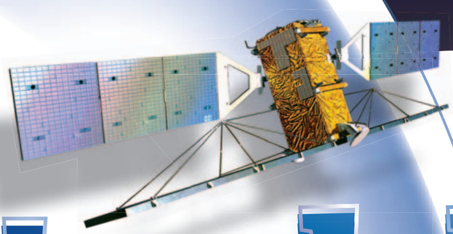

World View

Canadian remote sensing at home and abroad

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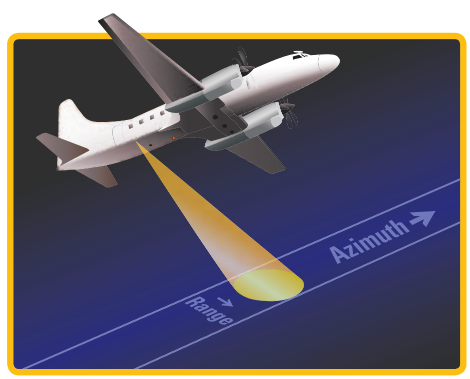
Canada's world-leading spaceborne radars give planners and decision makers a unique capability to monitor our ocean territories, aid in resource development and assess humanitarian needs.

Anytime, anywhere – Earth Imaging using Spaceborne Radar

Since the dawn of the space age, orbiting satellites have provided planners and decision makers with a unique vantage point from which to routinely observe the Earth and gather information for applications as diverse as weather forecasting, crop assessment, strategic surveillance, and geology. Until the late 1970s, however, virtually all Earth observation from space was based on optical images produced from reflected light in the visible and infrared.

While optical imagery from space has proven to be extremely useful, producing it requires both adequate illumination and clear skies. At night, or when clouds, fog or smoke obscure the ground, the quality and utility of such images suffer greatly. Radars provide their own illumination and operate at wavelengths that easily penetrate clouds, fog and smoke, but conventional side looking radars lack the resolution required to generate useful radar images of the Earth's surface from orbit.

The advent of Synthetic Aperture Radars mounted on fast moving airborne platforms introduced the first practical way to generate high resolution two-dimensional radar images of the land below.[1] As in conventional radar images, the intensity of individual pixels corresponds to the radar reflectivity of the scene. Unlike conventional radar images, however, the azimuthal or "along-track" resolution of SAR images is independent of range, yielding the possibility of creating photograph-like images with high resolution.



In Synthetic Aperture Radar (SAR), resolution in the azimuth direction is independent of range. SAR was first developed for airborne application.

Canada has made significant contributions to SAR research, development and application during the past 40 years including development of fundamental SAR image processing techniques and providing SAR image processors and systems engineering expertise to major U.S., European, Asian and other international customers. Since the advent of Canada's RADARSAT program in the mid 1990s, Canada has played a leading role in demonstrating the routine use of SAR imagery in both public and private sector applications.

Today, Canadian decision makers benefit from a wide range of Canadian-produced SAR image products. Marine surveillance and

[1] Polarimetric and interferometric SARs go a step beyond conventional SARs and allow special types of multi-channel or multi-image SAR data to be processed to yield image products useful in the identification of targets, interpretation of target structure, observation of fine ground movement and production of terrain elevation maps. In this manner, the utility of advanced SAR imagery can fundamentally surpass (and complement) conventional optical imagery.

ice-mapping have become routine applications. Geotechnical mapping and environmental monitoring are becoming increasingly important. Humanitarian disaster relief is a less common application — thankfully — but is of immense benefit when needed.

The “Magic” of SAR (Synthetic Aperture Radar)

The linear path traversed by the simplest form of SAR as it moves along the scene is called the track. Resolution in range or the cross track direction – the direction in which the radar antenna points – is determined by the effective duration of the radar pulse. In this respect, SAR functions in the same manner as conventional radar and conventional pulse compression techniques can be used to improve resolution. A monostatic SAR uses the same antenna for transmission and reception and is sensitive to the diffuse waves reflected back from the target (backscatter response). In bistatic SARs, the transmitting and receiving antennas are separate.[2]

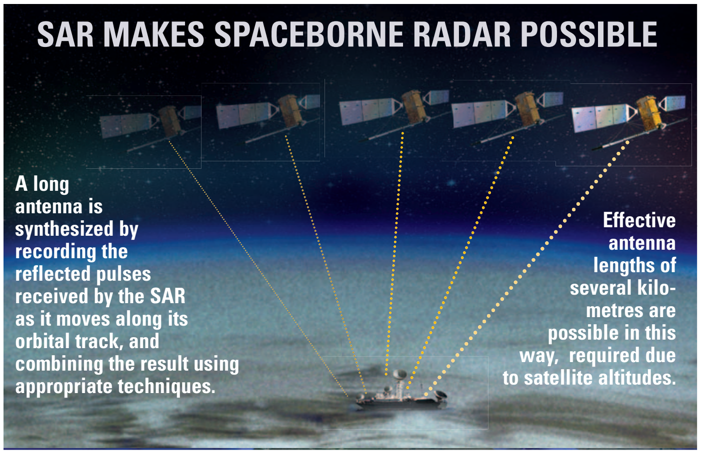
Resolution in the azimuthal or along track direction is determined by the radar antenna’s length. It is well known that an antenna’s beamwidth becomes finer as the antenna lengthens. There are limits to how long a physical antenna can be realized given the many constraints imposed upon satellite payloads. However, it is possible to synthesize an arbitrarily long antenna by recording the signal received by the SAR as it moves along its orbital track and combining the result using appropriate techniques.

However, a side-looking radar that simply synthesizes a large antenna with a very fine beamwidth using simple beamforming techniques is not sufficient. A simple geometric construction reveals that the width of the pixels in the radar image will increase linearly with the range to the target. Satellite orbits increase that range to hundreds of kilometres and fatally degrade the azimuth resolution. A new approach is required.

Synthetic aperture radar is based upon the observation that the energy from a given point target is spread in both range and azimuth. In SAR image reconstruction, this dispersed energy is collected or focused into a single pixel in the output image using advanced signal processing techniques. The underlying principle also forms the basis for the well known medical diagnostic tool commonly called CAT Scan, short for Computer Aided Tomography, that yields high resolution images of the body using low power X-rays. In radar application, the result is also a high-resolution image. But unlike conventional side-looking radar, the azimuth resolution is independent of range.

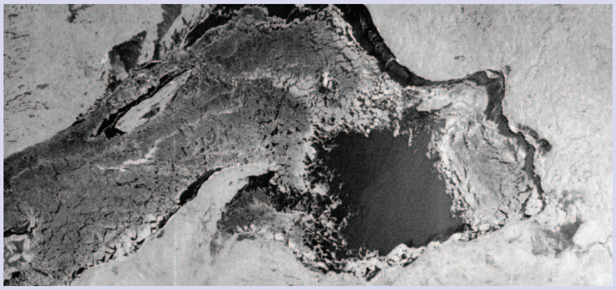
Such fine and uniform resolution in both the azimuth and range directions means that a SAR can create photograph-like images of the landscape, as seen in the RADARSAT-1 image in the sidebar to the right. *This is the magic of SAR*. However, because the location of a point target in a SAR image is based upon the time of flight, not the line of sight as in an optical image, SAR images suffer from a characteristic distortion in which higher terrain appears to be folded towards the observer. This is most apparent in SAR images of mountainous terrain.

[2] They may even be carried by different platforms, either to permit characterization of forward scatter from the target, to allow a secondary receiver to take advantage of existing transmitter in a parasitic mode of operation, or to make it difficult for a third party to detect the receiver.

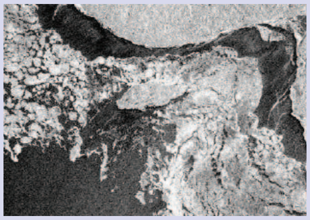


SAR creates photograph-like images

Lake Superior is easily recognized in this RADARSAT-1 image. Taken in late winter, the lake is almost entirely ice covered. The SAR was operating in ScanSAR Wide mode, giving a swath width of 500 km.

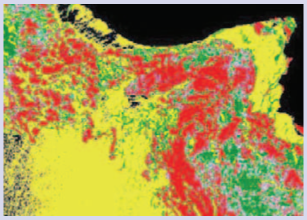


RADARSAT Data © Canadian Space Agency (CSA) 1997



An enlargement of the north shore near the east end of the lake. RADARSAT-1 operated at an altitude of about 800 km. In ScanSAR wide mode, the resolution of pixels in the azimuth direction was about 100 m.

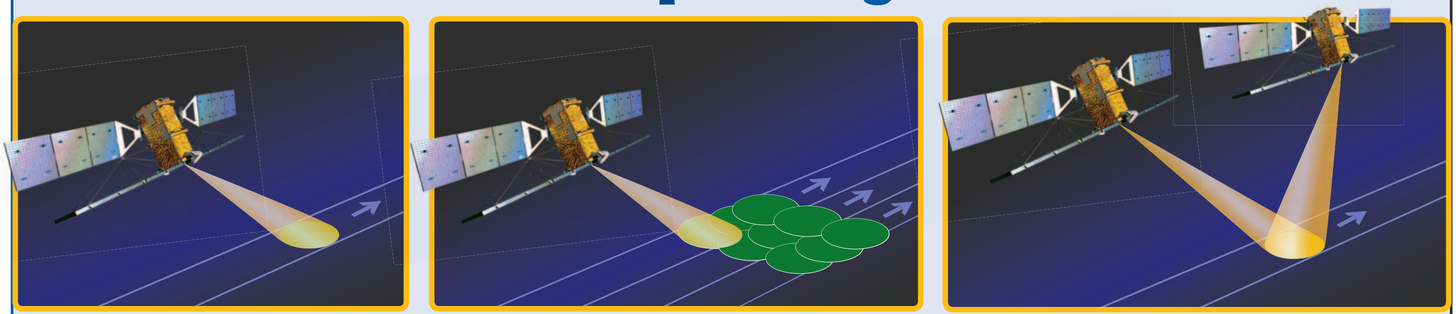
A satellite equipped with conventional real aperature radar operating at the same altitude would yield a resolution in the azimuth direction in excess of 5 km. Very little useful information would be obtainable.



Processing of the RADARSAT-1 image using calibration software and a library of backscatter signatures allows classification of ice coverage. Image created by George Leshkevich and Son Nghiem, 2007 [REF: 1]

Consolidated ice flows | Brash ice | Stratified ice | Calm water

RADARSAT Operating Modes



Stripmap Mode | **ScanSAR Mode** | **Spotlight Mode**

The basic SAR configuration in which the radar antenna is pointed broadside to the direction of travel permits formation of a continuous image of the ground. This is called **Stripmap SAR**. Synthetic aperture radars can be configured to operate in other modes in order to enhance certain aspects of SAR performance.

In **ScanSAR**, as orginally developed, the radar antenna is electronically steered to different angles in order to illuminate multiple swaths. This permits a wider area to be imaged than is possible in conventional SAR systems. Canada's RADARSAT-2 ScanSAR uses two or more physical beams operated sequentially, each producing separate image blocks that are then electronically merged together.

In **Spotlight SAR**, the radar antenna is electronically steered in order to keep the target in view for a longer period. Because this extends the size of the synthetic aperture, it increases the azimuthal resolution of the image but at the expense of spatial coverage.

A Brief History of SAR

The synthetic antenna concept was first successfully applied to radar by Carl Wiley at the Goodyear Aircraft Corp. in 1953. He used an aircraft for the moving antenna platform and a storage tube display that was configured to mimic a conventional Plan Position Indicator to present the radar returns. SAR literally took flight. [REF: 2]

Early data storage and processing was only practical using Fourier optics. By the mid 1970s, minicomputers with sufficient processing power to process SAR imagery digitally became available. The earliest computer algorithms in this area processed data from airborne SAR, developed by researchers at the Communications Research Centre (CRC) and The Defence Research Establishment Ottawa (now DRDC Ottawa). These algorithms were shared with Canadian industry in keeping with the commercialization mandate of the CRC dating back to its creation in 1969.[3]

In 1978, a Canadian startup company, MacDonald, Dettwiler and Associates, won the race to demonstrate that the general-purpose minicomputers available at the time could be used to reconstruct a viable SAR image from data collected by NASA's SEASAT spaceborne SAR (see IEEE Milestone article in the previous issue). In 1979, a CRC-designed processor yielded the first full-resolution SAR images from SEASAT.

[3] Historically, the vast majority of SAR image reconstruction has been conducted using frequency domain processing where computationally intensive convolution operations are replaced by much simpler multiplications in the frequency domain after application of a Fast Fourier Transform. Canadian SAR researchers played key roles in the development of three of the four common SAR processing algorithms in use today: Range-Doppler, Chirp Scaling, and SPECAN. A fourth, Omega-K, was developed at Politecnico di Milano in Italy. In recent years, advances in computing technology have made it possible to reconstruct SAR images using direct methods such as back projection and thereby avoid the need to satisfy some of the simplifying assumptions inherent to frequency domain approaches.

RADARSAT

In 1990 Canada created the Canadian Space Agency (CSA) within the Department of Industry. The RADARSAT-1 project was not only its first major project, but also the world's first operational civilian SAR satellite mission. Launched in 1995, the spacecraft lasted nearly 18 years and fundamentally changed the nature of Canada's Earth observation program.

Building on lessons learned, Canada developed RADARSAT-2 and launched it in 2007. Continuing Canada's world-leading role in operational SAR solutions, we will be launching the new three-satellite RADARSAT Constellation Mission (RCM) in 2018. [REF: 3, 4, 5, 6]

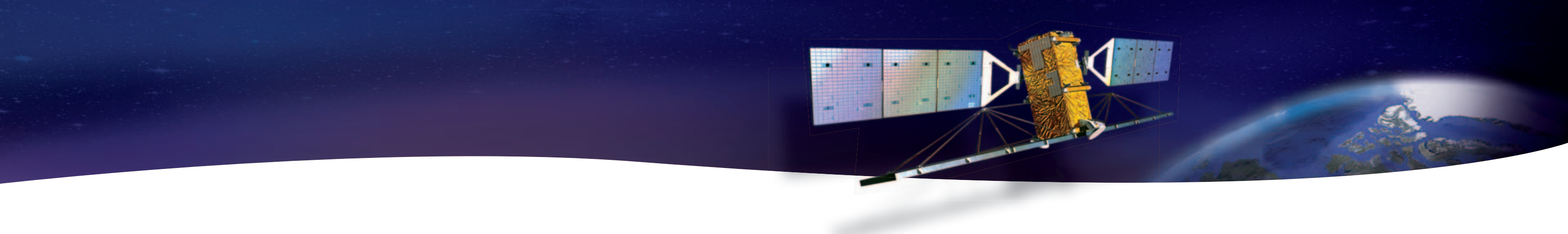
RADARSAT-1

The Canadian spaceborne SAR story began with RADARSAT-1, launched in 1995. The CSA managed the RADARSAT-1 project as a key component of the Canadian space program in the early 1990s. The total development contract was about $620 million (almost $1 billion in today's dollars), and the CSA owned and operated the final system. The major Canadian industrial team members who designed and built RADARSAT-1 for the CSA included

- **SPAR Aerospace (prime contractor, now part of MDA Corp.)**
- **MacDonald, Dettwiler & Associates**
- **COM DEV International Ltd.**
- **CAL Corporation (now part of COM DEV International Ltd.)**
- **SED Systems**
- **Fleet Industries (now Magellan Aerospace Corp.)**
- **IMP Group**
- **FRE Composites**

In exchange for access to SAR data, the National Aeronautics and Space Administration (NASA) supplied the Delta II rocket used to launch RADARSAT-1.

RADARSAT-1 followed a dusk-to-dawn sun-synchronous polar orbit with an altitude of about 800km. It always passed over the same Earth location at the



In 1990 Canada created its Canadian Space Agency (CSA); the RADARSAT-1 project was its first major crown project.

same time of day, which was important for consistent imaging through time and comparison with visible light imagery produced by other platforms. It also meant downlink ground stations had a consistent window of time to receive data sets. Being sun-synchronous also meant the satellite's solar panels were almost always in sunlight, ensuring that RADARSAT-1 ran primarily from solar rather than battery power.

The on-board SAR payload had the following specifications:

- **Frequency band: C-Band,**
- **Centre frequency 5.3 GHz**
- **Bandwidth 30 MHz**
- **Polarization HH (Horizontal transmit, Horizontal receive)**
- **Polarization isolation > 20 dB**
- **Aperture length 15 m**
- **Aperture width 1.5 m**
- **Mass 679 kg**

RADARSAT-1 had seven beam operating modes, with resolutions from 8m to 100m (depending on the mode) but could only look-right from the spacecraft. It would revisit its orbital path every 28 days. However, it could provide daily coverage of the Arctic. This was important, because at the time Canadian Ice Services needed a better method to monitor sea ice. RADARSAT-1 had its basic operating parameters (C-Band, HH polarization) optimized for ice mapping. And using one of its wider but lower resolution beam modes, the SAR could view almost any part of Canada within three days, and places near the equator every six days.

CSA planners had projected a 5-year lifespan for RADARSAT-1. So when it eventually failed in late March 2013, RADARSAT-1 had outlived all expectations. It delivered data products to more than 60 countries. But more important was its legacy as a civilian-based research tool, working hard to advance SAR Earth observation technologies. Though inoperable today, RADARSAT-1 still follows its dusk-to-dawn orbit — one more piece of space junk now.

RADARSAT-2

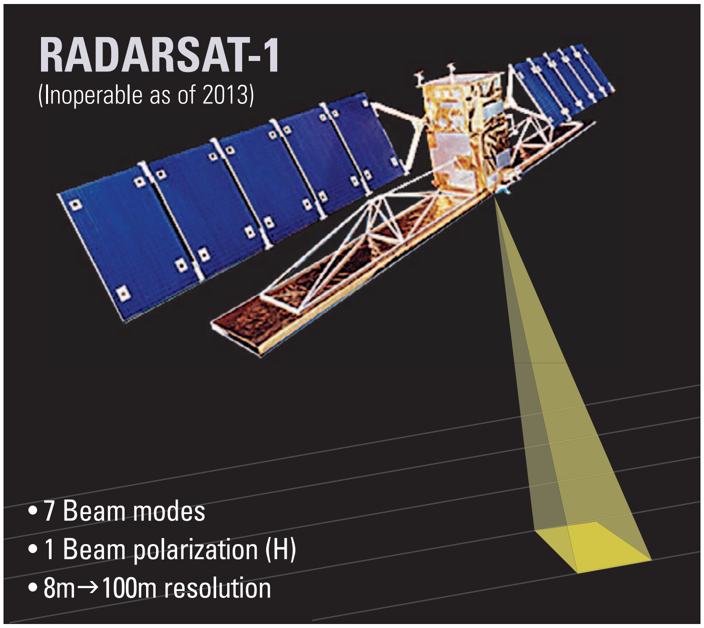
The follow-on CSA project, RADARSAT-2 was a direct descendent of the lessons learned from RADARSAT-1. It was a unique Public-Private Partnership (P3) project between CSA and MDA, with MDA owning and operating the final system. The development contract was approved in 2004 for a total of $528.8 million (about $641 million today) – slightly more than half the cost of RADARSAT-1. The Government of Canada contributed $437.1 million to the project. Though it had no ownership interest in RADARSAT-2, the government did receive about $446 million in data product credits from MDA.

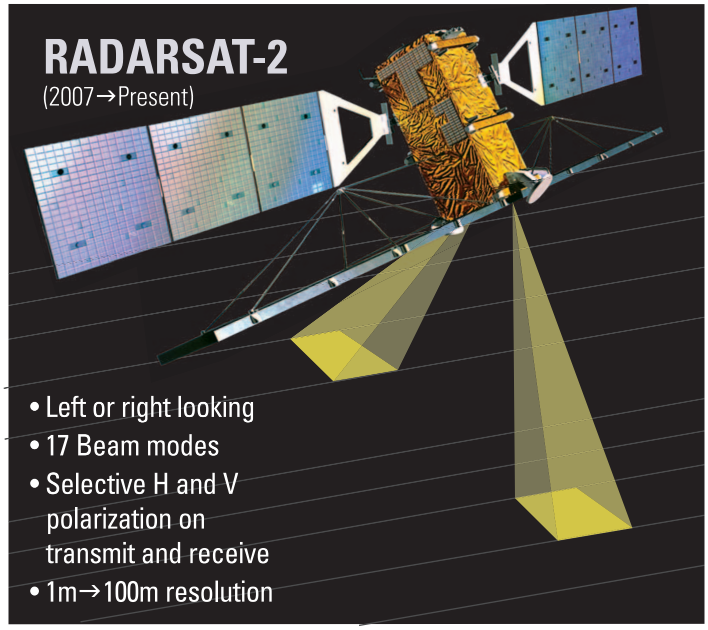
One limitation of RADARSAT-1 was its single polarimetry mode of Horizontal Transmit / Horizontal Receive (HH). Previous work had shown that much more information about the nature of the target can be extracted from radar pulse returns when a system can operate with multiple polarizations in both transmit (TX) and receive (RX). With flexible polarimetry modes, RADARSAT-2 SAR does a better job of discriminating different surface types and can classify terrain more accurately. It is particularly useful for detecting returns from artificial objects, such as ships at sea. Artificial objects tend to incorporate right-angled corners and, as a consequence, generate strong radar reflections with distinctive polarimetric features. [See sidebar on page 18]

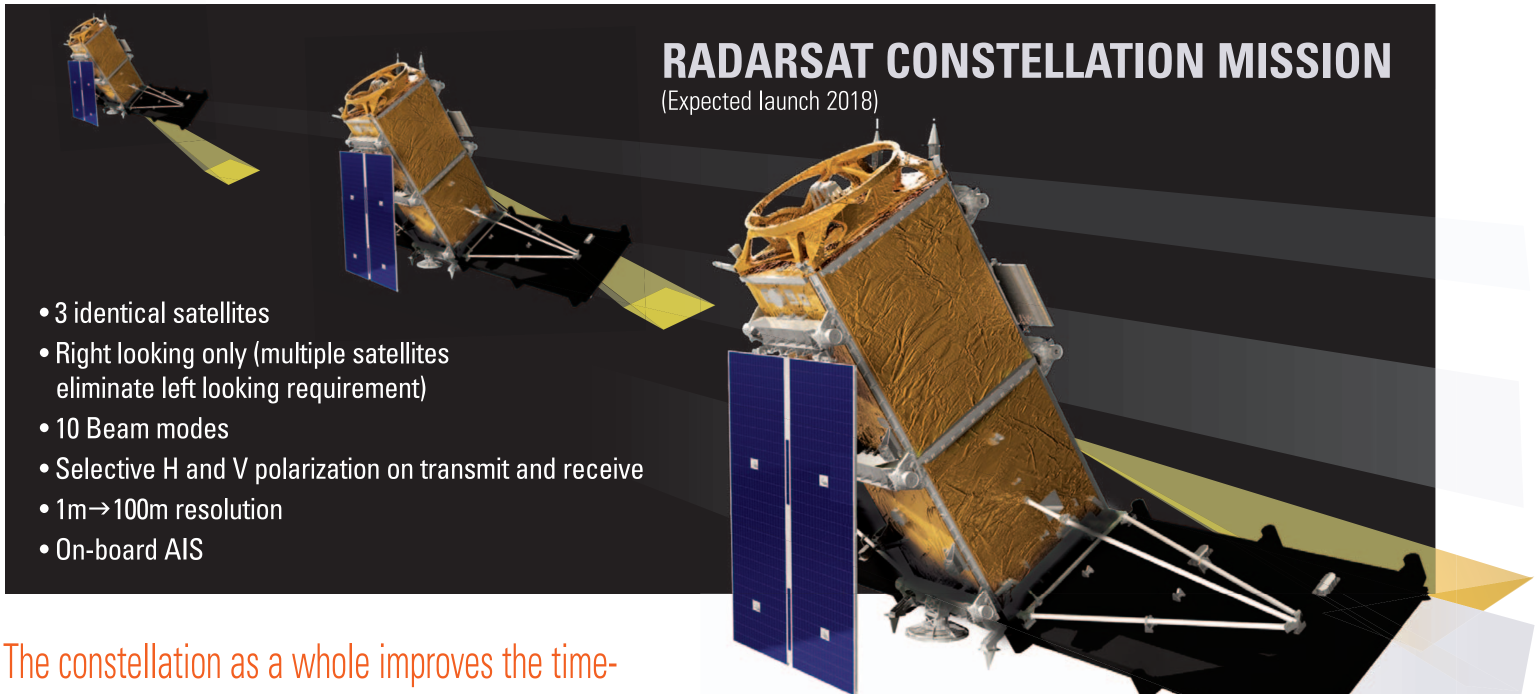
RADARSAT-2 also added routine look-left or look-right capabilities. This meant that from the same orbital path as RADARSAT-1 it could re-visit the same Earth locations more often. More frequent image capture increased the change detection capabilities of the RADARSAT-2 data products.

While RADARSAT-1 relied mostly on analog tape recorders, RADARSAT-2 employed solid-state memory devices for data storage. With solid-state memory came higher reliability and faster access to data.

Finally, RADARSAT-2 could use GPS to geo-locate itself to +/- 60m on orbit in real-time.







The constellation as a whole improves the time-availability of image updates. Conceivably, the constellation could be expanded to six satellites. They will pass over the Northwest Passage and the rest of Canada several times per day.

RADARSAT-2's SAR has the following specifications:

- **Frequency band: C-Band**
- **Centre frequency 5.405 GHz**
- **Bandwidth 100 MHz**
- **TX/RX Polarization HH, VV, HV, VH**
- **Polarization isolation > 25 dB**
- **Aperture length 15 m**
- **Aperture width 1.37 m**
- **Mass 750 kg**

The SAR has 17 beam modes that achieve resolutions from 100m down to 1m. It can look left or right from the spacecraft (but not both sides simultaneously).

Designed to last seven years, RADARSAT-2 has already exceeded its lifespan. It was launched in 2007, but not after some push-back from U.S. government policy. The original plan was to utilize another NASA-led Delta II rocket launch.

But at the time, U.S. government policy evolved to frown upon supporting foreign technology launches that could compete with their own interests – commercial and security. A launch contract was instead awarded to the Russians, and RADARSAT-2 was delivered into orbit on a Soyuz FG rocket.

RADARSAT Constellation Mission (RCM)

For about five years, both RADARSAT-1 and RADARSAT-2 co-existed. This provided an opportunity to combine SAR data from two separate satellites and made it easier to collect interferometric data sets (see sidebar on pg 17 for explanation of InSAR) to be used in the creation of geophysical elevation data for monitoring land structural stabilities. The results showed the value of having a constellation of SAR satellites working cooperatively to image the Earth.

But moreover, the ship detection capabilities of SAR proved to the Department of National Defence (DND) that SAR is a real solution to help monitor Canada's marine traffic, all the way out to 2,000 nautical miles.

Over about five years, beginning in 2005, the Government of Canada spent $216 million on RCM concept studies with MDA Corp. In 2013, the government entered a $706 million fixed-price contract with MDA Corp. to complete operational development of the RCM.

RCM will initially launch three identical SAR satellites in 2018. The final system will be owned and operated by the CSA. The major Canadian contractors delivering the space project are:

- **MDA Corporation**
- **COM DEV International Ltd.**
- **Magellan Aerospace Corp.**

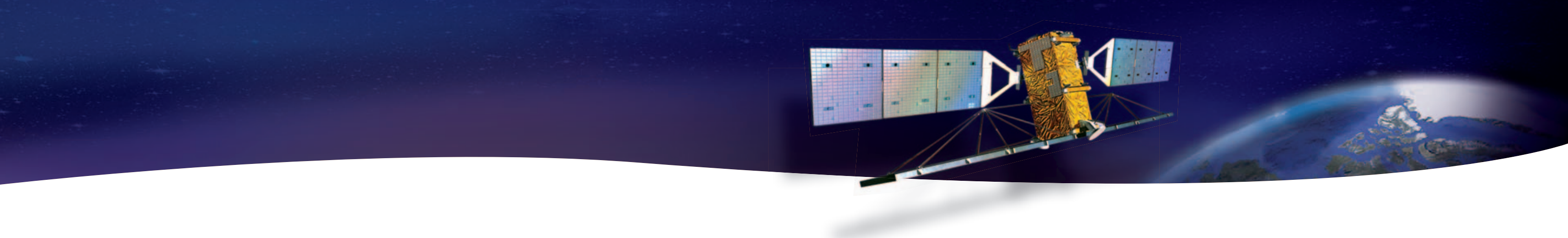
Working as a constellation, these satellites will monitor the Arctic with four overhead passes daily, and will pass over the Northwest Passage and the rest of Canada several times per day.

The constellation will also follow a sun-synchronous polar orbit, but at 586km – lower than RADARSAT-2. Space Exploration Technologies (more commonly known as SpaceX) has been awarded the contract to launch all three RCM satellites on one Falcon 9 launch vehicle.

As a constellation, there's no longer a need to have both left- and right-looking SAR features. The constellation as a whole improves the time-availability of image updates. If required, the constellation could later be expanded to six satellites.

Each RCM satellite will have the following specifications:

- **Frequency band: C-Band**
- **Centre frequency 5.405 GHz**
- **Bandwidth 100 MHz**
- **Polarization HH, VV, HV, VH, Compact Polarimetry (Circular TX, H&V RX)**
- **Polarization isolation > 30 dB**
- **Aperture length 6.75 m**
- **Aperture width 1.38 m**
- **Mass ~400 kg**



Each satellite will have 10 beam modes with resolutions from 100m down to 1m. Its ship detection mode should be able to detect vessels down to at least 25m in size. To support the DND's operational objectives for marine surveillance, the RCM will also have an Automatic Identification System (AIS) payload. [See sidebar to the right]. The SAR and AIS systems can be used in synergy to improve ship detection. SAR can image vessels whose transponder signals are not detected by AIS, and vice-versa.

Automatic Identification System (AIS)

Automatic Identification System (AIS) is a ship-to-ship and ship-to-shore transponder based system of identifying marine vessels. AIS-equipped ships broadcast identification, heading, ship size and type, and hazardous cargo information. Other ships use this to aid in collision avoidance and shore systems use the data to manage maritime control. AIS signals can also be received by satellite, and RCM will have an on-board AIS. With the addition of satellite surveillance, a more complete picture of maritime traffic flow and control can be achieved.

The rules of the International Maritime Organization mandate that most ships greater than 300 gross tonnage operate AIS transponders. Today, more than 60,000 ships worldwide carry AIS transponders. The data AIS provides is valuable to accurately tag and identify vessel traffic identified by space borne SAR. It allows maritime operations controllers like the DND to quickly discern known vessel traffic from unknown, perhaps rogue vessels.

exactEarth Ltd. (jointly owned by COM DEV International Ltd. and HISDESAT Strategic Services, S.A) has a commercially operating constellation of 7 AIS satellites providing global ship detection capability. Since 2012 they have been under contract to provide data to the CSA and DND. **[REF: 8]**

SAR Data Applications

Canada has three primary interests in using SAR imagery:

- **Maritime surveillance** (ice, surface wind, oil pollution and ship monitoring)
- **Ecosystem monitoring** (agriculture, wetlands, forestry and coastal change monitoring)
- **Disaster management** (mitigation, warning, response and recovery)

Each RADARSAT mission has included project objectives to meet these application demands. And RCM will continue to support these objectives. RCM also continues the research opportunity to expand the scope of applications through further operating mode analysis projects in Canada and around the world. **[REF: 7]**

Coast-to-Coast-to-Coast – Keeping an Eye on Our Oceans

Continuous monitoring of Canada's vast ocean frontiers would be a tedious, time-consuming impracticality if we did it all at the Earth's surface. With space-based SAR data, even from the first generation RADARSAT-1 system, Canada enhanced its overview of offshore interests.

Marine Surveillance

Canadian expertise in this particular application of SAR actually began emerging in the late 1970s. Defence Research and Development Canada (DRDC), the Science and Technology arm of the Department of National Defence, had been developing high-resolution airborne SAR signal processing algorithms for military coastal surveillance applications. In June 1978, NASA's Jet Propulsion Laboratory launched Seasat, the first Earth-orbiting SAR-equipped satellite designed for remote sensing of the Earth's oceans. Although it functioned for only about three months, Seasat produced a wealth of ocean imagery.

Applying their expertise in airborne SAR surveillance, DRDC scientists were able to exploit the vast number of Seasat images made available, including many of ships and their wakes, imaged in varying ocean conditions. With colleagues from Natural Resources Canada (NRCan) and the Canadian Coast Guard, they began evaluating the use of space-based SAR for monitoring ship traffic off Canada's coasts. So when RADARSAT-1 was being designed, its benefit in this area was well understood.

The later introduction of differently polarized radar pulses greatly enhances SAR vessel recognition capability (see sidebar on pg. 18 for polarization techniques). Reflected cross-polarized backscatters provide well-correlated sea-state wind speeds. The ocean surface appears fuzzy, and ship returns stand out clearly. The resulting picture can be used for monitoring ocean traffic.

The DND has integrated SAR imaging into their Polar Epsilon maritime surveillance system. Ground stations use satellite SAR data to aid the DND with monitoring naval traffic around all of Canada's coastal waters, east, west and north. When combined with AIS ship data, positive maritime ship tracking, of both friendly and rogue vessels, becomes possible. In fact, the DND's next generation Polar Epsilon-2 project will employ the RCM for this very purpose, using the co-located AIS system on board each satellite to enhance the system's capabilities. **[REF: 9, 10, 11]**

Since SAR imaging produces detailed land maps, the world's coastal areas can be monitored for changes over time too. Observers can routinely map and compare coastal erosion, monitor aquaculture activities and potentially locate productive fishing grounds. Construction of new islands in disputed waters can be detected.

Marine Wind Monitoring

From hurricane monitoring to wind farm site selections, SAR data can be used to build ocean surface wind-speed images.

The radar cross-section (the effective area that an object presents to a normally incident radar pulse) of ocean wave surfaces correlates well with wind speeds. The intensity of the ocean surface returns tends to increase with the wind-state of the ocean. Cross-polarized SAR returns can be used to further refine estimates of the wind state of the sea. The SAR data can be used to build wind maps to help identify the best sea-based locations for wind farms – often a better option than placing them on land. **[REF: 12]**

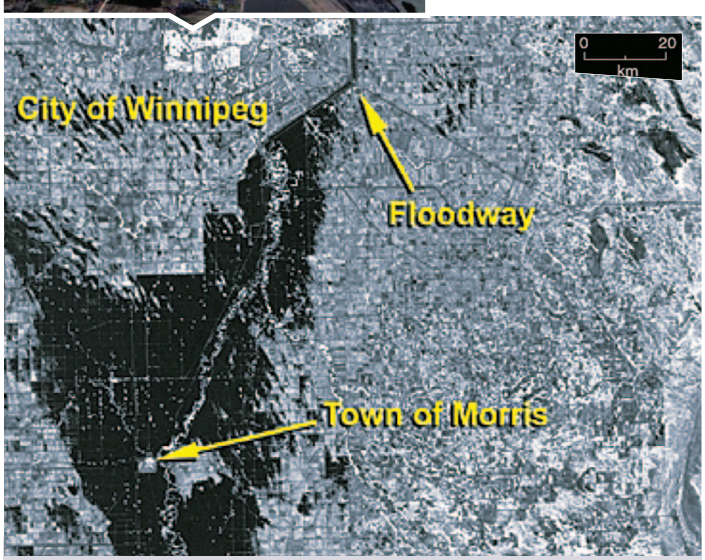
Useful for disaster prediction and response, though, are the hurricane maps that can be built. Optically, we rely on mapping the change in cloud cover to predict a hurricane's trajectory. But if wind speed can be correctly extracted from the data within the SAR return image, then forecasters can more accurately monitor and predict a hurricane's destructive path. SAR can see through the swirling cloud cover down to the ocean surface, and provide a dimension to hurricane analysis that has not been previously available using optical imagery.

Ice Mapping

With our large polar ice areas, shrouded in darkness throughout the winter, SAR imaging provides detailed ice mapping capabilities. RADARSAT-1's design was optimized for this. Experience has confirmed the practicality of using radar data to produce daily ice maps throughout the year and use them to chart safe shipping routes and aid supply trips to offshore exploration, research and drilling operations.

"RADARSAT data has proven to be a very cost-effective way of monitoring ice conditions throughout Canadian waters and has enabled us to expand our service and reduce the Canadian Ice Services budgets by about $6 million dollars a year in terms of data acquisition." - B. Ramsay, Canadian Ice Services [REF: 13]

Processing the intensity of the SAR return data creates ice maps that ships can use to safely navigate our waters. Sea ice reflections are far more coherent than returns from ocean water. Different ice types themselves display measureable reflection characteristics too, especially if cross-polarized backscatter returns are available. [REF: 14] The Compact Polarimetry mode of the RCM provides a promising tool to map large ice-area SAR swaths with very useful ice-type content. [REF: 15]



Upper Image: Red River Floodway, spring 2007. *Photo Credit: Natural Resources Canada 2012, courtesy of the Geological Survey of Canada (Photo 2000-118 by G.R. Brooks)*

Lower Image: RADARSAT-1; dark areas represent flooding. The Floodway was able to provide protection for the city of Winnipeg; a ring dike around the town of Morris keeps the waters at bay. *Photo Credit: RADARSAT Data © Canadian Space Agency (CSA) 1997 ; data enhancement and interpretation by Canada Centre for Remote Sensing*

Making comparative maps of polar ice over months and years also allows us to measure and report the changing effects of global warming. The breadth and depth of our ice will help us know where we stand on the global temperature continuum. From the beginning of our SAR story, Canada has supported these global interests. In 1997, we helped to produce the first seamless image of Antarctica using RADARSAT-1 data. [REF: 16]

Oil Spill Monitoring

Like ice, oil also displays an easily detectable SAR reflection characteristic. Detailed mapping and tracking of oil spills allows accurate deployment of marine clean-up efforts, saving time and possibly saving sensitive coastal areas from environmental disasters.

Land and Environmental Monitoring Lead to Disaster Relief

Poor ambient light, clouds, and difficult physical access create barriers to detailed land mapping. None of these stand in the way of SAR. Radar backscatter returns can be correlated to various land matter, like forests, grasslands, lakes, mountains and urban development.

Land Monitoring and Cartography

The polarization response of a target is sensitive to the structure and spatial arrangement of surface and vegetation features, like forests, grasslands and wetlands. Radar scattering properties can be used to retrieve geophysical and biophysical parameters such as soil dielectric constants, ground surface roughness, slope as well as forest height and biomass.

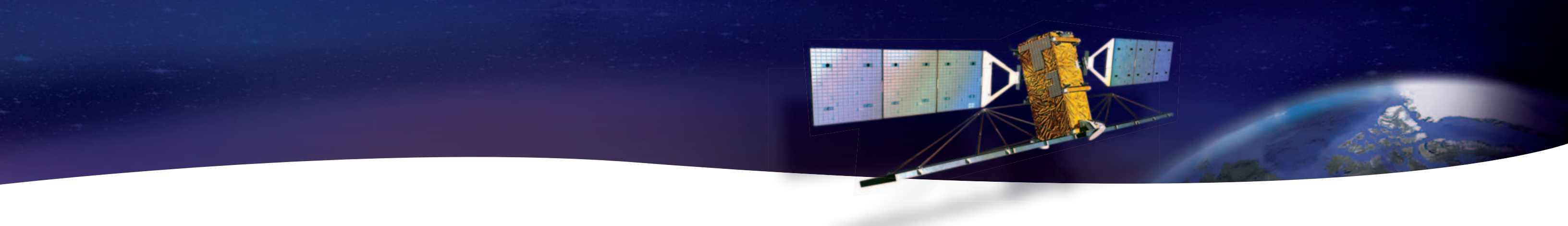
The resulting geophysical and biophysical SAR images can be used to better manage forestry growth and use, agricultural land use, and wetland growth or erosion. These types of SAR images can also be used to monitor land use threats to wildlife, including Polar Bears around Hudson Bay, or Grizzlies in the National Parks. Officials can make better informed land management decisions to protect our wildlife habitats and their biodiversity.

Combining SAR images with optical satellite imagery vastly increases the utility of the data. During Manitoba's "Flood of the Century" in 1997, RADARSAT-1 image data was overlaid on maps of the Winnipeg area. The Canadian Forces were able to see washed-out roads and bridges that couldn't be used. They directed their relief efforts around the obstacles and quickly got aid on the ground to where people needed it. [REF: 17]

Frequent satellite overpasses of a particular location also allow detailed image building. Interferometric SAR (InSAR) can be accomplished using one SAR satellite operating in so-called Spotlight mode: taking many localized snapshots of a smaller area during the satellite's overhead tracking time.

But results are more efficiently obtained — with higher resolution possibilities — if SAR data can be combined from more than one satellite passing overhead in a small time window. From this data a stereographic 3-D image can be built. This produces a detailed Digital Elevation Model (DEM) that can be used to prepare engineering site drawings and opens the possibility to remotely monitor site integrity.

K. Mattar and J. Secker at Defence R&D Canada looked at the feasibility of using RADARSAT Spotlight Mode InSAR data to monitor the landfill integrity at four of Canada's decommissioned Distant Early



Warning (DEW) Line radar sites. These remote sites are strung across the Canadian Arctic from Alaska to Greenland. To maintain Canada's stewardship of the North, we need to monitor these sites for landfill changes like surface slides, soil depressions, water ponding, frost-induced changes and even human alterations. **[REF: 18]**

Mattar and Secker found the concept is feasible, though it really needs a better coherent repeat imaging cycle than the 24-day cycle offered by RADARSAT-2. The upcoming launch of the RCM will address this shortcoming with its four-day coherent repeat visit interval.

Also, Mattar and Secker propose a method to aid surface deformation monitoring in the future: place radar corner reflectors at key geographic measurement points to "amplify" the return. From such a reflector, a SAR signal return would have an expected constant amplitude and site-surveyed location. Over time, it would be possible to build a centimetre-accurate SAR image of the reflector's location – opening the possibility to detect minor surface movements before they become major catastrophes.

Disaster Management and Humanitarian Relief

Using InSAR, key geographic locations around the globe can be monitored for disaster response. Minute changes in the height of terrain in the vicinity of volcanic structures can be measured, enhanced if necessary with corner-reflector markers. The results can be used by authorities to alert the nearby population of an impending eruption. Similar InSAR mapping can be applied to aid prediction of flash floods and landslides.

Along the same lines, pipeline corridors can be monitored with SAR images. Geological shifts that might indicate unstable slopes or similar instabilities before a ground team needs to be dispatched. Remote oil pipeline breaks might be seen earlier if sampled with the appropriate beam mode.

Wildfire mapping, hurricane monitoring, catastrophic flooding – if we can't predict the disaster we can use SAR imaging data to support our relief efforts. Pre- and post-tsunami SAR images were used to assess coastline damages and to help direct aid and rescue efforts after the South Asian ocean tsunamis of December 26, 2004.

Already mentioned was the support SAR provided in response to the 1997 Manitoba "Flood of the Century." Earlier, though, RADARSAT-1 images were used to support humanitarian relief assistance during the 1994-1996 Rwandan "Great Lakes Refugee Crisis." Millions of Hutu refugees massed in the Great Lakes region of Africa. Comparing before and after RADARSAT-1 images, ground picture changes were easily seen. This allowed pin-point determination of refugee encampments and even showed new obstacles on nearby airstrips, likely making them unusable to support delivery of humanitarian shipments.

SAR continues to be a key technology for the relief of human suffering. A new SAR satellite program jointly sponsored by NASA and the Indian Space Research Organization (ISRO)—dubbed NISAR—is a good example. With broad capability to measure changes to the earth's surface through polarimetric InSAR, it will assess the extent and severity of damage in natural disasters, and will have a host of other humanitarian applications. A launch date by 2021 has been suggested by the ISRO. **[REF: 19, 20]**

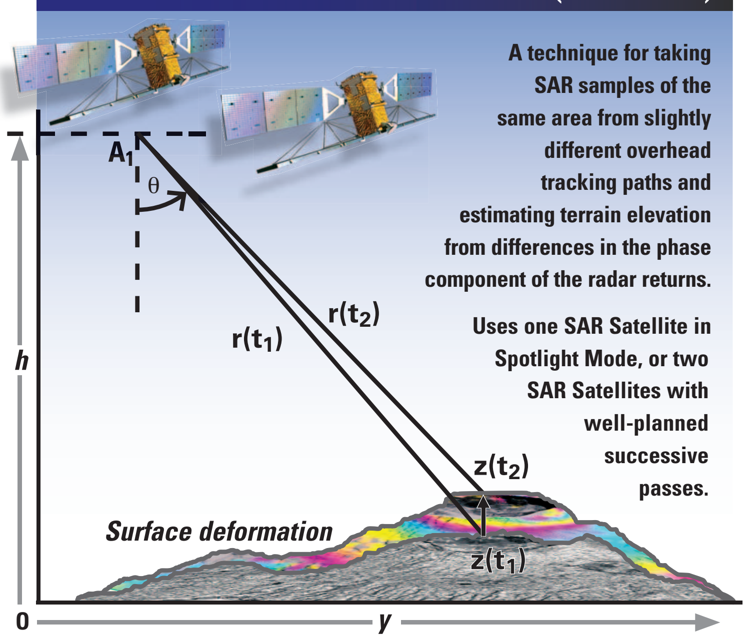
Spaceborne Earth Observation — Canada's Legacy

The capability for monitoring of Canada's natural resources from space began with the creation in 1971 of the federal government's Canada Centre for Remote Sensing (CCRS), recently renamed the Canada Centre for Mapping and Earth Observation (CCMEO). This coincided with the advent of earth observation satellites such as ERTS (Earth Resources Technology Satellite, later renamed Landsat), which could return high-resolution imagery of the ground in several different optical wavelengths or spectral bands.

Through the CCRS, the newly available data products could be reliably obtained by policy makers, decision makers and the general public. Monitoring and managing of Canada's natural resources were fundamentally changed. Over the next few decades, optical Earth observation satellites proved their value and steadily increased in number, sophistication and capability.

Beginning with the RADARSAT-1 project, the Canadian government has had a specific policy objective to produce and operate the most advanced SAR-based earth observation satellites in the

Interferometric SAR (InSAR)



Civil Engineering InSAR Applications

Able to detect changes in elevation in the order of a centimetre or less, InSAR is becoming increasingly important in ensuring the safety of large civil engineering installations. Applications include monitoring movement of bridge footings and pipeline sections, and monitoring the stability of slopes in roads, reservoirs, etc. The increased frequency of InSAR data to be available with RCM will reinforce this trend. Development of such commercially viable data products is key to supporting ongoing remote sensing research.

world. We were the first to market with an operational civilian spaceborne SAR in 1995, and are continuing to lead into the future with RCM.

The sidebar to the right lists the Canadian Government organizations that use RADARSAT-2 data. Each has a mandate that covers wide remote swaths of the Canadian land and ocean scape. This list implies how valuable SAR Earth observation has become to our national interests. Of particular note, Canada today is the global fore-runner in space-based Maritime Domain Awareness; although government led, integral to this success is the strong participation of industry and academia.

CSA's RADARSAT-2 Project was a Public-Private Partnership. At the project conclusion MDA became the owner and operator of RADARSAT-2. This put MDA into the business of selling SAR ground station equipment and image data nationally and internationally. However, it's been a business of first educating the users. It is one thing to identify usable SAR data. It's another thing to develop actual user readiness to put that data to work. The market development continues to evolve. For example, MDA has SAR product contracts with the oil industry, European agencies and the US Department of Defence. Canadian SAR expertise has become an international export product.

The RADARSAT family of CSA space missions have fostered the development of the Canadian aerospace industry. The legacy is wide and deep. Canadian universities like University of Toronto, University of Manitoba and University of British Columbia have industry-partnered research and development programs that feed engineering and science talent into the Canadian aerospace industry.

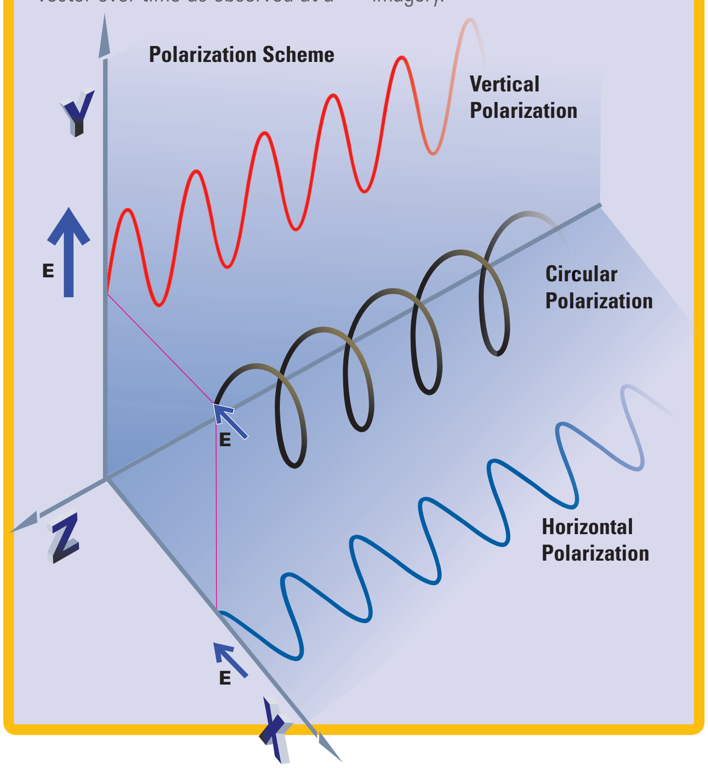
The University of Toronto Institute for Aerospace Studies – Space Flight Laboratory (UTIAS-SFL) has been doing exciting work on micro/nano-satellite spacecraft. These satellites are about half the size of a typical bar fridge, whereas RADARSAT spacecraft are more the scale of a small car.

Horizontal-Vertical-Circular EM Wave Polarization

Electromagnetic (EM) waves are polarized in one of three basic senses: horizontal, vertical or elliptical/circular. The amplitude of each polarized EM field vector (E) will oscillate with respect to the normal pointing direction of the antenna. An antenna tuned to transmit in one polarized sense will likewise be tuned to receive that sense. Earth reflections (ground structures, vegetation, ice, ships, varying soil moisture, etc.) provide unique radar reflections based on the incident polarized EM waves.

The polarization state of an electromagnetic wave describes the behaviour of the electric field vector over time as observed at a fixed point in space. Often, the polarization state divides into randomly polarized or /unpolarized/ and fixed or /fully polarized components. The fully polarized component is completely specified by a 2 x 2 complex-valued polarization scattering matrix referred to orthogonally polarized bases, e.g., horizontal and vertical, right and left circular, etc. By comparing the polarization states of the incident and reflected waves, much can be inferred about the geometry and symmetry of the radar target.

Thus, polarization response supports both identification and classification of targets seen in SAR imagery.



THE TOP 5 Canadian Government organizations that use RADARSAT-2 data* are:

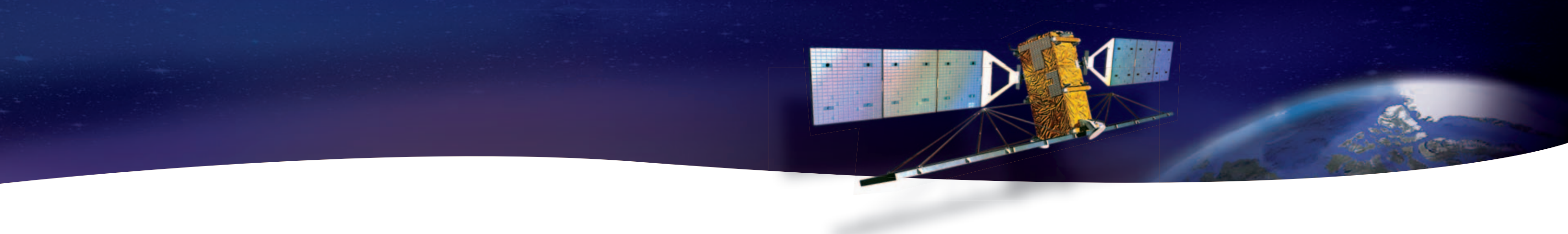
- Canadian Ice Services
- Department of National Defence
- Natural Resources Canada
- Canadian Space Agency
- Canadian Coast Guard (Department of Fisheries and Oceans)

(* as of 2009) [REF: 5]

UTIAS-SFL built and launched the twin nanosatellite mission CANX-4 and CANX-5. It successfully proved that two satellites can orbit in close proximity and even maneuver around each other at the same time. Perhaps this points in the direction of Canada's next generation space-based SAR constellation.

In March 2015, Magellan Aerospace and the University of Manitoba (U of M) launched their new Advanced Satellite Integration Facility (ASIF) inside Magellan's Winnipeg buildings. The ASIF can support all three RCM satellites in 6,000 square feet of ISO Class 8 cleanroom space. Magellan will use the ASIF to assemble and test the RCM satellites. And it positions the company to win more national and international satellite assembly projects.

Magellan went beyond providing real estate for the ASIF. They also used $625,000 to create an Industrial Research Chair in satellite development at U of M's Faculty of Engineering. Together, the ASIF and the Chair give faculty and students opportunities for world-class research and hands-on experiences in satellite technology development.



The RADARSAT family of CSA space missions have fostered the development of the Canadian aerospace industry. The legacy is wide and deep.

The University of British Columbia has a long history of collaborating with MDA in the areas of SAR image reconstruction and image interpretation. From 1992-2007, MDA sponsored an NSERC Industrial Research Chair in Radar Remote Sensing that was held by SAR pioneer Ian G. Cumming. Many of the graduate students trained under the Chair went on to become MDA employees. More recently, MDA has begun to collaborate with the UBC Radio Science Lab to develop more sophisticated models of radar targets in both terrestrial and maritime environments.

Numerous other universities have also participated in satellite or interplanetary missions including: Alberta (U. of), Athabasca, Calgary (U. of), Dalhousie, Guelph (U. of), Lethbridge (U. of), McMaster, Montréal (U. de), New Brunswick (U. of), Québec à Montréal (U. du), Royal Military College, Saint Mary's, Saskatchewan (U. of), Simon Fraser, Victoria (U. of), Waterloo (U. of), Western Ontario (U. of), and York.

While MDA Corp. plays a leading role in the industry side of Canada's SAR efforts, many other Canadian companies are playing important roles in SAR and in other satellite-related technologies. Examples include: Array Systems Computing, Inc of Toronto, which provides technical investigations and software engineering support services to develop signal processing and display software for SAR and related fields; PCI Geomatics, based in Toronto and Gatineau, which provides specialized tools for processing SAR data in a standard remote sensing or GIS environment.

Moving west, the prairies are home to Saskatoon-based SED Systems, a major supplier of satellite ground stations to the European Space Agency. In B.C., 3V Geomatics of Vancouver provides InSAR data analysis services in support of the oil and gas, mining, infrastructure management, and offshore sectors. Also in Vancouver, UrtheCast Corp., which has announced plans to build, launch and operate the world's first fully-integrated, multispectral optical and SAR commercial constellation of Earth Observation satellites, to be deployed over multiple launches expected in 2019 and 2020.

Continuing Our Proud Heritage of Innovation

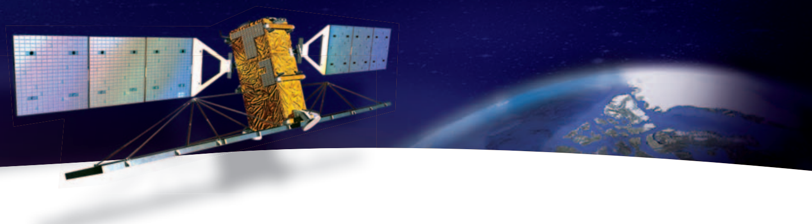
Canadian government agencies, universities and industry have been playing a world-leading role in advancing Earth observation using SAR. For our small population, we have the second biggest country in the world to keep watch over. By building a space-based observation system like RADARSAT to help keep an eye on it all, we've leveraged some of the best engineering talents our country has ever produced.

We are well positioned to take advantage of recent trends in spaceborne remote sensing. With further electronics miniaturization and faster processing speeds, there will be more "small" SAR-equipped satellites (500 kg or less). A whole host of microsatellites are also under development—less capable, yes, but less expensive as well. These will complement traditional large satellites.

SAR Operating Modes and Applications

Application	Geographic Coverage	SAR Polarization Mode	End Use
Ice and iceberg monitoring	Great Lakes, Coastal zones (3 oceans), Shipping lanes	Dual co-cross	Ice Charts
Marine winds	Great Lakes, Coastal zones (2 oceans)	n/a	Weather forecasts
Oil pollution	Shipping lanes, Coastal zones	Dual co-cross	Integrated Satellite Tracking of Pollution (ISTOP), Spill response
Ship detection	1200nm (above 42° N)	Dual co-cross	Domain awareness product
Forestry	Forest areas of Canada	Quad	State of the forest report
Protected areas and wildlife habitat	Parks and sensitive areas	Quad	Change map
Agriculture	Cultivated land in Canada	Quad	Crop classification, crop yield products, tillage practice product
Wetlands	Wetlands in Canada	Quad	Change map
Coastal change	Coastlines 3% highly sensitive	TBD	Change map
Disaster mitigation	Canadian urban areas, Transport and energy corridors	Variable	Risk maps
Disaster warning	River basins, Geohazard risk areas	Variable	Warning bulletins
Disaster response	Global	Variable	Situational awareness; damage assessment
Disaster recovery	Global	Dual co-cross or Quad	Maps

[Information in table extracted from REF: 7]



At the same time, the technological advances mentioned above are opening up new possibilities for satellites in time-sensitive applications such as Maritime Domain Awareness. Until now, raw data has been transmitted to ground stations in a relatively slow process, given the volume of data. Onboard processing of SAR data will mean that immediately useful information can be sent directly to decision makers, rather than waiting for ground stations to first construct the imagery.

Future articles will explore a range of novel satellite trends, including the capabilities of upcoming Canadian nanosatellites (weighing one kilogram or less) and the combining of SAR data with that of other remote sensing technologies. ■

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N.Ed. A five-part series on radar remote sensing was published in the *IEEE Canadian Review* in issues #19 to #23 inclusive (Spring 1994 to Fall 1995). The topics included the latest commercial and government-operated airborne SAR systems, DND's Spotlight SAR project, and the design and capabilities of the then yet-to-be launched RADARSAT-1 satellite. Those interested in the background to Canada's current leadership in remote sensing will find these articles a most worthwhile read.

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Maria Rey bio
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David Michelson bio
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