RADARSAT, A REMOTE SENSING SYSTEM FOR THE 1990'S

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ABSTRACT

This paper presents the new baseline for a potential bilateral Radarsat program between Canada and the United States. Within this program, Canada would be responsible for provision of the spacecraft and ground systems and the United States for the launch. The paper explains the imaging and user requirements for the mission and describes the spacecraft and payload, with particular emphasis on the Synthetic Aperture Radar (SAR). The ground processing required to produce the images is outlined and potential applications for the final data are indicated. Some of the major design trade-offs are also presented.

1. PROGRAM STATUS

The project definition phase of the Radarsat program was completed in the spring of 1987. At that time approval in principle was given to the program by the Government of Canada.

During the intervening year, space policies in the UK and the USA have evolved and impacted the program. This paper presents the basis of the restructured program which, at the time of writing, is being considered by the Government of Canada.

2. PROGRAM OBJECTIVES

From a Canadian perspective, the objectives of the Radarsat program have remained unchanged through its various phases and evolutions of design. These objectives can be summarized as follows:

- To provide the domestic user with remotely sensed data of the vast Canadian territories.
- To provide all collaborating nations with data acquired either by Canadian sensors and/or by any instruments of their own.
- To provide data on a non-discriminatory basis worldwide.
- To enhance the Canadian industrial capability in remote sensing both in the space segment and ground segment.

The principal sensor selected to meet these objectives is the Synthetic Aperture Radar (SAR). This instrument provides day and night, all weather imagery of the earth's surface. When launched in 1994, Radarsat will be the first operational system providing radar remote sensing data on a global scale. The first satellite is designed to operate for more than five years. During that period it will provide data for Ice Monitoring, Ocean Observation as well as for exploitation of both Renewable and Non-Renewable Resources.

Ice Monitoring

A fundamental requirement of the system, and a major driver in its design, has always been that it be capable of monitoring the extent and types of ice in the polar regions and along the coasts of North America and Europe. This capability is valuable both commercially, through support in shipping movements, and scientifically, in helping to determine the impacts of polar ice on the global climate, for example.

For these applications, high sensitivity is required to detect the weak radar reflections from first-year ice, and to enable this thinner new ice to be distinguished from the harder old ice. In addition, a wide coverage capability is needed for comprehensive mapping of these ice types and their extent. The conflicting requirements of sensitivity and coverage led to a radar design which can provide rapid switching between the wide swath capabilities of ScanSAR and the higher sensitivity of narrower beams.

Renewable Resources

The basic imaging operations of a spaceborne radar allow forest, crop and water areas to be mapped. The Radarsat SAR will be particularly valuable for these applications because its wide coverage and multiple swath capabilities will permit rapid and frequent updating of information. This will enable the current state of reserves of these resources to be monitored, allowing them to be more effectively managed and utilized.

The Radarsat SAR design additionally provides a range of alternative incidence angles that can be used for imaging. This will ensure that an appropriate imaging geometry can be chosen for each application. For estimation of soil moisture content, for example, an incidence angle of around 20^{o} is optimum for a C-band radar. For forestry, different choices of angle will allow imaging either of the canopy or the ground cover.

Ship Navigation

The user interest here is to monitor and control coastal navigation and to provide information for ship routing through ice infested waters. Of particular importance to Canada is the assistance this will provide in the extraction of natural resources around the coasts.

The large scale coverage of the instrument permits the necessary regular updating of information. In addition, its high sensitivity ensures that medium to large vessels can be detected in all sea states.

Non-Renewable Resources

The data generated by Radarsat will help geologists better understand the continental structures, and thereby assist in the search for mineral deposits. The variable look angle of the radar will allow stereo imaging of selected sites of particular interest. It will be possible to obtain worldwide coverage with this imagery through the use of an on-board data recording capability or of local ground receiving stations.

Scientific

The operational flexibility which has been designed into the Radarsat instrument will allow it to be used in a wide variety of modes, giving a range of different imaging geometries, resolutions and swath widths. The operations are not restricted to the set of standard modes: alternative options can be defined in flight for use on an experimental basis. Of particular interest will be the extension of the range of incidence angles out to about 60°. With a wide variety of imagery available, it will be possible to determine the appropriate choices for different applications. These images might either be from the SAR alone or in combination with data generated by other sensors, both microwave and optical.

Fundamentally, Radarsat has been designed to provide a flexible capability which can respond to a wide range of user requirements. The hardware design is such that this flexibility can be exercised while the spacecraft is in orbit.

3. RADARSAT SYSTEM CONCEPT

The system concept is shown in Figure 1. The system is managed by a Mission Management Office (MMO), which has executive control of operations. The MMO receives requests for data from the various user groups, sets priorities for the operation of the spacecraft, and makes inputs to the detailed scheduling.

The detailed operation of the spacecraft is controlled by the Mission Control Centre (MCC) on a 24 hours a day, 7 days a week basis. The MCC is responsible for monitoring the status of the spacecraft, for scheduling the imaging sessions, as well as for specifying any necessary orbital and attitude corrections. The MCC also monitors the use of spacecraft resources such as high power amplifier, tape recorders, batteries and fuel. Detailed scheduling information is provided to the other elements in the network to ensure correct downlinking and processing of data. Information is fed back from the Data Processing Centre to the MCC so that sensor operating parameters can be modified and image quality maintained.

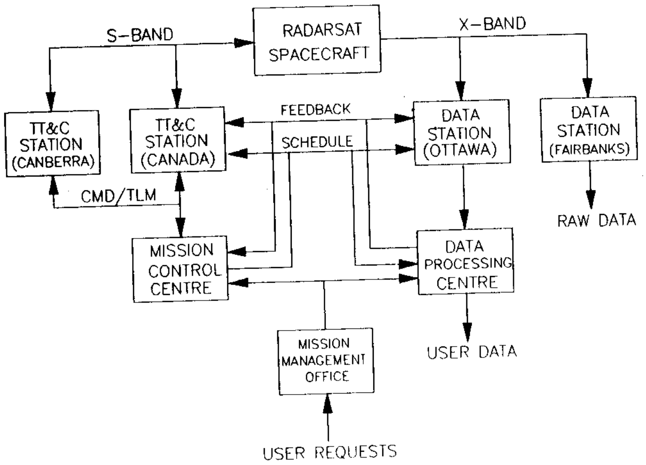

Figure 1 - Radarsat system architecture

The three axis stabilized satellite will be placed in the operational orbit by the launch vehicle. In flight, communication of telecommands and telemetry to and from the spacecraft is effected through a dedicated TT&C station also located in Canada. The link will be made at S-Band and will be operated while the spacecraft is in sight of the ground station. During the majority of each orbit, and sometimes for a continuous period of up to 10 hours, the spacecraft will not be visible from the ground station and must operate autonomously.

Although a single TT&C station will suffice during the operational phase of the mission, additional ground stations will be required during and immediately after launch. The NASA Canberra station is shown as an example in the figure.

Radar data will be downlinked at X-band to the primary Data Acquisition Station located near to Ottawa (which will also be used to collect ERS-1 data). Although this facility is envisaged as the primary station, other international users can be provided with direct access to the spacecraft downlink data stream. For the purposes of illustration, the Fairbanks, Alaska station is shown in this role in the diagram.

The Radarsat data will be recorded at the Ottawa Acquisition Station using high rate digital tape recorders and then transmitted to the Data Processing Centre (DPC). The DPC will archive data in both raw and processed form, will perform all the necessary processing, correction and on-line quality control functions, and will then distribute the data to users.

It is intended that the Processing Centre be capable of processing at a rate of approximately one quarter real time. This would enable all data acquired from the spacecraft during a 24 hour period to be throughput within a similar period. For priority users, data will be available within 4 hours.

Figure 2, which is a pictorial representation of the system, shows data being distributed from the Canadian Ice Information Centre to remote users via an Anik spacecraft built by Spar Aerospace for Telesat, Canada.

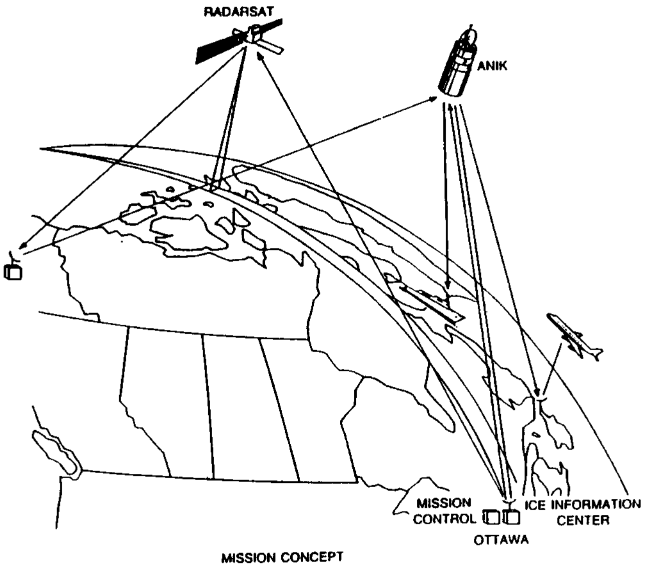

Figure 2 - Radarsat data network

4. SPACECRAFT

At this time a number of spacecraft configurations are still being evaluated. The selection will depend on the configuration of the bus and will probably be the subject of a competitive procurement. A typical configuration is given in Figure 3. This shows the separate bus (platform) and payload modules. The former provides propulsion, power, attitude control, and telemetry and command, whilst the latter houses the radar and data handling systems.

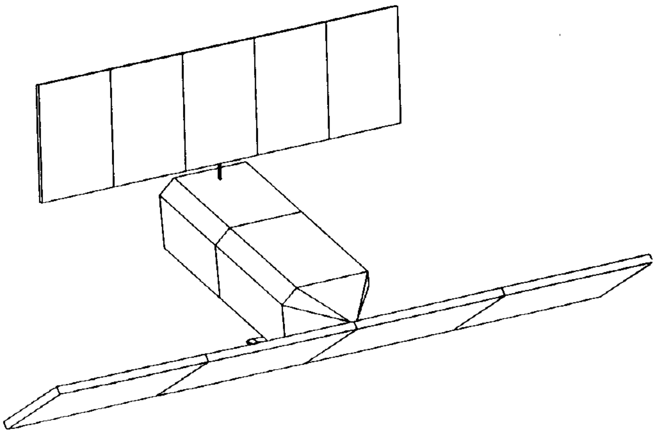

Figure 3 - Deployed configuration

Under the evolving NASA launch policy, the MLV (Medium Launch Vehicle) is currently identified as the probable launch vehicle for Radarsat. Figure 4 shows one candidate configuration for accommodation of the spacecraft within the MLV. The principal concern is to fit the 15m by 1.5m SAR antenna into the relatively small fairing. This has been achieved by adopting a 4 panel design accommodated along the length of the launch vehicle shroud.

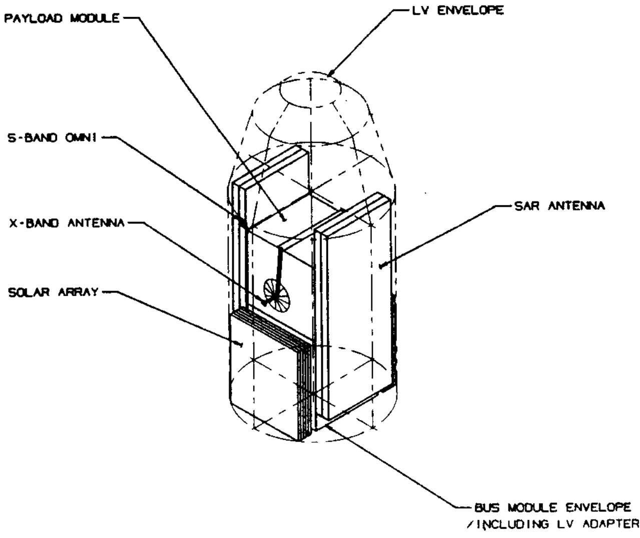

Figure 4 - Stowed Configuration

5. ORBITAL AND OPERATIONAL CHARACTERISTICS

The orbit has been chosen to provide daily coverage of the high Arctic, complete accessibility to regions above 55°N over a three day period, and global accessibility within seventeen days. An orbit which satisfies these requirements lies within the range 777 km to 804 km. In Figure 5, which shows the coverage of the radar over a three day period, the shaded diamonds indicate the areas which are not accessible. Over the full seventeen day period the shaded areas retreat towards the equator and finally disappear.

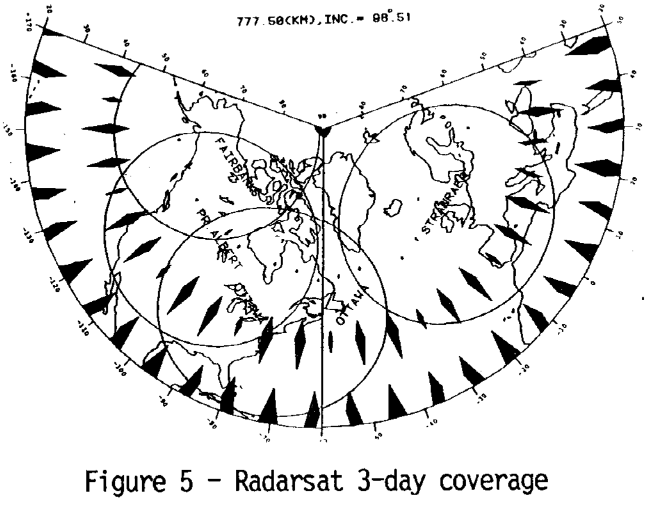

Figure 5 - Radarsat 3-day coverage

The nominal orbit is sunsynchronous, at 800 km altitude and with an inclination of 98.5°. Since the spacecraft does not carry any optical sensors, the choice of ascending node can be made without consideration of local lighting conditions. The dawn/dusk orbit, with an ascending node of 18:00 hrs and a local crossing time of around 6.00, provides the spacecraft with a more benign thermal and better power-raising environment.

The SAR is required to operate for up to 28 minutes in each orbit, but operation is not foreseen as being scheduled during eclipse. With the chosen orbit, eclipses occur only over the south pole during a period of about two months in the summer. The maximum duration of any eclipse is 17 minutes. The restriction on imaging therefore has little impact on the data collection capabilities of the spacecraft.

The United States has expressed a desire to collect data over the Antarctic during times of maximum and minimum ice extent. These periods occur during October and February and are therefore well away from the eclipse season. In standard operation, the Radarsat SAR looks to the right of the suborbital track and therefore looks away from the South Pole. In order to provide the Antarctic coverage, the satellite will be reorientated for a period so that the radar is left-looking. The spacecraft design ensures that it can support operations in either orientation, making the system intrinsically capable of imaging to either side.

6. SAR SYSTEM

The Synthetic Aperture Radar (SAR) is a form of sensor which produces maps of the radar backscatter from the earth's surface. Only a very limited resolution can be achieved with real aperture radar from the distance of space. The SAR overcomes this limitation by coherently combining a series of signal returns from an area of ground to one side of its flight path. Effectively, a very long aperture is synthesised, giving much finer resolution in the along-track dimension of the image. Commonly, the full interval of signal from any one point is divided into sections or "looks". Each look is processed separately and the set are combined incoherently to reduce the effects of the statistical variations known as "speckle" which arise in coherent imaging sensors.

The principal performance requirements for the Radarsat SAR at the beginning of the definition phase are listed in Table 1. This specification was intended to define a form of image which is reasonably consistent over a range of incidence angles and is "better than Seasat". Particular emphasis was placed on achieving low minimum detectable scattering cross-section (as measured by the noise-equivalent σ_0 parameter) and hence, for example, good discrimination between different ice-types.

TABLE 1:
RADARSAT SAR STANDARD IMAGE REQUIREMENTS

Accessibility region	500 km minimum
Incidence angles	20° - 45°+
Swath widths	100 km minimum
Overlap between swaths	> 10% of width
Resolution ground range x azimuth	25m x 28m
Multiple looks	4
Noise-equivalent σ_0 (minimum detectable scattering cross-section)	-23 to -28 dB (design goal)

The data applications and the system technology were both taken into account in the choice of an operating frequency in C-band. Although higher frequencies give better discrimination between different ice types, the power requirements are unacceptably high. Systems operating at lower frequencies, besides giving poorer discrimination, require larger antennas and more complex processing.

The SAR images a strip of ground, known as the "swath", to one side of the satellite (see Figure 6). Because of the inherent timing limitations of conventional satellite SAR operation, it is impossible to obtain coverage of a 500 km wide region in a single pass. The coverage requirement was given therefore in terms of an "accessibility region" and a minimum swath width. The full accessibility region must be covered by a set of swaths, any one of which can be selected for a given pass. Effectively, this means that any point within the full 500 km is accessible (i.e. can be imaged) during the pass.

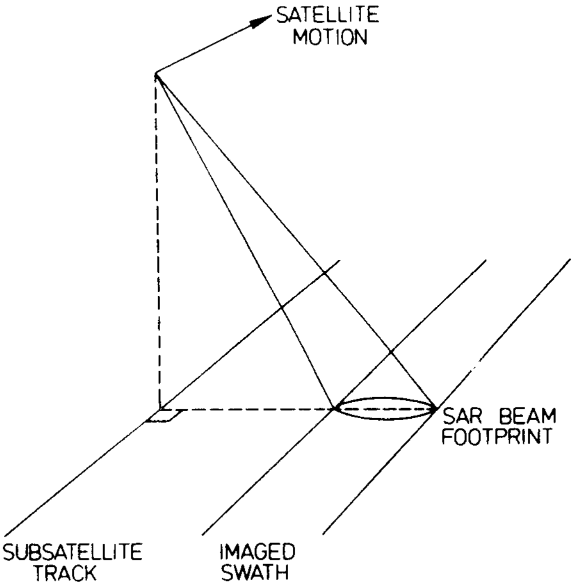

Figure 6 - SAR imaging geometry

In order that the system can provide a choice of swaths at different angles in the plane broadside to the satellite, a multiple beam-forming capability has been built into the antenna design. This capability is achieved using adjustable phase shifters at each of the 32 elements across the antenna width. This approach allows a large number of different beams to be formed without any additional complexity in the hardware.

Because of this inherent beam-forming flexibility, it has not been necessary to reduce the number of standard beams to the minimum compatible with the coverage requirements. At the current altitude of about 800 km, seven beams, commonly referred to as the Basic Beams, have been defined to satisfy these requirements.

Each of these beams covers a swath of approximately 100 km and overlaps the next beam in the set by at least 35 km (except where other system constraints make this impossible). Together, they cover the full 500 km accessibility swath. By reducing the swath width to near the specified minimum, the gain of the beam can be maximized and so optimum sensitivity to low scattering cross-section can be obtained. The large overlaps between swaths are advantageous to users because they allow a better choice of beam to image any specific area and its surroundings.

The fine resolution in the across-track or "range" dimension of the image is achieved in the SAR system through pulse compression techniques. Linearly frequency modulated (or "chirp") pulses are transmitted by the radar and an effectively very short pulse is obtained by matched processing applied to the signal return. When projected onto the ground, the resolution provided by this compressed pulse varies in inverse proportion to the sine of the incidence angle. Thus, for any given pulse, the ground range resolution will be approximately twice as fine at the far edge of the accessibility region as it is at the near edge.

In order to obtain the reasonably consistent resolution specified in the requirements, two separate pulses were incorporated into the SAR design. The compressed pulse length, which determines the range resolution, is approximately equal to the reciprocal of the bandwidth covered by the "chirp" of the transmitted pulse. The two pulse bandwidths, 17.3 and 11.6 MHz, are approximately in the ratio 3:2. For the purposes of standard imaging, each of the Basic Beams is associated with one of these pulses: the first pulse is used for the two beams nearest the subsatellite track, and the second for the remainder of the set. The ground range resolution variation is thereby restricted to about ±20% of the specified 25 m. Since the sampling rates used for the return signal are approximately proportional to the pulse bandwidths, the data rate and the ground processing load are also kept reasonably uniform for all beams.

The swaths in the basic set are significantly narrower than those defined in earlier phases of the Radarsat design. However, because the beamforming network in the antenna is not restricted to only a few beam patterns, it is still possible to image wider swaths if required. Two Wide Swath Beams have been specifically defined to give swaths of the maximum possible width, covering adjoining regions within the normal accessibility region of the SAR.

Because a lower sampling rate can be used for operations with a narrower bandwidth pulse, both Wide Swath Beams are defined for use with the 11.6 MHz pulse so as to maximise the swaths within the current 100 Mbps data rate limit. The increased coverage relative to the Basic Beams, from 100 km to around 150 or 160 km, is therefore obtained at less fine range resolution.

The original SAR coverage and performance specifications listed in Table 1 naturally lead to a design with a flexible beamforming capability and a choice of pulse bandwidths. Once these two features are incorporated in the system, it is possible to provide a number of other products with little or no additional complexity in the instrument hardware. During the evolution of the SAR design, increasing use has been made of this operational flexibility to broaden the range of different types of image that can be produced. This has been achieved without compromising the performance for the Basic Beams. The instrument should therefore be able to satisfy the requirements of a wider community of users.

As one example, Wide Swath operation involves the use of a narrow bandwidth pulse to image a region which, for the Basic Beams, would be imaged with the wide bandwidth pulse. At the other extreme, it is possible to use a wide bandwidth pulse at the far side of the accessibility region in order to obtain images with finer ground range resolution. This approach has been adopted in the definition of five Fine Resolution Beams. In order to make the resolution significantly finer than for the Basic Beams, a third pulse with a bandwidth nominally of 30 MHz has been added to the system. With this pulse, a single-look image with resolution of better than 10 m in each dimension can be obtained for an area at 45° incidence angle. Since the wider bandwidth of signal must be sampled at a correspondingly higher rate, the data rate of the link to ground limits the width of the swath that can be imaged to between 40 and 50 km.

The basic set of beams allow imaging of any region from 20° incidence angle to beyond 45°. For some applications, even higher incidence angles are regarded as optimum and the flexible design allows imaging to be performed at these higher angles on an experimental basis. As the elevation angle of the beam increases, the timing constraints and range ambiguity effects become more restrictive and so coverage and performance estimates are tentative at this stage. Provisionally, however, an extra six Experimental Beams have been defined for imaging out to near 60° incidence angle.

The final addition to the range of Radarsat SAR operational modes was ScanSAR. As with the other modes that have been introduced to supplement the Basic Beam operations, it makes optimum use of capabilities already built into the system in order to provide a distinct new form of image. The principle of ScanSAR operation is to share the imaging time between two or more adjoining subswaths, so as to enable much wider total coverage to be obtained in a single pass. The feature of the system which this mode of operation exploits is the antenna's inherent rapid beam-switching capability.

In ScanSAR operation, pulses are transmitted and returns received for a period in one subswath before operations are switched to another, and so on around the full set of subswaths. Each period must be sufficiently long to allow a synthetic aperture to be formed (i.e., to allow an image of a section of the subswath to be produced), but short enough that the successive periods in any one subswath cover adjoining or overlapping sections. (See Figure 7.)

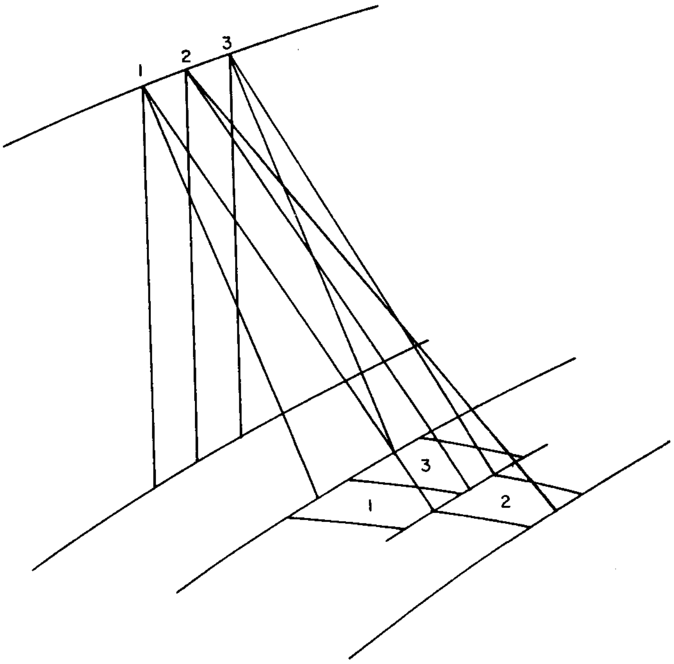

Figure 7 - ScanSAR imaging

Many combinations of subswaths, switching periods, and resolutions are possible, but two principal forms of ScanSAR operation have been defined:

a) Two-subswath ScanSAR, combining the coverage of the two Wide Swath Beams to give a total width of over 300 km.
b) Four-subswath ScanSAR, covering all or most of the 500 km + accessibility region of the Basic Beams.

Because the raw data for any one subswath is only a fraction of that from conventional imaging, there is a corresponding degradation either in the number of looks or in the azimuth resolution. For the two-subswath ScanSAR, an azimuth resolution of about 30 m could be obtained for one look and about 50 m for two looks. For the four-subswath ScanSAR, single- and dual-look azimuth resolutions of about 55 m and 100 m can be expected.

Both proposed forms of ScanSAR operation are designed for use with the narrowest bandwidth pulse. Because of the large change in incidence angle across the full swath, there is a wide variation in ground range resolution: from about 45 to 25 m for two-subswath operations and from about 45 to 20 m for four subswaths.

The full set of SAR imaging modes are summarized in Table 2 which contains information about both coverage and image quality. In Figure 8, each rectangle shown on the earth's surface indicates the region that can be covered with one of the defined beams. Only short lengths are shown for each beam here, but in normal operation one beam would be retained for an extended period, providing an image of a much longer strip of the ground.

TABLE 2
RADARSAT SAR PERFORMANCE SUMMARY

BEAM/MODE	SWATH WIDTH (KM)	RESOLUTION (M) RANGE	RESOLUTION (M) AZIMUTH	NO. OF LOOKS	NOISE EQUIV. σ_0 (dB)
BASIC BEAMS					
1	106	24 - 32	28	4	-21
2	105	21 - 27	28	4	-21
3	105	27 - 32	28	4	-21
4	105	25 - 29	28	4	-21
5	105	24 - 27	28	4	-21
6	105	22 - 25	28	4	-21
7	100	21 - 23	28	4	-21
WIDE SWATH BEAMS					
W1	164	31 - 48	28	4	-18
W2	148	26 - 32	28	4	-18
FINE RES. BEAMS					
F1	50	10	8	1	-21
F2	49	9 - 10	8	1	-21
F3	44	9	8	1	-21
F4	43	9	8	1	-21
F5	43	8 - 9	8	1	-21
SCANSAR					
2 - BEAM	305	24 - 45	31 - 26	1	-18
4 - BEAM	511	20 - 45	62 - 45	1	-18 - -21

Although the various defined beams already provide a very wide range of options, the Radarsat SAR is not limited to these modes. Other beam patterns and sets of operational parameters can be transmitted to the satellite in-flight to define alternative modes as required. The flexibility built into the design should therefore allow the Radarsat SAR to be not just a valuable operational sensor, but also one which can be used as an experimental and educational tool for users of remotely-sensed data.

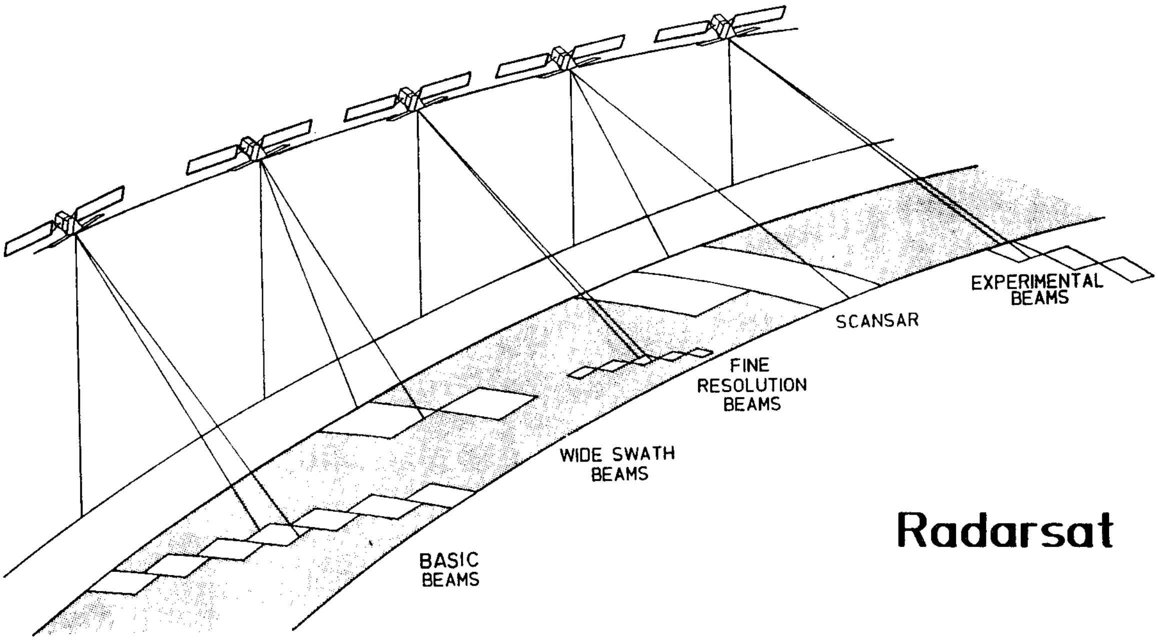

Figure 8 Radarsat SAR modes

7. TRADE-OFF AREAS

During the project definition phase, significant trade-off studies were undertaken in various areas of both the SAR and spacecraft designs.

Several major decisions had to be taken before the SAR antenna design reached its current state. Early in the program, a reflector antenna was rejected in favour of a slotted waveguide planar array. Of greater significance in the final system design was the choice of beamforming technology to be used in such an array. The candidates included a Blass Matrix, a Butler Matrix and a discrete phase shifter design based on ferrite technology. It was found that the hardware complexity of the two matrix approaches increases proportionately with the number of alternative beams it is required to form, whereas for the phase control solution the hardware remains constant. This trade-off was being conducted at a time when greater instrument flexibility was being sought. Since this flexibility can be provided through the addition of extra beams, the two activities converged with the adoption of the current multiple-beam ferrite phase shifter approach.

At the same time, consideration was given to the various technologies available to implement the radiating structure of the antenna. In order to satisfy the elevation beam steering requirements, the waveguide must run the length of the antenna, a 15m array divided into 3.75m sections. At the time, it was considered beyond the limits of plated GFEC, and a thin-walled aluminum waveguide approach was adopted with only minor mass implications.

Several different approaches were considered for generation of the high radiated power necessary for the radar. These included:
- distributed solid state amplifiers, considered at the time to be a too immature technology for space applications,
- a Klystron based single amplifier solution, requiring a new tube development, but giving higher power output, and
- a TWT based amplifier.

It was eventually decided to adopt the latter, making use of a development undertaken for ERS-1. The TWTA provides 300 W of RF power, as opposed to the 500 W expected from the klystron. It was possible to maintain the sensitivity of the radar, however, because this decision was accompanied by a reduction in the nominal altitude from 1000 km to 800 km.

Prior to 1987, it had been assumed that Surface Acoustic Wave (SAW) technology would be used for generating the radar chirp. When a third (30 MHz) pulse bandwidth was added to the SAR design, the advantages of digital chirp generation, which had been under development by several companies, became apparent. This approach allows greater flexibility in the choice of the radar waveform and provision has been made in the system design for reprogramming from the ground during the mission.

The most significant decision in the spacecraft design concerned the possible extension of the mission through in-orbit servicing (IOS). In order to enable failed or life-limited hardware to be replaced, it would have been necessary to bring the spacecraft back from its operational orbit to an altitude accessible to the shuttle, and subsequently to transfer it back to the operational altitude. Although the bus was capable of carrying 1600 kgs of fuel, this was insufficient for the mission and consideration was given to either using the Orbital Manoeuvring Vehicle (OMV) or refuelling the spacecraft during IOS. Although OMV had not received a formal go-ahead at the time, this solution was adopted since NASA had no firm plans for a bi-propellant refuelling system. Due to the expected astronaut involvement in the IOS, all necessary safety features must be built into the spacecraft. A number of elaborate designs, including the use of quick release mechanical and electrical connections, were considered. Because the three year extension in mission life was not seen to justify the additional complexity and cost associated with IOS, it has not been adopted in the final design.

8. GROUND PROCESSING

The SAR data transmitted on the telemetry link to the receiving station on the ground consists of raw radar returns. In order to generate the image that will be supplied to users, a major processing operation must be performed. The principal function in the processing is a two-dimensional correlation of the signal with a reference function, but there are many subsidiary functions which are required before the final geometrically and radiometrically corrected and calibrated product emerges.

The Radarsat SAR processor contract has been awarded to MacDonald Dettwiler and Associates (MDA) of Vancouver. MDA are currently developing a Canadian processor for ERS-1 data, which will subsequently be enhanced to handle the higher throughput and the greater flexibility of operation required for Radarsat. Although the same basic algorithms can be used for data from most of the Radarsat modes as well as from ERS-1, the ScanSAR data require the development of a new technique for one dimension of the correlation.

Other major functions performed by the ground processing facility include calibration of the images, verification of the SAR operation, archiving of the data and images, and logging of major imaging parameters. Three principal forms of product will be made available to customers:

a) Georeferenced products with systematic geometric correction and location based on data supplied from the satellite.
b) Geocoded products on a standard map projection after rotation, resampling and location using ground control points.
c) Special products such as raw data, complex-valued images.

9. DATA DISTRIBUTION

Radarsat's objective is to provide a global service for radar remote sensing. To achieve this, a data distribution company, Radarsat International, has been established. Modelled somewhat on EOSAT and Spot Image, this company will market raw images to global users on a non-discriminatory basis. This approach should generate a wide distribution of value-added companies. In addition, countries can negotiate with Radarsat International to obtain direct access to the satellite's data stream.

10. OUTLOOK

Radarsat will provide the remote sensing community with a highly sensitive and flexible imaging sensor. The Radarsat sensor is seen as an important stage in the development of satellite C-Band SAR, conveniently bridging the gap between ERS-1 and the polar platforms. By the time of the Brazilian Remote Sensing Symposium, it is hoped that the program will have been approved by the Canadian Government and that the design process leading to the production of the first images in 1994 will be underway.

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Both authors had similar responsibilities during the project definition phase of the ERS-1 Active Microwave Instrument (AMI).