SIGNAL: Mission Concept and Performance Assessment

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Abstract

SIGNAL (SAR for Ice, Glacier and oceaN globAL dynamics) is a proposal for an innovative Earth observation mission, under study at German Space Agency. The mission objectives include the determination of ice topography and its temporal changes, the monitoring of fast-flowing glaciers, and the characterisation of ocean currents, by using Ka-band synthetic aperture radar (SAR). Two approaches to the mission, including a single satellite with multiple antennas and two free flyers, are presented and critically discussed. A preliminary performance analysis for the key mission measurements has been performed and will be presented.

1 Introduction

The research activities, carried out within the International Polar Year 2007/2008, indicate that dramatic changes have occurred in the Arctic and Antarctica over recent years [1]. In particular, there is a wide agreement among the science community on the following statements:

- the global surface temperature has increased, especially at higher northern latitudes;
- the average sea level has risen by about 3.1 mm/year since 1993 – this is only partly due to the thermal expansion of oceans, as the melting of mountain glaciers and ice sheets also plays an important role;
- the average snow-covered area has decreased by about 5% since 1980.

Climate models foresee a further increase in temperature and sea level. According to these models, a complete melting of the Greenland ice sheet might occur over the millennia, determining a 7 m rise in the sea level. Recent studies predict a global mean sea level rise more than twice as large as this projection. The inputs and outputs of these models, however, suffer from considerable uncertainties.

A reliable estimation of the total mass balance can be based on the measurement of the topographic changes in the Artic and Antarctica [2]. By systematically monitoring the latter regions, SIGNAL would provide precise measurements of these changes.

2 Project Description

2.1 Objectives

The primary objectives of SIGNAL are:

- the quantification of the topographic changes of Greenland and Antarctic ice sheets;
- the systematic observation of the dynamics of fast-flowing glaciers;
- the characterisation of ocean currents and their temporal and spatial changes, to which the sea level elevation and the water temperature and salinity are closely related.

2.2 Frequency selection

In order to accomplish the above mentioned objectives, a Ka-band radar sensor has been selected. As far as the selection of the carrier frequency is concerned, the Ka-band frequency range (35.75 GHz) offers distinct advantages in the observation of ice structures.

Firstly, only an insignificant part of the energy of the electromagnetic wave penetrates through ice / snow at those wavelengths. The scattering centre therefore lies on the ice / snow surface, thus allowing precise topographic measurements.

In addition, the larger possible bandwidth (up to 500 MHz are available) allows to achieve finer spatial resolutions, leading to a more accurate feature-tracking, to the detection of coherent changes within the cell, and to the identification of quasi-deterministic scatterers.

As far as the atmospheric losses are concerned, in the event of heavy rain, a significant attenuation would occur, making the received signals useless. Those events, however, are expected to be rare.

As far as the system is concerned, the short wavelength enables the employment of rather small antennas on-board, and a light-weight and low-cost satellite bus.

2.3 Measurement techniques

The radar sensor is flown on a satellite, according to one of the approaches described in the following section. Synthetic aperture radar (SAR) images of the areas of interest are taken. In particular, the mission has to be designed so that the Antarctic continent and Greenland are observed frequently enough to track the movements of fast-flowing glaciers.

Quantitative measurements of the ice topography are obtained by means of across-track interferometry. Due to the short wavelength (λ = 8.6 mm), the height sensitivity of the interferometer is high, even when the baseline is relatively small. Topographic measurements taken at different times are then subtracted to obtain the topographic changes.

Fast flowing glaciers, instead, are observed by using speckle and feature-tracking techniques, which, in contrast to interferometry, allow the detection of rapid changes and the direct measurement of the two-dimensional motion of the glacier, even when coherence is lost [3].

The ocean currents, finally, can be monitored by means of along-track interferometry [4].

3 Mission Concepts

Interferometric techniques require that a given scene is observed from slightly different incidence angles. In case these observations are taken at different times (repeat-pass interferometry), temporal decorrelation occurs. The effect of such a decorrelation is particularly pronounced at Ka-band and the accuracy of the digital elevation models (DEMs) suffers from it.

Two different approaches, both compatible with single-pass interferometry, are therefore considered and are currently under discussion.

3.1 Single satellite with a boom

One option is to employ a single satellite with multiple antennas. Single-pass interferometry can be performed and highly accurate DEMs can be obtained.

A single satellite leads to a simpler mission scenario, as collision risk has not to be accounted for. On the other hand, the interferometric baseline is fixed and rather short, resulting in a lower height sensitivity of across-track interferometry.

3.2 Two free flyers

As an alternative to the single satellite with multiple antennas, it is possible to consider two satellites flying in a close formation.

In this case, it is possible to employ very large baselines, leading to increased height sensitivity. Moreover, this option offers much flexibility and adaptation to the scientific requirements. Not only are repeat-pass and single-pass interferometry available, but new bistatic geometries can also be exploited to retrieve additional information.

4 Performance Analysis

The feasibility and the performance of the three outlined techniques (across-track interferometry, speckle tracking, along-track interferometry) have been evaluated.

4.1 Across-track interferometry

As already stated, one of the main goals of SIGNAL is to measure changes of the surface topography of ice sheets and glaciers. The interferometric performance of the system is limited by noise-like phenomena, which cause loss of coherence, and by systematic (system or baseline induced) phase errors. The latter can be mitigated through mutual calibration of a large set of repeated and overlapping acquisitions.

Regarding the first ones, single pass interferometry eliminates temporal decorrelation and atmospheric artefacts. A relatively fine range resolution, combined with very short penetration results in very small geometric and volumetric decorrelation effects. Thus the main sources of coherence loss are thermal noise, co-registration errors, quantization noise, and range and azimuth ambiguities. Using as a reference the values considered for the TanDEM-X mission, the last three terms account for a total coherence loss of 0.9.

Noise-like phase errors are mitigated by multi-look filtering of the interferograms. The high resolution achievable by the instrument and the relatively relaxed product posting requirements results in a massive multi-looking scenario, with numbers of looks up or above 500. In converting these phase errors to height errors, the key parameter is the height of ambiguity. In order to make it as small as possible the preferred option is a formation flying solution.

The preliminary performance in terms of height error is provided in **Figure 1**.

Table 1 Instrument parameters assumed for across-track interferometric performance assessment.

Reflector diameter	2 m
Average power	300 W
Receiver Noise Figure	4.5 dB
Pulse bandwidth	40 MHz
Total swath	100 Km
Normal baseline	100 m
Orbit height	780 Km

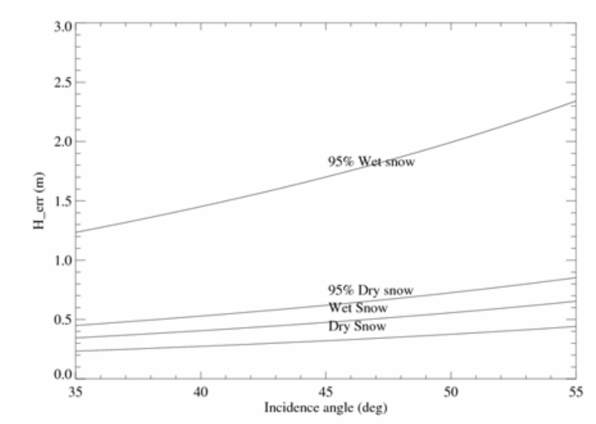

Figure 1 Height error (90% confidence interval) as a function of the incidence angle, for dry and wet snow, considering the average and 95% above back-scattering coefficients reported in [5]. The main mission and instrument parameters assumed are summarized in **Table 1**. A posting of 100 X 100 m, an azimuth resolution of 1 m, and a range resolution corresponding to the given pulse bandwidth and incidence angle have been assumed. Better performance can be achieved by using larger baselines and/or coarser geometric resolutions.

4.2 Interferometric measurements of ocean surface currents

Ocean surface currents can by characterized by means of along-track interferometry. The change in phase, observed between two images of the same surface, taken from the same location and at slightly different times, allows to infer the mean line-of-sight (LOS) velocity of the surface scatterers.

The accuracy of such measurements is strongly dependent on the coherence time of the ocean surface. In particular, very short baselines are required when the coherence time approaches 1 ms (**Figure 2**).

In principle, a short baseline could be synthesised by splitting a single antenna in azimuth. However, from a technological point of view, a reflector is much easier to realise than a Ka-band phased array.

Finally, a very short coherence time limits the azimuth resolution of the SAR image, making the requirements on the posting of the final product (100 X 100 m) difficult to fulfil.

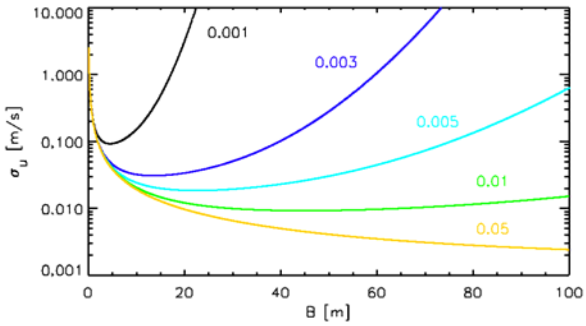

Figure 2 Accuracy of the velocity estimation as a function of the baseline (standard mode), for different coherence time of the ocean surface [s]. Assumed parameters: wavelength = 0.0086 m; satellite velocity = 7500 m/s, number of looks = 300, SNR = 10 dB.

4.3 Monitoring fast-flowing glaciers by means of feature-tracking

According to [6], the velocity of fast-flowing glaciers, up to 10 km/y, should be estimated to an accuracy of 1%, with a spatial posting of 20 to 10 m and a temporal resolution of a few months to one month.

In speckle and feature-tracking techniques, the mean velocity over a given time interval (above referred to as the temporal resolution) is estimated from the mutual shift of patches of SAR images taken over the same area and at different times.

In case the temporal baseline between two consecutive acquisitions is small enough to retain coherence, the mutual shift can be estimated by cross-correlating patches taken from the complex images, thus achieving a considerable accuracy [7]. When the temporal baseline is relatively large and coherence is lost, instead, the mutual shift can only be estimated by exploiting the feature characteristics of the image. In the latter case, as the speckle patterns of the two images are completely uncorrelated, despeckling before correlating the intensity images can be of advantage.

In order to fulfil the scientific requirements, the spatial resolution of the SAR images after despeckling has to be at least as fine as the required spatial posting of the final product. Moreover, in order to meet the requirements on the estimation accuracy of the mean velocity σ_v over the temporal resolution T_r, the accuracy of the mutual shift between two consecutive images $\sigma_{\Delta x}$ has to be no larger than:

$$\sigma_{\Delta x} = T_r \sqrt{\frac{T_b}{T_r}} \sigma_v = \sqrt{T_r T_b} \sigma_v \qquad (1)$$

where T_r is the temporal baseline. For instance, in order to achieve an accuracy of 1% of the velocity (0.2 m/day for a 20 m/day velocity), for a temporal resolution of 60 days and a temporal baseline of 20 days, a shift estimation accuracy of 7 m is required.

As the temporal baseline increases, the features tend to change their shape and orientation, and the matching performance suffers from frequent failures.
Issues like understanding how the feature deformation affects the shift estimation and determining the maximum temporal baseline, can be addressed by analysing real data. A time series of TerraSAR-X images (strip-map mode, 3 X 3 m resolution) from the Helheim glacier, Greenland, has been considered and analysed.
Helheim glacier's velocity during summer is very close to the upper bound of the measurement range (10 km/y), therefore it represents a worst case to test the feature preservation and determine the maximum temporal baseline.
The shift maps depicted in **Figure 4** have been obtained by cross-correlating patches of despeckled intensity images (one of which is provided in **Figure 3**), after having estimated the overall average mutual shift.
No failures are present for a temporal baseline of 11 days. For a temporal baseline of 22 days, some failures appear in those areas, characterised by an abrupt variation of the shift and/or by a low contrast. Finally, a temporal baseline of 33 days leads to a significant number of failures over large areas of the image. In the latter case, it is not even possible to estimate the average mutual shift between the images. A temporal baseline of 11 days is likely to be chosen for the monitoring of such glaciers.
Once a coarse estimation of the mutual shift is available, it is possible to compensate for it, thus establishing a correspondence between the features of the images, e.g. the blocks of ice in a cracked area. These features can then be co-registered individually, leading to a very precise estimation of the shift, well within the accuracy imposed by the scientific requirements.
Lower resolution images have then been obtained by exploiting only part of the range and Doppler available bandwidth. Those degraded resolution data have been processed, showing that it is still possible to obtain coarse shift maps, but the individual matching of the features results in a lower estimation accuracy, because of the lower resolution.

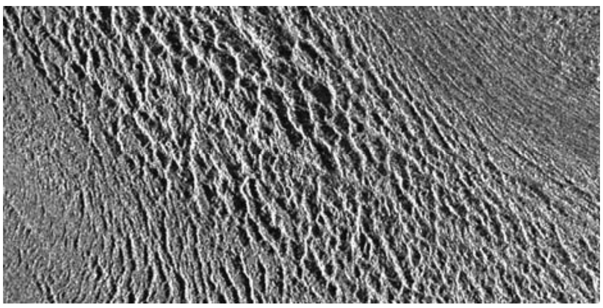

Figure 3 Despeckled X-band SAR amplitude image from the Helheim Glacier, Greenland.

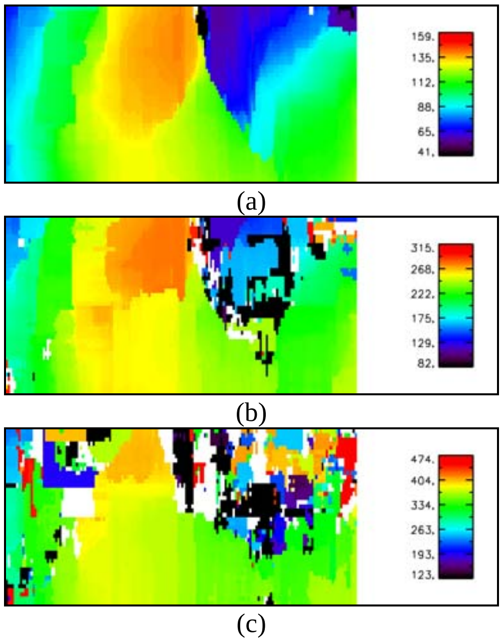

Figure 4 Range shift maps (in pixels) from the Helheim glacier for different temporal baselines (ground range pixel spacing = 1.5 m). (a) 11 days. (b) 22 days. (c) 33 days.

5 Conclusions

A new Earth observation mission for the monitoring of ice, ocean currents and fast-flowing glaciers, has been proposed. A Ka-band sensor has been chosen to take precise measurements by means of interferometry and a performance analysis has been carried out.

References

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