RADARSAT-2 System and Mode Description

Dr. C.E. Livingstone, Dr. I. Sikaneta, Dr. C. Gierull, Dr. S. Chiu, Mr. P. Beaulne
Defence Research and Development Canada – Ottawa
3701 Carling Avenue
Ottawa, Ontario K1A 0Z4
CANADA

Chuck.livingstone@drdc-rddc.gc.ca, Ishuwa.sikaneta@drdc-rddc.gc.ca,
Christoph.gierull@drdc-rddc.gc.ca, Shen.chiu@drdc-rddc.gc.ca, Pierre.beaulne@drdc-rddc.gc.ca

ABSTRACT

The Canadian RADARSAT-2 satellite, due for launch in Fall 2006 carries a commercial synthetic aperture radar system that extends the capabilities of RADARSAT-1 in several ways. All RADARSAT-1 modes have been retained, a fully polarimetric SAR mode has been added, a single polarization 3 m (ground range) mode has been added, for two channel operation either H or V transmit polarization can be selected, an experimental Ground Moving Target Indication (GMTI) mode has been added, and the radar can look either side of the satellite track.

The imaging modes of RADARSAT-2, like those of RADARSAT-1 promise to have significant military utility for situational awareness and change detection applications. For RADARSAT-2 the ability to detect and monitor features of interest will be enhanced by polarization diversity, polarimetric imaging capability, the high-resolution mode and the ability to look to either side of the satellite track.

The experimental GMTI mode has been implemented through collaboration between the Department of National Defence (DND), the Canadian Space Agency, and the satellite builder, Macdonald Dettwiler and Associates. Because of the orbit and resulting revisit rate, this mode is not expected to provide a significant operational capability for military use in its current implementation on RADARSAT-2. It is expected to provide information on the performance of future space-based GMTI sensors for operational military use and is expected to be an important tool for the development of concepts of operation for space-based GMTI measurements.

This paper outlines the technical properties of RADARSAT-2 and its operating modes. The experimental GMTI mode and associated data processing is briefly discussed.

1.0 INTRODUCTION

RADARSAT-2 is a 2300 Kg medium sized satellite that has been designed around a single, multi-mode, synthetic aperture radar (SAR) earth observation instrument. Conceived in 1998 in response to a Canadian Space Agency (CSA) request for proposals to define a successor to Canada's RADARSAT-1 earth observation SAR satellite, the RADARSAT-2 concept expanded on the RADARSAT-1 functionality to create a two channel radar that can transmit either H or V linear polarization and can simultaneously receive both

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like and cross polarizations and by interleaving H and V polarized pulse transmissions, RADARSAT-2 is capable of polarimetric measurements. The range of selectable bandwidths has been increased to add higher resolution modes. By selecting a subset of its operating characteristics, RADARSAT-2 is fully backward compatible with its predecessor.

The ~$500 M RADARSAT-2 development program has been largely funded by the CSA with some contributions from the developer, Macdonald Detwiler and Associates (now, formally MDA). On the Canadian government side CSA is the primary government interface. Defence Research and Development Canada (DRDC is the research arm of the Canadian Department of National Defence) has funded and provided technical support for the development of an experimental Ground Moving Target (GMTI) mode (called MODEX) for RADARSAT-2 and Canada Centre for Remote Sensing (CCRS) has provided support for satellite receiving system and data archiving issues. On the industrial side MDA is supported by the payload sub-contractor EMS (Ste. Anne de Bellevue, Quebec), extendable support system sub-contractor AEC-Able (Goleta California) and the bus subcontractor Alenia spazio (Rome Italy).

The RADARSAT-2 program has two major components: the development of the spacecraft and radar (space segment) and the development of the ground infrastructure for satellite operations and data product generation (ground segment). Both the space segment and the ground segment developments have drawn heavily on experience obtained in developing and operating RADARSAT-1. The spacecraft and radar are wholly new systems that provide improved performance over RADARSAT-1 and correct a number of its operating quirks. The ground system developed for RADARSAT-2 has reused some elements created for RADARSAT-1 (mainly the Telemetry, Tracking and Control (TT&C) system and the data receiving stations) but was redesigned using lessons learned from RADARSAT-1. The Order handling, Mission planning, Mission control, Data quality control and Data archiving, Processing and Distribution functions have been extensively redesigned to improve performance.

At launch, the satellite and ground segment will be operated on a commercial basis under the ownership of MDA. The Canadian government contributions to the system’s development and build will be repaid in data services. Canadian National interests are protected by legislation in Bill C25 (2005) [1]. This legislation also makes provision for the imposition of shutter control by the government. This bill has not passed into law at the time of writing.

The aim of this paper is to present a sufficiently detailed description of the RADARSAT-2 system to enable the reader to identify possible uses. Discussions focus on the space component and its performance. Some performance goals of the ground segment are also noted.

2.0 ORBIT

Like most remote sensing radars, RADARSAT-2 will fly in a circular sun-synchronous, minimum battery-mass orbit on the dawn-dusk terminator. The planned orbit details for RADARSAT-2 are outlined in Table 1. Note that these will be updated after launch.

Table 1: RADARSAT-2 Orbit parameters

Inclination	98.6^0
Altitude	798 km
Eccentricity	<0.0006
Period	100.7 minutes
Ascending node	18:00
Orbits per day	14.3
Repeat cycle	24 days
Spacecraft position stability	± 5 km, goal ± 1 km
Spacecraft position knowledge	± 60 m real time, ± 15 m post processing

The real-time position knowledge of the spacecraft is derived from on-board GPS measurements. Post processing position knowledge is derived using a refined orbit model that makes use of the GPS data. Position stability is determined by the orbit boost cycle used.

3.0 SPACECRAFT

The spacecraft bus was developed by Alenia spazio from designs prepared for the proposed Cosmo-Skymed constellation (PRIMA bus variant) [2,3]. The bus is a box design with dimensions 1.34 x 1.34 x 3.2 m and carries the spacecraft control computer, power system components, three pairs of orbit maintenance thrusters, momentum wheels and magnetic torque rod attitude control components, sun sensor, 3-axis magnetometers and star-tracker attitude measurement components, S-band TT&C transceivers, X-band data downlink transmitters and the bulk of the radar components. Power is provided by six solar panels that are arranged in two wings and are designed to deliver 2400 W at the predicted end of the spacecraft life. Power buffering is supplied by a set of NiH_2 batteries.

The bus is stabilized in three axes and flies with its long axis inclined ± 29.8^0 to the orbit plane to allow the radar system to image on either side of the flight track. The bus inclination is changed by a roll maneuver that is commanded from the radar control schedule and is executed by the spacecraft momentum wheels. The roll maneuver and settling time is estimated to require less than 10 minutes. In addition to the static roll pointing, the attitude of the spacecraft is dynamically controlled over each orbit to steer the azimuth pointing of the radar antenna (the antenna long axis is nominally pointed along the flight direction), so that earth rotation effects in the radar data can be cancelled near the mid-point of its access swath.

Orbit control, orbit maintenance and deorbit capability at end of life is provided by a set of six, hydrazine-fueled thrusters. The spacecraft carries approximately 126 kg of fuel to support this activity.

The bus carries redundant Laben LAGRANGE GPS receivers for position determination on orbit and a pair of star trackers provide attitude knowledge. Spacecraft data interpretation and control is provided by the spacecraft management unit (SMU).

The S-band TT&C channels are encrypted for control security. The spacecraft employs two X-band 105 MB/s downlink channels to provide 210 MB/s data downlink capacity. These channels can be encrypted for data security. The data down link design employs a fixed, broad beam antenna and provides sufficient transmitter power to allow the use of 3 m ground receiving antennas within a 5^0 station elevation mask for either right or left of track bus inclination.

Table 2 summarizes the properties of the spacecraft.

Table 2: RADARSAT-2 spacecraft properties

Bus dimensions	1.34 m x 1.34 m x 3.2 m
Spacecraft mass	2300 kg at launch (including 784 kg antenna mass)
Orbit maintenance	six 1 N hydrazine thrusters
Fuel reserves	126 kg at launch
Spacecraft position accuracy	± 5 km required, ± 1 km goal, control on orbit
Spacecraft position knowledge	12 channel, 2 frequency GPS receivers, ± 60 m (3σ, each axis) knowledge real time
Spacecraft attitude	Control ± 0.05^0, knowledge ± 0.02^0 (3 σ)
Spacecraft attitude reference	Sun sensor (2), gyro (4axis), magnetometer (3 axis), star tracker (2)
Attitude control	4 reaction wheels plus 3 magnetic torque rods
Spacecraft orientation	± 29.8^0 roll, Dynamic azimuth steering for earth rotation compensation, 0^0 at the poles, ±3.9^0 at the equator
Roll maneuver time	<10 minutes including stabilization
Spacecraft primary power	2, 3 solar panel wings (3.7 m x 1.8 m each) delivering 2.4 kW at end of life
Spacecraft power storage	89 Ah, 28 V NiH_2 battery (23 cells)
TT&C link	Uplink 2053.458 MHz, Downlink 2230 MHz
Data downlink	8105 MHz (105 MB/s), 8230 MHz, (105 MB/s), EIRP 24 dBW
Design life	7.25 years

4.0 RADAR

RADARSAT-2 carries a C-band (5.405 GHz) synthetic aperture radar that has been designed to satisfy commercial earth observation applications. This instrument incorporates a number of features that represent significant improvements over its predecessor, RADARSAT-1:

- Two parallel receiver channels
- Pulse-interleaved polarimetric operation
- SAR-MTI mode
- High resolution (1.5 m slant range) strip-mapping mode
- 2 x 150 GB Solid-state recorders
- 210 MB/s data downlink
- Encryption of down-liked data

The RADARSAT-2 radar instrument was designed to provide new modes for earth-observation operations while maintaining backwards compatibility with data sets available from RADARSAT-1. The operating modes of RADARSAT-1 form a subset of the RADARSAT-2 modes.

The radar component of the payload consists of two major subsystems [4], the antenna and the sensor electronics (SE). These execute all radar functions under the control of up-linked software instructions that are captured by the SMU and are stored in the SE in the form of a time-tagged operating schedule. Interfaces to the SMU from the SE and the antenna subsystems provide coupling to the S-band TT&C transceivers that form the control link to ground facilities. Interfaces from the SE to the solid-state recorders, crypto unit and X-band data downlink transmitter provide the radar data storage and output links.

All radar operations are scheduled by an internal clock synchronized to GPS time as provided by the spacecraft GPS receivers.

4.1 Antenna Subsystem Description

The radar antenna used for RADARSAT-2, Figure 1, is a 1.5 m x 15 m active array that distributes the transmitter final amplifier and receiver front-end over 512 transmit-receive (TR) modules [4, 5]. The radiating elements are cavity-backed patches grouped in azimuth -oriented arrays of 20 radiators that are fed in-phase by a single TR module. Sixteen columns of 32 radiator arrays each are distributed over 4 panels to form the antenna. The radiator row spacing was selected to allow electronic beam pointing and beam forming over a 500 km swath without exciting grating lobes. Each patch radiator has H and V feeds that are selected by the TR module on transmit and can be used simultaneously for signal reception.

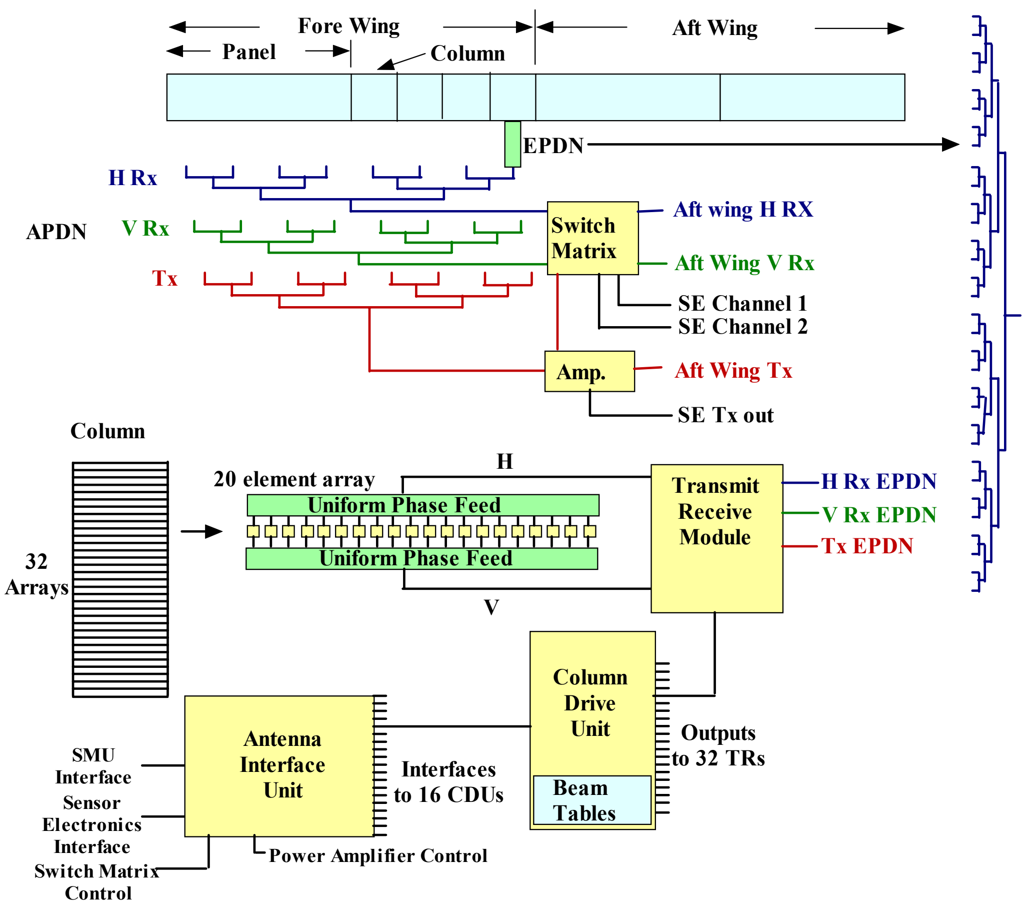

Figure 1: RADARSAT-2 Antenna Subsystem.

To minimize time lost in internal communications, all beam forming and beam steering functions are controlled locally on the antenna by 16 column drive units (CDU), one per each column of radiating arrays. Each CDU individually controls its 32 TR modules by assigning the transmit polarization, controlling the transmitted signal phase, controlling the phase shift and gain of each receive channel and assigning active TR model channels by controlling the power distribution. Each CDU stores the control data for 230 right-looking and 230 left looking radar beams as phase and gain settings for each of the 32 TR modules in the column. In addition to commanding the operating state of each of the 32 TR modules in its column, each CDU compiles telemetry packets that describe the state of each TR module, validates received commands, monitors and reports the outputs of temperature sensors distributed over the column, provides TR module temperature compensation by adjusting phase and gain commands, and controls heaters for the column. Commands from the sensor electronics that define scheduled antenna configurations are distributed to the CDUs by an antenna interface unit (AIU).

The AIU receives and interprets commands and data from the SMU as well as commands and timing signals from the sensor electronics unit. The received commands are validated and commands are issued to the 16 CDUs to control beam formation during radar imaging. The AIU commands the switch matrix and power amplifier settings during radar operation in response to the software command sequence that defines each radar mode. Telemetry packets from the CDUs are processed, collated and sent to the spacecraft management unit. During radar programming activities, the AIU serves as a gateway for loading beam control data into the CDU memories and for reading CDU memory data for transmission to ground control.

At the column level, RF interconnection between the TR modules and the rest of the radar is provided by three, identical, 1:32, suspended strip-line elevation power divider networks (EPDNs). One EPDN distributes signal waveforms to the TR modules for transmission, the other two combine received signals from the H and V TR receiver ports into H and V column outputs. The column EPDNs are linked by 3 wave guide 8:1 azimuth power divider networks (APDN) on each wing of the antenna. The receive channel APDNs terminate in a switch matrix, located in the bus, that assigns either both polarization channels, or the two halves of the antenna, or a replica of the transmitted pulse to the two receiver channels in the SE. The transmit channel APDN is driven by a power amplifier that raises the power level of the transmit pulse waveform supplied by the sensor electronics subsystem. Table 3 summarizes the properties of the antenna subsystem.

Table 3: Antenna subsystem properties

Parameter	Properties	Comments
Antenna Length	15 m	
Antenna Height	1.5 m	
Azimuth beam width	0.202^{0}	Full antenna active, uniform phase distribution.
Number of Panels	4	Aluminum box beam with structural cells
Array columns	16	4 per panel
Array rows / column	32	
Row spacing	0.77 wavelengths	
Active vertical Aperture	1.37 m	
Radiators / array	20	Rectangular, cavity-backed, H and V linear polarization
Polarization isolation	> 25 dB	Specification. (Measured values are much better. ~ 40 dB is typical at beam centers [5])
Radiator feeds	H and V	20:1 strip line, uniform phase
Number of TR modules	512	1 per array
TR transmit channels	2	H and V, one active at any time. Can be individually disabled
Output power / channel	6 W or 10 W	Nominal values
Transmit channel control	On/off, power, phase	5 bit phase control
TR receive channels	2	H and V one or both or none active
Receive channel control	On/off, gain, phase	5 bit phase control, 6 bit gain control
Column Drive Unit	16	One per array column
CDU Functions		TR control, Beam tables, status monitor / reports, column temperature monitor / control, low-level commands
Antenna Interface Unit	1	Antenna programming
AIU functions		CDU control; SMU interface for operations, CDU programming, status reporting; macro command interpretation, Power amplifier control, switch matrix control.
Elevation power distribution networks	48	3 per column, 32:1 suspended strip line power dividers, uniform phase, uniform amplitude
Azimuth power distribution network	3	8:1 wave guide power divider per panel, uniform amplitude, uniform phase, 2 series networks per wing (2 panels)
Switch matrix	1	Transmit waveform distribution between wings, Receive channel assignment to wings, polarizations, calibration pulse assignment to two receive channels
Power Amplifier	1	2 parallel TR transmitters, temperature compensation for gain and phase
Design life	7.25 years	

4.2 Sensor Electronics Subsystem Description

The sensor electronics subsystem [4, 6, 7] Figure 2 performs the: frequency and timing, exciter, receiver, and data formatting functions of the radar. As is the case for the antenna subsystem, the SE forms a node on the ARINC 1553 bus that relays commands and data from and to the SMU for radar operation, parameter uploads, and status reporting. The SE design is based on the Astrium Core Radar.

Except for the one pps GPS time reference, all frequencies and timing signals used in the SE are derived from a single master oscillator by custom synthesizer circuits. Two master sample clocks, 63.34 MHz and 56.30 MHz are generated from the master oscillator signal and are used to create the exciter pulse waveforms, the ADC sampling signals, the pulse repetition rate, the range sampling windows, and other, related timing functions.

The oscillator signals used to up-convert the pulse waveform to 5405 MHz for transmission and to down-convert the received signal to complex base-band form for digitization are derived from the same master oscillator as is used for timing signal derivation.

The transmitted pulses generated by RADARSAT-2 are constant amplitude, phase modulated waveforms that are generated for each range resolution by reading up-linked and stored phase waveform tables at the selected sample clock rate. Four transmitted pulse bandwidths are supported by the system's RF filter design: 11.56 MHz, 17.28 MHz, 30 MHz, and 50 MHz. Nominal lengths of the generated pulses are either 21 µs or 42 µs. Generated pulses are up-converted to 5.405 MHz and are sent to the Antenna subsystem for transmission.

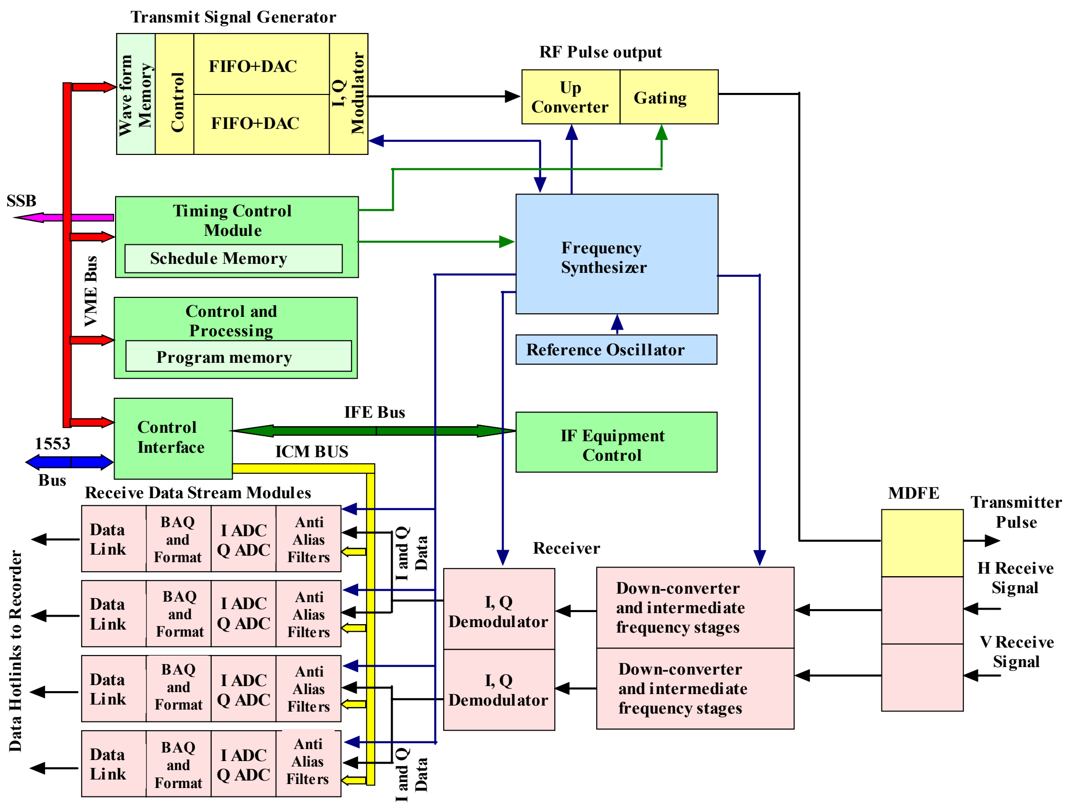

Figure 2: The Sensor Electronics sub-system.

In principle, any phase-coded pulse waveform can be used. In practice, all of the standard modes of RADARSAT-2 use linear FM codes with up-chirp codes being the most common. Some modes transmit alternating up and down chirps to minimize range ambiguity effects at high pulse repetition frequencies [6]. Other phase-coded waveforms may be investigated as part of the MODEX [7] research. In principle, any pulse bandwidth less than 50 MHz can be used to create radar pulses. In practice, bandwidths that do not match the selectable analogue filters at the exciter output of the SE will suffer from aliasing problems associated with the digital waveform generation technique used. In the special case of the 100 MHz bandwidth mode of RADARSAT-2, two frequency-offset 50 MHz chirps are transmitted sequentially at high PRF and are later stitched together in processing to generate the full bandwidth.

The radar pulse repetition frequency (PRF) is derived from the sample clock and is programmed in the radar mode software as a pulse repetition interval in units of 12 sampling clock periods. Although any PRF in the operating range can be specified, only those that allow the transmitted pulse length, a post pulse buffer time, the swath start time delay and the specified swath width to fit into one PRI are useful. The swath start time delay is the fractional part of the propagation time between the radar and the start of the swath. The “integer part” is given by the number of pulses in flight between pulse transmission and pulse reception.

The SE contains two parallel, simultaneously active, radar receiver channels. Each channel accepts received signals from the switch matrix through an analogue filter system whose band selection was mentioned previously. The signals are down-converted for amplification in gain-controlled intermediate frequency stages, coherently down-converted to in-phase, I, and quadrature, Q, base-band signals , filtered, and digitized to four, parallel, 8 bit data streams. The data quantization rate is coupled to the selected signal bandwidth and is programmed in the uploaded mode definition software. The swath width and swath start time are programmed in sample clock period units as components of the uploaded mode definition software. The four output data streams are parsed into blocks of 128 range samples and are compressed using block-adaptive quantizer (BAQ) algorithms whose compression rates are programmed in the uploaded mode definition software. For the high-resolution (100 MHz bandwidth) mode of RADARSAT-2, the first down-conversion frequency is varied in correspondence with the chirp frequency offset to eliminate offsets at base-band.

The BAQ compressed data and its scaling, are formatted according to the radar mode and compression used and are pre-pended with an auxiliary data block to form the science data package. The radar data for each received pulse is formatted into channel blocks of interleaved I, Q samples. The auxiliary data block contains all radar parameters needed by ground data processing systems to form and geographically position calibrated SAR images. The auxiliary data block contents include all radar settings, spacecraft attitude, a GPS estimate of the orbit state vector, and selected system health data. For some radar modes, an uncompressed replica of the transmitted waveform is sparsely inserted into the science data package (typically for every eighth transmitted pulse). The science data packages are routed to two 150 GB solid-state read-while-write recorders for immediate or subsequent delivery to a ground data receiving station. The maximum data transfer rate is 400 Mb/s.

In addition to performing the timing, exciter, receiver, and formatter functions for the radar, the SE also stores the time-tagged command sequences that define the mission, stores waveform data, stores software sequences and interprets received macro commands into sets of operating instructions. Resident signal properties such as pulse waveforms are uploaded from the ground control stations and are stored in SE look-up tables. Some key parameters of the sensor electronics subsystem are shown in Table 4.

Table 4: Sensor electronics subsystem properties

Parameter	Properties	Comments
Radar frequency	5405 MHz	± 25 KHz
PRF	1000Hz to 3800 Hz	In units of 12 sample clock periods
Pulse length	21μs or 42 μs	Selected in mode definition. Linked to PRF through power constraints.
Standard pulse bandwidths	11.56, 17.28, 30.0, 50.0 MHz	Bandwidth specified and filters selected in mode definition.
Pulse waveforms	Constant amplitude, phase coded	These can be custom designed for upload. Linear FM codes are standard.
Standard pulse waveforms	Linear FM	Up or down chirp
Number of stored waveforms	16	
Master sample clock	56.30, 63.34 MHz	Selected in mode definition
Receiver channels	2	Parallel
Receiver output	Base band I, Q	
Receiver gain control range	32.5 dB	Selected in mode definition
Quantization	8 bits	Four, parallel, 8 bit , analogue to digital converters
Sampling rate	Bandwidth dependent	Selected from table of available rates
BAQ compression	None, 8:4, 8:3. 8:1	Selected in mode definition
Data output rate	400 MB/s maximum	

4.3 Data recording and downlink

RADARSAT-2 carries two 150 GB solid-state recorders to capture and store data acquired by the radar [2]. The maximum data input rate is 400 Mb/s. The recorders are controlled by the payload data handling and transmission assembly (DHSA) and are synchronized with the radar operation by time-tagged command sequence that operates the radar by commands from the SMU. The recorders are random access devices in which the science data packages from each data collection are organized as an image segment file. Data downlink operations do not need to follow the data acquisition sequence and specific acquisitions (image segment files) can be output to defined ground reception stations following programmed instructions while previously stored data is retained for downlink elsewhere. Data output rates are governed by the downlink transmitter capacity and are limited to 210 Mb/s when both channels are active. The recorders are a read-while-write design and can: store data for later downlink, simultaneously downlink and store data as received from the radar, or store data from the radar while down-linking data from another acquisition.

During downlink operations, recorder outputs are routed through encryption modules where they can be passed unencrypted, DES encrypted or triple DES encrypted as commanded by the control software. Encrypted data are packetized in the DHSA and are radiated to ground station as QPSK modulated data streams in one or both X-band downlink channels (8105 MHz and 8230 MHz). The X-band downlink EIRP is 24 dBW whether one or both channels are active. The selection of a single channel (105 Mb/s data rate) allows downlink to ground stations with small (3 m) antennas.

4.4 Operating modes

The term "mode" changes meaning with the topic under discussion. At the RADARSAT-2 instrument level the term "mode" describes operating states of the equipment. At the antenna subsystem level the equipment modes are:

- Off — No power is applied to the antenna
- Configuration — Cover the actions of loading configuration data tables, loading software or performing self-tests
- Idle — This is the quiescent state between imaging operations and allows status reporting and background monitoring operations
- Image — Imaging operations

At the sensor electronics subsystem level the equipment modes are:

- Off — No power is applied to the payload
- Standby — The equipment responds to macro-commands and accepts uploads
- Heater — Oscillator warm-up, selection of redundant systems and basic radar function definition
- Ready — This is the normal mode between closely spaced, consecutive images
- Operate — The radar is in its normal imaging configuration. Antenna control is enabled

The details of the equipment modes, their transitions and the functions allowed within each are beyond the scope of this paper and are of little interest to the data users. In this section we will focus on the "user modes" of RADARSAT-2.

From the payload's point of view, a radar "user mode" is a block of software [6] that specifies the radar parameters to be used, selects previously uploaded tables (beam definitions, pulse modulations, etc.) and defines operating sequences. The mode definition software is up-linked from the ground control stations as a set of macro-commands that carry the radar settings to be used and the execution steps (Event Control Code or ECC) to be implemented for imaging operations. The ECC is the primary means by which event patterns are created for radar operation and is generally specific to a given image. Each ECC can have up to 2000 entries and up to 1000 instructions. Table 5 outlines the macro command set that defines the radar configuration that creates each imaging mode. Up to 500 command sets can be resident in the SE memory at any time. Each is activated at a scheduled future time (time tag) that has been selected to image specified terrain at a specified observation geometry and radar parameter set. The number of possible and potentially useful radar modes exceeds the standard mode set offered for normal use.

Table 5: Macro Command contents summary

Macro command	Parameters/Functions	Identifier
Set Swath	PRI	Swath Data Set Number
	Receive data stream module set up	
	Rx Sampling window length	
	Tx pulse waveform	
	Tx blanking	
	Local Oscillator switching	
Set Transmit Pulse	Tx pulse I, Q data input	Transmit pulse number
	ALC reference level	
	Local oscillator control	
Set Swath Start	Swath Data Set Number	Swath start data base
	Base time	
	Offset time	
	Swath start times	
Set Operate Sequence	Pulse timing pattern	ECC Program Number
	Swath Data Set Number	
	SSB beam select to antenna	
	SSB window duration to antenna	
	Image duration (number of pulse repetitions)	
	ECC program	
Heater	Receive data stream module pre-select	
	Calibration signal level	
Operate	Time Tag (image start time)	Image ID
	Receive data stream module select	
	Up-converter output level	
	Sample clock frequency	
	ECC program number	

The macro-command sets that create the RADARSAT-2 modes use a pre-loaded antenna beam tables to select the antenna beam shape, beam pointing, and polarization. Each beam is defined by a set of parameters shown in Table 6.

Table 6: Antenna Beam Tables

Table	Identifier
Transmit phase shifter settings	Beam ID
Receive phase shifter and attenuator settings	
Transmit power	
Transmit pulse width	

Depending on the suitability of previously uploaded Swath Data Sets and Transmit Pulse Data, that reside in memory in the SE, these sets may not need to be refreshed each time that an new command set is loaded in response to a data request and may be addressed by their number. In some cases resident ECCs can be reused as well. In general each data request results in a command set being transmitted to the spacecraft. These are normally up-linked to define the next 12 hours of operation and are activated by the SE scheduling software as the Operate command time tag becomes current. The Image ID number associated with each captured data set becomes the key to sequence data downlink transmissions at times corresponding to the pre-selected receiving station masks. The macro-command set that defines a specific image data acquisition is generated within the ground segment of the radar system by the radar system owner and requires an accurate orbit model, an ac curate image geometry mode, and equipment status information to be executed successfully. This information is transparent to the RADARSAT-2 data user.

From the viewpoint of most RADARSAT-2 data users, the standard modes of the radar are defined in terms of a set of radar imaging properties and the details of how these are achieved are of little or no interest. Users of the experimental modes such as MODEX require much deeper familiarity with the details of RADARSAT-2 operation and programming to specify valid mode properties but still must interact with ground segment personnel to have the mode definition software generated and validated.

The advertised standard user modes [4] of RADARSAT-2 are specified in terms of incidence angle range, ground range (WGS 84 geoid projection) resolution, azimuth resolution, and swath width. Transmit and receive polarization options and the option to look either to the left or to the right of the satellite track are offered for all RADARSAT-1 heritage modes. The quoted range and azimuth resolution are expressed in terms of detected image properties. For each swath type, successive beams overlap in range and incidence angle. The user modes of RADARSAT-2 have been designed to include the existing modes of RADARSAT-1 with the extension that the satellite can transmit either H or V polarization and can receive either or both H and V polarizations. Where both polarizations are received, one channel is cross polarized. In addition to this mode set, the user modes of RADARSAT-2 also include polarimetric modes and an ultra-fine resolution mode. The user modes can be summarized as follows:

1) Standard modes provide medium resolution coverage over nominal swaths of 108 km.
    - 7 beams S1 to S7 cover the incidence angle range 19.6^0 to 49.4^0
    - Near beams S1 and S2 (incidence angles 19.6^0 to 31.2^0) have 17.28 MHz bandwidth
        - Ground range resolution 29.2 m to 18.8 m, Slant range resolution 8.68 m
        - 4 look azimuth resolution 25.6 m, 1 look azimuth resolution 7.9 m
    - Far beams S3 to S7 (incidence angles 30.5^0 to 49.4^0) have 11.56 MHz bandwidth
        - Ground range resolution 28.8 m to 19.2 m, Slant range resolution 12.98 m
        - 4 look azimuth resolution 25.6 m, 1 look azimuth resolution 7.9 m

2) Switching. Two ScanSAR-wide and two ScanSAR narrow modes have been defined. Multi-look image processing is applied in both range and azimuth.
    - The radar bandwidth is 11.56 MHz
    - ScanSAR-wide (1 and 2) cover 527 and 460 km swath respectively
        - Ground range resolution 183 m to 82 m (4 looks). Slant range resolution 12.98 m (1 look)
        - Azimuth resolution 90 m to 113 m (2 looks)

- ScanSAR-narrow 1 covers 314 km swath over the incidence angle range 20^0 to 39.5^0
    - Ground range resolution 91 m to 61 m (2 looks), Slant range resolution 12.98 m (1 look)
    - Azimuth resolution 45 m to 52 m (2 looks)
- ScanSAR-narrow 2 covers 298 km swath over the incidence angle range 30.8^0 to 46.6^0
    - Ground range resolution 61 m to 47 m (2 looks). Slant range resolution 12.98 m (1 look)
    - Azimuth resolution 68 m to 77 m (2 looks)

The RADARSAT-2 quad-polar modes provide polarimetric imaging capability by alternately switching the transmitted polarization from pulse to pulse and by receiving both H and V polarization data simultaneously for each pulse. Data from polarimetric imaging operations are normally used in single-look complex form to preserve phase relationships between the channels. Several derived, multi-look image products are possible and useful. Polarimetric SAR measurements are generally most useful at large incidence angles. The quad-polar modes are not available from RADARSAT-1.

3) Standard quad-polar modes provide polarimetric SAR imaging at medium resolution. Two different swath widths are offered, 26 km and 50 km, by applying different BAQ data-compression rules in the radar sensor electronics subsystem. These modes are described as “standard quad near” and “standard quad far”. 29 quad-pol beams have been defined to span the incidence angle range 17.3^0 to 42.2^0. Full performance is expected up to 35.7^0 incidence angle.

   Examples follow.

   - “Standard quad near” covers incidence angles 19.6^0 to 21.4^0 at 26 km swath and 19.6^0 to 23.1^0 at 50 km swath.
       - Bandwidth 17.28 MHz
       - Ground range resolution 28.6 m to 23.9 m (50 km swath). Slant range resolution 8.28 m.
       - Azimuth resolution 7.9 m (1 look)
   - “Standard quad far” covers incidence angles 39.8^0 to 41.2^0 at 26 km swath and 38.6^0 to 41.2^0 at 50 km swath.
       - Bandwidth 11.56 MHz
       - Ground range resolution 23.7 m to 22.3 m. Slant range resolution 12.98 m.
       - Azimuth resolution 7.9 m (1 look)

4) Fine quad-polar modes have similar properties to the standard quad-polar modes but have finer range resolution. Two swaths described in [4] cover 26 km and 50 km in both near and far categories.

   - “Fine quad near” covers incidence angles 30.1^0 to 31.7^0 at 26 km swath and 19.6^0 to 23.1^0 at 50 km swath.
       - Bandwidth 30 MHz
       - Ground range resolution 16.8 m to 14.3 m at 50 km swath. Slant range resolution 6 m.
       - Azimuth resolution 7.9 m (1 look)

- "Fine swath far" covers incidence angles 39.8^0 to 41.2^0 at 26 km swath and 38.6^0 to 41.2^0 at 50 km swath.
    - Bandwidth 30 MHz
    - Ground range resolution 8.9 m to 8.4 m at 50 km swath. Slant range resolution 6 m.
    - Azimuth resolution 7.9 m

A set of fine-resolution, multi-look, image modes have been added to the RADARSAT-2 repertoire. These modes allow 4 look images to be generated over swaths greater than 50 km by trading the sensor electronics bandwidth, required to support two channels, for a single channel output of either H or V polarization. Either polarization can be transmitted. Multi-look averaging is applied to both range and azimuth dimensions.

5) Multi-look fine modes are based on 2 look averaging in range and two look averaging in azimuth to produce 4 look detected images.
    - A total of 9 beams corresponding to "extended far 1 to 4" and "fine 1 to 5" are available. Two examples follow.
    - "Multi-look fine near" covers incidence angles 30.1^0 to 33.6^0 over a 57 km swath.
        - Bandwidth 50 MHz
        - 2 look ground range resolution 10.9 m to 9.9 m. Single-look slant range resolution 3 m.
        - 2 look azimuth resolution 7.9 m
    - "Multi-look fine far" covers incidence angles 47.2^0 to 49.4^0 over a 52 km swath.
        - Bandwidth 50 MHz
        - 2 look ground range resolution 7.5 m to 7.2 m. Single look slant range resolution 3 m.
        - 2 look azimuth resolution 7.9 m.

The ultra fine modes of RADARSAT-2 generate the required 100 MHz bandwidth by frequency-shifting and later recombining two, sequentially transmitted 50 MHz waveforms. The number of active columns is reduced and the antenna is partitioned into two halves that are recorded in parallel to provide the required azimuth bandwidth and sampling and the transmit antenna beam-width is broadened by a reduction in active columns and azimuth phase spoiling to match the individual wings. Either H or V polarization can be transmitted and either polarization can be received.

6) Ultra-fine modes provide single-look, high-resolution image data at a single polarization.
    - A total of 48 beams have been defined to cover the incidence angle range 26^0 to 50^0. Two examples follow.
        - "Ultra-fine near" covers the incidence angle range 30.1^0 to 31.7^0 over a 26 km swath.
            - Bandwidth 100 MHz
            - Ground range resolution 3.4 m to 3.2 m.
            - Azimuth resolution 3.0 m
        - "Ultra-fine far" covers the incidence angle range 39.0^0 to 40.1^0 over a 22 km swath.
            - Bandwidth 100 MHz
            - Ground range resolution 2.6 m to 2.5 m.
            - Azimuth resolution 3.0 m

Unlike the user modes of RADARSAT-2 the experimental MODEX modes [7] do not have preset parameters but make use of the programming flexibility of RADARSAT-2 to create a number of custom modes that use parallel recording of active apertures on the tow halves of the antenna to measure the speed of moving objects on the earth's surface. The radar has two fundamentally different operating sequences for MODEX imaging: "Dual receive MODEX" and "alternating-transmit, dual-receive MODEX".

For "dual receive MODEX" the radar transmits from the full antenna (beam broadened by phase spoiling and/or a reduction of the active transmit columns. Each wing of the antenna is received simultaneously as a separate channel to provide two spatially separated observations of the same terrain. Either H or V polarization can be selected. The antenna function is similar to the multi-look fine case.

For "alternating-transmit, dual-receive MODEX" the radar transmits alternately from the two wings and simultaneously receives signal channels from the two wing apertures. Again either H or V polarizations can be used. For alternating transmit MODEX it is possible to control aperture separation baselines between pulses by setting the active and inactive antenna columns. The alternating-transmit, dual-receive mode allows the synthesis of three phase centers for Moving object measurements during data processing.

The radar configurations for MODEX can be assembled from the various standard components stored in the radar subsystems or can use new beams and waveforms that are specially designed for moving object measurement studies. Work with airborne research systems has identified a number of variable combinations that need investigation. These are combinations of:

1) Resolution
2) Waveform
3) Polarization
4) PRF (over-sampling ratio)
5) Aperture baseline separation
6) Radiated power

Each defined set will become a MODEX mode and will provide data for a broad range of experiments. The definition process is in progress at the time of writing.

From the brief overview of the radar design and operation potential in this paper and its references, it is evident that there are many potential RADARSAT-2 modes that are not covered by the user set or by MODEX. These can be defined and implemented by engaging the satellite owner and operator (MDA) in discussions about their definition and use.

5.0 GROUND SEGMENT

From the previous discussion it is evident that the space component of the RADARSAT-2 system provides a very flexible SAR imaging tool. The intelligence required to use this tool effectively resides in the ground component of the system, which has been extensively redesigned using lessons learned from the operation of RADARSAT-1 [10].

The ground segment consists of a number of interacting subsystems that have been tightly linked using electronic communication protocols, experienced personnel and automated software to improve response times and minimize errors.

1) Order Handling subsystem

The order handling subsystem (OHS) [8] provides the interface between the end-user and the RADARSAT-2 system. The end-users interact with customer service representatives (CSRs) to define data requirements that can be met either from archived data or from new acquisitions. During this process, new acquisitions are identified, assigned a priority and are scheduled. The CSRs interact with the RADARSAT-2 ground segment through the order handling subsystem to:

- Generate a detailed description of the user requirements including alternate acquisition possibilities
- Identify potentially useful archived data
- Identify known acquisition conflicts
- Generate detailed acquisition and product orders
- Track orders in progress

The order handling subsystem generates acquisition and processing requests, interacts with the acquisition and reception planning subsystem to generate an acquisition plan and schedule data reception, interacts with the reception and archiving subsystem to update data catalogues and interacts with the processing and distribution subsystem to specify processing and track product delivery.

2) Acquisition and reception planning (ARP) subsystem

The acquisition and reception planning subsystem [8] is composed of a number of software tools and operating personnel whose functions are:

- Maintenance of a data base of system resources and activities
- Maintenance of a spacecraft and reception facility resource model
- Development of acquisition, downlink, and spacecraft slew (right or left of track) schedules
- Resolution of conflicts in resource usage. (this includes conflicts between imaging requests)
- Monitors timelines for system activities
- Generates and distributes decryption keys

The ARP interacts with the order handling system to identify and resolve conflicts; interacts with the image quality subsystem to capture beam mode definitions; and interacts with the spacecraft control subsystem to receive orbit predictions and to forward decryption keys and acquisition schedule requests.

3) Spacecraft control subsystem

The spacecraft control subsystem (SCS) [9] interfaces with all ground segment subsystems except the OHS to maintain and operate the satellite. The SCS is the owner of the: data acquisition, reception, maintenance and testing, TT&C, and spacecraft maneuver schedules. It compiles and relays spacecraft -+.

4) Reception and archiving subsystem

The reception and archiving subsystem consists of two Canadian X-band receiving stations (Prince Albert and Gatineau) and TBD licensed off-shore stations to provide data down-link and archiving services for RADARSAT-2. Received data packets from the satellite are assembled into RADARSAT-2 files and decrypted (if the keys are available at the station) and are automatically archived in encrypted or decrypted form in framed expanded data (FRED) format for processing. In special cases where the data is particularly sensitive, the data can be written directly to export media for delivery to the client without entering the archive. The archive communicates with ARP and OHS to update catalogues as data is received.

5) Processing and distribution subsystem

The processing and distribution subsystem [11] responds to orders from the OHS by extracting the specified data from the raw data archive, applying standard SAR processing to generate the ordered data product, performing data quality analysis and packaging the data products and related metadata for delivery to the customer. In the final product the image data is prepared in GeoTIFF format and the metadata is prepared in XML format. Data is either delivered electronically to the customers using an FTP protocol. CDROM, tape and DVD distribution media are available.

6) Image quality subsystem

The image quality subsystem (IQS) is responsible for the definition and maintenance of the radar beams, for the calibration of the SAR system, the generation and maintenance of payload characterization parameter files and for image quality maintenance. The IQS staff execute the subsystems functions with the aid specialized software developed for this purpose.

5.1 Tasking and Data Ordering

RADARSAT-2 tasking and data ordering are done through the RADARSAT-2 order handling subsystem. The tasking and ordering process is as follows for defined modes of the radar:

- The customer contacts a customer service representative at the appropriate order desk (Commercial desk or Government desk) and defines the image requirements:
    - Where to image is defined in terms of geographic coordinates
    - When to image is normally identified as a time window and is refined to possible dates by interaction with the CSR. Several alternative times are preferable
    - What radar mode to use can be defined directly or can be defined from a description of:
        - Resolution
        - Polarization(s)
        - Swath
        - Incidence angle constraints

      to the CSR and interactively defining the mode or acceptable modes.
    - Look direction (right or left of track) constraints need to be defined
    - Imaging priority need to be defined
    - Security and confidentiality requirements need to be defined.
    - Payment terms and mechanisms need to be defined (In many cases this is predefined by contract or other agreements.)

- During the interaction to define the order, the CSR will check on the spacecraft availability for the defined modes, locations, times, constraints, and priority. If the time windows allow or if interferometric or change detection work is desired, the CSR will also check the catalogue of archived data to identify captured scenes that may be useful in satisfying the customer's requirements.

In normal operations the ARP operators develop detailed satellite acquisition plans for approximately 12 hours windows from the anticipated uplink time. In practice this provides sufficiently accurate orbit data to correctly position narrow swath data acquisitions. Where a high-priority request is in conflict with a lower priority request, the lower priority request is removed.

The elapsed time from a data acquisition to its image product delivery also has several components:

1) The image data acquisition time: ~5 seconds to ~70 seconds for one scene.
2) The on-orbit satellite flight time from the acquisition system to the selected receiving station mask. For acquisition within the receiving station mask this has a minimum value of 0 seconds. For acquisition at an arbitrary geographic location delays may be several 100.7 minute orbit periods.
3) The data downlink time is of the order of the image acquisition time to approximately four times the image acquisition time) depending on the mode being used and the down-link bandwidth. The read-while-write capability of the recording system allows the downlink to start near the start of the acquisition when the data acquisition lies within a station mask.
4) The time required to ingest the data into the archive including the communications link unpacking and data decryption is of the order of the downlink time. The reception to ingest functions occur in a streaming operation.
5) The processor throughput is scaled to produce up to 8 specified products (2 ScanSAR, 1 standard, 1 wide, 1 fine, 1 standard quad-pol, 2 ultra fine scenes) in 13 (test result) minutes.
6) The fastest end to end acquisition, downlink and processing time has not been announced.

A critical factor in the ordering, reception and processing time sequence is the job priority. RADARSAT-2 data policy has established the following priority list [8].

1) Spacecraft health and safety
2) National security
3) Emergencies
    a) National emergency
    b) Socio-political emergency request
    c) Canadian response to international humanitarian efforts
    d) Environmental emergency request
    e) Commercial emergency request
4) Image quality and calibration
5) Time-critical requests
    a) Guaranteed observation
    b) Non-guaranteed observations
        i) Time-critical operational requests
        ii) Time-critical completion of request

6) Non time-critical requests and non guaranteed observations
    a) Commercial transaction or Canadian government operational requests
    b) Research requests
    c) Promotional or program development requests
7) Background mission requests

Where schedule conflicts exist they are automatically resolved by deleting the lower priority requests. A premium will be charged for emergency and time-critical requests. Priority-scaled spacecraft programming services are offered and the customer may choose regular, rush or near real-time processing options.

Confidentiality and data security [8] is maintained throughout the data acquisition and delivery process. For data acquisition and planning there are four levels of screening that limit access to the details of an order. These are specified in the ordering process.

1) Level 0 means that no details of the acquisition are displayed when CSRs of another client service group or remote office requests availability information. The spacecraft and other resources are simply identified as being available or not.
2) Level 1 means that the start and end times of the acquisition are available to other CSRs and that the spacecraft is reported as being busy between listed times.
3) Level 2 means that technical information about the acquisitions area available to all CSRs but no commercial information is released.
4) Level 3 means that all information about the order is visible to all CSRs.

Confidentiality levels are protected by data encryption on the spacecraft and by data handling procedures at the processor. Higher levels of security are provided by employing more sophisticated encryption and by ensuring that the data is delivered to the client in encrypted form (possibly without an archive entry) In this case it is the users responsibility to decrypt and process the data.

5.2 Processing and Delivery

For all standard products of RADARSAT-2 data are processed at approved Canadian and foreign data processing centers. The processing system ingests raw data from the archive, decrypts it if required, performs error checking and some corrections unpacks the FRED formatted data into signal data files and auxiliary data files, performs I and Q channel balancing operations and inverts the BAQ compression that was applied at the satellite and then applies standard SAR processing algorithms to generate the SAR images specified in the data order. During this process, radiometric and phase corrections from system calibration measurements are applied, as appropriate, to calibrate the data. Also during this process, data quality checks are performed and the data is transformed into the form defined in the order. Output files will be in single look complex form or in one of several detected and geometrically registered or corrected forms that are supported output product types [11]. Test results reported by MDA [11] show that the time required to process an "average square scene" is somewhat less than 2 minutes when an eight processor UNIX machine is used for processing. This time is scalable by employing more capable equipment.

Data processing is scheduled according to the priority assigned in the data order with emergency response outputs requesting immediate delivery having the highest priority. In this case the data will be processed upon completion of reception and will be delivered immediately. Image data delivery will use electronic (FTP) links, tapes, CDROM or DVD media as requested in the data order. Delivered image data will be in GeoTIFF format and delivered auxiliary data will be in XML format.

Clients with appropriate privileges and/or high security requirements can receive raw, data (in some cases this will be encrypted) in FRED format for processing and analysis at their own facilities. These data will not be delivered electronically unless secure lines are installed.

The MODEX data will be handled as secure information, will be encrypted using triple DES algorithms, will be delivered to Defence Research and Development Canada-Ottawa (DRDC-Ottawa) on "hard" media, and will receive initial processing in a secure environment. The initial processing phase for MODEX will use a modified version of the MDA PGS (product generation system) SAR processor to:

- Decrypt the data,
- Unpack the FRED format to signal and auxiliary data files,
- Perform error checking on the received data,
- Perform BAQ inversion,
- Perform I, Q channel balancing,
- Generate range-compressed raw data files (with or without deterministic range cell migration correction),
- Generate single-look complex image data files using a stationary-world [12] matched filter,
- Format the data for output to GMTI processors. (flat-raster, short-real complex signal data files and ASCII auxiliary data files).

The classification of data outputs from the MODEX initial processing system will range from Unclassified to Secret according to the requirements of the problem being addressed and the needs of research or operational collaborators in other nations.

GMTI processing at DRDC-Ottawa partitions the GMTI processing problem into two parts: detection of moving objects in a stationary world and, estimation of the measurable properties of the movers. Of these two, the detection problem is easiest and is readily automated [14, 15]. Detection and estimation can be accomplished in the range-compressed raw signal domain [16] or in the complex SAR image domain [17]. Both domains are used in the DRDC-Ottawa GMTI processor [18]. The primary outputs of this processor will be attributed target lists that define the position, velocity and properties of moving objects in a Nato 4607 format. Other image and data set products will be generated.

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