV coverage of Great Lakes and major Canadian tundra lakes sites; ~ 1 coverage every 12 days

SECTION 4 - PERMAFROST

Section Overview

This section is subdivided into four parts. The permafrost theme area is introduced first, outlining science issues and requirements related to satellite SAR data acquisitions. This is followed by compilation of SAR data set that were acquired over polar regions prior to the PSTG, as well as those data collections that are currently coordinated through the PSTG's SAR CWG. A listing of permafrost-related SAR data sets currently under consideration by the SAR CWG concludes this section.

Thematic Area: Permafrost

The permafrost requirements are summarized in a community white paper (PSTG-4/doc.08-03 http://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-4_Doc_08-03_Permafrost-Recommendations-Final.pdf) in relation to the key parameters permafrost extent, soil temperature profiles, and active layer thickness. Also of interest is thickness and spatial patchiness of permafrost. Permafrost cannot be directly measured from space, however satellite data can be used in a number of ways:

- ◆ **Identify hot spots of surface change and thus advice on extension of in-situ monitoring networks**
- ◆ **Support modelling of sub-surface conditions (such as subsurface temperature and active layer depth)**
- ◆ **Provide higher resolution (spatial and temporal) measurements in the proximity of long-term in-situ monitoring sites**
- ◆ **Place the in-situ measurements into a wider spatial and temporal context**

The GTN-P and CALM networks of *in-situ* stations are measuring active layer thickness and temperature. The GTN-P data are accessible in standardized form through the Arctic Portal, along with satellite-related metadata (e.g. LST from MODIS). Projects that are using satellite data for inferring permafrost conditions include ESA DUE Permafrost, ESA STSE ALANIS, EU FP7 PAGE21, and, most recently, the ESA GlobPermafrost project (<http://www.globpermafrost.info>). Initial areas of interest were identified in the ESA DUE project. Other projects of interest are NASA ABOVE (Alaska, Canada), ADAPT (Canada), and DEFROST (Scandinavia).

In general, all regions underlain by permafrost are of interest for dedicated acquisition of SAR satellite data. In a reduced scenario, particularly applicable to highest spatial resolution datasets, transects across permafrost zones as well as Arctic coasts should be considered. Priority should be in the polar regions and areas where no other data are available. Other permafrost areas could be added later, such as in the Andes and the European Alps. In addition, science mission requirements include acquisitions with higher resolution modes over long-term *in situ* monitoring sites ('cold' spots).

Surface parameters observable from satellite, which are of highest interest to the permafrost community include:

- ◆ **Land surface temperature**
- ◆ **Land cover and disturbance (vegetation) (current land cover products are often limited in polar regions, e.g., mosses are mostly classified as "bare soil")**
- ◆ **Snow properties**
- ◆ **Soil moisture**
- ◆ **Terrain changes (coastal migration, polygons/patterned ground, active layer detachments)**

Long records of SAR data are used to measure subsidence due to thawing permafrost. Requirements documents include IGOS 2007, ESA DUE 2009, NRC 2014 (specifically looking at the remote sensing role for inferring on permafrost).

Satellite-based observing requirements for permafrost-related phenomena include the following:

- ◆ **Thermokarst and subsidence (still a research area)**
- ◆ **Rock glacier and landslides**
- ◆ **Coastal erosion (occurring at rates of 1-10 m per year in some areas; optical data at this resolution would be useful for tracking).**
- ◆ **Thaw lakes and wetlands (these are typically of <30 m size and not visible in 300 m optical imagery and land surface products)**

Previous SAR Data Collections

Prior to the re-enactment of the Polar Space Task Group in 2013, comprehensive SAR data sets of permafrost area were collected:

Northern Canada - RADARSAT-1

AGENCY: CSA
 SATELLITE: RADARSAT-1
 TIME FRAME: 2008 to 2009
 SCIENCE THEME: Permafrost
 OBJECTIVE:

- ◆ Canadian Interferometric Mission-2
- ◆ Follow on from CIM-1 (September 2000 to February 2001)
- ◆ Provide complete interferometric data coverage over Canada's northern land mass

APPROACH:

- ◆ Utilize RADARSAT-1 and RADARSAT-2 to collect interferometric data over permafrost areas
- ◆ Fine 1 mode
- ◆ December 2008 to April 2009
- ◆ Four cycles

METRIC ESTIMATE:

- ◆ Data available through Polar Data Catalogue at www.polardata.ca

Permafrost - COSMO-SkyMed

AGENCY: ASI
 SATELLITE: COSMO-SkyMed constellation (4 satellites)
 TIME FRAME: 2015 -
 SCIENCE THEME: Permafrost

OBJECTIVE:

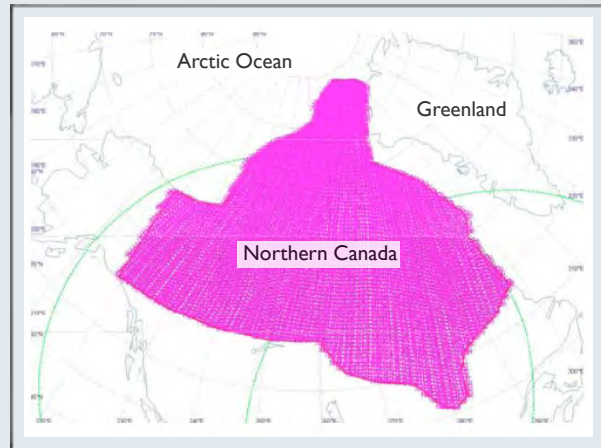
CSK AO projects to be considered also in the PSTG framework

APPROACH:

- ◆ Stripmap mode (3-5 m resolution, 40 km swath)
- ◆ ScanSAR wide region mode (30 m resolution, 100 km swath)
- ◆ ScanSAR huge region mode (100 m resolution, 200 km swath).

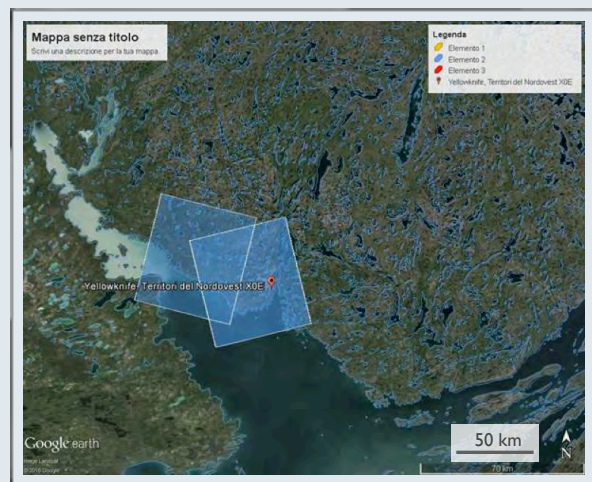
METRIC ESTIMATE:

- ◆ Data sets are available in the CSK archive



RADARSAT-1 SAR coverage map for permafrost related data collection in northern Canada, 2008 to 2009.

Credit: CSA, Canada



Examples of CSK imagery collected for permafrost related studies in the Yellowknife area of northern Canada, 2008.

Credit: ASI, Italy

Northern Canada - TerraSAR-X

AGENCY: DLR
 SATELLITE: TerraSAR-X
 TIME FRAME: 2008 to 2011
 SCIENCE THEME: Permafrost

OBJECTIVE:

Support IPY common super-sites with multi-frequency and fully polarimetric SAR data; temporal series of displacement maps.

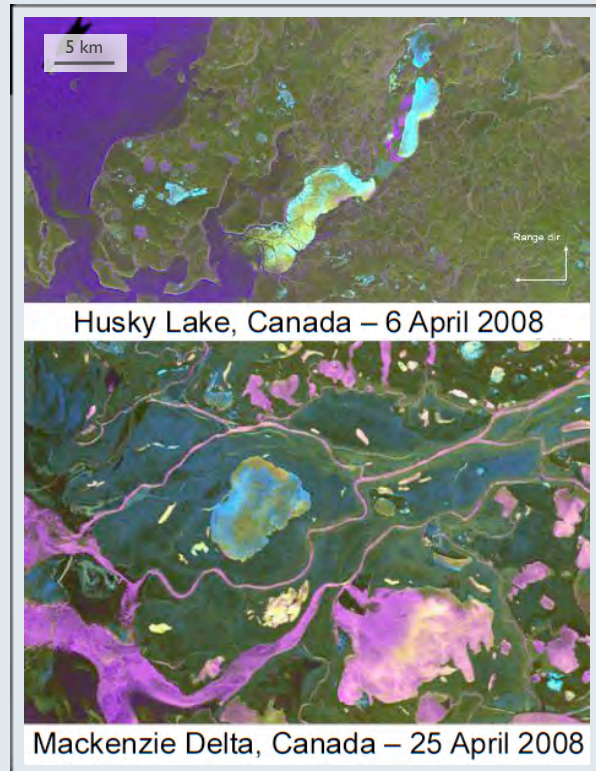
APPROACH:

- ◆ Site-specific data acquisitions
 - Husky Lake, Canada – April 6, 2008
 - Mackenzie Delta, Canada – April 25, 2008
 - Alaska North Slope – 2007 to 2011
 - Northwest Territories Mackenzie River Delta – 2007 to 2011
- ◆ Stripmap mode, dual polarization, varying incidence angles
- ◆ Vertical Accuracy - ± 1 cm
- ◆ Data Format – GeoTiff

METRIC ESTIMATE:

<http://doi.pangaea.de/10.1594/PANGAEA.783307>

http://epic.awi.de/30466/7/DUE_Permafrost_v1_subsidence_guide.pdf



Examples of TerraSAR-X imagery collected for permafrost related studies in Northern Canada, 2008.

Credit: DLR, Germany

DUE-Permafrost - Envisat ASAR

AGENCY: ESA

SATELLITE: Envisat ASAR

TIME FRAME: 2007 to 2010

SCIENCE THEME: Permafrost; freeze-up timing

OBJECTIVE

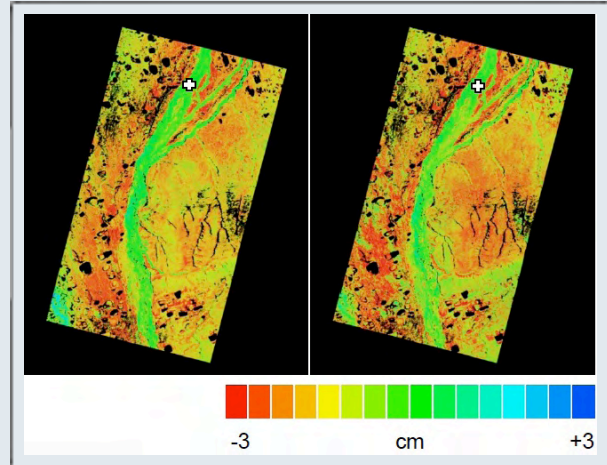
- ◆ Annual freeze-up and thaw map for 2007 to 2010
- ◆ Regional focus: Alaska, Mackenzie and Ob River delta and estuarine regions; Laptev Sea coast; Central Yakutia

APPROACH:

- ◆ ASAR Global Monitoring Mission SAR data, 1 km resolution, GeoTIFF format

METRIC ESTIMATE:

- ◆ ESA DUE Permafrost SAR F/T Product Guide: https://epic.avi.de/30305/1/ESA_DUE_Permafrost_SAR_FT_version2_product_guide_v1.0.pdf
- ◆ SAR Freeze/Thaw product version 2 can be accessed via <http://doi.pangaea.de/10.1594/PANGAEA.780111>



Examples of TerraSAR-X based products for permafrost related studies in northern Canada, 2010 to 2011.

Credit: ESA DUE Permafrost Report, March 2012, p. 77.

Wetland Dynamics - Envisat ASAR

AGENCY: ESA

SATELLITE: Envisat ASAR

TIME FRAME: 2007

SCIENCE THEME: Permafrost; ESA STSE ALANIS

OBJECTIVE

- ◆ Assessment of wetland dynamics

APPROACH:

- ◆ ASAR Wide swath mode (150 m resolution), GeoTIFF format

METRIC ESTIMATE:

The Wetland Inundation product is a ten-day composite with a spatial resolution of 150 m. The product covers a large extent of northern Eurasia (north of 50° N) in regions where the Regional Wetlands product shows occurrence of wetlands. The full dataset (160 GBytes) can be obtained from Annett Bartsch (e-mail: annett.bartsch@zamg.ac.at) and is also available through Pangaea at <https://doi.pangaea.de/10.1594/PANGAEA.834502>



Mosaic of Envisat ASAR derived wetland classification maps of northern Russia in 2007, showing maximum open water in blue and permanently high saturated areas in green.

Credit: ESA STSE-ALANIS / ASAR WS Local Wetlands products

Permafrost - TerraSAR-X

AGENCY: DLR

SATELLITE: TerraSAR-X

TIME FRAME: 2012 to 2015 (ongoing)

SCIENCE THEME: "Cold Spot" monitoring

OBJECTIVE:

Routinely monitor 10 polar cold spot sites:

- ◆ Lena Delta - Samoylov Station (Russia)
- ◆ Spitzbergen - Ny Alesund Station (Spitzbergen, Norway)
- ◆ Yukon Coast - Herschel Island (Canada)
- ◆ Alaska Ngee Site - Barrow Observatory (United States)
- ◆ Kytalyk - Chokurdakh Station (Russia)
- ◆ Bolshoy Lyakhovsky, Anzhu (North Siberian Islds) (Russia)
- ◆ Abisko Station (Sweden)
- ◆ Nuuk Station (Greenland)
- ◆ Zackenberg Station (Greenland)
- ◆ Marre Sale Station (Russia)

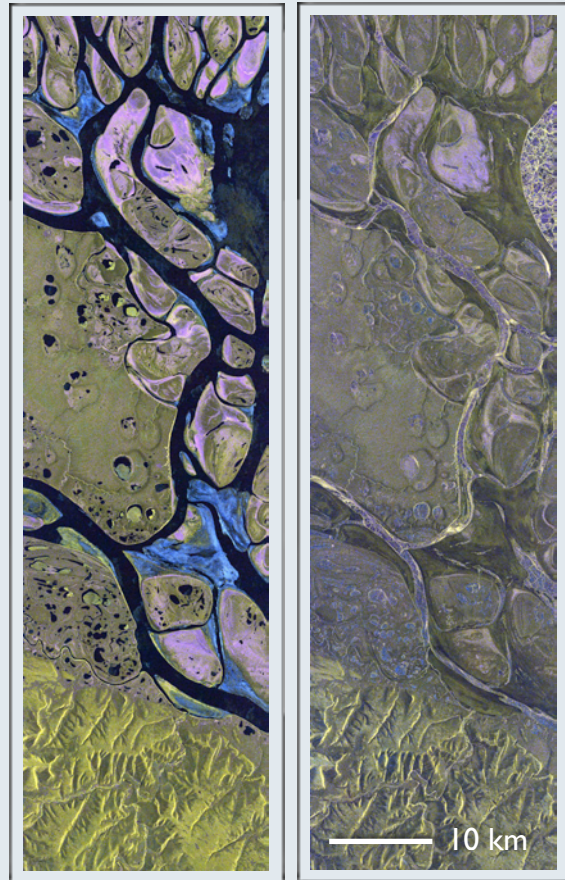
APPROACH:

Modes and polarizations:

- ◆ StripMap: HH, HH/VV, HH/HV
- ◆ Spotlight: HH/VV

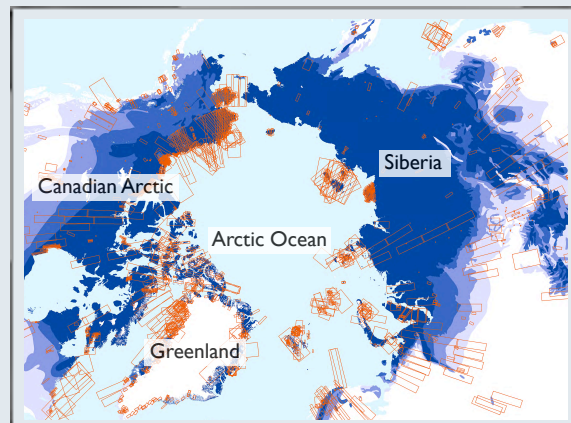
METRIC ESTIMATE:

- ◆ 1621 data takes in total



TerraSAR-X image products in HH/HV polarization acquired over the Kytalyk / Lena Delta region in Russia on July 6, 2015 (left, open water conditions) and on October 24, 2015 (right, frozen).

Credit: DLR.



Map of TerraSAR-X data acquisitions (orange) from 2008 to 2015; permafrost areas are shown in blue.

Credit: ZAMG; NSIDC; DLR

Planned SAR Data Collection for Permafrost Coordinated through PSTG

The following table shows the acquisition plans discussed at recent meetings of the SAR CWG. This refers to a commitment to investigate acquisitions, and if possible, execute them. It is recognized that individual representatives cannot commit their

agency without management approval. These acquisitions are limited by availability of satellite resources. The table is being modified and updated two to four times per year.

Table S4: PSTG SAR CWG activities related to Permafrost

Strategic Priority	Agency	Location	Plan 2015-16 / Status / Gaps
Routine high-resolution circumpolar coverage for monitoring variability in carbon pools			Sentinel-1 routine coverage not yet assured; zonal mapping running with two to three revisits per year. Potential RADARSAT-2 support when the National Monitoring Framework is in place for Canadian portion.
Multi-sensor monitoring around key research locations where GTN-P and in-situ measurements are made (“cold spots”); (bi-weekly InSAR for permafrost modeling).	DLR	10 cold spot sites	<i>Plan:</i> Routinely monitored by TerraSAR-X in Stripmap mode HH and HH/VV and Spotlight mode HH/VV in 2015 to 2016; <i>Status / Gaps:</i> other cold spot sites not covered
	ESA	Sample of cold spots and five mountain permafrost areas (focus on rock glaciers) (TBC)	<i>Plan:</i> At least one complete Sentinel-1 IW mode VV-VH coverage of global permafrost zone during relevant season (within Sentinel-1 zonal mapping frame) + 2-3 local subsequent acquisitions over a total of 5+ cold spots in order to achieve pairs/triplets for time-series analysis. Global Permafrost ITT
	ASI		<i>Plan:</i> Evaluation of applicable acquisitions of the COSMO-SkyMed constellation, considering the acquisitions and information provided within CSK specific projects.
Quantify rates of pan Arctic coastal erosion (annual circumpolar Arctic coastline mapping at <10m optical resolution; InSAR estimates of erosion/degradation)	DLR	Limited areas	<i>Plan:</i> Demonstrations using TerraSAR-X in 2015 to 2016. <i>Status / Gaps:</i> no comprehensive coverage defined yet to observe changes
	ASI		<i>Plan:</i> Evaluation of applicable acquisitions of the COSMO-SkyMed constellation, considering the acquisitions and information provided within CSK specific projects.
Establish SAR monitoring of Arctic permafrost transects on routine basis to supplement existing 30 to 300 m pan-Arctic multispectral imaging (Antarctic Peninsula covered by sea ice requirements)	ESA	Transects as defined in Requirement Document	<i>Plan:</i> <ul style="list-style-type: none"> - Scandinavian transect: Complete Sentinel-1 coverage all year IW VV-VH, 12 d repeat acquisitions. - West Siberian Lowlands transect: Sentinel-1 all year EW HH-HV, 12 day repeat acquisitions north of 65.5 deg (Gulf of Ob and surrounding coastal areas); at least one complete IW VV-VH coverage during summer season (zonal mapping). - East Siberian transect: Sentinel-1 all year EW HH-HV, 12 day repeat acquisitions over Lena Delta and surrounding coastal areas; at least one complete IW VV-VH coverage during summer season (zonal mapping). - East Canada/Mackenzie Delta/Alaska Highway: Sentinel-1 all year EW HH-HV, 12 day repeat acquisitions over the northern coastal regions of the transects; southern parts of transects covered on routine basis in IW VV-VH or IW HH-HV (Mackenzie).
	CSA	Coverage of NASA ABoVE transect in North America	National Terrestrial Ecosystem Monitoring System (NTEMS) implementation TBC
Derive SAR DEM and land surface classification map suitable for permafrost community needs.	ESA		CCI Land cover TBC

SECTION 5 - SNOW

Section Overview

This section is subdivided into four parts. The snow-related theme area is introduced first, outlining science issues and requirements related to satellite SAR data acquisitions. This is followed by compilation of SAR data set that were acquired over polar regions prior to the PSTG, as well as those data collections that are currently coordinated through the PSTG's SAR CWG. A listing of snow-related SAR data sets currently under consideration by the SAR CWG concludes this section.

Thematic Area: Snow

The white paper *Coordinated SAR Acquisition Planning for Terrestrial Snow Monitoring* (PSTG-4/doc.08-01, http://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-4_Doc_08-01_UserReq-Snow-SARCWG-v0-9.pdf) contains detailed requirements for satellite SAR data collections regarding wet snow. The document was developed with support from a range of users and contains tabulated summaries of science requirements, sensor SAR specifications, as well as recommendations for regional observations. The focus is on SAR-related user requirements that demand higher spatial resolution than passive microwave radiometry (PMR) or VIS/IR optical datasets. Snow mapping with space-borne PMR and optical sensors is adequately covered by routine operations in the near future from satellite instruments such as GCOM-W1 AMSR-2, SNPP VIIRS and Sentinel-3 OLCI/SLSTR.

The key science requirements for wide area monitoring of snow are snowmelt area and snowmelt liquid water content, at ~100 m spatial resolution and with daily resolution. For moving from PMR (~25 km spatial resolution) or optical products (~300 m) to SAR-based products (<100 m), radiometric terrain corrections are necessary to isolate the snow melt signal from terrain effects, particularly in areas with marked topographic features. Snowmelt data for mountainous and alpine regions is an important component of several hydrological applications, including water availability for hydropower (energy), agriculture and human consumption.

It is possible to overcome the limited revisit time of a single SAR satellite mission and achieve shorter revisit intervals by using multiple missions through local resolution weighting as demonstrated by *Small et al., 2012*. The approach was applied to a

long time series of ASAR data to demonstrate the capability for monitoring the retreat of the snow melt line with the onset of spring over the Swiss Alps. Wide swath SAR imaging (>100 km) is favourable, preferably with relatively low speckle noise.

In order to constrain observation planning and resulting data volumes, a seasonal observation window for SAR missions observing snow at northern temperate latitudes should include high temporal resolution acquisition between February 15 and May 30. Outside this window, regular (e.g. bi-weekly) observations are also important to observe winter events such as avalanches or rain-on-snow events. A SAR polarization mode of VV/VH is preferable. The accuracy of the geolocation of Sentinel-1A stripmap data is on the order of 6 cm in range and 17 cm in azimuth (with compensation for a processor bias term), as estimated in a recent calibration campaign in Switzerland, confirming the suitability of Interferometric Wide (IW) data for snow mapping in alpine topography (*Schubert et al. 2015*, <http://www.mdpi.com/2072-4292/7/7/9431/hlm>).

Acquisition planning should start with the objective of first achieving contiguous, weekly ascending and descending SAR coverage in limited geographical regions, such as the European Alps and parts of the Nordic countries and Canada. Subsequent plans could incorporate a ramp up in temporal revisit using a combination of SAR sensors in order to progress towards the ultimate goal of daily coverage.

Initial steps in a PSTG response to the presented snow requirements should include:

- ◆ ***Pilot activities for SAR-based wet snow monitoring, and steps for scaling up, noting that high spatial resolution is needed in complex terrain***
- ◆ ***Taking into account operational services delivered by NOAA and the EUMETSAT H-SAF to provide snow water equivalent (SWE) and snow cover extent***
- ◆ ***Considering Central Asia and the Third Pole as focal areas in data acquisition strategies, involving users and space agencies from China, India, and Japan in refining SAR data acquisition campaigns***

Previous SAR Data Collections

Prior to the re-enactment of the Polar Space Task Group in 2013, comprehensive SAR data sets were collected for snow-related studies:

Northern Canada - RADARSAT-1

AGENCY: CSA
SATELLITE: RADARSAT-1
TIME FRAME: 1998 to 1999

SCIENCE THEME: Snow

OBJECTIVE

- ◆ Canadian Arctic Land Mass Mosaic
- ◆ CSA background mission
- ◆ Mosaic utilizing ScanSAR Narrow
- ◆ Summer and winter coverage

APPROACH:

- ◆ Acquisition using ScanSAR Narrow

METRIC ESTIMATE:

- ◆ 600 scenes
- ◆ Single images and mosaics at 250 m, 500 m and 1000 m pixel size
- ◆ Data source <https://www.polardata.ca/pdcsearch/>

Northern Hemisphere Land Cover Mapping - ALOS PALSAR

AGENCY: JAXA
SATELLITE: ALOS - PALSAR
TIME FRAME: 2006 to 2011

SCIENCE THEME: Snow

OBJECTIVE:

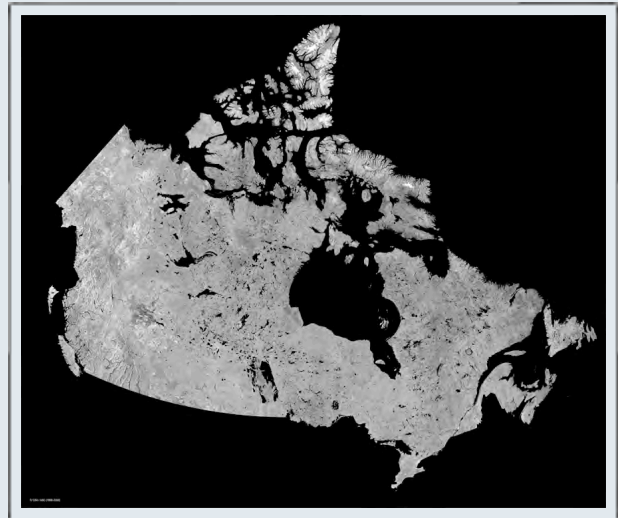
- ◆ Northern hemisphere land cover mapping

APPROACH:

- ◆ WB1 – ScanSAR 5-beam short burst
- ◆ Cycle 7~18
- ◆ Mapping between October 6, 2006 and April 23, 2008

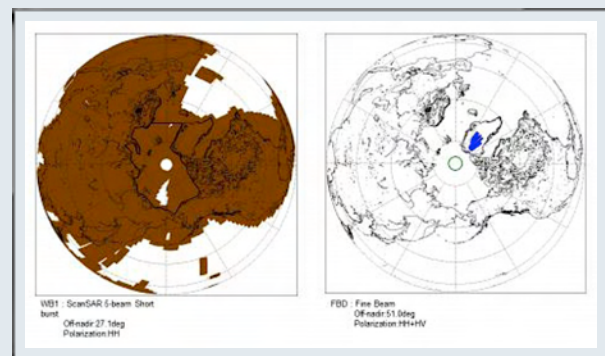
METRIC ESTIMATE:

- ◆ Data are available through ASF at <https://www.asf.alaska.edu/sar-data/palsar/>



RADARSAT-1 SAR mosaic of Canada, collected over a seven-day period in 1999.

Credit: CCRS, CSA, MDA



ALOS PALSAR coverage maps of the northern hemisphere land cover mapping project, 2006 to 2008.

Credit: JAXA, Japan

SAR Data Collections Coordinated through PSTG

European Alps, and parts of the Nordic Countries and Canada - Sentinel-1A

AGENCY: European Commission (EU), ESA

SATELLITE: Sentinel-1A SAR

TIME FRAME: October 2014 to 2016

SCIENCE THEME: Wet Snow mapping

OBJECTIVE

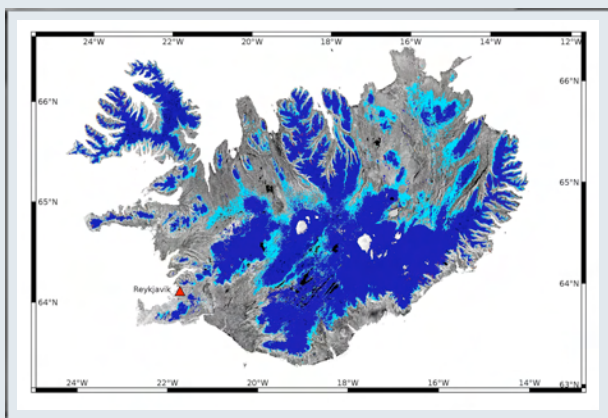
- ◆ Seamless multi-temporal SAR backscatter mosaics
- ◆ Regional focus on European Alps, Nordic countries, Coastal mountains of British Columbia, Canada, and Ellesmere Island, Nunavut, Canada

APPROACH:

- ◆ Acquisition using Sentinel-1A SAR data
- ◆ Radiometric terrain correction
- ◆ Automated, seamless backscatter map generation for regional wet snow cover

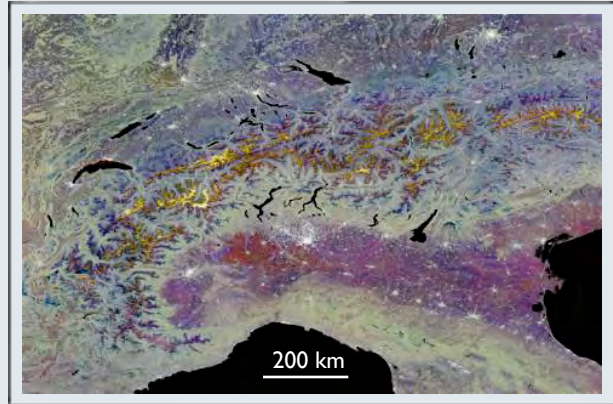
METRIC ESTIMATE:

- ◆ Data access via the Sentinels Scientific Data Hub at <https://scihub.copernicus.eu/> Further detail is available at <https://indico.esa.int/indico/event/84/session/2/contribution/27>



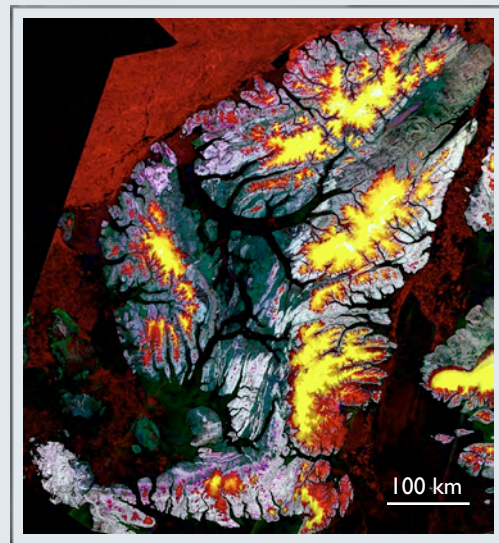
Map of snow melt conditions in Iceland, derived from Sentinel-1 IW mode data (light blue: change of wet snow extent from May 17 to 22 and June 10 to 15, 2015; blue: wet snow extent on June 10 to 15, 2015).

Credit: Nagler et al. 2016; ENVEO IT GmbH.



RGB snow backscatter map of the European Alps (R=March 14 to 29, 2015; G=April 7 to 22, 2015; B=May 25 to June 9, 2015), based on Sentinel-1A data analysis, indicating the height progression of springtime melting. Yellow indicates regions where melting began in late May.

Credit: University of Zurich, Switzerland; map contains modified Copernicus Sentinel data (2015)



RGB snow backscatter map of Ellesmere Island, Nunavut, Canada (R=May 24 to 27; G=June 29 to July 2; B=July 23 to 26, 2015), based on Sentinel-1A (EW, 4-day C-HV composite) data analysis. Yellow indicates areas where melting began in late July.

Credit: University of Zurich, Switzerland; map contains modified Copernicus Sentinel data (2015)

Planned SAR Data Collection Coordinated through PSTG for Snow

The following table shows the acquisition plans discussed at recent meetings of the SAR-SAR CWGCWG. This refers to a commitment to investigate acquisitions, and if possible, execute them. It is recognized that individual representatives cannot

commit their agency without management approval. These acquisitions are limited by availability of satellite resources. The table is being modified and updated two to four times per year.

Table S5: PSTG SAR CWG activities related to Snow

Strategic Priority	Agency	Location	Plan 2015-16 / Status / Gaps
Plan SAR data as complement to passive microwave and 300m optical data for continental scale snow extent/SWE and in Alpine regions and rugged topography where other methods fail.	CSA	British Columbia	<i>Plan:</i> Routine RADARSAT-2 coverage to test methods. <i>Status:</i> CSA provided comprehensive coverage of mountain snow in unified dual-pol. strategy over British Columbia.
		Ellesmere Island	<i>Status:</i> Environment Canada provided Canadian Ice Service archive data of Ellesmere Island (454 images, albeit in CIS 8-bit format).
	ESA	European Alps	<i>Plan:</i> Sentinel-1 routine coverage over European Alps, British Columbia (IW mode) and Ellesmere Island (EW) (planned). <i>Status / Gaps:</i> European coverage extended eastwards to Caucasus TBC.
Establish less than three day repeat SAR monitoring (ascending/descending combinations) of European Alpine region and other selected mountain regions (Scandinavia / Nordic countries, Canadian Pacific mountains) during seasonally-limited snow melt time window	ESA		<i>Plan:</i> Sentinel-1A alpine monitoring of European Alps, with Sentinel-1B in 2016 the monitoring will be more complete. Sentinel-1A acquisitions over British Columbia (IW VV/VH), and Ellesmere Island (mainly EW HH/HV) offering subdaily coverage. Tight time series over Ellesmere allowed demonstration of 4-day temporal resolution. In more temperate latitudes, temporal resolution will be moving down towards these values with the addition of Sentinel-1B. EU-DEM to be investigated for demonstrating capability in Scandinavia.
Establish common polarization/mode observation strategy between SAR missions	CSA and ESA		<i>Plan:</i> RADARSAT-2 and Sentinel-1 wide swath acquisitions over Alps in VV/VH when possible. <i>Status / Gaps:</i> more complete ascending / descending coverage over British Columbia. Considering potential RADARSAT-2 data acquisition conflicts, having extra ScanSAR (SCNB preferably, best matching Sentinel-1 IW) during the springtime melt period would be beneficial.

ANNEX: List of acronyms

ABoVE	Arctic-Boreal Vulnerability Experiment	IV	Ice Velocity
ADAPT	Arctic Development and Adaptation to Permafrost in Transition	IW	Interferometric Wide
ALANIS	Atmosphere-LANd Interactions Study	IWS	Interferometric Wide Swath (a mode of Sentinel-1)
ALOS	Advanced Land Observation Satellite	JAXA	Japanese Aerospace Exploration Agency
AMM	Antarctic Mapping Mission	JCOMM	Joint Committee of WMO and ICSU
AMSR-2	Advanced Microwave Scanning Radiometer – 2	km	kilometre(s)
ASAR	Advanced Synthetic Aperture Radar	KSAT	Kongsberg Satellite Services
ASF	Alaska Satellite Facility	L1	Level 1
ASI	Agenzia Spaziale Italiana (Italian Space Agency)	LST	Land Surface Temperature
CALM	Circumpolar Active Layer Monitoring	m	metre(s)
CCI	Climate Change Initiative	MAMM	Modified Antarctic Mapping Mission
CFL	Calving Front Location	MB	megabyte
CIM	Canadian Interferometric Mission	MDA	MacDonald, Dettwiler and Associates Ltd.
CIS	Canadian Ice Service	MEaSURES	Making Earth System Data Records for Use in Research Environments
CMEMS	Copernicus Marine Environment Monitoring Service	MOU	Memorandum of Understanding
CSA	Canadian Space Agency	n/a	not available
CSK	COSMO-SkyMed	NASA	National Aeronautics and Space Administration
CWG	Coordination Working Group	NOAA	National Oceanic and Atmospheric Administration
DEM	Digital Elevation Model	NRC	National Research Council
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)	NRT	Near Real-time
DUE	Data User Element	NSIDC	National Snow & Ice Data Center
EC-PORS	Executive Council Panel of Experts on Polar Observations Research and Services (of WMO)	NTEMS	National Terrestrial Ecosystem Monitoring System
ECV	Essential Climate Variable	NWP	Numerical Weather Prediction
EH4	Extended High 4 (beam mode of RADARSAT-2)	OIB	Operation Ice Bridge
ERS	European Remote Sensing Satellite	OLCI	Ocean and Land Colour Instrument
ESA	European Space Agency	PALSAR	Phased Array type L-band Synthetic Aperture Radar
EU	European Union	PMR	Passive Microwave Radiometry
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites	PSTG	Polar Space Task Group
EW	Extended Wide	RCM	RADARSAT Constellation Mission
FP7	Seventh Framework Programme	S	South
GB	Gigabyte	S5	Standard 5 (beam mode of RADARSAT-2)
GCOM-W1	Global Change Observation Mission – Water 1	SAR	Synthetic Aperture Radar
GCOS	Global Climate Observing System	SAR CWG	SAR Coordination Working Group
GCW	Global Cryosphere Watch	SEC	Surface Elevation Change
GIIPSY	Global Interagency IPY Polar Snapshot Year	SLC	Single Look Complex
GLL	Grounding Line Location	SLSTR	Sea and Land Surface Temperature Radiometer
GRDM	Gigabit Rate Data Mux	SnowPEX	Satellite Snow Product Intercomparison and Evaluation Exercise
GTN-P	Global Terrestrial Network for Permafrost	SNPP	Suomi National Polar-Orbiting Partnership
H-SAF	Satellite Application Facility on Support to Operational Hydrology and Water Management	SSC	Single Look Slant Range Complex
HH	horizontal transmit - horizontal receive polarization	STSE	Support to Science Element
HV	horizontal transmit - vertical receive polarization	SWE	Snow-Water Equivalent
ICSU	International Council of Scientific Unions	TB	Terabyte
IGOS	Integrated Global Observing Strategy	TBC	to be confirmed
IIP	International Ice Patrol	TBD	to be determined
IMBIE	Ice Sheet Mass Balance Intercomparison Exercise	TOPS	Terrain Observation with Progressive Scans in azimuth
InSAR	Interferometric SAR	U.	University
IPY	International Polar Year	UCI	University of California, Irvine
IPY-4	Fourth IPY (2007 – 2009)	VH	vertical transmit - horizontal receive polarization
IPY-STG	IPY Space Task Group	VIIRS	Visible Infrared Imaging Radiometer Suite
		VV	vertical transmit - vertical receive polarization
		WMO	World Meteorological Organization
		ZAMG	Zentralanstalt für Meteorologie und Geodynamik

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 Maria Girolamo Daraio, Alessandro Coletta
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DLR – Deutsches Zentrum für Luft- und Raumfahrt (Germany)
 Manfred Gottwald, Dana Floricioiu, Achim Roth

EUMETSAT

European Organisation for the Exploitation of Meteorological Satellites
 Francois Montagner

ESA – European Space Agency

Pierre Potin, Johannes Roeder, Mark Drinkwater (*Chair, PSTG*)

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