OBSERVING THE ANTARCTIC ICE SHEET USING THE RADARSAT-1 SYNTHETIC APERTURE RADAR[1]

Kenneth C. Jezek
Byrd Polar Research Center, The Ohio State University
Columbus, Ohio 43210

Abstract: This paper discusses the RADARSAT-1 Antarctic Mapping Project (RAMP). RAMP is a collaboration between NASA and the Canadian Space Agency (CSA) to map Antarctica using the RADARSAT -1 synthetic aperture radar. The project was conducted in two parts. The first part, which had the data acquisition phase in 1997, resulted in the first high-resolution radar map of Antarctica. The second part, which occurred in 2000, remapped the continent below 80°S Latitude and is now using interferometric repeat-pass observations to compute glacier surface velocities. Project goals and objectives are reviewed here along with several science highlights. These highlights include observations of ice sheet margin change using both RAMP and historical data sets and the derivation of surface velocities on an East Antarctic outlet glacier using interferometric data collected in 2000.

INTRODUCTION

Carried aloft by a NASA rocket launched from Vandenburg Air Force Base on November 4, 1995, the Canadian RADARSAT-1 is equipped with a C-band (5.3 GHz) synthetic aperture radar (SAR) capable of acquiring high-resolution (25 m) images of the Earth's surface day or night and under all weather conditions. Along with the attributes familiar to researchers working with SAR data from the European Space Agency's Earth Remote Sensing Satellite and ENVISAT as well as the Japanese Earth Resources Satellite, RADARSAT-1 has enhanced flexibility to collect data using a variety of swath widths, incidence angles, and resolutions. Most importantly, for scientists interested in Antarctica, RADARSAT-1 can be maneuvered in orbit to rotate the normally right-looking SAR to a left-looking mode. This "Antarctic Mode" provided the first capability for nearly instantaneous, high-resolution views of the entirety of Antarctica on each of two mappings. The first, Antarctic Mapping Mission (AMM-1) began on September 9, 1997 and was successfully concluded on October 20, 1997. The second, Modified Antarctic Mapping Mission (MAMM) began on September 3, 2000 and was successfully concluded on November 17, 2000. For both projects, The Ohio State University (OSU) provided overall project and scientific direction as well as production of final products. The Alaska SAR Facility acquired and processed all the signal data to images. The Jet Propulsion Laboratory developed acquisition strategies and the initial signal data processing system. Vexcel Corporation developed the RADARSAT Antarctic Mapping System used by OSU to create

[1]This work was supported by grants from NASA's Pathfinder Program and NASA's Polar Oceans and Ice Sheets Program, and with the support of the Canadian Space Agency (CSA).

Polar Geography, 2003, **27**, No. 3, pp. 197-209.

final products and provided ASF with the data processing system for the MAMM activity. Geodetic control for the final map and velocity products was provided by the Environmental Research Institute of Michigan and by contributions of measurements from international participants in the Scientific Committee for Antarctic Research (SCAR).

ANTARCTIC MAPPING MISSION-1

Antarctica is the coldest, windiest, and—on average—highest continent on earth. Shrouded in darkness during the austral winter and often obscured from view by persistent cloud cover, Antarctica has remained one of the most poorly mapped parts of our planet. That situation changed in 1997, when RADARSAT-1 began to scan Antarctica from space. The goal of the project was to create the first high-resolution radar image of the continent. The resulting map was intended to serve as a benchmark for gauging future changes in the polar ice sheet, to understand more about the behavior of the glacier and its interaction with the polar atmosphere and coastal ocean, and to simply expand our ability to explore the vast, remote, and often beautiful southernmost continent.

The Approach

The first Antarctic imaging campaign was made possible by the unique capabilities of RADARSAT, including an electronically steerable antenna array that provided a range of selectable beam pointing angles. This capability was essential for maximizing the range of the acquisition swaths away from the satellite nadir track. The satellite also can maneuver in orbit, enabling it to change the look direction of the SAR. These two capabilities permitted acquisitions to the Earth's South Pole and represent technical abilities afforded by no other civilian spaceborne radar (Jezek, 1999).

AMM-1 acquisitions began seven days earlier than the anticipated start of the nominal acquisition plan. The early data constituted an important contingency against anomalies encountered later in the mission. Nominal acquisitions started on schedule shortly after noon Eastern Standard Time (EST) on September 26, 1997. The nominal plan was designed to obtain complete mapping coverage within 18 days. The nominal plan proceeded nearly flawlessly through completion on October 14. It was executed in parallel with acquisition plans for other RADARSAT-1 users and with CSA's Background Mission. An additional opportunity was realized because of the early start on September 19. Radar data collected after the conclusion of the nominal mission were acquired exactly 24 days after the beginning of the early start data. This schedule repositioned the spacecraft to within a few hundred meters of its position 24 days earlier. Consequently, the data are suitable for interferometric analysis—a demonstrated technique for estimating ice sheet surface displacement. Exact repeat data collections started on October 14 and continued through October 20 (Fig. 1).

Preparations to return the satellite to normal operations began on October 20. Arctic mode operations resumed on October 23. Acquisitions for customers resumed on October 26. This occurred nine days ahead of the planned schedule.

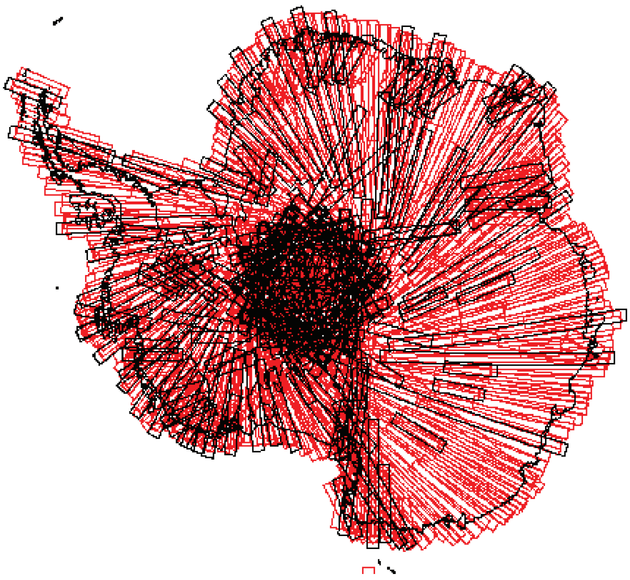

Fig. 1. AMM-1 swath coverage. Red swaths are the nominal acquisitions. Black swaths show 24-day repeat passes suitable for interferometry.

The Mosaic

Satellite signal-data were captured at several ground receiving stations and were then forwarded to the Alaska SAR Facility (ASF). The ASF processed the data to images, which were later orthorectified and mosaicked at OSU using software tools developed by Vexcel Corporation. We used the OSU Antarctic Digital Elevation Model during the orthorectification process (Liu et al., 1999; Jezek et al., 2000). The final mosaic covers the entire continent at 25 m pixel size. The map is a polar stereographic projection with a standard latitude of 71°S and is referenced to the WGS84 ellipsoid.

The RAMP mosaic is truly a new view of Antarctica (Fig. 2) and it reveals new and exciting features about Antarctica. First, there are large-scale spatial variations in radar brightness. The bright portion of Marie Byrd Land and the eastern sector of the Ross Ice Shelf probably represent the region where significant melting and refreezing occurred during an early 1990s melt event. Most of the coastal areas and much of the Antarctic Peninsula also appear bright because of summer melt. But unlike Greenland, where most of the large-scale brightness patterns are associated with firn melt facies, the remaining, strong variations in radar brightness are poorly understood. At a somewhat smaller scale, thousands-of-kilometers-long curvilinear features snake across East Antarctica. These appear to follow ice divides separating the large catchment areas. The reason why the ice divides appear so prominently in the radar imagery is unknown.

On an intermediate scale, the East Antarctic Ice Sheet appears to be very "rough." The texturing is probably due to the flow of the ice sheet over a rough glacier bed. Textures are particularly strong paralleling the flanks of the Transantarctic Mountains

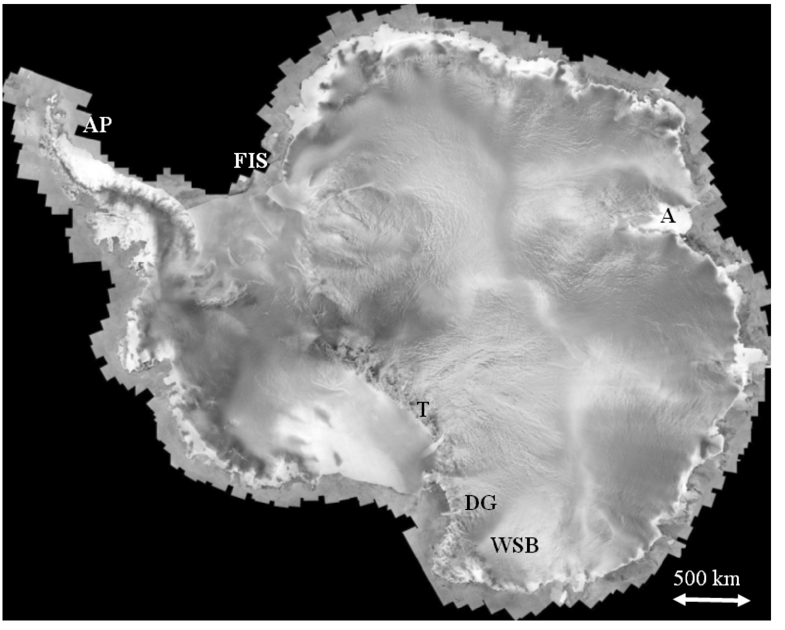

Fig. 2. RADARSAT-1 SAR mosaic of Antarctica. Light shading indicates strong backscatter. Dark shading indicates weak backscatter. Locations noted in the text are: AP = Antarctic Peninsula; T = Transantarctic Mountains; DG = David Glacier; WSB = Wilkes Subglacial Basin; A = Amery Ice Shelf; FIS = Filchner Ice Shelf.

and extending deep into adjacent portions of the East Antarctic Plateau. Long linear patterns are strongly suggestive of subglacial geology and may indicate that the ice sheet in this area is resting on relatively resistant basement rocks. The texture changes abruptly across the northernmost section of the Wilkes Subglacial Basin located in George V Land. There the imagery shows remarkable, subtle rounded shapes similar in appearance to the signature of subglacial lakes such as Lake Vostok.

Most intriguing are ice stream and ice stream–like features in Queen Maud Land that were partly described in previous research using optical imagery. Ice streams are made visible by the intense crevassing along the shear margins where chaotic surface roughness results in a strong radar echo (Fig. 2). Fast, channeled flow, which are two of the diagnostic characteristics of ice streams, are evident in the surface velocity field computed from repeat-pass interferometry (described in the next section) (Fig. 3). Slessor Glacier is located on the northeastern margin of the Filchner Ice Shelf. The upper reaches of the glacier consist of a network of tributaries that feed a funnel-shaped midsection. Patches of crevasses punctuate the interior of the funnel. The ice stream is about 450 km long from the grounding line to the upstream area.

An enormous ice stream, reaching at least 800 km into East Antarctica, feeds Recovery Glacier. It too is fed by a funnel-shaped catchment. Down-glacier, crevasses cascade across the ice stream at several locations, suggesting that strong variations in basal topography modulate the flow. The confluence of a thin, elongated, 280 km-long tributary ice stream with Recovery Glacier is located approximately 250 km from the constriction where Recovery Glacier enters the Filchner Ice Shelf.

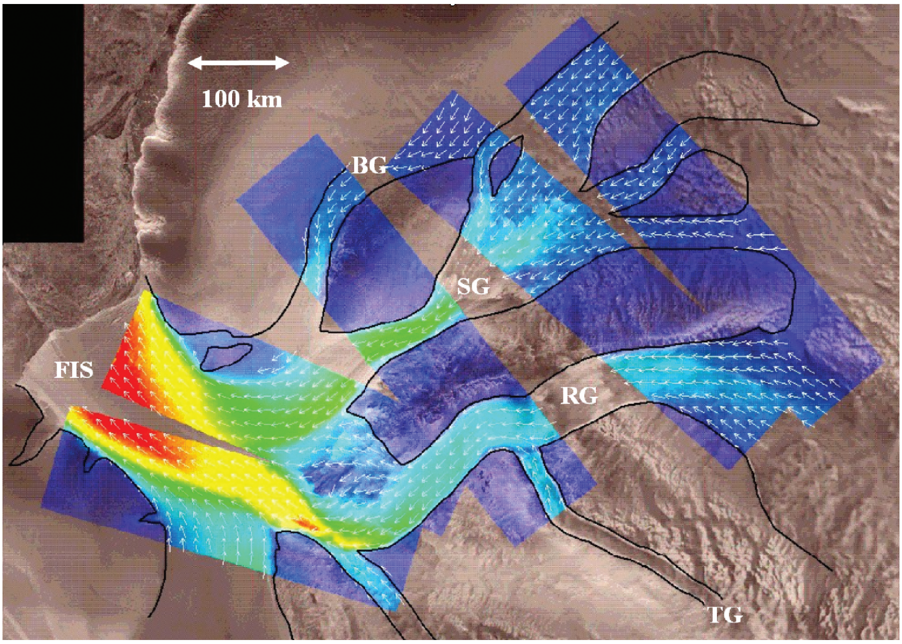

Fig. 3. Ice streams draining into the Filchner Ice Shelf (FIS). Velocities are from radar interferometry (10 m/yr purple to over 1 km /yr red). The largest streams are Bailey (BG), Slessor (SG), Recovery (RG), and a tributary glacier (TG) feeding into the Recovery Glacier. Glacier margins are outlined in black.

The central body of the pipe-like tributary is crevasse free, indicating that shear stresses are concentrated only at the margins. The tributary is an enigma in that there is little evidence for ice flow into the tributary from the adjacent ice sheet and there is little if any indication as to the source of ice from the up-glacier catchment region.

MODIFIED ANTARCTIC MAPPING MISSION

Why MAMM?

Glaciers and ice sheets move under the load of their own weight. They spread and thin in a fashion dictated by their thickness, the material properties of ice, and the environmental conditions on the glacier surface, sides, and bottom. Measurements of Antarctic ice sheet surface motion are of keen interest to geoscientists. The rate and direction of motion reveals important information about the forces acting on the glacier, provides knowledge about the rate at which ice is pouring into the coastal seas, and enables scientists to predict how the ice sheet might respond to changing global climate.

Glacier motion has intrigued scientists and lay people for over a century. In 1880, the American author Mark Twain wrote of his experiences with alpine glacier motion in his book *A Tramp Abroad*:

> I was aware that the movement of glaciers is an established fact; so I resolved to take passage for Zermatt on the great Gorner Glacier. The next thing was, how to get down the glacier comfortably. I marched the Expedition down the steep and tedious mule-path and took up as good a position as I could upon the middle of the glacier—because Baedeker said the middle part travels the fastest. I waited and waited, but the glacier did not move. Night was coming on, the darkness began to gather—still we did not budge.

While Twain was disappointed in the outcome of his adventure, his approach was essentially correct. Since the International Geophysical Year of 1957–1958 and before, scientists have placed markers on the ice sheet and then, using a variety of navigation techniques from sun shots to GPS, have measured and remeasured their positions to calculate motion. More recently, scientists have used high-resolution satellite images to track the position of crevasses carried along with the glacier to compute surface motion. But all of these approaches are time consuming and result in patchy estimates of the surface velocity field.

During the early 1990s, researchers at the Jet Propulsion Laboratory showed that synthetic aperture radar (SAR) offered a revolutionary new technique for estimating the surface motion of glaciers (Goldstein et al., 1993). Here, the SAR is operated as an interferometer. That is, the distance from the SAR to a point on the surface is computed by measuring the relative number of radar-wave cycles needed to span the distance between the radar and the surface. Later, another measurement is made from a slightly different position and the number of cycles is computed again. The difference in the number of cycles is used to estimate displacement to about one quarter of a radar-wave cycle (just a few centimeters for RADARSAT-1). The demonstration of this technique for SARs in general and the demonstration during AMM-1 that the technique worked for RADARSAT-1 in particular (Joughin et al., 1999; Gray et al., 2001; Gray et al., 2002) (see Fig. 3) were the impetus for the Modified Antarctic Mapping Mission (MAMM), which occurred during the fall of 2000.

MAMM had two primary science objectives (Jezek, 2002). The first was to remap the perimeter of the continent and the majority of Antarctica's fast-moving glaciers. Intuitively, these are the areas that are most likely to have experienced change over the intervening three years. The second MAMM objective was more ambitious, that being to obtain as much surface velocity data on the ice sheet as possible.

The New Approach

Acquisitions were planned in two ways to attain this goal. First, data were acquired so that, where possible, the position of structures on the glacier could be compared between the 1997 and 2000 data sets so as to measure point velocities. Second, and the real challenge of MAMM, was to acquire interferometric data to estimate velocity fields. The second approach required the use of RADARSAT-1 fine and standard beams, and unprecedented control of the spacecraft orbit and attitude. As the mission unfolded, CSA spacecraft engineers demonstrated a remarkable ability to navigate the satellite in the manner dictated by the science requirements. The outcomes of this combined effort are extraordinary observations of glacier motion captured over three 24-day RADARSAT cycles.

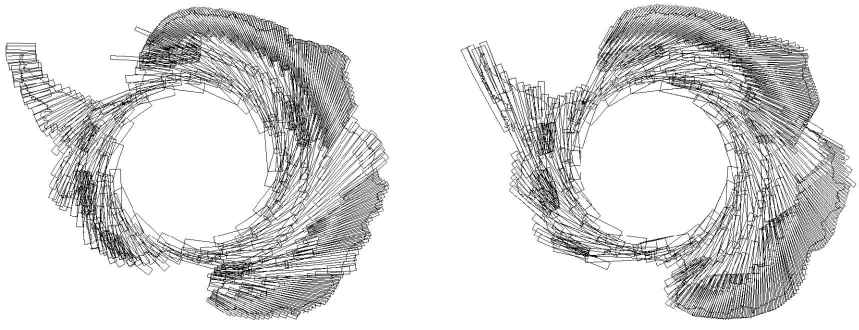

Fig. 4. Ascending (right) and descending (left) cumulative coverage maps for the three MAMM acquisition cycles. Maximum southerly coverage is 80.1°S Lat.

MAMM acquired data from about 80°S Lat. to the Antarctic coast (Fig. 4). Interferometric SAR calculations required that this area be imaged six times during the mission (three times in descending orbit mode and three times in ascending orbit mode). The number and orientation of acquisitions then enable us to measure two components of the surface velocity vector. The third sequence of observations allows for the removal of terrain effects—but in fact, the additional redundancy has proved crucial for dealing with temporal decorrelation effects.

We enjoyed an additional benefit from acquiring RADARSAT-1 Fine-1 beam data. Along with optimizing the interferometric acquisition, this beam mode has azimuth resolution of 8.4 m and a slant range resolution of 5.2 m for a single look (J. Lipscomb, pers. comm., 2001). As part of the processing scheme (Jezek et al., 2003), we create orthorectified, one-look images at 10 m pixel size. We assembled these into minimosaics that capture the finest possible detail from the data set. We compare 10 m and 25 m images in Figure 5, which illustrates the additional detail captured in the minimosaic product. Interestingly, the 25 m MAMM product is superior to the 25 m AMM-1 standard-beam products, because we can average more samples from the fine-beam data and achieve improved speckle reduction. Minimosaics are assembled for all of the fast glacier areas observed in the AMM-1 mosaic (Jezek, 1999). Moreover, because we acquired three cycles of fine-beam data over the fast glaciers, it is possible, in some locations, to use simple correlation feature tracking techniques to derive surface velocities from the MAMM image data directly. This is advantageous in areas where surface velocities are relatively high but where there is strong interferometric decorrelation. Moreover, repeat-pass subcycles can be exploited to measure displacement intervals over a variety of time intervals.

MAMM Science Results

RADARSAT imagery is well suited for mapping the Antarctic ice sheet margin (Liu and Jezek, 2004), and even over just three years, the margin can change appreciably. Some of the most dramatic changes on the continent are occurring along the Antarctic Peninsula, imaged in 2000 by RADARSAT-1 (Fig. 6). The results document the continued retreat of the northern Larsen Ice Shelf. Here we can observe several

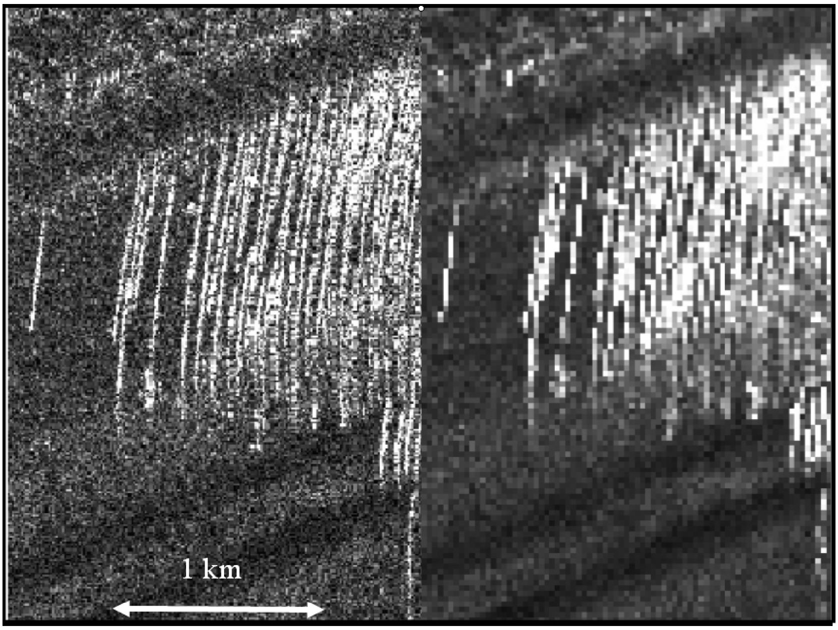

Fig. 5. 10 m single-look (left) and 25 m three-look fine-beam data of a surface crevasse field. The 10 m data, used to produce MAMM minimosaics, provide crisp images of individual crevasses that, when used with additional repeat-pass observations, can be tracked and used to compute surface velocity.

places along the Antarctic Peninsula coastline where the ice shelf edge has retreated over 30 km (18.6 miles) in just three years. But as might be expected, we also observe places where the ice sheet is advancing, such as the Amery Ice Shelf. The RAMP data will help us determine whether the local changes we see represent expected, episodic behavior or whether they represent continental-scale trends.

The principal objective of the MAMM project is to produce surface velocities about the continent. As an example, we discuss interferometrically derived data acquired over the David Glacier and the Drygalski Ice Tongue located in Northern Victoria Land, Antarctica. The ice tongue is a long, relatively narrow, extension of David Glacier onto the Ross Sea. Near the coast, several small outlet glaciers flank the David Glacier, which itself is fed by a system of tributaries (Fig. 7). Surface speeds derived from MAMM interferometric data increase from about 100 m/yr in the upstream portions of David Glacier to about 750 m/yr at the tip of the Drygalski Ice Tongue. The Drygalski Ice Tongue has been studied since the early 1900s. Holdsworth (1985) compared historical, airborne photographic, and Landsat data to estimate a velocity of 730 m/yr ± 36 m/y for a point 50 km from the coast. This is similar to our result of 710 m/yr ± 10 m/y (point 2 in Fig. 7) to within the estimated errors. Several other investigators analyzed sequential Landsat scenes by co-registering images with tie points. Our result at the landward end of the velocity profile (578 m/yr) (point 3 in Fig. 7) compares favorably with Swithinbank's (1988) estimate of 580 m/yr but less than the estimate of Lucchitta et al. (1993)—ca. 640 m/yr. Our

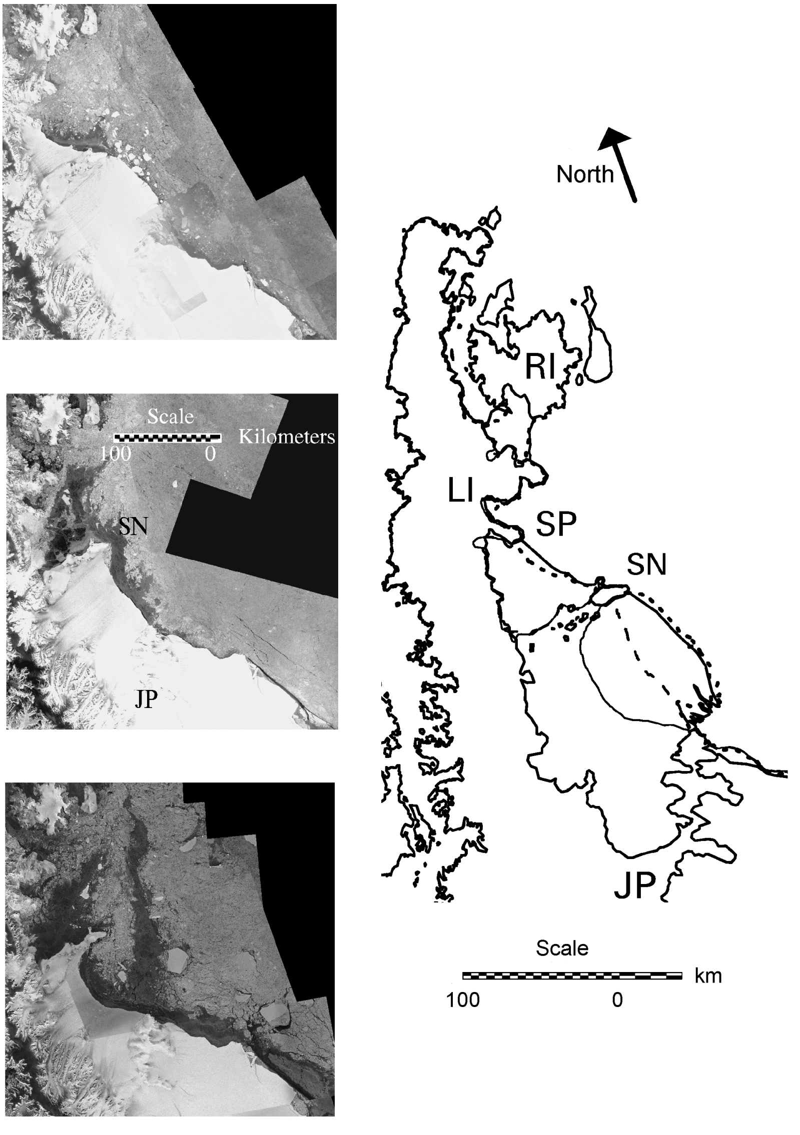

Fig. 6. Northern Larsen Ice Shelf imaged by ERS-1 in 1992 (upper left image), RADARSAT-1 in 1997 (middle left image), and RADARSAT-1 in 2000 (lower left image). Images are centered at 64°43' S and 59°15' W. Line map on the right shows ice margins and grounding lines from the Antarctic Digital Database Version 1 (1989) as the solid line, 1992 ERS-1 SAR data as the short dashed line, 1997 RADARSAT-1 data as the long dashed line, and 2000 RADARSAT-1 data as the thin solid line. The images depict the retreat of the ice shelf that bridged James Ross Island (RI) to the Antarctic Peninsula. Also shown is the retreat of Larsen "A" between the Sobral Peninsula (SP) and the Seal Nunataks (SN) as well as the retreat of ice shelf remnants in Larsen Inlet (LI). A small glacier, located in the southerly junction of the Sobral Peninsula with the Antarctic Peninsula, retreated an additional 3 km from 1997 to 2000. Larsen "B." located between Seal Nunataks and the Jason Peninsula (JP), retreated 31.5 km from 1997 to 2000. We note that the ice shelf south of the Jason Peninsula (Larsen "C") is little changed over the observation period (from Jezek, 2002).

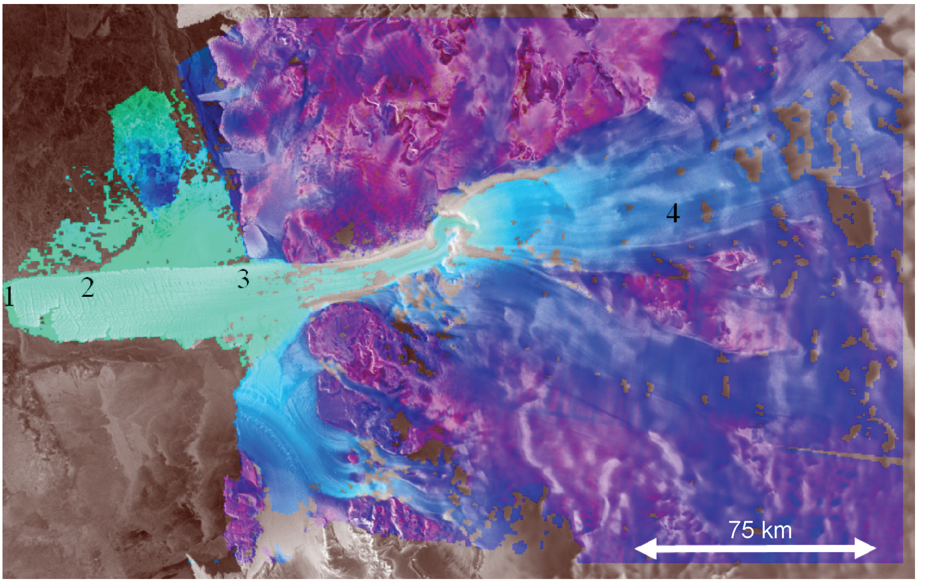

Fig. 7. Surface speed on the Drygalski Ice Tongue and David Glacier derived from MAMM interferometry. Color variations correspond to the scaled logarithm of the velocity so as to highlight streaming patterns in tributaries and smaller glaciers. Speed at point 1 is 755 m/yr; 710 m/yr at point 2; 578 m/yr at point 3; 100 m/yr at point 4.

maximum value (755 m/yr) (point 1 in Fig. 7) is similar to 15-year average-maximum velocities (719 m/yr over 1973–1988) quoted by Frezzotti (Frezzotti, 1993; Frezzotti et al., 2000) but less than Lucchitta et al. (1993), whose estimated 15-year average velocities (1973–1988) near the tip are approximately 800 m/yr. Our maximum values are also less than Frezzotti's 13-month average-maximum velocity of 912 m/y (1988–1990). Frezzotti et al. (1998) compared their Landsat derived velocities with global position data collected on the ice tongue. They found that the GPS velocities agree with the Landsat feature retracking data on the landward half of the ice tongue.

MAPPING WITH RAMP DATA

Geodetic quality of the final AMM-1 and MAMM map products is primarily determined by our knowledge of spacecraft position and instrument pointing directions. Navigational data for RADARSAT-1 are acquired by the Canadian Space Agency using a facility in western Canada. CSA then uses those observations to estimate satellite position along the entire orbit. Prior to the mapping missions, the quality of the position and pointing data over the Antarctic were uncertain. Consequently, ground control points were needed to refine position knowledge over the Antarctic and to act as a validation of the final map products. Many control points were needed about the continent and several were required in the interior. Such a data set was unavailable prior to RAMP and a solution had to be found.

Based on discussions with colleagues at the Environmental Research Institute of Michigan and with the assistance of many organizations that participate in the

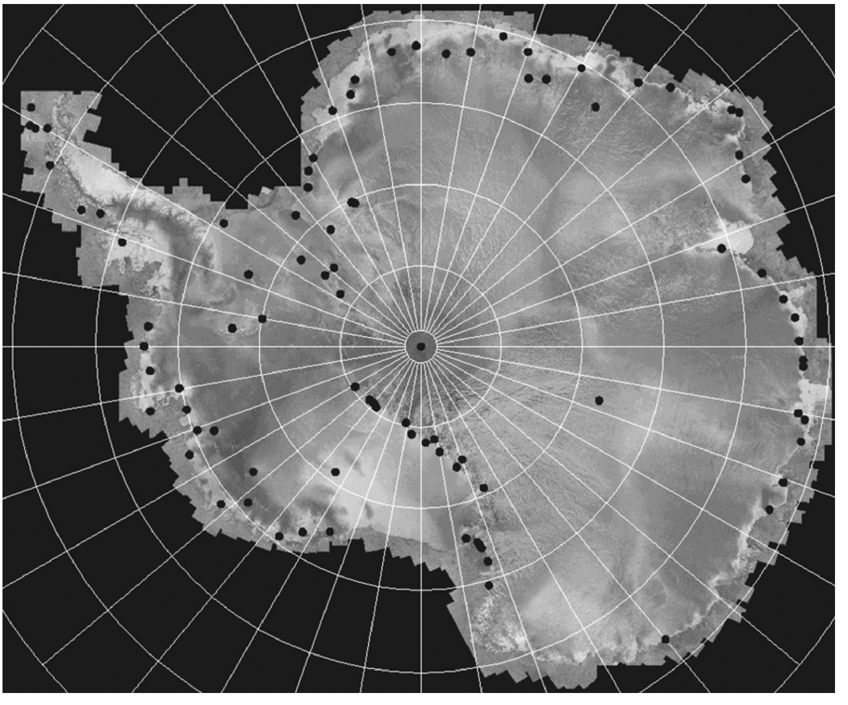

Fig. 8. Distribution of ground control points used to constrain the AMM-1 mosaic. AMM-1 control points and tie points from the AMM-1 mosaic are used to control the MAMM image geometries.

Scientific Committee for Antarctic Research (SCAR) we compiled a database of ground control points (Fig. 8). In addition, an active radar transponder was deployed at South Pole Station, a site visible on every pass of the satellite. Integration of the data into the mapping calculation resulted in at least a twofold increase in expected map accuracy. In places with good knowledge of surface elevation, the positional accuracy is estimated to be better than 200 m. Just as importantly, the control points withheld from the calculation represented an important validation of the map accuracy.

There is a second control issue associated with the interferometric data acquired during MAMM. Interferometry only yields relative displacements across a scene. These then have to be adjusted by knowledge of absolute motion for several points in each radar image. Once again, information from a variety of sources including SCAR and the National Snow and Ice Data Center VELMAP project have been able to provide the required information.

SUMMARY

RAMP is demonstrating the technical capability to acquire nearly instantaneous high-resolution microwave imagery of the entire Antarctic continent. The technical achievement is being followed by an unfolding scientific examination that is revealing the glaciology and geology of Antarctica in unexpected detail. Of equal importance is the fact that the acquisitions provide an important benchmark for gauging and understanding future changes in the Antarctic.

As this new century unfolds, it is interesting to reflect on the fact that we now possess the ability to regularly observe the entirety of our world with unprecedented detail and across a wide portion of the electromagnetic spectrum. The RADARSAT program, building on a scientific, engineering, and political heritage dating back to the early days of the Corona missions, is a demonstration of that ability and of the requisite international commitment necessary to achieve such a goal. In turn, that ability levies a responsibility on the science community to forcefully argue for regular acquisition of such information in a fashion that is accessible and understandable to anyone interested in the results and pondering their implications.

LITERATURE

Frezzotti, M. "Glaciological study in Terra Nova Bay, Antarctica, inferred from remote sensing analysis," *Annals of Glaciology*, Vol. 17, 1993, pp. 63-71.

Frezzotti, M., A. Capra, and L. Vittuari. "Comparison between glacier velocities inferred from GPS and sequential satellite images," *Annals of Glaciology*, Vol. 27, 1998, pp. 54-60.

Frezzotti, M., I. E. Tobacco, and A. Zirizzotti. "Ice discharge of eastern Dome C drainage area, Antarctica, determined from airborne radar survey and satellite image analysis," *Journal of Glaciology*, Vol. 46, No. 153, 2000, pp. 253-264.

Goldstein, R., H. Engelhardt, B. Kamb, and R. Frolich. "Satellite radar interferometry for monitoring ice sheet motion: Application to an Antarctic ice stream," *Science*, Vol. 262, 1993, pp. 1525-1530.

Gray, A. L., N. Short, K. Mattar, and K. C. Jezek, "Velocities and flux of the Filchner ice shelf and its tributaries determined from speckle tracking interferometry," *Canadian Journal of Remote Sensing*, Vol. 27, No. 3, 2001, pp. 193-205.

Gray, L., N. Short, R. Bindschadler, I. Joughin, L. Padman, P. Vornberger, and A. Khananian. "RADARSAT interferometry for Antarctic grounding-zone mapping," *Annals of Glaciology*, Vol. 34, 2002, p. 269-276.

Holdsworth, G. "Some effects of ocean currents and wave motion on the dynamics of floating glacier tongues," *Antarctic Research Series*, Vol. 43, 1985, pp. 253-271.

Jezek, K. C. "Glaciologic properties of the Antarctic Ice Sheet from spaceborne synthetic aperture radar observations," *Annals of Glaciology*, Vol. 29, 1999, pp. 286-290.

Jezek, K. C. "RADARSAT-1 Antarctic Mapping Project: Change detection and surface velocity campaign," *Annals of Glaciology*, Vol. 34, 2002, pp. 263-268.

Jezek, K., R. Carande, N. Labelle-Hamer, K. Noltimier, and X. Wu. "RADARSAT-1 synthetic aperture radar observations of Antarctica: Modified Antarctic Mapping Mission 2001," *Radio Science*, Vol. 38, No. 4, 2003, p. 8067-8073.

Jezek, K., H. Liu, Z. Zhao, and B. Li, "Improving Antarctic digital elevation model by using radar remote sensing and GIS techniques," *Polar Geography*, Vol. 23, No. 3, 2000, pp. 209-224.

Joughin, I. and 7 others. "Tributaries of West Antarctic ice streams revealed by RADARSAT interferometry," *Science*, Vol. 286, No. 5439, 1999, pp. 283-286.

Liu, H. and K. Jezek. "A complete high-resolution coastline of Antarctica extracted from orthorectified Radarsat SAR imagery," *Photogrammetric Engineering and Remote Sensing*, Vol. 70, No. 5, 2004, pp. 605-616.

Liu, H., K. Jezek, and B. Li. "Development of Antarctic digital elevation model by integrating cartographic and remotely sensed data: A GIS-based approach," *Journal of Geophysical Research,* Vol. 104, No. B10, 1999, pp. 23,199-23,213.

Lucchitta, B. K., K. F. Mullins, A. L. Allison, and J. G. Ferrigno. "Antarctic glacier tongue velocities from Landsat images: First results," *Annals of Glaciology*, Vol. 17, 1993, pp. 356-366.

Swithinbank, C. "Antarctica," in R. S. Williams, Jr. and J. G. Ferrigno eds., *Satellite Image Atlas of Glaciers of the World*. Washington, DC: U.S. Geological Survey Professional Paper 1386–B, 1988, 278 pp.