Probing Ice Sheets with Imaging Radar

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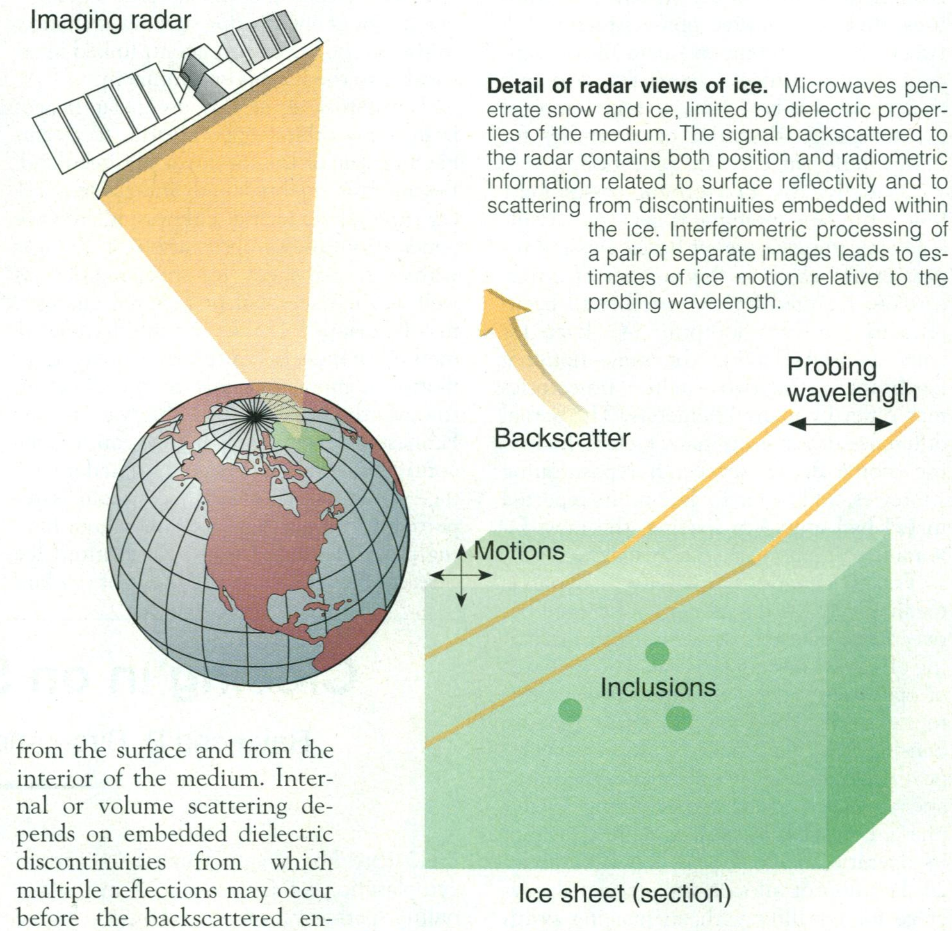
Polar ice sheets are essential elements in the Earth's energy budget; changes in the ice environment are expected to signal trends in global warming. Imaging radar systems are able to observe changes in certain ice parameters with remarkable precision, even from satellite altitudes. Given the operational availability of space-based radar data expected for the next decade and more, the Articles (*1, 2*) of this issue are both pertinent and timely. These results exploit quantitative radar techniques to observe ice sheet movement and metamorphosis, demonstrated over extensive regions of both Greenland and Antarctica.

There are two spatial scales of concern, set by the system resolution and by the radar wavelength. Coherence is the key system characteristic that is exploited. Coherence implies that the phase of the reflected field is defined well enough and contains information about the scene that may be used in signal processing. Coherence is required of a synthetic aperture radar (SAR) so that fine-resolution imagery can be produced, on the order of 25 m for civilian space radars. This is accomplished through the coherent addition of data to yield an effective antenna aperture much larger than its physical size. Having a coherent system also opens the way for radar interferometry. Through interferometry, motions in the scene may be observed relative to the size of the probing wavelength, which typically is on the order of 5 cm.

A typical satellite scenario is illustrated in the figure. The radar, operating from an altitude of 800 km, illuminates the scene. The backscattered field is received and recorded, then processed to form an image. Changes in the scene are expressed through differences between two images, which are collected at different times. Fahnestock *et al.* (*1*) examine the implications of different ice reflectivity seen in one image and consider changes during a relatively long interval of many months to a year or more, using conventional image comparison. In contrast, Goldstein *et al.* (*2*) use interferometry with pairs of images obtained with a relative short interval of 6 days. Both approaches have advantages and limitations.

Electromagnetic energy penetrates an illuminated surface to a depth that is proportional both to radar wavelength and to the inverse loss tangent of the medium. The loss tangent of ice is increased with increased salinity; new and first-year sea ice give rise primarily to surface reflectivity. On the other hand, glacial ice and snow packs, such as those found on Greenland and the extensive ice shelves of Antarctica, have very small loss tangents. For such low-loss materials, the radar echo arises both from the surface and from the interior of the medium. Internal or volume scattering depends on embedded dielectric discontinuities from which multiple reflections may occur before the backscattered energy escapes. The dielectric properties of ice and snow change with changes in the temperature history and profile in the ice and are particularly affected by cycles of freezing and thawing. Thus, the strength of the radar backscatter is correlated with the internal structure. It follows that reflectivity patterns in the image of an extended ice sheet may be used to identify areas of similar physical characteristics (*1*). Between one image and another gathered after a long interval, differences in radar brightness reflect seasonal or annual changes in the mean physiography of the ice sheet, and spatial shifts of 100 m or more may be observed in the boundaries of isomorphous zones.



Detail of radar views of ice. Microwaves penetrate snow and ice, limited by dielectric properties of the medium. The signal backscattered to the radar contains both position and radiometric information related to surface reflectivity and to scattering from discontinuities embedded within the ice. Interferometric processing of a pair of separate images leads to estimates of ice motion relative to the probing wavelength.

For a radar image composed of a file of complex numbers, which is the natural output of a coherent radar such as a SAR, the conventional (real) image of scene backscatter may be formed by multiplying the complex file by a conjugate of itself. For interferometry, the same algorithm is followed, but there is an essential difference: Rather than starting with a pair of identical data files, interferometry uses two files from the same scene but gathered under different circumstances. Ideally, the only significant difference between them is in their phase structure. When this is true, then their complex product leads to a real image of the scene, modulated by the fringes arising from the pattern of phase differences between the two files. For the work of Goldstein *et al.* (*2*), the fringes describe patterns of ice movement with a precision of less than a centimeter.

A classical interferometer consists of two (nearly) simultaneous paths, and it registers phase differences in response to changes in one path. Simultaneous two-path observation is not a practical ap-

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proach for spacecraft radars. Some years ago in a brilliant concept, it was observed that coherence should obtain for two separate passes of a single space-borne radar if the two orbits were sufficiently close together (*3*). The technique has been demonstrated repeatedly for the derivation of terrain height profiles, for which an orbital separation on the order of a kilometer is typical. For observation of displacements in the scene, such as vertical or horizontal motion between the two radar observations, the two orbits should be nearly identical.

Coherence of the radar is necessary, but not sufficient, for interferometry. There also are conditions on both the viewing geometry and the scene reflectivity. The two reflected fields must be such that they are mutually coherent. Even when the viewing geometry may be identical, if the backscattered field is different on the two opportunities, then the relative phase structure between the two (complex) data files is random, and no fringes can result. It follows that there are both spatial and temporal constraints on the orbit opportunities for SAR interferometric data collection.

Spatially, the two orbital passes must follow the same nominal trajectory. Available opportunities are set by the mission repeat cycle, which is the number of orbits, or days, required for the satellite to begin retracing its Earth footprint (*4*). Even for pairs of orbits having the same nominal Earth track, the two satellite trajectories may differ by many kilometers. The actual difference depends on many factors, including orbital decay, spacecraft repositioning strategies, and so forth. The orbits reported in (*2*) had only 4-m spacing, the most favorable pair among the set available.

For all situations involving a dynamic medium such as ice, mutual coherence between two data sets decreases with increasing observation time interval. The intervals of opportunity are determined by the orbit repeat cycle. For example, Earth Remote Sensing Satellite-1 (ERS-1) used a 3-day repeat cycle during the commissioning phase and again for a few weeks during a later phase, but a 35-day cycle is more typical of its operational life. Cycles less than about 25 days do not allow complete global coverage for satellites with an imaging swath width of only 100 km, so there is pressure from most users to avoid shorter periodicity. Even with a relatively short interval such as 3 days, if there is temperature change or precipitation in the meantime, then coherence sufficient for useful fringes may not be sustained. It follows that short repeat cycles are preferred for interferometry and that several opportunities should be available for each interferometric pair desired. Moreover, the coherence image (fringe contrast) may be interpreted as a mapping of the degree of change in the reflectivity process, which is complementary to the fringes themselves, whose spacing is proportional to the gradient of bulk movement of the scatterers. Goldstein *et al.* (*2*) apply interferometric motion measurement to the Rutford Ice Stream, one of the main outlets of the West Antarctic ice sheet. Such flows, with rates on the order of 0.5 km/year, account for about 90% of the outflow from the sheet. Details of flow dynamics are difficult if not impossible to observe using standard techniques. The interferometric estimates reported by Goldstein *et al.* are sensitive to differential motions of a millimeter per day, mapped simultaneously over the ice flow width approaching 100 km. Estimates over the area of the sheet derived from interferometry compare favorably with data from in situ observations. Quantitative monitoring of the Rutford Ice Stream and similar phenomena is one means of anticipating significant changes in the Arctic ice environment, linked inextricably to the Earth's environment.

Fahnestock *et al.* (*1*) use radar images from many orbital opportunities to assemble a mosaic of the ice cover of Greenland. Beyond the usual radar advantages of imagery through cloud and darkness, microwave penetration allows observation of changes within the ice sheet. Ice sheet regimes, as well as their seasonal or regional changes, may be mapped. Unlike the interferometric method, which is limited to estimation of motion components only in the direction toward the radar, the observations by Fahnestock *et al.* show changes on a near-continental scale independent of radar vantage point. A significant ice stream is reported in the northeast of Greenland, having physical similarities to the Rutford Ice Stream. Flow rates on the order of 0.5 km/year are estimated using two sets of imagery taken one year apart, although details of differential flow structure are not readily observable. Both articles offer comments on the relative advantages and disadvantages of various satellite techniques for monitoring changes in ice sheets.

There are two imaging radar satellite systems now in Earth orbit and at least four more planned for operation during the next 10 years (*4*). All of these have high resolution (nominally 25 m or better) and are capable of routine and repeated observation of the Earth's ice distribution. From the standpoint of ice studies and global change, it would make sense to establish a set of test sites in both the Arctic and Antarctica for regular observation by these systems over many years. In principle, both the image registration technique and the space-borne radar interferometer technique may be used with these radars. However, none of them have been designed with interferometric capability as a mission requirement. With the exception of commissioning phases of certain systems, only the ERS-1 and ERS-2 radars include 3-day revisit cycles, from which they have access to only a fraction of the globe, and then only during the northern winter season. The value of these satellite radars would be enriched if short revisit intervals were adopted for a part of each mission so that interferometry, both in the polar regions and for other global applications, could be supported.

References and Notes

1. M Fahnestock *et al.*, *Science* **262**, 1530 (1993).
2. R M. Goldstein *et al.*, *ibid.*, p 1525.
3. A. K. Gabriel, R M. Goldstein, H. A. Zebker, *J. Geophys. Res.* **94**, 9138 (1989).
4. For a review of imaging radar satellites, see *Proc. IEEE* **79**, 6 (1991).

Closing in on SH2 Specificity

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SH2 (Src homology 2) motifs in certain cytoplasmic proteins are crucial in the signaling pathways of the tyrosine kinase growth factor receptors (*1*, *2*). SH2 domains are 100–amino acid stretches of protein that bind to other proteins containing phosphotyrosine. Short, conserved motifs, primarily three to four amino acids on the carboxyl-terminal side of a phosphotyrosine residue, may actually carry the sequence-specific information for SH2 recognition. The mechanisms behind this specificity are now being unraveled.

Evidence of sequence specificity outside the phosphotyrosine was first inferred from the observation that not all tyrosine kinase receptors (which autophosphorylate on tyrosine residues) bound the same SH2-containing proteins (*3*). Subsequently, small phosphopeptides derived from the primary structure of the platelet-derived growth factor (PDGF) receptor were shown to interfere with guanine triphosphatase (GTPase)–activating protein (GAP) and p85 [a subunit of phosphatidylinositol (PI) 3-kinase] binding to the kinase insert region of the PDGF receptor (*4*). The motif identified,

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