ASF Alaska Satellite Facility
15th Anniversary Special Edition
August 2006

## Message from the ASF Director

What is now the Alaska Satellite Facility (ASF), started out as a single-purpose imaging-radar receiving station conceived by a small working group formed by the National Aeronautics and Space Administration (NASA) in 1982. The central idea started with the brief success of the Seasat mission in 1978. After Seasat's premature demise, researchers at NASA and the Geophysical Institute (GI) at the University of Alaska Fairbanks (UAF) speculated what synthetic aperture radar (SAR) could do for polar research. Bill Campbell and Jay Zwally of the Goddard Space Flight Center, among others, convinced NASA to commission the Ice and Climate Experiment study for a dedicated polar ice satellite. Frank Carsey [Jet Propulsion Laboratory (JPL)] and Willy Weeks (GI) examined the benefits of an Alaskan ground station to receive data from foreign satellites, given the lack of funding support for a United States' mission. From those beginnings, the concept to build a station in Fairbanks, Alaska emerged.

Tom George

Geophysical Institute, then and now

Jeff Pederson

The discussions then focused on where to build the receiving station. The idea of reusing the existing Gilmore Creek Satellite tracking station was eliminated due to the 25% increase in antenna mask afforded by locating the antenna at the West Ridge campus of UAF. Keeping in mind that the planned satellites would have no onboard recording capability, the mask dimensions directly determined the data gathering capability of the mission.

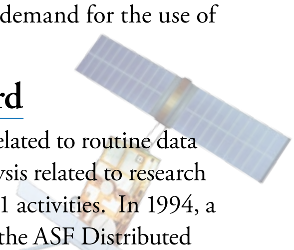
JPL issued a Request for Quotation for the implementation of a receiving ground station (RGS), the Alaskan SAR Facility, at UAF in 1986. Chancellor O'Rourke preferred placing the proposed 10-meter antenna on top of the Natural Science Facility (NSF), which was scheduled to be completed by January 1989. With delays to the NSF building, the Elvey annex expansion project on West Ridge was enhanced with money appropriated by the State of Alaska to include the needed building modifications to host ASF in the GI. (NSF was not completed until September 1995, 4 years after ASF's first downlink.) The 10-m structure and ancillaries were mounted on the 8th floor (rooftop) of the Elvey building, with the control and signal processing center in the Elvey annex.

The annual operating costs associated with this Alaskan receiving station were originally estimated to be under $250 K, including overhead. At that time, the expected data volume for the envisioned station was about 10 minutes of reception per day, compared to the approximately 360 minutes per day ASF currently handles. Later, in the operations phase, data flow was increased due to changing requirements from flight agencies and government sponsors. In the beginning, ASF was seen as a modest, but valuable, cost-effective addition to the GI's Alaska-centric research and applications program.

NASA entered into Memoranda of Understandings (MOU) with the European Space Agency (ESA) [1986] and the National Space Development Agency of Japan (NASDA) [1988] concerning the acquisition data from ESA's ERS-1 (European Remote Sensing) satellite and NASDA's JERS-1 (Japanese Earth Resources) satellite. An agreement between UAF and NASA assigned ASF to carry out some of the responsibilities that NASA was obligated to perform under those MOUs as well as making provisions for possible future MOUs. In both cases, the data were restricted to supporting scientific and technical projects agreed upon between NASA and the appropriate foreign flight agency. No rights were granted for other uses of the data, including uses for commercial or profit-making purposes.

The Elvey construction was completed in 1988. Completion of the Alaska SAR Facility was marked at a ribbon cutting ceremony on April 24, 1991. Later that year, ASF began downlinking ERS-1 data. The expected 10 minutes of data a day quickly grew to over 70 minutes per day for this first satellite. With the addition of new missions, the demand for the use of ASF grew as fast, sometimes faster, than the capabilities.

## The ASF DAAC and new missions come on board



The scope of the original grant to UAF from NASA included tasks related to routine data acquisition and processing of the ERS-1 data, as well as specialized analysis related to research objectives. Addenda to the agreement added JERS-1 and RADARSAT-1 activities. In 1994, a Memorandum of Agreement (MOA) between NASA and UAF formed the ASF Distributed Active Archive Center (DAAC) complementing, without modifying, the existing MOA for ASF.

The ASF DAAC is one of eight DAACs funded by NASA to support earth observations from ground-based, in-situ, airborne and satellite sensors. The ASF DAAC processes, distributes, and archives data products as assigned by NASA. Tasking and missions have been added to or deleted from the agreement when deemed appropriate by NASA program managers who manage NASA's earth science programs, by Goddard Space Flight Center personnel who manage the DAAC contract, and by ASF Management.

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A significant example of the modifications made was the addition of funding to install a second antenna in 1994 in anticipation of the launch of the Advanced Earth Observing Satellite (ADEOS) by the Japanese. The 11-m antenna was installed in 1995 on University-owned land within walking distance from the GI. It has served ASF well, even though the original mission ended prematurely when the ADEOS satellite malfunctioned.

With the launch of RADARSAT-1 in November 1995 by NASA on behalf of the Canadian Space Agency, ASF was handling data from the original three satellite missions that spurred the science community into envisioning this facility: ERS-1, JERS-1, and RADARSAT-1. RADARSAT-1 is still going strong after almost 11 years of successful flight, not bad for a predicted 5-year mission! The many achievements of NASA's Pathfinder RADARSAT-1 Antarctic Mapping Program (RAMP) are examples of the impact the creation and continuation of the ASF vision has on both science and technology (the history of RAMP is discussed at length in Ken Jezek's article found later in this issue).

The much anticipated launch of ADEOS-I resulted in ASF simultaneously supporting four missions until the loss of the two Japanese missions. The demise of ADEOS-I and JERS-1, and the decommissioning of ERS-1 with the launch of ERS-2 in 1996, changed the missions ASF supported, but not the general functions. It did not squelch the enthusiasm for L-band SAR data. In November 2002, NOAA appointed UAF as exclusive administrator of a data acquisition, processing, and distribution center to support the Advanced Land Observing Satellite (ALOS) mission. With the successful launch of ALOS by the Japanese in January 2006, ASF's implementation of the Americas ALOS Data Node (AADN) is moving forward in anticipation of going operational in the fall of 2006.

activities, is evidence that ASF has touched many lives over the years. The continued utility of the facility, after the loss of the original satellite missions, speaks highly for the significance of the data and services generated by ASF. ASF is deeply rooted in the University research environment and focused on satellite data products, services, and science support.

We updated our mission to carry us forward and we continue to evolve. To complement ASF's new mission, a new name, the Alaska Satellite Facility, was announced in the fall of 2003. This has served us well in ASF's preparations for the future.

This newsletter reflects on the last fifteen years of service at ASF from several perspectives. Many talented people have been gainfully employed at ASF over the years and careers of countless students have been launched. As we progress and adapt to the changing remote sensing environment, we will continue to honor our heritage and serve the science community. We currently at ASF thank those who came before us, the user community, our sponsors and the University for the opportunity to continue this exciting work.

*Nettie La Belle-Hamer - Director, ASF*

## Changing with the times

ASF has had its share of controversy, both big and small, through the years. The first was the very public, erroneous accusation in 1984 by a member of Teamsters Local 959 that, by proposing to establish ASF, the University was somehow responsible for NASA's decision to pull out of the Gilmore Creek tracking station. Since this accusation was in writing and included libelous personal statements about Dr. Juan Roederer, GI Director at that time, it quickly ignited the community, not to mention the lawyers. It was soon handled and the plans moved forward, but like most public controversy, traces of the arguments remain today.

In 1998, ASF underwent a major reorganization that formed the functionally-defined Centers; the essence of which is still in use today. For ASF staff, the reorganization meant a stressful time of wondering how long their jobs would last. For the world outside of ASF, the reorganization served to refocus the facility on its core functions. More recently, cutting 500 trees to clear the antenna mask and plowing the access road for maintenance on the 11-m have been issues that brought ASF to the front page of the Fairbanks Daily News Miner.

What have not necessarily made the papers are the many benefits of a thriving ASF. For example, over 350 terabytes of data processed and archived at ASF has serviced both general science advancements and operational support for NASA, NOAA, USGS, NIC, IIP, and other U.S. government agencies. Advancements in both SAR technology and remote-sensing science applications have lead to both innovative technology and new scientific discoveries. On the human side, the integration of remote-sensing data into the daily lives of scientists and laymen alike, through extensive outreach

Tom George

Jim Coccia

10-meter antenna construction underway

Evelyn Trabant

Evelyn Trabant

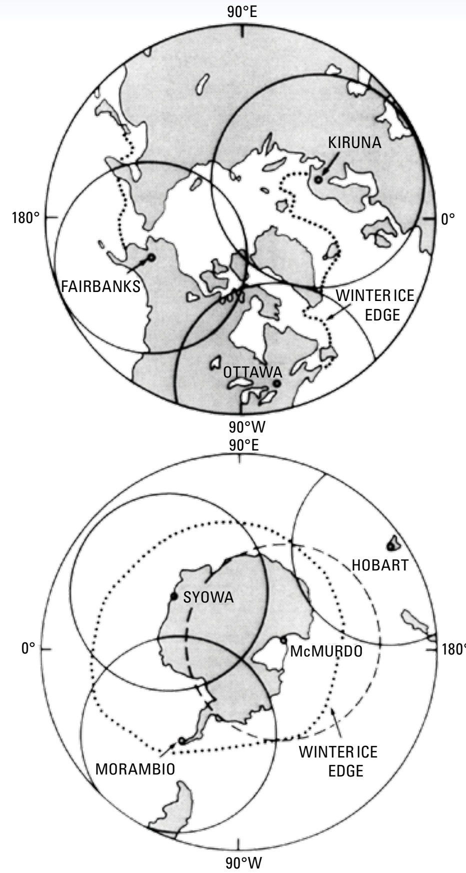
# ALASKA SAR FACILTY: In the Beginning

*by Gunter Weller - Director, ASF, 1986-1993*

Synthetic Aperture Radar (SAR) satellites, when they were introduced, provided a new and exciting tool to look at Earth. The United States pioneered the scientific use of these satellites with Seasat, but the satellite had only a short lifetime and the European Space Agency (ESA) had proposed to launch its own SAR satellite. The question at NASA was whether to push for the launch of another U.S. SAR satellite or to work with the Europeans, making use of their data in return for launch and other help. NASA decided that it would be more cost-effective to build a receiving station rather than a new satellite. To get maximum area coverage and data downlink from these polar-orbiting satellites, the receiving station would have to be at high latitude. A multiple high-latitude receiving station network would ensure almost complete coverage of the polar regions. A report titled "Science Program for an Imaging Radar Receiving Station in Alaska" was written by a science working group in 1983.

In 1986 I was asked by Stan Wilson of NASA to explore the possibility of the Geophysical Institute (GI) hosting such a station. The GI had worked with NASA in the past therefore it seemed a good location, combining a high latitude on US soil with proven expertise and experience in both satellite tracking and geophysical research. At the time I was the chairman of the National Research Council's Polar Research Board and Stan proposed that I become the director of the ASF. The person who would be essential for the success of the entire enterprise was John Miller, a senior engineer at the GI with considerable experience in the technical aspects of satellite tracking stations, including the Minitrack station and early ESRO (later ESA) tracking stations in Fairbanks.  He agreed to become the Operations Manager. Professor Willy Weeks added scientific expertise as the Chief Scientist of the ASF.

A Memorandum of Agreement between NASA and the University of Alaska was drawn up and signed by the NASA Administrator and the President of the University. It stipulated that NASA would provide the equipment needed for the station and pay for its operating costs while the University would provide the necessary facilities, including housing the equipment and providing a suitable platform for the large satellite antenna,  and it would also provide the staff to operate the facility. The University also insisted in being included in any research conducted with the satellite data so that it would not simply provide a service function for NASA.




*Approximate station masks for the ERS-1 SAR satellite. With the proposed satellite receiving stations in both polar regions, there was almost complete coverage of the sea ice regimes, a major research objective for ERS-1.*

## Location, Location, Location

A site for the ASF had to be found and the obvious choice was to locate it in the Elvey Building, the home of the GI. Considerable modifications were needed for this. For a start, room had to be created for the location of the receiving and processing equipment and for the staff to operate this equipment. This was done by enclosing the patio that existed between the main tower of the Elvey  Building and its annex. More importantly, where was the heavy 10-m diameter steerable receiving antenna to be located? After looking at various options it was decided that the roof of the seven-floor building would be ideal since it provided a good unobstructed horizon and station mask. Fortunately, the building was originally designed to have two more floors, which were deleted due to budget constraints, so the concrete core was strong enough to hold the antenna on top, after additional concrete was poured to provide a suitable platform. The construction work began in 1988  and was completed a year later. It was paid for completely by the University as agreed under the MOA.

In 1990, ASF was fully operational and awaited the launch of ERS-1. Due to limited data storage on the satellite, most of the data could only be received while the satellite was above the horizon as seen by a station. This was the reason to have several stations covering the polar region. Coverage of the region was a key objective of the ERS-1 program. ERS-1 was launched successfully in 1991 and the Japanese JERS-1 satellite in 1992. ASF began to receive and process massive amounts of data. One copy of the data was kept at ASF and another sent to either the European or Japanese satellite agencies.

ASF was also involved in the research made possible by the use of SAR data. Only approved researchers had access to the data and ASF submitted an omnibus proposal from University researchers called ALASKA (Arctic Lands and Shelves: Key Assessments) which was discussed and approved by ESA at several meetings in  Frascati, Italy,  and Noordwijk, Netherlands.  The SAR data provided unique opportunities to examine sea ice and algorithms were developed with colleagues at JPL in Pasadena to track and quantify sea-ice movement. Geographical features, including volcanoes, glaciers, and other land forms were also studied.

Much has happened since the early days, but ASF has become an efficient and successful activity at the GI, and continues to provide excellent services to numerous researchers around the world.

*Evelyn Trabant*

# A Brief History of the RADARSAT-1 Antarctic Mapping Project

*by Kenneth Jezek*

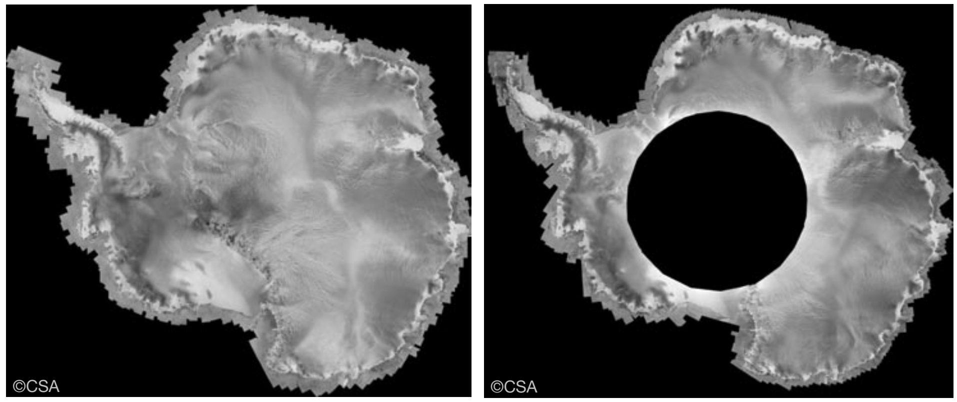



*Figure 1. AMM-1 1997 mosaic (left). MAMM 2000 mosaic (right)*

The RADARSAT-1 Antarctic Mapping Project (RAMP) was conceived in the early 1980's by Stan Wilson, Bob Thomas, and Bill Townsend. The idea developed as part of negotiations over participation by NASA in the Canadian Space Agency's (CSA) RADARSAT-1 project. Both Ed Langham at CSA and Shelby Tilford at NASA reacted favorably to the exciting concept, and two complete mappings of the Antarctic were included in the Memorandum of Understanding.

Recognizing the importance of radar mapping of polar ice sheets, Frank Carsey and Ben Holt, both of the Jet Propulsion Laboratory (JPL), prepared a brief report titled "Mapping Antarctica and Greenland with Shuttle Imaging Radar" (Carsey and Holt, 1985).
The report sketched the scientific objectives for radar mapping of ice sheets and discussed a possible mapping campaign to be conducted as part of the SIR-B reflight. The advantage of the shuttle project was provision of data much sooner than the planned free-flying SARs. The key technical innovation was to launch the shuttle from Vandenburg Air Force Base so as to place the shuttle in an 88-degree inclination orbit. SIR-B was planned for launch in March 1987 and the crew was to include Kathy Sullivan, who worked with Carsey, Holt, Ken Jezek and the science team to prepare for the mission. With the report as background material, Carsey and Holt convened a meeting at JPL during October of 1985. The meeting was followed-up by a late 1985 draft proposal and, with help from the National Science Foundation (NSF) and Ian Whillans, the installation of several corner reflectors in Antarctica during that austral summer. Regrettably, the SIR-B reflight plans were abandoned when, after the catastrophic loss of the Challenger Space Shuttle in January of 1986, NASA designated the Kennedy Space Center as the sole location for future shuttle launches. That decision precluded launch of the shuttle into polar orbit. Nevertheless, Carsey and Holt's effort laid the foundation for understanding the operational constraints behind a future mission.

At about the same time, NASA was solidifying plans for the construction of a northern ground receiving station. After consideration of several sites, NASA selected the Geophysical Institute (GI) of the University of Alaska Fairbanks (UAF) as the optimal site based on the station mask which stretched far out over the western basin of the Arctic Ocean. NASA also recognized the mutual benefits of colocating a satellite station within the GI's already strong research environment. Much of the scientific focus of the Alaska SAR Facility (ASF) at that time was concentrated on Arctic sea ice as set forth by the Program for International Polar Oceans Research (PIPOR). The agencies continued background plans for mapping the polar ice sheets in anticipation of the early 1990's launch of the European Space Agency ERS-1 satellite, but with an eye toward the additional capabilities expected for JERS-1 and, in particular, RADARSAT-1 (NRC, 1989).

In November 1990, The Byrd Polar Research Center (BPRC) hosted a conference to examine capabilities for collecting data over the southern continent and the surrounding ice covered waters. The main objectives of the meeting were to review potential science payoff from a major SAR mapping campaign and to look at limitations associated with the planned instrument suite of that time. The report concluded that given constraints on downlink capabilities (ERS-1, for example, had no onboard recording) and limitations in expected onboard tape recorder data volume, Antarctic coverage could be optimized by developing a ground receiving station at McMurdo Ground Station Antarctica (MGS). The report recommended that the station operations be modeled after ASF and that data received at the MGS be transferred to ASF for processing, distribution and archival. The recommendation was accepted by NASA and the NSF in 1992, and the McMurdo Ground Station became operational in 1994.

With the successful launch of ERS-1 in 1991 and the beginning of routine operations at ASF, the science community began to concentrate on plans for a complete mapping of Antarctica using RADARSAT-1. BPRC hosted a second meeting in March 1993 to prepare more detailed requirements for the proposed mission. The meeting was attended by Martha Maiden who represented NASA's Pathfinder Project, members of the glaciological community, representatives from CSA and the four partners in the RAMP activity, namely BPRC, ASF, Vexcel and JPL. John Crawford from JPL and Ed Oshel from Ohio State University (OSU) provided the first estimates of acquisition duration at the meeting. They estimated that 24 days were required to fulfill mapping and stereo mapping goals. They later found that about 17 days were required to meet the mapping requirements. This estimate was later refined by Crawford who concluded that the acquisition period required a minimum of 18 days.

Mission preparations intensified during the mid-1990's and detailed plans were developed during a series of meetings between the team members, NASA and CSA. The plan was refined to specify acquisitions at both ASF and MGS as well as at Canadian Ground Receiving Stations. ASF would be responsible for accumulating and for processing signal data to images using SAR processing systems developed by JPL. OSU would construct the image mosaics using software developed by John Curlander, Lynne Norrikane and Bob Wilson from Vexcel. JPL would develop the mission plan and together with OSU would be on hand to monitor and modify the acquisition plan as needed during the mission. With the successful launch of RADARSAT-1 in 1995, final responsibilities for each aspect of the mapping plan were formalized in a series of requirements documents in early 1996, and which aimed at a mapping mission during the fall of 1997.

In 1996, Erick Chiang of the Office of Polar Programs of the NSF arranged for Frank Carsey to visit the McMurdo Ground Station. The objective was to observe the overall operation of the facility, and also to discuss preparations for a 1997 imaging campaign. Ken Jezek and Robert Onstott joined Carsey on the trip to install radar transponders at the McMurdo and South Pole Station and get a better understanding of operations at MGS. The NSF transponders and other ground control would be used to constrain the orbit ephemeris to be used in later data processing.

Vanessa Griffin and Dick Monson, both from NASA, and Ken Jezek traveled to St. Hubert in January 1997 for the RADARSAT-1 Antarctic Imaging Campaign kick-off meeting. George Harris was identified as the CSA Project Manager under Dan Showalter. Ken Lord and Ken Ashworth discussed initial thinking on the implementation of the imaging campaign which required a rotation of the satellite for southerly observations. The objective of the meeting was the formal go-ahead from Rolf Mamen and Ed Langham. In addition, operational procedures were discussed for mission planning, rehearsals and contingencies.

Refinements of John Crawford's acquisition plan and project rehearsals continued throughout the summer of 1997. Crawford and Rejean Michaud, with help from Nettie La Belle-Hamer and Jean Muller, assumed most of the responsibility for the mission planning preparations under the watchful eye of Ken Lord. Planning for receipt of data at ASF and MGS was organized by Carl Wales of ASF with much of the daily responsibility falling on Marc Forbes, Dick Harding and Greta Reynolds. Tom Bicknell, Dave Nichols. Pat Liggett and Dave Cuddy from JPL were responsible for SAR processor preparations. Jason Williams from ASF and Satish Srivastiva from CSA were responsible for calibration preparation and Jamie Marshner was responsible for simulations and testing of the end-to end system at ASF. Verne Kaupp led the ASF science team preparations along with Ben Holt. Prasad Gogineni, was responsible for overall management of the effort and Paul Ondrus was responsible for day-to-day crisis management.

Final preparations for the 1997 imaging campaign included positioning people at various stations across the northern hemisphere. Katy Farness and Biyan Li from OSU were stationed at the Gatineau and Prince Albert Ground Stations to monitor downlinks at those sites. Ben Holt, Rick Forster, Frank Carsey, Rick Guritz and Sue Digby were stationed at ASF for similar work and to conduct preliminary science analysis. Rick Austin joined the mission planning team to help with replanning work. Hong Xing Liu and Hong Gyoo Sohn remained at OSU to help with acquisition summaries and swath mapping.

Satellite rotation began on September 10 and proceeded as planned. Antarctic data acquisitions began within a few days of the Antarctic maneuver and lasted until October 20, when satellite orbit maintenance requirements dictated that the satellite operators prepare for the return to right-looking mode on October 23. Processed image data from the acquisition phase of the 1997 campaign (over 2170 minutes of SAR signal data) have been mosaicked to achieve the primary goal of producing the first, high-resolution, SAR image map of the entire Antarctic continent (Figure 1). The project also acquired 24-day, exact-repeat observations because of the contingency pre- and post-nominal plan acquisitions. Those data have been analyzed to extract surface velocity and topography data using radar interferometric techniques. The resultant velocities are critically important for studying ice-sheet dynamics and assessing ice-sheet mass balance, which in turn is a key parameter influencing global sea level.

Several years of data processing followed the 1997 imaging campaign. By mid-1999, processing was sufficiently complete that the RAMP team began to inquire about the anticipated second mapping mission. Kim Partington, at NASA HQ, endorsed the idea and project planning began in January 2000. The scope of the new project, deemed the Modified Antarctic Mapping Mission (MAMM) by Rolf Mamen, was different from the 1997 Antarctic Imaging Campaign. MAMM would focus on interferometric coverage north of 80 degrees south latitude. The complex mission plan was developed by John Crawford and Rick Austin from JPL and provided to Stephanie Ruel who led the CSA mission planners. Dick Monson

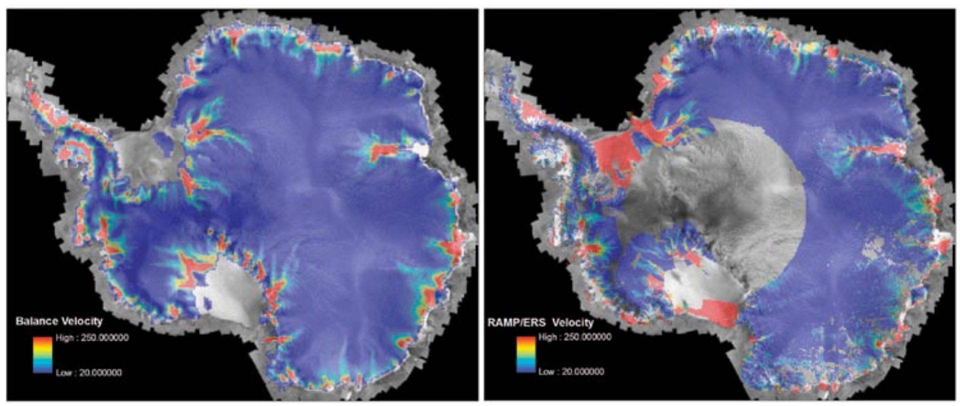



*Figure 2. Modeled velocity (left) and measured velocity from RAMP, and from ERS (courtesy of R. Kwok). ERS data fill coherence gaps along Amundsen Sea Coast.*

along with Ian Joughin and Ramachand Bhat provided guidance on interferometric constraints on orbit maintenance to Greg Hammel of CSA who was responsible for the difficult orbit maintenance maneuvers required for this mission. Richard Carande, Xiaoqing Wu and James Miller from Vexcel worked to develop automated software for processing the huge volumes of interferometric data. Verne Kaupp, ASF director at the time, added Jeremy Nicoll, Paul Brown, and Dave Fluetsch to the ASF team. Bill Potter from Goddard Space Flight Center (GSFC) helped with crisis management. With the concurrence of NASA and of Surendra Parashar from CSA, the team prepared for a second acquisition plan starting in September 2000.

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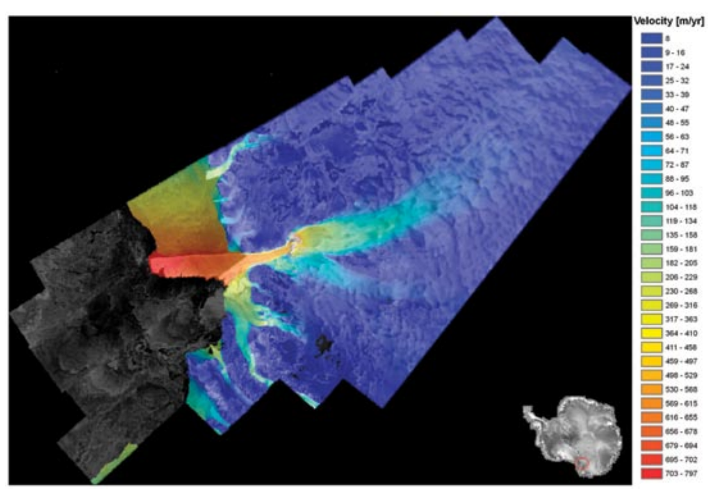
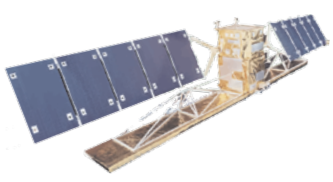



*Figure 3. Interferometrically-derived velocities over David Glacier obtained during MiniMAMM.*

MAMM began on September 3, 2000 and lasted until November 14, 2000, an interval corresponding to three repeat cycles. Data were acquired so that, where possible, the position of features on the glacier (such as crevasses) could be compared between the 1997 and 2000 data sets 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 the unprecedented control of the spacecraft orbit and attitude. As the mission unfolded, CSA spacecraft engineers demonstrated their ability to navigate the satellite in the manner dictated by the science requirements. The outcomes of the MAMM effort were a second high resolution map of much of Antarctica (Figure 1) and extraordinary observations of glacier motion captured over three, 24-day, RADARSAT-1 cycles (Figure 2). These data provide an unprecedented opportunity to study many of Antarctica's fast glaciers, whose extent was revealed through the Antarctic Mapping Mission (AMM-1) data.

With mounting evidence for rapid changes in the polar regions, follow-on measurements were requested by the RAMP team and then approved by Waleed Abdalati at NASA HQ and Nettie La Belle-Hamer, the current Alaska Satellite Facility Director. These were scheduled in 2004 and designed to be coincident with the MAMM data over the target areas. The MiniMAMM mission was planned by Michelle Harbin and Vicky Wolf of ASF. MiniMAMM acquired additional interferometric data over four fast glacier areas around Antarctica. The interferometric results from this data set are of a very high quality because the acquisitions occurred off the peak of solar activity (Figure 3). This means there is less ionospheric distortion in the data.

The success of the RADARSAT-1 program in general and the achievements of the RAMP project in particular are the successes of the many people deeply committed to the venture. As of this writing and through the efforts of many, RADARSAT-1 continues to provide exceptional data about the Earth from pole to pole. Hopefully, a combination of old and new faces will be willing to try it again with RADARSAT-2!



# Global Forest Mapping with JERS-1 SAR

*by Kyle C. McDonald and Bruce Chapman*

The Japanese Aerospace Exploration Agency (JAXA; formerly known as NASDA) successfully launched the Japanese Earth Resources Satellite (JERS-1, nicknamed FUYO) in late 1992 into a polar sun-synchronous, 44-day, repeat orbit that allowed image coverage of most of the Earth. The JERS-1 instrument package included an L-band, HH-polarized SAR, along with two optical instruments. A primary element of the JERS-1 mission was to acquire imagery of ocean, land, and ice-covered regions with the purpose of demonstrating the technological applications of L-band SAR. Because of some difficulties after launch, the JERS-1 SAR operated at less-than-planned power, yet still was able to complete most of its mission objectives. In spite of its reduced performance, the sensor was well suited for forest studies, and in mid-1993 began a global initiative of systematic image acquisition of tropical forests. Subsequent to the tropical forest data acquisitions, a similar systematic acquisition of boreal forest imagery was undertaken. An important element of this initiative was acquisition of multiple temporally contiguous data sets to allow characterization of the SAR's ability to discern crucial seasonal processes across broad tropical and boreal landscapes. For some regions, two or more coverages at different seasons (i.e. boreal winter and summer seasons or tropical high-flood and low-flood seasons) were acquired.

The initiative consisted of two projects: the Global Rain Forest Mapping (GRFM) project, and the Global Boreal Forest Mapping (GBFM) project. The initiative was lead by the NASDA Earth Observation Research Center (EORC), with participation by ASF, the Jet Propulsion Laboratory (JPL), the European Commissions Joint Research Centre, and others. The GRFM and GBFM goals were to acquire spatially and temporally contiguous JERS-1 SAR data sets over Earth's tropical and boreal regions, and to generate continental scale, 100-m resolution image mosaics to be provided for research and educational purposes world wide. Project efforts were focused on several geographical regions, including Boreal North America, Boreal Eurasia, South and Central America, Equatorial Africa, and Southeast Asia, including northern Australia. Each region was mapped at least once between September 1995 and September 1998. In total, more than 25,000 JERS-1 SAR scenes were acquired and assembled into continental-scale products. The SAR data processing of this large undertaking was shared by ASF and NASDA. ASF processed the data from the Americas, while NASDA was responsible for the remaining collections. The related science activities, which are still ongoing, have been conducted by agencies around the world, and thus far have resulted in more than 50 publications. The mosaic products were published on CD ROMs and DVDs and made available to the scientific community at no cost.

ASF contributed substantially to the GRFM and GBFM through acquisition and processing of substantial amounts of JERS-1 imagery covering the Americas (Figure 1). The entire Amazon Basin, from the Atlantic to the Pacific, was acquired in a single acquisition period during the generally low-flood time of the Amazon River in September-December 1995. This portion of the data set covers an area of about 8 million km$^2$ comprising some 1500 ASF-processed scenes. The same area was covered again in May-August 1996, during a high-flood period of the Amazon River. Imagery of Central America, from Panama to Mexico's Yucatan Peninsula, was acquired in July-August 1996, complemented by the Pantanal wetland regions in central Brazil in February 1997. Wetland regions in Bolivia, adjacent to the Pantanal were also covered. Boreal North America, extending from Alaska to the Northeastern U.S., was covered during two acquisition campaigns from 1997 and 1998. Summer 1998 and winter 1997/1998 imagery capture these seasons at the continental scale. In addition, more frequent coverage was obtained for the areas surrounding the ASF station mask. Project team members at JPL assembled these data into continental scale mosaics. SAR image mosaics covering these and the other regions mapped by GRFM/GBFM partners are featured on CD-ROM and DVD media available through ASF. Mosaic products include tiles of 100-m and 2-km resolution backscatter and image texture. As of this writing, the final mosaic products of Northern Eurasia are still under development and have not yet been published for distribution.

## Landscape Mapping with GRFM/GBFM Products

Results of the GRFM and GBFM projects have demonstrated the crucial need for consistent, systematic, continental-to-global scale observations of these important biomes. Regional landscape mapping with SAR is important for the information it provides about distribution and characterization of vegetation and wetland ecosystems, including estimation of forest carbon pools, assessment of disturbance and associated changes in biome extent and state, characterization of treeline position, and mapping of river typology. Rapid changes, including those driven by deforestation, fire, permafrost heat balance, flooding, and insect outbreaks can dominate portions of these ecosystems. Landscape features are expected to change as climate and land use patterns change, with significant consequences for global biogeochemical cycles. Forest extent and distribution is changing with human-induced deforestation, with changing frequency and severity of natural fires, and with climate-induced changes in distribution of forest species.

The mapping of wetland regions contributes to studies of intra-annual and inter-annual change. Inundation is an important predictor of methane flux in tropical and boreal wetlands. Inundation may be caused by changes in surface runoff, groundwater, and permafrost heat balance. Thermokarst activity, caused by melting processes in permafrost, has major effects on landforms in both arctic and boreal ecosystems, affecting the distribution of wetlands and tundra ecosystems in arctic regions, the expansion of wetland complexes, and forest succession across the biome. As most of Alaska is underlain by continuous or discontinuous permafrost, changes in thermokarst activity can alter carbon flux significantly.

GRFM and GBFM products have provided for establishment of baseline information, setting the stage for longer-term change detection. JERS-1 mosaic products have been demonstrated to be very useful for wetland delineation, inundation mapping, and discrimination between woody and non-woody vegetation. The availability of subsequent data sets, such as those expected from the ALOS PALSAR, will allow for comparisons of derived products across several years, providing additional information about short-term landscape change.

## Landscape Mapping: Tropical Rain Forest Regions

Tropical rain forests straddle the Earth's equatorial regions, covering an area of roughly 10-million-square kilometers. These regions serve as a major pumping mechanism for the cycling of water, energy and carbon. The health of these forests is of global importance, particularly since continued development and deforestation from logging and agriculture threaten these regions. Seasonally inundated forests, woodlands, and grasslands are widespread in tropical rainforest basins. The duration and extent of wetland inundation are critical for the ecological, biogeochemical, and hydrological functioning of these ecosystems, as they impact carbon storage, trace gas fluxes, and the prospect of sustainable land use in these areas.

Tropical wetland ecosystems are experiencing increasing threat, including clearance and conversion, rising sea levels, extreme climate events, and sediment deposition. These degrade erosion control, fisheries conservation, and wildlife habitat. The capabilities of JERS-1 SAR for tropical wetlands mapping were clearly demonstrated by several GRFM studies. Time series imagery has been used to map inundation periodicity in major portions of the Amazon basin and wetland extent for the lowland Amazon. Results were employed to estimate methane emissions from wetland regions as well as to estimate carbon dioxide release from Amazonian rivers.

## Landscape Mapping: Boreal Forest Regions

The boreal forest consists of a circumpolar band of predominantly evergreen coniferous trees interspersed with a smaller component of hardy deciduous species. Conifers include spruce, pine and fir, while deciduous species include larch, birch, aspen, and poplar. Seasons cycle between dark cold winters and brief warm summers. The presence of permafrost leads to shallow rooting depths and pooling of surface water. The timing of spring thaw and length of the growing season govern annual cycles of forest growth, fire and other successional processes. Fire is an integral component of the boreal landscape, unlocking nutrients from vegetation and cold soils, releasing them for new plant growth. Animal and insect life cycles are also controlled by the seasons.

Variations in seasonal freeze/thaw processes can be spatially and temporally complex. Landscape complexity can affect the timing of seasonal freeze/thaw transitions as a result of local-scale variations in land cover, snow cover, or topography, including elevation, and slope aspect. JERS-1 SAR imagery collected under the GBFM project has been used to characterize this heterogeneity in focused study regions of the North American high latitudes. Observed variations in freeze/thaw transition have been delineated by landcover, slope aspect, and elevation. These considerations underscore the importance of a combined temporal and spatial accuracy particularly for complex landscapes.

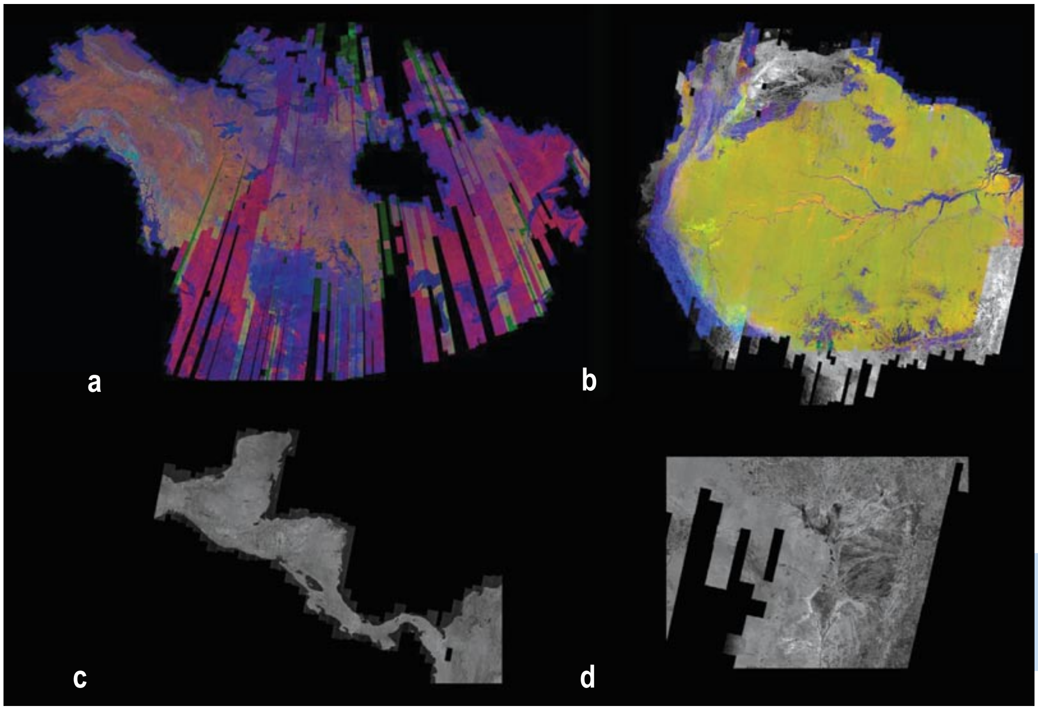



*Figure 1. Four JERS-1 SAR mosaics constructed at JPL through the GRFM project and the GBFM project;*
*a) Boreal North America false-color composite mosaic with contrast enhancement applied. The three-color composite employs red for summer backscatter, green for winter backscatter, and blue for summer texture.*
*b) Amazon River basin false color composite of high (red) and low (green) flood seasons of the main stem of the Amazon River. Blue represents the radar texture.*
*c) Central America (1996).*
*d) Pantanal Region, South America (1997).*
*Courtesy of GRFM*

## 1978

Seasat Mission

## 1982

Single-purpose imaging-radar receiving station conceived by a NASA working group

## 1986

JPL issues request for quotation for the implementation of a receiving ground station at UAF

Alaska State Legislature appropriates funds for Elvey Building modifcations

MOU between NASA and ESA

RGS Functional Design Review

*1986*
*Young Park - JPL*
*John Miller - GI, UAF*
*Don Kluba - Tokyo*
*Hajime Furuta - MITI*
*Stan Wilson - NASA*
*Shohei Otaki - MITI*

## 1987

NASA workshop for ASF investigators (led to the formation of the Prelaunch Science Working Team)

Interactive Image Anaysis System Design Meeting

*Preparing GI annex for renovations*

## 1988

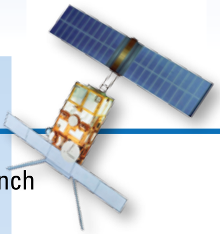
MOU between NASA and NASDA (now JAXA)

Elvey modifications begin, concrete poured in the spring for 10-m antenna addition

Elvey Building complete

RGS installed

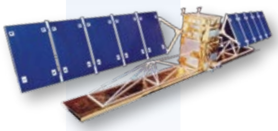
## 1995



ERS-2 Launch

11-m antenna installed

RADARSAT-1 Launch

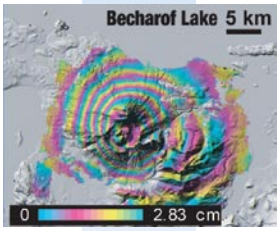


## 1996

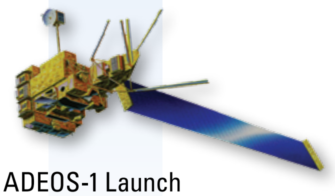
ACS replaced by IMS/DADs system

October '95 - June '96
ERS-1/ERS-2
Tandem Mission

ASF Interferometry Meeting




ERS-1 goes to minimal level of activity

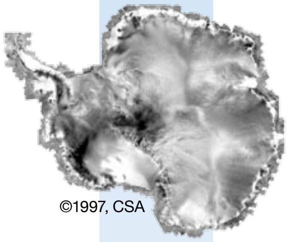


ADEOS-1 Launch

## 1997

ADEOS-1 Mission Ends

Antarctic Mapping Mission (AMM-1)




*Antarctic mosaic*

## 1998

ASF reorganization

JERS-1 Mission Ends

## 2000

ERS-1 Retired

Modified Antarctic Mapping Mission (MAMM)

## 1991

Alaska SAR Processor and the archive (ACS) and operations systems installed

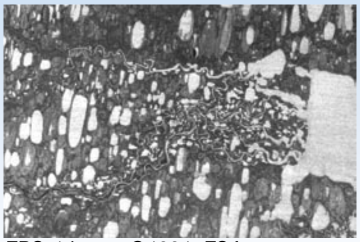
MOU between NASA and CSA

ASF Operational Readiness Review

Ribbon-cutting ceremony for ASF, and toasting the 10-m antenna

ERS-1 Launch

August, first successful downlink of SAR data from ERS-1 at ASF



*ERS-1 image ©1991, ESA*

## 1992

ERS-1 SAR data released to ASF Users

JERS-1 Launch

First successful downlink of JERS-1 data to ASF

*JERS-1 image ©1992, JAXA*

## 1994

MOA between UAF and NASA forms ASF DAAC

First RADARSAT-1 processor delivered

December 2, McMurdo Ground Station starts downlinking SAR data, which is archived and processed at ASF

*10-meter Antenna McMurdo Ground Station, Antarctica*

## 2002

RADARSAT-1 100th Cycle Celebration


*RADARSAT-1 Fine Beam image*

NOAA appoints UAF as AADN operator

ADEOS-2 Launch

## 2003

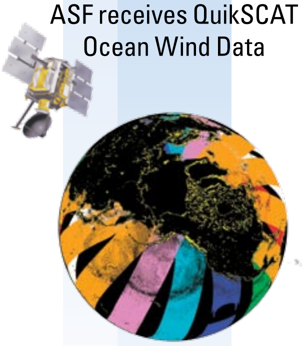

*RADARSAT-1 8th anniversary*

Alaska SAR Facility becomes Alaska Satellite Facility

ADEOS-2 Mission Ends

## 2004

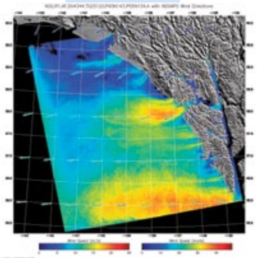
ASF receives QuikSCAT Ocean Wind Data



## 2005

RADARSAT-1 50000th orbit

MiniMAMM



*SAR-Derived Coastal Winds*


*Alaska mosaic*

Ends of the Earth CD

## 2006

ALOS Launch

AMERICAS ALOS DATA NODE

First ASF Uplink

URSA on the web

URSA Alaska Satellite Facility

August, ASF Open House

# From Airborne to Spaceborne:

## Reflections on the Alaska Satellite Facility by a User *by Martin O. Jeffries*

The first radar images that I ever saw were those in a publication that is, or should be, familiar to anyone associated with ASF - *Seasat Views Oceans and Sea Ice with Synthetic Aperture Radar* by Lee-Leung Fu and Ben Holt. I ordered a copy soon after its publication in February 1982 when I read that it contained images of ice island (tabular iceberg) T-3, sometimes known as Fletcher's Ice Island.

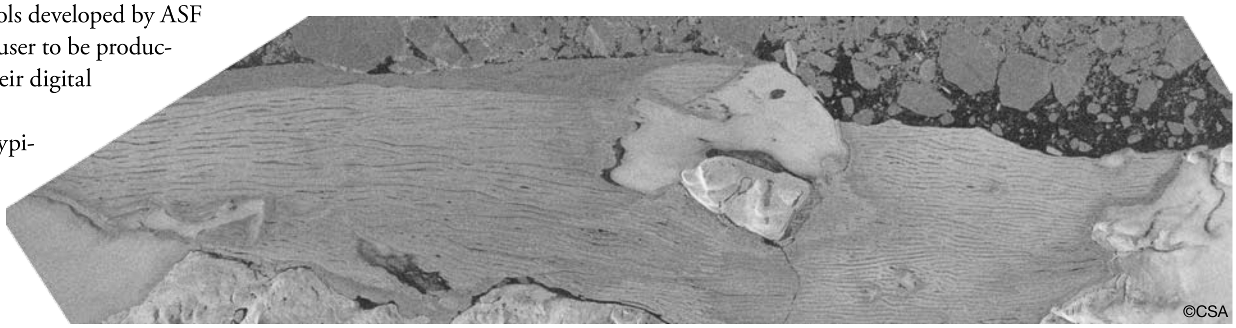
I was interested in T-3 because, roughly 40 years earlier, it had calved from the once extensive Ellesmere Ice Shelf along the northernmost coast of Ellesmere Island, then in the Northwest Territories, now Nunavut, Canada. By 1982, disintegration and further ice island calvings had reduced the Ellesmere Ice Shelf to a number of smaller ice shelves. I first saw some of those ice shelves in April and May 1982, when I completed my first field season of doctoral research on ice shelf formation and structure.

After seeing T-3 in Fu and Holt (1982) and completing a second field season on the Ellesmere ice shelves in April and May 1983, I saw radar images of the ice shelves for the first time in November 1983 at the Canadian Ice Service (then known as the Ice Centre) in Ottawa. I had heard rumours that occasionally, budget permitting, the Ice Centre would include the northernmost coast of Ellesmere Island in round-robin flights that were obtaining real aperture radar (RAR, also known as side-looking airborne radar - SLAR) images of the Queen Elizabeth Islands. The budget gods must have been feeling generous in 1981 and 1983, because, when I visited the ice centre in November 1983, I saw the ice shelves in X-band ($\lambda$ = 32.5 mm) RAR images that had been obtained in September 1981 and April 1983.

The images were not the radiometrically-calibrated, high-spatial-resolution SAR images (e.g., Figure 1a) that we take for granted today after raw signal data have been received, archived, processed and distributed by ASF. No, those SLAR images (e.g., Figure 1b) were low resolution (~200 m) photographs with bright, near-vertical slashes to mark time (and thus provide a scale if the air speed had been recorded), heavy shadows (due to the low flight altitude and thus low incidence angle), and numerous artifacts due to aircraft motion and processing factors. Nevertheless, it was a revelation for me to have this active microwave view of the ice shelves sandwiched between the land and the pack ice of the Arctic Ocean (Figure 1b).

I still have the 1981 and 1983 SLAR photographs of the Ellesmere ice shelves. They remind me of many things, including the fact that it was once possible to order photographic products (paper and transparency) from ASF. They have long since ceased to be available. Everything is digital now, with products delivered on a choice of tape, CD or DVD, or delivered direct to your desktop computer via ftp. Moreover, a variety of freely available computer tools developed by ASF make it easier for the user to be productive once they have their digital SAR data.

Product delivery typically takes a few days, but under some circumstances, ASF will deliver much more quickly.



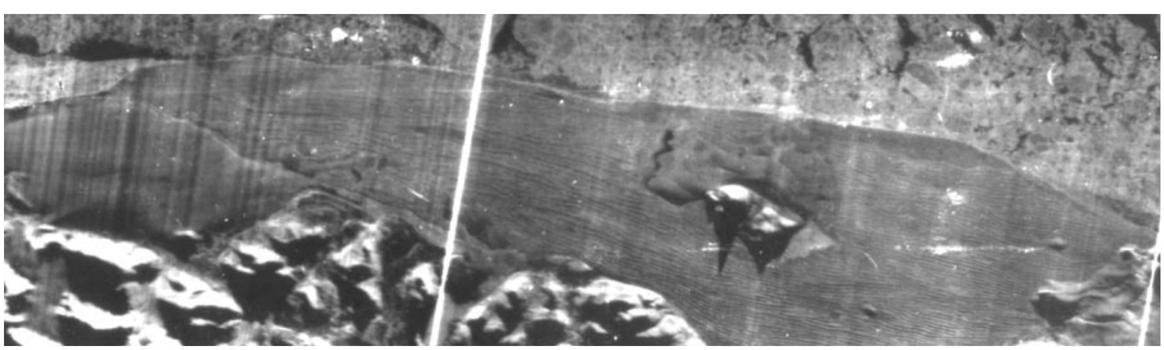



*Figure 1. RADARSAT-1 Fine Beam SAR image of the Ward Hunt Ice Shelf on 30 August 2002 (a, top), and airborne RAR image of the ice shelf in September 1981 (b, bottom). The width of the RAR image is equivalent to about 50-km on the ground.*

For example, I enjoyed outstanding service in early August 2002, when Derek Mueller (then a graduate student at Université Laval, Québec, and now a NSERC Post-doctoral Fellow at the Geophysical Institute, UAF) reported from the Ward Hunt Ice Shelf that he had found many long, wide fractures in the ice. Thanks to ASF, I had RADARSAT-1 standard beam images on my computer less than 24 hours after I had placed the order and was able to confirm many of Derek's observations. ASF then expedited a RADARSAT-1 fine beam data acquisition request for late August that not only showed the fractures in greater detail, but also confirmed the calving of more ice islands (Mueller, et al., 2003).

The ASF archive now contains a large volume of RADARSAT-1 data of northernmost Ellesmere Island. On the other hand, the archive contains very little ERS SAR data of the region. This is primarily a function of the reluctance of ESA to use ASF for data acquisition over a region that lies at the extreme northern edge of the ASF station mask for the ERS satellites. ASF personnel expended a lot of time and energy on my behalf trying to convince ESA that the ERS satellites could simultaneously illuminate the ice shelves and transmit the data to ASF. Although ESA eventually agreed to what turned out to be a successful demonstration of ASF's argument that it could be done, ESA preferred to

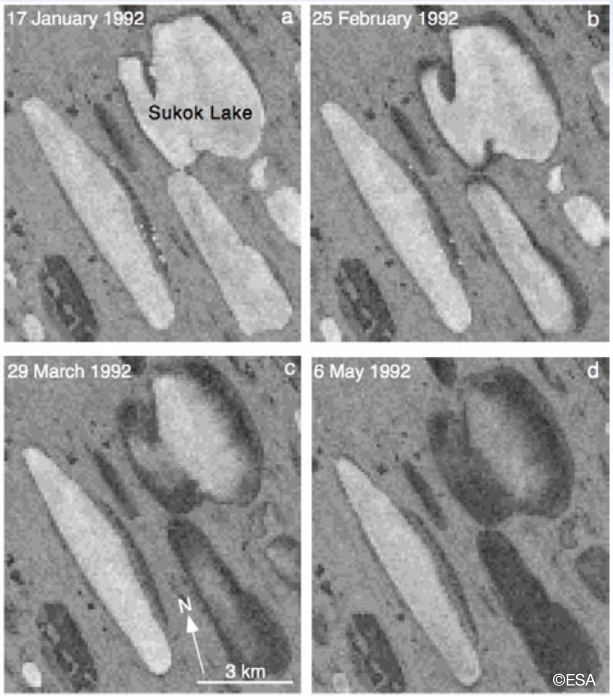



*Figure 2. ERS-1 images of frozen, shallow lakes about 30 km south of Barrow, AK. The width of each image is equivalent to about 10 km on the ground.*

continue to use Tromsø for receiving data from the northernmost Ellesmere Island.

SAR data received at other ground stations are available to ASF users, but they cost real money, unlike the hundreds, perhaps thousands, of images I have "bought" from ASF with data credits. Like the majority of ASF users, I have benefited from an enlightened and generous NASA data policy based on its agreements with ESA, CSA, and JAXA. This policy has placed large numbers of images in researchers' hands and allowed them to pursue exciting, and often ground-breaking, investigations with minimal anxiety about the financial costs. Rationing remote sensing data by charging high prices surely hinders scientific progress.

ERS-1 and ERS-2, JERS-1 and RADARSAT-1 images would not reach the researchers without the skill of an ASF staff that is dedicated to receiving, archiving, processing and distributing high quality data in a timely fashion. There have always been such dedicated people at ASF, but there was a time when the complex ASF electronics and electrical engineering systems were viewed by some as an end in themselves rather than a means to a more vital end — getting data into the hands of users so they could apply their talents to answering interesting and important questions.

For a short time in the early to mid-1990s, I found myself in the unexpected position of being a "super user" of ASF data. That is, my name was on all the orders being placed, mainly by Kim Morris, for our studies of the landfast ice/pack ice interface in the East Siberian Sea and ice on shallow lakes the North Slope of Alaska. The East Siberian Sea ice study, a collaboration with Shusun Li (Geophysical Institute, UAF), used the original Geophysical Processor System (GPS) to obtain pack ice motion vectors and interferometry to examine landfast ice motion. Graduate student Ken Schwartz also placed many orders for his study of summer sea ice in Beaufort and Chukchi seas.

The lake ice study will always be a favourite because I had not previously studied any freshwater ice, and this, my first study of lake ice, was done in partnership with Willy Weeks, the first ASF Chief Scientist. The study was inspired by Willy's earlier reports on interesting lake ice signatures in airborne X-band RAR and airborne X- and L-band SAR images (Weeks, et al., 1977, 1978). With ERS-1 data, we were able, for the first time, to follow at regular intervals the course of lake ice growth, grounding on the bottom (Figure 2) and decay between freeze-up in the autumn and break-up in the spring. This was possible because we had access to a large number of frequently acquired images, which were available in digital form and could, therefore, be studied using computer techniques.

Sigma-nought, a Macintosh application developed by Tony Freeman at JPL, was a wonderful tool that enabled our investigation of the changing backscatter of the lake ice. We also benefitted from the numerical modelling talents of Hiro Wakabayashi; his secondment to ASF from NASDA and his interest in doing more than observe ASF engineering activities contributed to a better understanding of the causes of backscatter variation from ice on shallow lakes. Another numerical modeller, Glen Liston (then at NASA GSFC, now at Colorado State University), simulated ice growth and thickness, and enabled us to map water depth variations from sequences of images of known date and thus simulated ice thickness, a proxy for the depth of water at the boundary between floating and grounded ice (Figure 2).

Being a "super user" was all very well, but it had its challenges, not the least when those many images had to be ordered. The original user interface, the Archive and Catalog System (ACS), provided no tools for seeing if your area of interest or target was in the images listed after the archive had been searched. For each image listed, you received its corner coordinates and then you were left to your own devices to determine if that image met your needs. It was rather hit or miss and certainly very time-consuming. Today, ordering just the right image is much easier, thanks to the EOS Data Gateway with its map tool to show you exactly where the image that interests you is located relative to your target. But will there ever be an image browse capability to make ordering even easier?

I arrived at the Geophysical Institute in August 1985, six years before ERS-1 was launched and ASF began receiving its first SAR data in August 1991. As a GI researcher and, for a brief time, the ASF DAAC scientist, I have seen ASF conceived, born, grow and mature. There were certainly growing pains, and maturity has brought new challenges, but ASF has survived and thrived, even in occasional adversity. The GI and UAF, NASA and the foreign flight agencies, and most importantly, the community of SAR data users, have benefited from and been well served by ASF. I wonder what the next 15 years have in store and who will write about what for the period 2006-2021?

This fall AGU has a session about ASF, H60: *Exploring Geoscience Applications of SAR Imagery From the Alaska Satellite Facility.*

The AGU abstract deadline is September 7, 2006. The meeting dates are December 11-15, 2006.

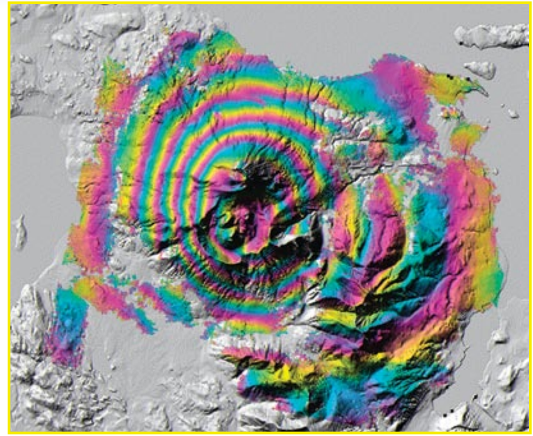
# Interferometric Synthetic Aperture Radar:

## Building Tomorrow's Tools Today *by Zhong Lu*

A synthetic aperture radar (SAR) system transmits electromagnetic (EM) waves at a wavelength that can range from a few millimeters to tens of centimeters. The radar wave propagates through the atmosphere and interacts with the Earth's surface. Part of the energy is reflected back to the SAR system and recorded. Using a sophisticated image processing technique, called SAR processing (Curlander and McDonough, 1991), both the intensity and phase of the reflected (or backscattered) signal of each ground resolution element (a few meters to tens of meters) can be calculated in the form of a complex-valued SAR image representing the reflectivity of the ground surface. The amplitude or intensity of the SAR image is determined primarily by terrain slope, surface roughness, and dielectric constants, whereas the phase of the SAR image is determined primarily by the distance between the satellite antenna and the ground targets, slowing of the signal by the atmosphere, and the interaction of EM waves with ground surface. Interferometric SAR (InSAR) imaging, a recently developed remote sensing technique, utilizes the interaction of EM waves, referred to as interference, to measure precise distances. Very simply, InSAR involves the use of two or more SAR images of the same area to extract landscape topography and its deformation patterns.

InSAR is formed by interfering signals from two spatially or temporally separated antennas. The spatial separation of the two antennas is called the baseline. The two antennas may be mounted on a single platform for simultaneous interferometry, the usual implementation for aircraft and spaceborne systems such as Topographic SAR (TOPSAR) and Shuttle Radar Topography Mission (SRTM) systems, where high-resolution, high-precision, digital elevation models (DEM) over large regions can be generated. Alternatively, InSAR can be created by using a single antenna on an airborne or spaceborne platform in nearly identical repeating orbits for repeat-pass interferometry (Massonnet and Feigl, 1998). For the latter case, even though the antennas do not illuminate a given area at the same time, the two sets of signals recorded during the two passes will be highly correlated if the scattering properties of the ground surface remain undisturbed between viewings. This configuration makes InSAR capable of measuring ground-surface deformation with centimeter-to-subcentimeter precision at a spatial resolution of tens of meters over a large region. This is the typical implementation for spaceborne sensors such as the U.S. Seasat (operated June to October, 1978, L-band, wavelength $\lambda$ = 25.0 cm), European Remote-sensing Satellite (ERS-1) (operated 1991-2000, C-band, $\lambda$ = 5.66 cm), Japanese Earth Resources Satellite (JERS-1) (operated 1992-1998, L-band, $\lambda$ = 23.5 cm), Shuttle Imaging Radar-C (SIR-C) (operated April to October 1994, X-, C-, and L-band, $\lambda$ = 3.1 cm, 5.66 cm, and 24.0 cm, respectively), ERS-2 (operating 1995-present, C-band, $\lambda$ = 5.66 cm), Canadian Radar Satellite (RADARSAT-1) (operating 1995-present, C-band, $\lambda$ = 5.66 cm), European Environmental Satellite (Envisat) (operating 2002-present, C-band, $\lambda$ = 5.63 cm), and ALOS (operating 2006-present, L-band, $\lambda$ = 23.6 cm).

An InSAR image (also called an interferogram) is created by co-registering two SAR images and differencing their corresponding phase values on a pixel-by-pixel basis. The phase (or range distance difference) in the original interferogram is due mainly to five effects: (1) differences in the satellite orbits when the two SAR images were acquired, (2) landscape topography, (3) ground deformation, (4) atmospheric propagation delays, and (5) systematic and environmental noises. The knowledge of a satellite's position and attitude is required to remove the effect caused by the differences in the satellite orbits of the two passes. The topographic effects in the interferogram can be removed by producing a synthetic interferogram, which is created from an accurate DEM and the InSAR imaging geometry, and then subtracting it from the interferogram to be studied. This is the so-called two-pass InSAR (Massonnet and Feigl, 1998). Alternatively, the topographic contribution can be removed through the use of a different interferogram of the same area. The procedures are then called 3-pass or 4-pass InSAR. These procedures will result in topography-removed InSAR images, where the component of ground deformation along the satellite's look direction can potentially be measured with a precision of centimeter or sub-centimeter for C-band sensors, and a few centimeters for L-band sensors. Because of problematic atmospheric propagation delays, repeat observations are critical to confidently interpret small geophysical signals related to movements of the Earth's surface. Please note, if the two SAR images are acquired simultaneously (single-pass InSAR), or the deformation during the SAR acquisition time is negligible or can be modeled and removed, then the InSAR image can be used to derive a DEM. The single-pass InSAR is the fundamental principle for the generation of SRTM DEM.



*An ERS-1/ERS-2 InSAR image showing ~17 cm of uplift centered on the southwest flank of Mt. Peulik volcano, Alaska, which occurred during an aseismic inflation episode from October 1996 to September 1998 [Lu, Z., et al., Journal of Geophysical Research, 107, B7, 2002]. Each fringe corresponds to 2.8 cm of range change.*

## InSAR Past

The launch of the ERS-1 satellite in 1991 significantly promoted the development of techniques and applications in the field of InSAR. InSAR-related research in the 1990s can be grouped into three categories: deformation mapping, DEM generation, and landscape characterization.

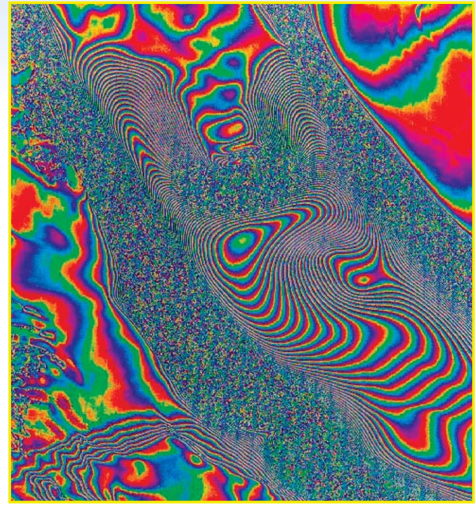
InSAR has been applied successfully to map ground surface deformation during volcanic eruptions and earthquakes. Early studies used SAR images acquired before and after an earthquake or volcanic eruption to image the co-seismic or co-eruptive deformation. Images of InSAR-derived surface deformation can provide essential information about magma dynamics and are extraordinarily useful for understanding slip distribution and rupture dynamics during earthquakes. In the late 1990s, InSAR studies also included the mapping of surface deformation immediately after an earthquake, i.e., post-seismic deformation, while for volcanic study, InSAR was used to map deformation of volcanoes during quiescent periods.

InSAR was applied to map land surface deformation associated with fluid withdrawal. Surface subsidence and uplift that were related to extraction and injection of fluids in groundwater aquifers and petroleum reservoirs could be seen in InSAR images that provided fundamental data on reservoir/aquifer properties and processes, and improved our ability to assess and mitigate undesired consequences. InSAR capability was also demonstrated as an effective way to map the slow movement of landslides, providing a new tool for landslide monitoring.

InSAR was successfully applied to record the movement of glaciers and ice fields, and it significantly advanced the studies of glacier and ice flows, and of ice-sheet mass balance. By regularly imaging ice sheets over the Arctic, Antarctic, and Greenland, InSAR has contributed to building an unprecedented series of snapshots that documents the short-term evolution of the ice sheet, aiding our understanding of their impact on sea level change and global warming.

InSAR was applied to map water-level changes over wetlands. InSAR (particularly at longer wavelengths) was found to be an effective tool in the accurate measurement of water-level changes in river valleys and wetlands, which can improve hydrological modeling predictions and enhance the assessment of future flood events over wetlands.

InSAR was applied to construct DEMs over areas where the photographic approach to DEM generation was challenged by inclement weather conditions. For example, repeat-pass InSAR was used to generate ice surface topography that determined the magnitude and direction of the gravitational force that drives ice flow and ice dynamics. In addition, volcano surface topography measurements from before and after an eruption were used to estimate the volume of extruded material. There are many sources of errors in DEM construction: inaccuate determination of the InSAR baseline, atmospheric delay anomalies, and possible surface deformation due to tectonic, volcanic, or other loading sources over the time interval spanned by repeat-pass interferograms, etc. To generate a high-quality DEM from repeat-pass InSAR images, these errors must be corrected.



*InSAR image of a portion (50 by 100 km) of the Rutford ice stream in Antarctica, based on two ERS-1 images taken six days apart [Goldstein, et al., Science, 262, 1525-1530, 1993]. The fringe pattern (color cycle) is essentially a map of ice flow velocity, with one fringe representing 28 mm of range change along the radar line of site.*

Finally, InSAR was applied to the study of landscape characterization and changes. InSAR images and their associated products have proved useful to the mapping of flood extents, fire scars, land cover types, changes in soil moisture content, etc.

## InSAR Present

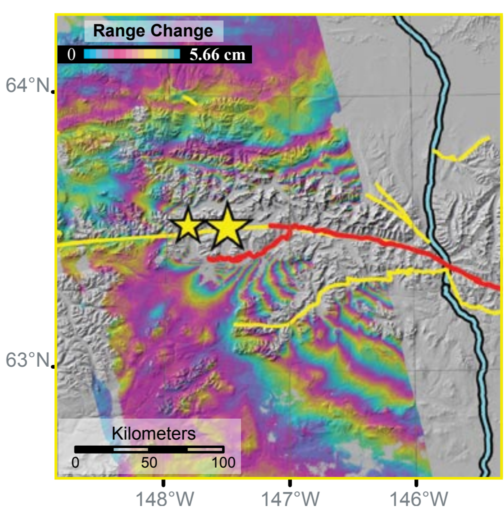
In the past few years, deformation mapping with InSAR has advanced from the interpretation of a few InSAR image pairs to the analysis of multi-temporal, time-series InSAR images. The ultimate goal has been to reduce artifacts due to atmospheric delay anomalies, orbit errors, and loss of coherence measurements in order to improve the accuracy of deformation measurements. Stacking and least-squares inversion approaches have been applied to multi-temporal InSAR images to remove atmospheric delay anomalies and improve temporal sampling in order to reveal transient, dynamic deformation patterns.

Persistent Scatterer (PS) InSAR (PSInSAR) represents the most significant advancement in InSAR research. PSInSAR uses unique characteristics of atmospheric delay anomalies and the distinctive backscattering of certain ground targets (called PS) to improve the accuracy of conventional InSAR deformation measurements from 1-2 cm to 2-3 mm (Ferretti, et al., 2001) . The SAR backscattering signal of a PS target has broadband spectra in the frequency domain, implying that the radar phase of this kind of scatterer correlates over much longer temporal intervals and over much larger baseline separations than other scatterers. As a result, if the backscattering return of a pixel is dominated by PS(s), this pixel will always be coherent over long time intervals. For PS pixels, the difficulty of decorrelation in the conventional InSAR can, therefore, be overcome. In addition, the atmospheric contribution is rather smooth spatially and is independent over time. At PS pixels, the atmospheric contribution to the received backscattering signal can be identified and removed from the data using a multi-interferogram approach. Therefore, the ultimate goal of PSInSAR processing is to separate the different contributions (surface deformation, atmospheric delay anomaly, DEM error, orbit error, and decorrelation noise) by means of least-squares estimations and iterations, taking into account the spatio-temporal distribution and the correlation between the PS samples. After removing errors due to the atmospheric anomaly, orbit error, and DEM error, deformation histories at PS points can be appreciated at millimeter accuracy. PSInSAR has been successfully applied to monitor landslides, urban subsidence, fault movement, and volcanic deformation.

## InSAR Future

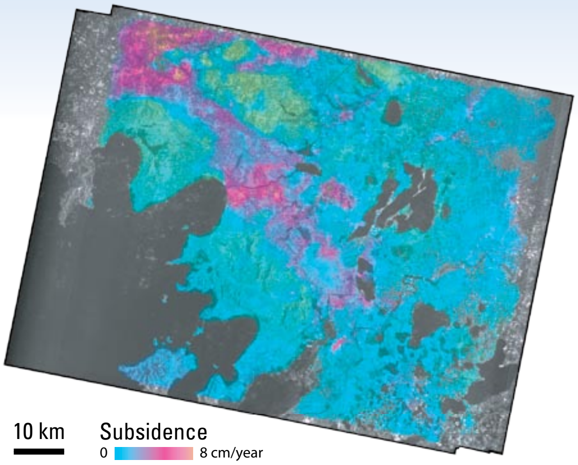
The next few years will witness more exciting technical and scientific breakthroughs in many aspects of InSAR. First, longer wavelength SAR images (such as L-band ALOS) will be available that will allow InSAR deformation mapping at global scales where C-band InSAR can be plagued by loss of coherent signal due to vegetation. Second, fully-polarized SAR sensors (ALOS, RADARSAT-2, TerraSAR-X, TanDEM-X, etc.) will allow better characterization of vegetation structure and ground features. The combination of polarimetric and interferometric analysis (called Pol-InSAR) will offer a new capability for landscape mapping and deformation monitoring (Cloude, et al., 2001).

*continued*




*RADARSAT-1 InSAR image showing the displacement over the western part of the 340 km long surface ruptures (red lines) associated with the M 7.9 November 3, 2002 Denali earthquake [Lu et al., EOS, Transactions, AGU, 84, 41, 425-431, 2003]. The yellow lines represent faults that show evidence of activity during Quaternary time. The interferogram is draped over the shaded relief images, and areas without interferometric coherence are uncolored.*

*Average deformation rate of a coastal area in southeastern China from multi-temporal L-band JERS-1 InSAR images [Z. Lu, unpublished data].*




Pol-InSAR will enable optimization procedures that maximize the interferometric coherence and target decomposition approaches to the separation of radar backscattering returns from the canopy top, from the bulk volume of the vegetation, and from the ground surface. The difference in interferometric phase measurements then leads to the difference in height between the physical scatterers that possess these mechanisms. Accordingly, future Pol-InSAR will introduce significant advances in many fields of application: 1) land cover mapping and wetland mapping, particularly over regions where weather conditions hinder optical remote sensing; 2) mapping soil moisture with a horizontal resolution (several meters) that is not attainable otherwise; 3) mapping forest height and biomass with generation of "bare-earth" DEM; 4) traffic monitoring over oceans, and much more.

A third breakthrough is ScanSAR, an advanced SAR imaging technique achieved by periodically switching the antenna look angle into neighboring subswaths in the range direction in order to increase the size of accessible range swath. ScanSAR will be equipped with InSAR capability to enhance spatial coverage of conventional InSAR for large-scale deformation measurement and to improve temporal sampling of InSAR deformation images. Fourth, the atmospheric delays that hamper InSAR accuracy will be lessened by routinely estimating water-vapor content from either the continuous global position system (CGPS) network or other satellite sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and European Medium Resolution Imaging Spectrometer (MERIS) to improve InSAR deformation measurements. Fifth, advances in multi-temporal, multi-dimensional data-mining techniques (such as PSInSAR) will continue to improve deformation measurement. Finally, automated SAR and InSAR processing systems will be more widely available, which will improve SAR/InSAR processing throughput and lay the foundation for routine monitoring of natural hazards and natural resources.

InSAR is one of the fastest growing fields in the Earth science and remote sensing arenas. With more and more operating SAR sensors available for rapid data acquisitions, armed with state-of-the-art information technologies such as data-mining and grid computation, InSAR will continue to address and unveil many scientific questions related to natural hazard monitoring and natural resource management.

# Sea Ice Motion: Science Driving U.S. SAR Research *by Ben Holt and Ron Kwok*

The ability to derive quantitative estimates of fine-scale ice motion and deformation from pairs of Seasat SAR images provided the primary scientific basis for implementing ASF. Being able to identify the detailed opening and closing of leads and how the ice cover moved and deformed over short time intervals provided basic knowledge of air-sea-ice heat and momentum fluxes. The value of such detailed measurements was a primary motivation of the Arctic Ice Dynamics Joint Experiment (AIDJEX) that took place in the Beaufort Sea in the mid-1970s, where an extensive suite of on-ice plus airborne and satellite (in that case Landsat and NOAA) remote sensing observations were employed to determine external forcing that impacted the mechanical deformation and heat balance of the ice cover, which in turn could be used to verify and improve various types of sea-ice models.

With the Arctic sea ice imagery obtained from Seasat in 1978, a means of making such detailed ice motion observations under all conditions was possible, as first described using Seasat SAR optically processed imagery (Hall and Rothrock, J. Geophysical Research,1981). When Frank Carsey arrived at JPL in 1981, where the Seasat project and data were located, he set out to examine the Seasat instrument suite including the SAR imagery. Carsey hired one of us (Holt) to help him out with his research; Holt having freshly completed the Seasat SAR Ocean and Sea Ice Atlas (Fu and Holt, JPL Publication 81-120, 1982). They scrounged together a few pairs of digitally processed SAR images that contained the same ice fields taken 3 days apart. The Seasat SAR digital processor was the first ever developed and at that time a single 100-km by 100-km SAR image frame took no less than 8 hours to process, if it was done correctly the first time. With the help of some clever folks in the JPL Image Processing Lab, a method was established of interactively tracking specific floes from image to image and quantifying the motion. Carsey invited Drew Rothrock and Alan Thorndike, both from the Applied Physics Laboratory at the University of Washington, down to JPL and everyone sat down for a week or so to tediously complete the detailed floe tracking of these sets of image pairs. The geometric fidelity of the Seasat SAR was quite good and the floes could be identified nicely from image to image with its fine resolution. Thus, a clear, unambiguous, detailed, repeatable and useful geophysical quantity was derived. This was in contrast to the detailed and rich array of ocean features detectable by SAR, including waves, internal waves, eddies, currents, and fronts, but whose value were fraught by pesky and significant non-linearities arising from ocean motion during the imaging process and the even now tricky part of how to turn these fascinating signatures of the ocean surface into meaningful quantities.

A small working group was setup by NASA to consider establishing a SAR receiving station at UAF for ESA's ERS-1 mission. This effort led to the initial science requirements document, Science Program for an Imaging Receiving Station in Alaska, published at JPL in December 1983. Some of the Seasat image pairs and motion vectors were prominently displayed and discussed in the report along with a broad spectrum of other important science topics, describing the wonderful things that could be done if we only had a receiving station to get this data regularly and that UAF was the best place to put it, both in terms of satellite accessibility and scientific interest. Published papers followed that discussed the derived vectors and their value as well as the geometric basis and accuracy of the measurements (Curlander, et al., IEEE J. Oceanic Eng., 1985; Carsey and Holt, J. Geophysical Res., 1987). A more complete Science Plan for the Alaska SAR Facility Program was published in 1989, following two highly entertaining and useful science meetings held at Chena Hot Springs, Alaska, in 1987 and 1988.

Next the effort moved toward figuring how to make an algorithm and system to derive ice motion in a more automated fashion that would be implemented at ASF. Towards this, two meetings of the Ice Motion Algorithm Group (IMAG) were held in October 1986 at JPL and May 1987 at ERIM in Ann Arbor, Michigan, where results were presented of various approaches toward such an algorithm. In addition to sea-ice researchers in both the U.S. and Canada, this effort was also embraced by specialists in Image Processing who were intrigued with the notion of how to identify features that moved and rotated between images. These meetings were interesting and valuable, but all ideas coalesced around a couple of approaches. First, a hierarchical scheme could be employed to identify and colocate the same general sea-ice field between a pair of images. Another approach was then needed to capture the portions of the ice field that had deformed/slid/rotated/broken-up during the time interval between acquisitions. It was clear that a well-defined procedure would have to be selected if we were to extract motion information routinely from SAR imagery.

A brief mention should be made of a parallel effort to derive ice type from the SAR backscatter. Ice type is a proxy observation for the still difficult-to-measure ice thickness, so reliable methods to identify ice type would provide a means to assess the varying composition of the major ice types (and then thickness). As with most surfaces, using a sensor response to clearly identify a surface type or feature is often ambiguous. If it's not the instrument properties itself, then it's the variation in the surface that muddles the signatures. Another workshop, entitled the Radar Age/Type Algorithm Group (RAGTAG), was held in Seattle in July 1988 to explore ways to identify ice types. One thing that was clear, was that this could be done better using C-band, with the upcoming ERS-1 SAR and, on the more distant horizon, RADARSAT-1, than with Seasat L-band SAR, and that the major thicker ice categories could be pretty well identified with backscatter. The muddling part was that the thinner ice types sometimes had signatures similar to those of the thicker ice types and confusion ensued. This effort to derive ice type was continued within the GPS development discussed below. But then the notion of Lagrangian tracking with RADARSAT-1 basically leapfrogged the issue of ambiguous ice signatures to jump straight into ice age, a more desirable and valuable quantify from which ice growth and volume increase could be determined.

## Implementation and products

At the time of the IMAG meetings, John Curlander (who headed the JPL SAR data processing group) and Carsey proposed to put together an operational system for producing sea-ice motion at ASF. The second author (Kwok) happened on the scene at around the same time — he was in Curlander's group working on the Venus radar and was asked whether the work would be of interest. Without experience in sea-ice remote sensing, Kwok got involved and was given the responsibility to refine the algorithms and to work with VEXCEL (Franz Leberl was Chief Executive Officer) in constructing a system to be delivered to ASF sometime before the launch of ERS-1. The system incorporated the best of the various methods from the IMAG group, plus some new bells and whistles, and the Geophysical Processing System (GPS) development was initiated. The implementation effort was monitored by a group called the "Plumbers" (coined by R. Thomas) who were tasked with making sure that the image matching schemes and system had the correct "plumbing" or design. Numerous meetings were held at the new facilities of the then young VEXCEL in Boulder, Colorado.

The GPS system was a rather modest system by today's standards (Kwok, et al., IEEE. J. Oceanic Engineering, 1990). It produced motion estimates from ~10 ERS image pairs daily and demonstrated the concept of producing geophysical information directly from SAR imagery. Processing speed was limited by the array processors of ~100 Mflops. There are only one-to-two -hundred vectors from each image pair (Fig. 1). Also, the production of the vectors required some attention because we were not familiar with the extent and range of deformation that one could expect within a single SAR image over 3 days. The GPS processed most of the ERS-1 SAR data of sea ice downlinked at ASF. The system was retired 3 years after it was installed.

The promise of routine coverage of the entire Arctic Ocean ice cover came with the RADARSAT-1 mission. The RGPS (RADARSAT Geophysical Processor System) was implemented to take advantage of its wide-swath mapping capability — the ScanSAR mode provides complete maps of the Arctic Ocean every 3 days, termed the Arctic Snapshot. This frequent and reliable coverage allowed us to follow drifting ice parcels for an entire winter and to record their evolving properties (i.e., deformation and ice age) in addition to ice motion on a uniform grid. Thus, the Lagrangian tracking approach was introduced. This idea was developed during a meeting of the second author with Drew Rothrock and Harry Stern at the University of Washington (Kwok, et al., IEEE Trans. Geosci. Remote Sens., 1995).

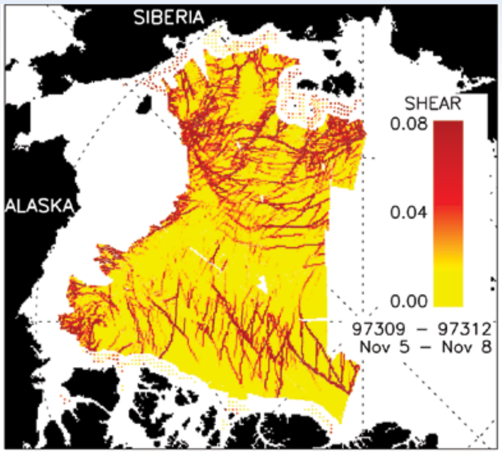



*Figure 2. Near basin-scale shear field derived from almost 100 (450-km by 450-km) RADARSAT ScanSAR images acquired over a 4-day period.*

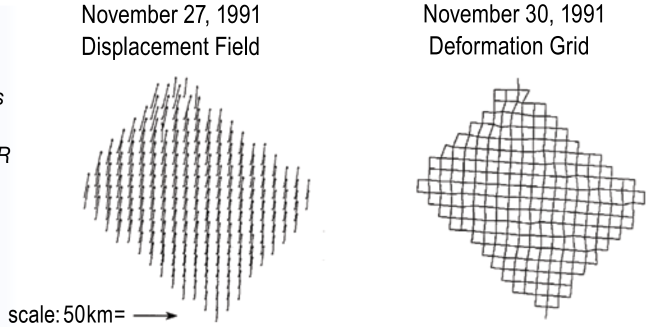
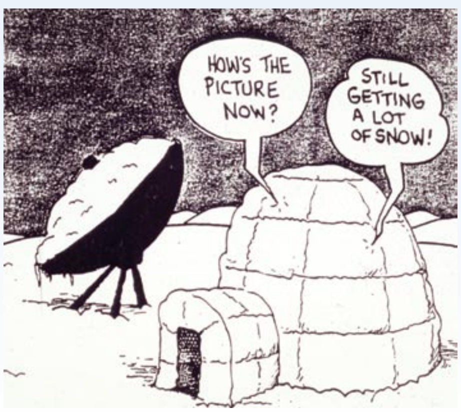



*Figure 1. Ice motion vectors and deformation field derived from two ERS-1 SAR images (100-km by 100-km) separated by 3 days.*

*continued*

The RGPS system was funded, built, and began operations at ASF in 1999. At this writing, both ASF and JPL are involved in a joint project to process the ongoing Arctic Snapshot data stream acquired by RADARSAT-1, which started in the winter of 1996/97.

More than a thousand motion vectors can be obtained from a single RADARSAT-1 image pair. The quality of the motion trajectories is comparable to that from drifting buoys – the only remaining advantage of buoy observations being that of temporal sampling. RGPS observations are nearly equivalent to deploying thousands of drifting buoys in the Arctic Ocean. The basin scale maps of deformation are quite spectacular, providing detailed information about the response of the ice cover to atmospheric and oceanic forcing. Large-scale gradients in these forcings are clearly concentrated at the small scale in fracture zones where most of the dynamic and thermodynamic interactions between the atmosphere and ocean take place (Figure 2). This data set has given new impetus to process/climate studies and model improvement. The hope is that RADARSAT-2 will allow us to continue to build up a new decadal record of observations at this scale in the years to come.

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GRFM and GBFM mosaic products are available on CD ROM and DVD ROM from ASF, and may ordered from http://www.asf.alaska.edu/dataproducts/unrestricted.html

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