# Glaciers and Ice Sheets Mapping Orbiter Concept

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## Abstract

We describe a concept for a spaceborne radar system designed to measure the surface and basal topography of terrestrial ice sheets and to determine the physical properties of the glacier bed. Our primary objective is to develop this new technology for obtaining spaceborne estimates of the thickness of the polar ice sheets with an ultimate goal of providing essential information to modelers estimating the mass balance of the polar ice sheets and estimating the response of ice sheets to changing climate. Our new technology concept employs VHF and P-band interferometric radars using a novel clutter rejection technique for measuring surface and bottom topographies of polar ice sheets from aircraft and spacecraft. Our approach will enable us to reduce signal contamination from surface clutter, measure the topography of the glacier bed at better than 1 km intervals with an accuracy of 20 m, and paint a picture of variations in bed characteristics. The technology will also have applications for planetary exploration including studies of the Martian ice caps and the icy moons of the outer solar system. Through the concept developed here, *we believe that we can image the base and map the 3-dimenional basal topography beneath an ice sheet at up to 5 km depth.*

## 1.0 Introduction

Glaciers and ice sheets modulate global sea level by storing water deposited as snow on the surface and discharging water back into the ocean through melting and via icebergs. Only recently have we recognized, primarily from satellite observations, that the size of this frozen reservoir can change quickly as demonstrated by the rapid thinning of Jacobshavn Glacier in Greenland [1], Pine Island and Thwaites Glaciers in Antarctica [2] and the demise of the Larsen Ice Shelf followed by thinning of interior Antarctic Peninsula Glaciers. Yet none of these events are captured by current glaciological models suggesting that there are critical gaps in observations and theory about the dynamics of large ice sheets.

Major observational gaps are associated with detailed knowledge of ice sheet basal topography and basal conditions. While much work has been done to measure ice thickness from aircraft, gaps in coverage remain especially over part of Antarctica [3]. Very little information is available anywhere about variations in properties of the subglacial bed where we believe critical changes in the controls on ice sheet flow takes place. Recent technical advances suggest that this situation will change. During 2004 experiments at Summit Camp, Greenland [4], we showed that it is possible to construct local, two-dimensional maps of basal reflectivity using a surface-based SAR approach. These tests demonstrate the first-ever successful imaging of the ice-bed interface through 3-km thick ice with a monostatic SAR operating at incidence angles between 9 and 20 degrees. We observed adequate signal-to-noise ratio both at 150 and 350 MHz. We also collected multiple phase history datasets along 3-km lines at 80, 150 and 350 MHz with HH polarization. These data were collected with offsets ranging from 2 to 10 m to study the use of an interferometric SAR to obtain additional basal topography data with fine resolution.

The success of our Greenland experiments motivated us to develop the conceptual design of a new spaceborne sensor to measure the regional scale 3-dimensional topography beneath the polar ice sheets and to probe, systematically and comprehensively, the base of the polar ice sheets. We call the concept the Global Ice Sheet Mapping Orbiter (GISMO). We ultimately seek to perform pole-to-pole measurements of glacier and ice sheet thickness, basal topography, and physical properties of the glacier bed that will help to answer three fundamental questions: *What is the impact of changing ice sheets on global sea level* *rise?; Can we predict changes in ice sheet volume and hence changes in global sea level as global climate changes?; Can scientific and technical lessons learned about Earth's ice cover be carried over to solving problems about icy bodies in the outer solar system?*

The conceptual design presented here offers two unique features compared to other spaceborne ice sounder designs: instead of providing one-dimensional profiles, a 50 km swath is imaged by each pass; it also uses radar interferometry in a novel way to remove the clutter contamination from the ice sheet surface. Previous spaceborne designs, such as the Europa sounder [5], or the currently operating MARSIS sounder, provide only profiling measurements. These previous designs rely on synthetic aperture (or delay-Doppler) processing to reduce the ice sheet clutter contribution from the ice sheet surface, but still suffer from clutter contamination in the cross-track direction. This clutter contamination is mitigated by increasing the antenna directivity (Europa sounder) or operating at very low frequencies (MARSIS).

## 2.0 Conceptual Design

We envision a unique spaceborne interferometric sounder instrument for obtaining information that will contribute to the understanding of polar ice sheets and glaciers sufficiently to assess their contribution to global sea level rise. The sounder will operate at VHF (130 MHz) and P-band (430 MHz) in interferometric mode at incidence angles near nadir. We have selected a fully polarimetric system to allow for corrections due to ionospheric distortions and Faraday rotation [6, 7]. It will consist of two antennas for interferometric imaging of ice sheets from a spacecraft in a polar orbit. We will employ a novel filtering scheme applied to the interferograms to remove surface clutter and to obtain swath coverage of basal topography and basal reflectivity. The instrument design is such that it can operate in nadir mode or swath mode at incidence angles near nadir and can collect interferometric data in single-pass mode with two antennas or repeat-pass mode. We specify the system in terms of the following observational goals: *1) determine total global ice sheet volume by mapping surface and basal topography; 2) determine basal boundary conditions from radar reflectivity; and 3) understand the phenomenology of radar sounding of ice for applications to planetary studies.*

We offer a novel interferometric system concept capable of overcoming the surface clutter problems and enabling two-dimensional swath mapping of the polar regions in a short duration mission. These attributes lead to significant gains in science capability over current approaches. Our conceptual system consists of a synthetic aperture radar interferometer (InSAR) operating at P-band using a 45 m interferometric baseline and at VHF. We restrict data collection to near nadir incidence angles leading to a 50-km swath that starts at a cross-track distance of 10 km from the nadir track.

An off-nadir swath requires an interferometric radar to estimate height. The height accuracy that can be achieved with an interferometer depends on the signal-to-noise (SNR) and signal-to-clutter (SCR) ratios, the number of radar looks, and the interferometric baseline [8], [9]. Modifying the equations in those references to include ray bending and the presence of a second surface that generates clutter contamination [10], we show that expected retrieved height accuracies better than 10 m for signal to clutter ratios of -10 dB and signal to noise ratios of -5 dB for 50 km wide swaths [11].

The idea behind interferometric filtering for clutter reduction is based on the fact that scattering from ice sheets consists of three components: a) ice-air interface and near surface density variations; b) ice-bed interface; and c) intermediate layers, due mainly to changes in conductivity. The intermediate layers are weakly scattering even in the specular direction (reflection coefficients of –60 to –80dB) and can be neglected at off-nadir incidence. Thus off-nadir scattering can be treated as resulting from two interfaces. The top interface is relatively smooth in the interior, whereas the bottom interface can exhibit varying degrees of roughness. Because the speckle from the two interfaces is not correlated, the average radar interferogram, a complex product between the two interferometric channels, can be modelled as the sum of the interferogram from the basal and surface layers. In the near-nadir direction, the basal fringes (which are due to scattering near nadir) will vary much faster with range (or cross-track distance) than fringes from the clutter (which is generated at larger angles). Basal layer slopes, and, to a lesser degree, ice sheet slopes, will modulate the fringe rate, but in the near nadir direction the main contribution to the fringe rate will be the flat surface term, and surface slopes only play a secondary role.

## 3.0 Simulations

To investigate the interferometric technique under more complex situations, we did a phase history simulation based on these system parameters: 430MHz center frequency; 6 MHz bandwidth; 20 μsec pulse width; platform height of 600 km; baseline of 45 m; PRF of 2000 Hz. For the scene, we selected a region in Greenland where both surface and base digital elevation models (DEMs) are available from the National Snow and Ice Data Center. The ice mass is assumed to lie on rock with a permittivity of 9. A permittivity of 3.24 is used for the ice. A two-layer scene model is adopted, which means that the scattering characteristics within the ice mass and within the base beneath the ice mass is uniform and there are only two boundaries with permittivity discontinuities. The attenuation within the ice mass is assumed to be 9 dB per one kilometer. The thickness of the ice mass varies from about 2000 to 2540 meters. The scene averaged ice thickness is about 2270. The right-looking sensor was assumed to fly on an ascending orbit from south to north with an orbit inclination angle of 85 degrees.

Figure 1 shows the filtered interferogram, which results mainly from the basal signal and so can be used to derive the basal topography and the ice thickness.

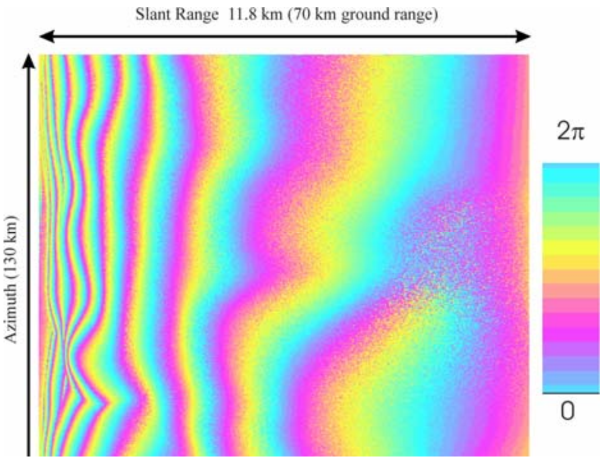


**Figure 1** Band-pass filtered interferogram derived. It mainly represents the basal interferogram contribution, which can be used to derive basal topography and the ice thickness.

Figure 2 shows errors in the derived ice thickness map. The central part of the simulation area shows 0 to 20 m errors. The right-center areas show the largest errors, which are caused by the limitations in our band-pass filter and phase unwrapping schemes. The problems arise in this region from the fact that there is only minimal separation between the surface and basal topography spectra. This effect is expected from purely geometrical arguments, since as the incidence angle increases, the incidence angle for the surface and subsurface approach each other, and the fringe rates of the clutter and subsurface cannot be differentiated [10]. This limitation restricts the swaths that can be achieved from space to be smaller than about 50 km. In practice, this is a small restriction, since complete polar coverage at 60 degrees latitude, can be achieved with fewer than 200 orbits leading to complete polar coverage approximately every 16 days. Additional artefacts are visible on the left side of Figure 2. These roughly vertically stripped patterns are caused by the particular frequency-domain band-pass filter used in this study. A new time-domain band-pass filter is under investigation [10] to improve the quality of the filtered interferogram and to reduce such artefacts.

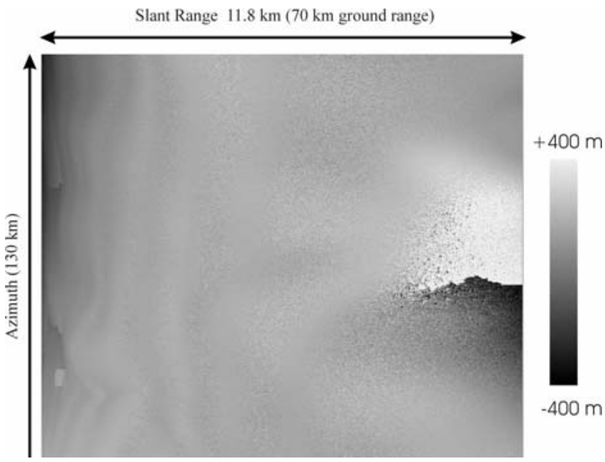


**Figure 2** Ice Thickness Errors.

## 4.0 Conclusions

We envision an instrument capable of generating swath maps of ice basal topography and reflectivity, a measurement not previously possible from space. Our concept is being developed to overcome limitations in conventional sounders that are profiling instruments. Their data consists of backscatter measurements as a function of return time, which can be interpreted as depth below the ice surface. Their spatial resolutions are typically limited by their bandwidth and viewing geometry (the pulse-limited footprint), which for spaceborne instruments is typically on the order of several kilometers. A further and greater limitation of spaceborne sounders is caused by the signal contamination due to surface clutter. Clutter suppression is very difficult to implement from space. For example, the ambiguous return for an ice depth of 1 km observed by a sounder from a height of 600 km would require that the antenna beam be much smaller than 3 degrees. Assuming that one must be at least 2 to 3 beamwidths away from the main lobe to reach the appropriate level of clutter cancellation, this would require an antenna width of 30 m to 40 m at UHF frequencies and approximately 3 times larger at VHF. These antenna sizes, although conceptually realizable, are not yet mature and will likely lead to large mission costs due to launch vehicle and bus requirements.

We plan to test our approach in late 2006 using 430 MHz and 150 MHz radars mounted in NASA's P-3 aircraft. Scaling analyses show we can simulate most spaceborne conditions (fringe rate, fringe separation, spatial correlation) by flying at elevations of about 9 km and using the wing span of the P-3. We will mount a 4-element dipole array under each wing. Our tentative plans are to conduct experiments on the western and central Greenland Ice Sheet. We plan to

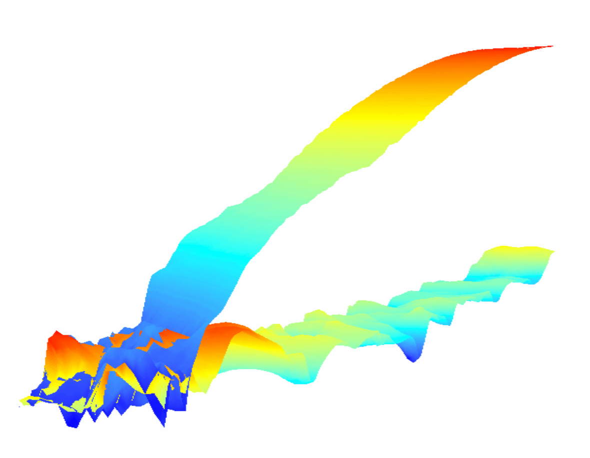

**Figure 3** Ice sheet surface (upper curve) and basal topography along a 780 km long 36 km wide swath from coastal Greenland to the ice sheet summit (data from National Snow and Ice Data Center). The maximum ice thickness is about 3 km. This model will be used for simulation studies of airborne experiments planned for late 2006.

simulate data returns for the airborne case using available topographic data (Figure 3).

Finally, we note that this technology has applications to the scientific exploration of extraterrestrial icy worlds. Surface clutter is a measurement obstacle common to studies of the Martian ice caps as well as to planned studies of the icy moons of the outer solar system. Our technical concept will find important applications for studying the dynamics of the Martian ice caps for and probing the volume of the ice shell suspected of enclosing a liquid ocean on Europa.

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