

## **RADARSAT-1 Antarctic Mapping Project**

Carried aloft by a NASA rocket launched from Vandenberg Air Force Base on November 4, 1995, the Canadian Radarsat-1 is equipped with a C-band Synthetic Aperture Radar (SAR) capable of acquiring high resolution (25 m) images of 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 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' provides capability for the first time of 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 mission (MAMM) began on September 3, 2000 and was successfully concluded on November 17, 2000. For both projects, The Ohio State University provides overall project and scientific direction as well as producing final products. The Alaska SAR Facility is responsible for data acquisition and processing signal data to images. The Jet Propulsion Laboratory is responsible for developing acquisition strategies and for data processing system development. Vexcel Corporation is responsible for developing the RADARSAT Antarctic Mapping System used by OSU to create final products. Geodetic control for the final map and velocity products is provided by NIMA and ERIM through an activity initiated by MEDEA.



*CSA illustration of the Radarsat Satellite. The SAR antenna shown in gold beneath the satellite is 15 m long and 1.5 m wide.*

### ***Antarctic Mapping Mission -1***

#### *The Goal*

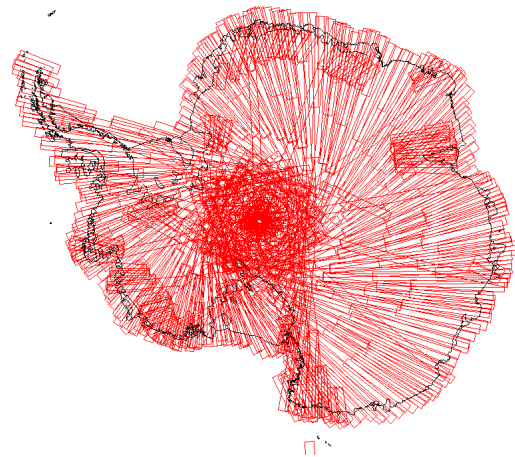
Antarctica is the coldest, windiest and on average, highest continent on earth. Shrouded in darkness during the austral winter and often obscured from view by persistent cloud cover, Antarctica has remained one of the most poorly mapped parts of our planet. That situation changed in 1997 when RADARSAT-1 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 (AIC-1) 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.

AIC-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 on September 26. 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.



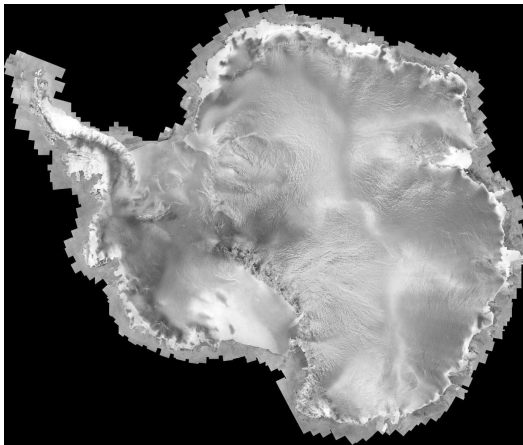
*AMM-1 swath coverage.*

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 9 days ahead of the planned schedule.

### *The Mosaic*

The RAMP mosaic, shown here at reduced (4 km) resolution is truly a new view of Antarctica. We observe several new and exciting features about Antarctica from the

mosaic. 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 1990's melt event. Most of the coastal areas and much of the Antarctic Peninsula appear bright also 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.



*1997 Radarsat Mosaic*

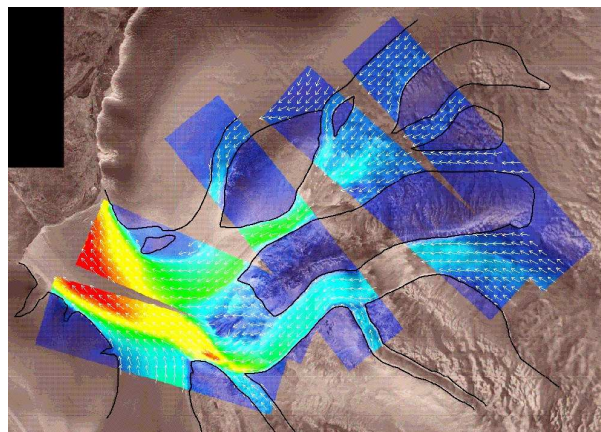
Thousands-of-kilometer long curvilinear features snake across East Antarctica. These appear to follow ice divides separating the large catchment areas. The reason that the ice divides appear in the radar imagery is unknown

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, Pensacola and Shackelton

Mountains 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 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. Complexities within the interior of the ice streams are revealed by radar flow stripes that probably originate from subtle variations in topography. Slessor Glacier is located on the northeastern margin of the Filchner Ice Shelf. The upper reaches of the glacier are funnel shaped with the interior of the funnel punctuated by patches of crevasses. The ice stream is about 450 km long from the grounding line to the upstream



*Ice streams draining into the Filchner Ice Shelf. Velocities are from radar interferometry (10 m/yr purple to over 1 km /yr red). The largest streams are Bailey (upper left), Slessor (middle), and Recovery (lower right).*

area that seems to be characterized by several long scars. The scars are probably shear margins but it is not possible to deduce whether they are recently initiated or relict ice stream flow.

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. 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. A less active pipe-like tributary merges with Recovery Glacier just upstream of the grounding line. The uppermost portion of that 300 km long tributary is dark and featureless, similar to the eastern companion. Down glacier, the tributary surface is similarly mottled to the adjacent ice sheet.

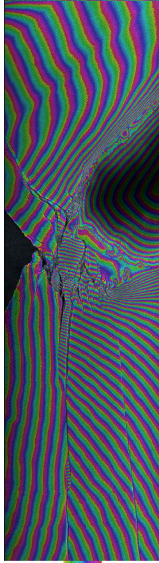
## ***Antarctic Mapping Mission - 2***

### ***Why AMM-2?***

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 scientist 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 idea, his approach was essentially correct. Since the International Geophysical Year of 1957-58 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 1990's, researchers at the Jet Propulsion Laboratory showed that synthetic aperture radar (SAR) offered a revolutionary new technique for estimating the surface motion of glaciers. 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 numbers 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 were the impetus for the Modified Antarctic Mapping Mission (MAMM) which occurred during the fall of 2000.

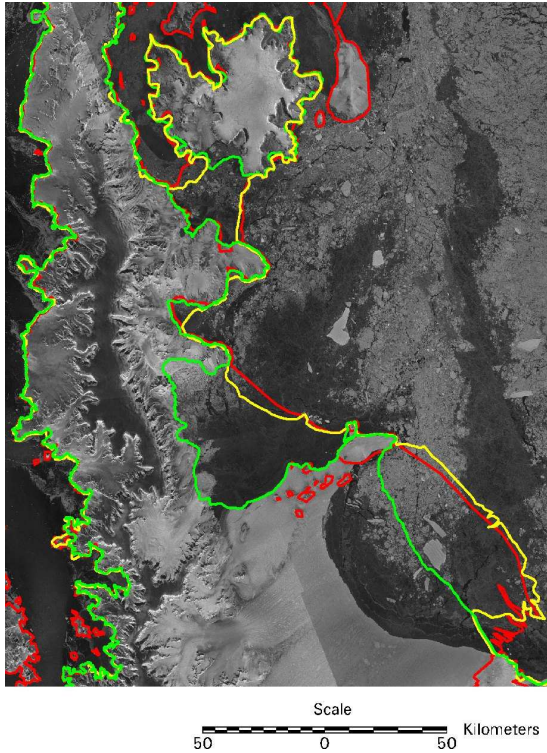
*Radar interferogram* MAMM had two primary science objectives. The first was to remap the perimeter of the continent and the majority of Antarctica's fast moving glaciers. Intuitively, these are the areas that are most likely to have experienced change over the 3 years that followed after the first mission – and already, we have results demonstrating that this objective is a success. 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 reach 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 so as to estimate velocity fields. The second approach required the use of RADARSAT-1 fine and standard beams, and the 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.

MAMM acquired data from about 80 degrees South Latitude to the Antarctic Coast. Interferometric SAR calculations required that this area be imaged 6 times during the mission (three times in descending orbit mode and three times in ascending orbit modes). The number and orientation of acquisitions then enable scientists to measure two components of the surface velocity vector and to remove the effects of surface topography.

### *Some MAMM Results*

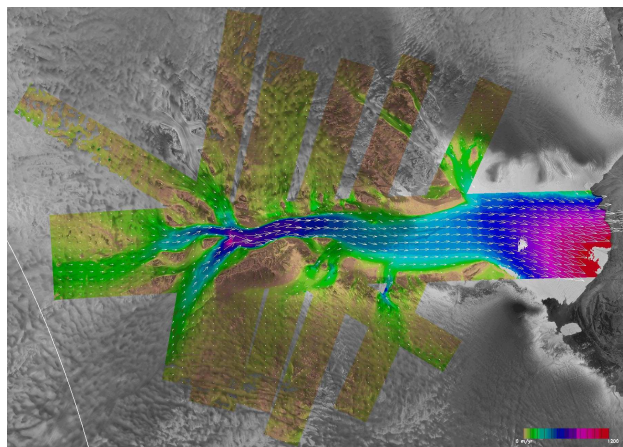


Even over just three years, the Antarctic ice sheet can change appreciably. Some of the most dramatic changes on the continent are occurring along the Antarctic Peninsula imaged in 2000 by RADARSAT-1. The green line on the image to the left is the coastline measured using RADARSAT-1 data acquired in 1997. The yellow and red lines are taken from data acquired in the early 90's. The results document the continued retreat of the northern Larsen Ice Shelf. Here we can already observe several glaciers along the Antarctic Peninsula coastline where the ice edge has retreated over 30 kilometers (18.6 miles) in just 3 years. But this is not the whole story. We also observe places where the ice sheet is advancing, such as the Amery Ice Shelf. The Antarctic Ice Sheet is huge, and this is the first time we have the data to study and compare ice sheet behavior around the entire

continent. These data will help us determine whether the local changes we see represent expected, episodic behavior or whether they represent regional trends driven by changing climate.

### *Lambert Glacier and Amery Ice Shelf*

Using RADARSAT SAR imagery obtained during the 2000 Antarctic Mapping Mission, ice velocity vectors were obtained over the Lambert Glacier. The areas of no motion (yellow) are either exposed land or stationary ice. The smaller confluent glaciers have generally low velocities (green, 100-300 meters per year) which gradually increase as they flow down the rapidly changing continental slope into the upper reaches of the faster flowing Lambert Glacier. Most of the Lambert itself has velocities between 400-800 meters per year, with a slight slowing in the middle section. As the glacier extends across Amery Ice Shelf, velocities increase up to 1000-1200 meters per year as the ice sheet spreads out and thins. Only a handful of in situ velocity measurements have been previously reported of this huge glacier

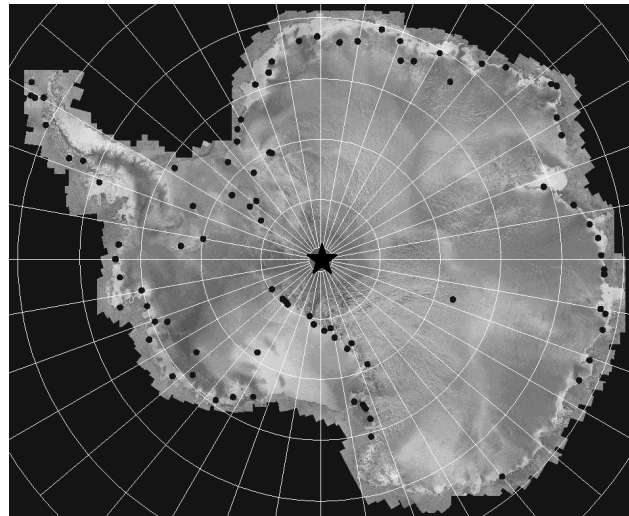


system. While the in situ and radar-derived measurements appear to be qualitatively similar, the extent and accuracy of the new measurements are unprecedented and provide quantitative baselines for future comparisons. The ice velocities are obtained from pairs of images obtained 24 days apart, using a technique called radar interferometry. This technique enables a highly precise alignment of image pairs that provides accurate measurements of topography as well as surfaces that have changed or moved over the short time interval, including glaciers.

## ***RAMP and the Intelligence Community***

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, which 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 in the intelligence community, an unexpected source of geodetic control information came available through the efforts of MEDEA. We learned that NIMA could provide latitude, longitude and elevation information for places in Antarctica, which could then be identified on RADARSAT image chips. Integration of the NIMA data (shown at the right) into the mapping calculation resulted in at least a two-fold increase in map accuracy. As importantly, the control points withheld from the calculation represented an important validation of the map accuracy and convinced cartographers of the quality of the map product.



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, the intelligence community has been able to provide that information through a combination of highly innovative techniques.

We are grateful to the intelligence community for two fundamentally important contributions to RAMP. Using sophisticated technologies, they have provided control on spacecraft position and pointing direction over Antarctica. They have also provided control on glacier motion necessary for interpreting interferometric data. *It is very important to recognize that the two products received from the intelligence community represent significant resources to the science community in and of themselves.* Future satellite mappings can rely on these invaluable data sets for geodetic purposes (in cases where the data are acquired over a stable region such as rocky outcrops) and for change detection studies. A worthy goal remains to archive the basic data for future users and to make some form of the existing data available to all potential users.

## ***The End?***

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. As importantly, the acquisitions provide an important benchmark for gauging and understanding future changes in the Antarctic.

As this new century begins to unfold, 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 going back to the early days of the Corona missions, is 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.

So is this the end of our looks at Antarctica? We hope not!

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