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Improved monitoring of polar land ice dynamics by means of SAR interferometry: ICEDANCE

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INTRODUCTION

Polar regions play an essential role in the complex climate system. They are characterized by very low temperatures, marked seasonality, huge continental ice sheets and large oceanic areas permanently or seasonally covered by sea ice. Taken together, the present global cryosphere (glaciers and ice sheets) contains enough water to rise sea level by almost 70 m. Thus, a small fraction of change in their volume would have a significant effect on sea level. However, the uncertainties in the knowledge of the cryosphere's mass balance are large. E.g., the mass imbalance of Antarctica is likely to be small, but even its sign cannot yet be determined [1]. The gross behaviour of ice sheets is controlled by the dynamics at a relatively small number of key areas. These are principally the grounding line and areas of concentrated flow in outlet glaciers and ice streams, which are responsible for the bulk of the ice transport towards the coast. Recent investigations especially based on satellite altimetry and interferometry, show a pattern of high spatial and temporal variability [2]. This is due to changes in mass balance and flow behaviour of outlet glaciers in the West Antarctic Ice Sheet (WAIS) [3] and the Antarctic Peninsula [4] [5].

Spaceborne interferometric SAR proved to be the powerful tool to investigate the changes in the cryosphere at the required high accuracy (Table 1) [6]. Suitable interferometric data are mainly available in C- band and were acquired in 1994 during the ERS-1 Ice Phase (3 day repeat pass), and the ERS-1/2 Tandem Mission (1995-1999). The main draw back of ERS in remote areas as Antarctica was the need for local ground data receiving stations which had not available continuously. The first complete coverage of Antarctica was obtained during the Radarsat Antarctic Mapping Mission (September/October 1997, 24 day repeat pass). The interferometric capabilities of L-, C-, and X-band were simultaneously demonstrated during the 2nd Space Shuttle SIR-C/X-SAR mission (SRL-2, 30th Sept. – 11th October 1994) for varying temporal (1 to 3 days) and spatial baselines. Operating between 60°N and 60°S, coherence was observed over snow and ice in C- and L-Band. In X-Band, coherence was observed only under exceptional conditions. Single pass interferometry was successfully applied with C- and X-Band SAR during the Shuttle Radar Topographic Mission (SRTM), showing up the accuracy differences between both bands. Although no global coverage was obtained with SRTM, these data are a baseline for direct glacier mass balance measurements in low and mid latitudes.

Table 1: SAR space missions which provided interferometric ice measurements

S/C	frequency Band	bandwidth (MHz)	incidence angle	Mission duration	repeat cycle
ERS-1	C	16	23	ice phase: (Dec.'91-Mar.'92, Dec.'93-Apr.'94)	3 days
ERS-1/2	C	16	23	Tandem Mission (1995-1999)	1 day
Radarsat-1	C	11.6/17.3/30	10-60	AMM (26th Sept.-14th Oct. 1997)	24 days
SIR-C/X-SAR	X/C/L	10/20 (X-band)	15-55	SRL-2 (30th Sept.-11th Oct. 1994)	1 to 3 days
SRTM	X/C	9.5 (X-band)	52 (X-band)	11th - 22nd Feb. 2000	single pass

At present, no comparable systems are available. ICEDANCE (Ice Mass Transport and Balance of Glaciers and Ice Sheets) is a concept for a dedicated SAR satellite mission for improved monitoring of the dynamics of the cryosphere, partly in combination with ice thickness measurements. The basic idea is a close formation flight for the measurement of digital elevation models (*DEM Mode*) and a separated formation flight (*Motion Mode*) for the measurement of ice motion (Fig. 1). Beside the primary mission objective, which is to quantify the contribution of polar ice sheets and glaciers to sea level change, this concept rises opportunities for other SAR applications and advanced SAR modes.

Fig. 1: Artist's impression of two ICEDANCE SAR satellites flying in close formation (DEM mode), precisely measuring surface elevation of cryospheric key regions of the greenlandic ice sheet.

REQUIREMENTS FOR DIGITAL ELEVATION MODELS AND SURFACE DISPLACEMENTS MEASUREMENTS

The various components of the cryosphere stretch over a wide spatial and temporal scale, which require different measurement accuracies and repeat pass intervals (Tab. 2) [7]. The highest spatial and temporal measurement accuracy is required for glaciers, which are subject to surface melt and seasonal changes in flow behavior as a consequence of meltwater penetration. The highest accuracy regarding surface height is needed for sea ice roughness measurements. Interferometric motion measurements of sea ice is not possible because of rapid vertical displacement and large drift. Feature tracking has to be used instead.

Table 2: Areas of interest (AOI), recommended acquisition intervals and measurement accuracies for various key regions.

AOI					*DEM*	*Motion*
Region (total size)	*key region*	*Size (km^2)*	*Spatial Scale*	*repeat interval*	*vertical accuracy*	*horizontal accuracy*
Antarctica ($13.5x10^6 km^2$)	margin of ice sheet	$3.8x10^6$	50-100m	5 y	3 m	5 %
	South Pole	$150x10^3$	10-50 m	5 y	1 m	5 %
	ice streams	$1x10^6$	5-10 m	1 y	1 m	5 %
	Grounding line position		5-10 m	1 y	10 m horizontal	
Greenland ($1.7x10^6$)	margin of ice sheet	$1.4x10^6$	10 m	1 y	1 m	5 %
	ice streams	$0.5 x10^6$	5 m	0.25 y	1 m	5 %
mountain glaciers and small ice caps ($0.7x10^6$)		$0.7x10^6$	5 m	0.25 y	1 m	5 %
surface roughness	sea ice				< 0.5 m	

Our concept concentrates on key regions of the cryosphere, such as fast flowing ice streams and ice shelves at the margin of continental ice sheets (Fig. 2) and ice caps, and non polar glaciers. These are the regions, where the most significant dynamical, volume, and areal changes are to be expected during the next decades.

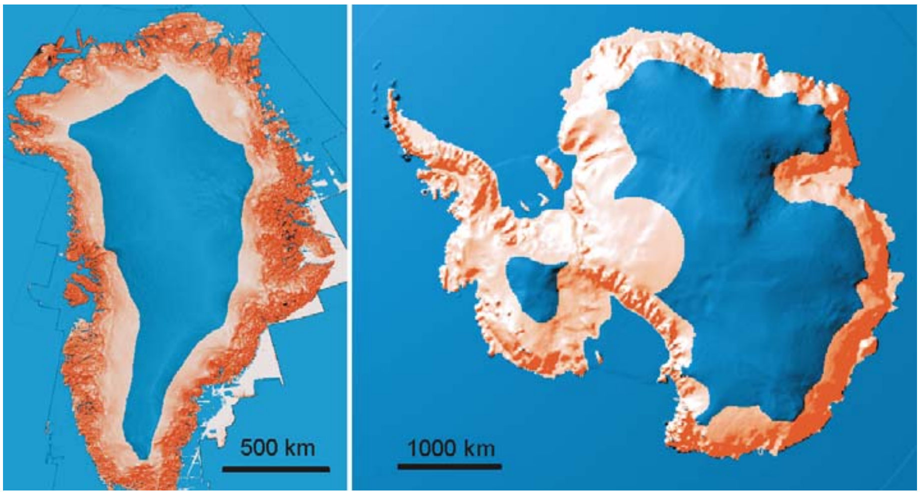

Figure 2: ICEDANCE key regions (red colour) of the Greenland and Antarctic ice sheet.

Compared to the overall size of polar ice sheets these regions are relatively small. For example, we estimate that 80-90% of the Antarctic inland ice is drained through about 200 outlet glaciers, which have a terminus width between 5-40 km, an ice thickness around 1000m and a mean flow velocity of 1m/day. For most of these glaciers, no precise measurements are available at all and a baseline for further investigations is needed.

SCIENCE MISSION OBJECTIVES, APPLICATIONS, AND POTENTIAL MISSION BENEFITS

Ice sheets still adjust to climate changes as far back as the last glacial period and their future contribution to sea level change also has a component related to the long term background evolution. The only way to estimate these contributions is to apply a combination of ice dynamic models [8] with comprehensive atmosphere-ocean global circulation models (AOGCM) [9]. The products of a satellite mission, such as surface elevation and ice motion especially in key regions (Fig. 3), are fundamental inputs to ice sheet models, and the physical accuracy of the models is crucially determined by the quality of this up to now sparsely available data. The accurate identification of the underlying physics of ice sheet dynamics together with the present day state of balance of the ice sheets will rise the confidence in the projected role of the cryosphere in the climate system.

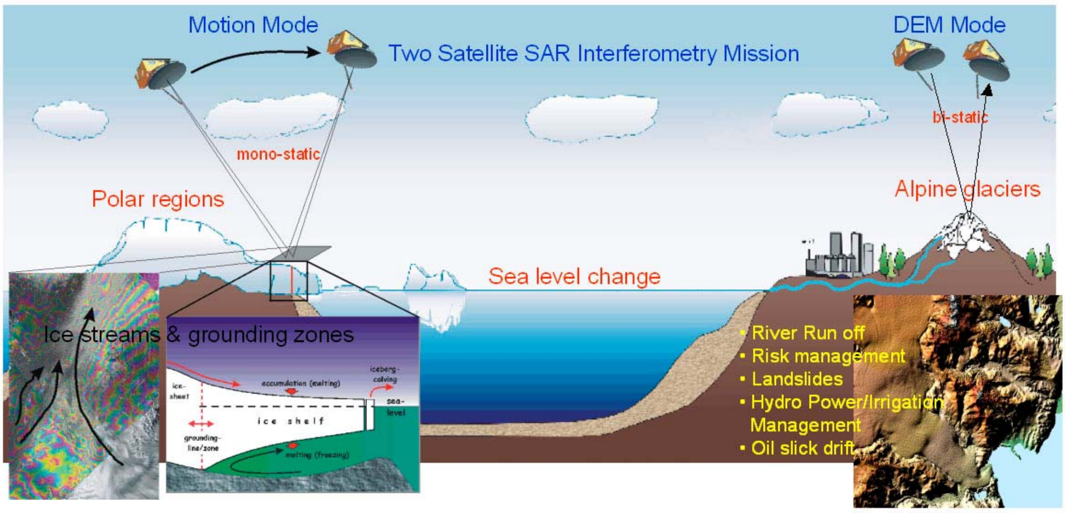

Figure 3: ICEDANCE mission objectives and characteristics.

The classification of sea ice types is important for studies of the interactions between ocean, sea ice, and atmosphere because of the variations of heat and salt fluxes, which affect the circulation patterns on regional scales in polar regions. The roughness of the ice surface affect the momentum transfer from the atmosphere to the sea ice cover and are indicators for the degree of ice deformation. The contribution of deformation features, such as ice ridges and keels, to the total ice mass per unit area has to be considered in sea ice mass balance studies. Furthermore, the roughness of the sea ice covered ocean is of vital importance for atmospheric weather and climate models as well as sea ice models and coupled ocean and atmosphere models.

Features like precise orbit control, autonomous formation keeping and synchronization of the SAR systems would offer the opportunity to demonstrate a series of new SAR modes beside river run-off measurements (Tab. 3). River runoff on a global scale with sufficient regional detail has not been done successfully today. To some extent this is due to an incomplete network of run-off gauges, but also due to an increasing degradation of the existing network. Politicians and climate scientist alike are therefore extremely interested in novel techniques to monitor river run-off from satellites. The *DEM Mode* with the close satellite formation flight can be used to demonstrate the potential of the SAR Along Track Interferometry (ATI) technology to monitor river run off. With additional information about the river bed and the height the volume flux leaving the river into the ocean can be determined [9]. At present ATI is the only known technique which allows to measure instantaneously the velocity of a fast moving objects like sea water currents from space [11]. The experience of some regional studies will be essential for later planning of global sampling strategies of a future mission.

Table 3: Innovative SAR modes

Mode	Feature	Product
Motion Mode	Coherence/Motion optimized time difference between satellite overflights	Ice motion
Bi-static SAR	Separation of satellites in along/across track	DEM, fast motion
Ground motion measurement	single pass along track interferometry	River run-off, ocean current monitoring
Forward Scattering	Shallow incidence angle, second satellite opposite to illumination	Deformation at shallow incidence angles
SAR-Train	A line of SAR satellites	Large swathes, improved spatial resolution
SAR Tomography	Acquisitions of objects with multiple baselines	3-D models of complex structures

MISSION CHARACTERISTICS AND OBSERVATION REQUIREMENTS

The mission objectives need a satellite system consisting of at least two active SAR satellites. Precise DEMs require a single pass bistatic across-track interferometer, comparable to that of the SRTM. Ice motion requires a repeat pass with adequate time span between measurements to limit decorrelation due to surface change but to maximize sensitivity to motion, comparable to that of the ERS-1/2 Tandem mission. Both can be accomplished with a pair of identical satellites, flying in formation at a distance of several tens to hundreds of meters in the *DEM Mode* and as a ‘Tandem’ separated by several hours in the *Motion Mode*. The mission shall thus be divided into phases separated by reconfiguration of the satellite formation. Although ICEDANCE is not restricted necessarily to X-Band, it is taken as a baseline in the following discussion because highest accuracy for both motion and elevation is expected.

One of major lessons learnt in the operational X-SAR SRTM data processing was concerned with mountainous terrain, were the final DEM data quality was partly deteriorated at steep mountain slopes [12]. This was caused by problems with the phase-unwrapping due to ambiguities, and with the weak signal from mountain slopes not oriented towards the sensor. The problem of phase ambiguities can be handled by proper choice and adjustment of short baselines in the DEM - phase.

For an X-band SAR satellite formation working in the bi-static *DEM Mode* at 600 km orbit altitude at least two different across-track baselines have to be adjusted in order to cover the different terrain types. A short baseline for strong topography with a height of ambiguity of 500 m and a longer baseline for moderate topography with a height of ambiguity of 50 m have to be foreseen. The corresponding desired across track baselines are approximately 40 m and 400 m, respectively. If we request an accuracy of only 20% the baselines must be adjusted within 8 m accuracy for strong topography and 80 m for moderate topography. For Along Track Interferometry (ATI) where the satellites fly in a tight along track tandem formation, time lags between the measurements of 3 to 6 ms are required, corresponding to ATI "baselines" between 42 and 84m. It shall again be possible to adjust the baseline length within 20% accuracy. The required range of interferometry baselines combined with bi-static interferometry leads to the need of extremely close formation flying, which requires a very good capability of formation control. Therefore an autonomous on-board orbit control unit is indispensable. It has been shown that the required satellite formation flight is possible with exciting technology [13].

Bi-static interferometry requires synchronization of the instrument oscillators and echo window timing. The space segment has to provide provide the necessary functionality with adequate performance.

Across track baselines should be avoided in the *Motion Mode* and for other differential interferometry applications like ground subsidence measurements, because the ground topography would introduce phase errors into the measurement of movements or ground subsidence. These phase errors can be compensated in case a sufficiently precise reference DEM is available, however this is not always the case. Therefore it shall be possible to manoeuvre the ICEDANCE satellites within a tight orbit pipe, at least for portions of the orbit over the test sites. For alpine regions this dead-band must be within +/-10m, and for moderate terrain it may be relaxed to 40m in case a precise reference DEM is available.

The ICEDANCE mission is planned to be a 8 year mission which allows to frequently measure surface height and velocity of cryospheric key regions by alternating between the two acquisition modes (Table 4). The orbit manoeuvres to change between the tight formation flight during the *DEM Mode* and the loose satellite configuration in the *Motion Mode* require several days or weeks, depending on the defined time difference for image acquisition. A possible plan foresees a change between the modes every 24 months, starting with a *DEM Mode* and finishing with a *Motion Mode* until the mission end.

Table 4: ICEDANCE observation characteristics for the primary mission objective.

Parameter/Mode	DEM Mode	Motion Mode
Ground resolution (image product)	5 m	
Preferred incidence angle range	30°-50°, left and right looking	
Revisit in DEM / Motion phase (ascending and descending orbit)	per phase twice minimum	per phase two coherent image pairs minimum
Preferred time of the day/year	Dry surface	Winter or Dawn/dusk/night
Coverage	global coverage of land ice covered surface including areas around poles	
Duration of mission	8 years	
Repeat cycle	35 days	
Orbit	polar, 600 km	
NESZ	-25 dB	

RETRIEVAL ALGORITHMS AND DATA PRODUCTS

The concept of ICEDANCE regarding the primary mission objective is based on standard methods to measure ice motion and height, partly in combination with airborne ice thickness measurements. The embedding of the main mission products in climate and ice dynamic process models and the combination with ice thickness in order to quantify the mass flux is for example implemented at AWI [8]. Data processing and algorithms for the derivation of the geophysical satellite products are implemented at DLR and several partner institutes based on both self-developed and commercial software. This includes the phase unwrapping of the relative phase, the derivation of height and velocity from the absolute phase, and the geocoding of SAR images and products derived thereof. An automatic processing chain was successfully demonstrated at DLR during the SIR-C/X-SAR and SRTM missions.

Besides the major products there are several further geophysical products under consideration which are listed in Fig. 4. All products based on image analysis (except fast sea ice drift) can be derived from images acquired either in the *DEM* or *Motion Mode*. Algorithms for generating these products are available.

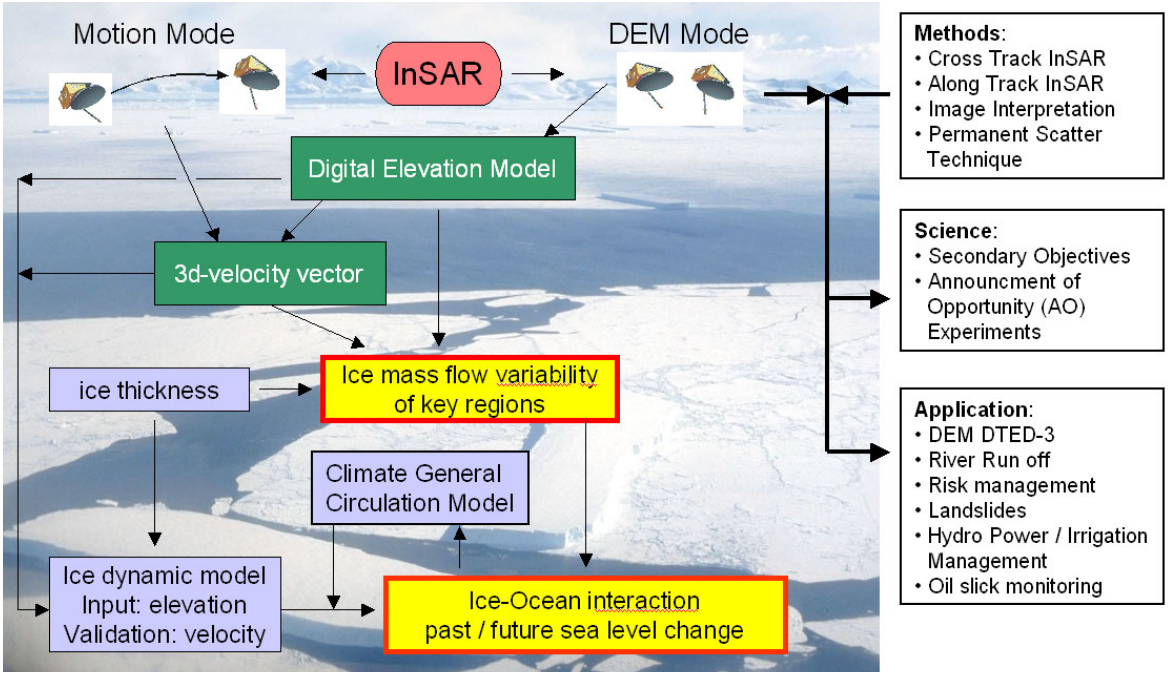

Figure 4: Scheme of the ICEDANCE data flow for the primary mission objective, as well as secondary and application mission objectives.

SUMMARY

We propose a two satellite mission two investigate the dynamics of the cryosphere. The mission shall be divided in two phases: a motion mode, where satellites are separated by several hours or days, depending on the carrier frequency of the system, and a DEM mode, where satellites fly in close formation, at a distance of tenths to hundreds of meters, in order to acquire high precision digital elevation models. Such a system would have, beside the application for cryospheric monitoring, a bundle additional benefits in order to test and apply a series of advanced SAR modes. ICEDANCE adresses key scientific aspects and contributes to major international programs related to processes of the dynamic earth and and of climate change. It will lead to a better understanding of sea level change, mass balance of glaciers and ice sheets, and freshwater influx to oceans, and thereby enhance our ability to generate more reliable scenarios of possible future change. Together with this mission goals and using the same space-borne sensors this mission will facilitate the generation of Digital Elevation Models of extended areas with unprecedented accuracy and resolution. These DEMs will be primary data sets for a number of scientific and operational applications.

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