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Technical Note / Note technique

The moving object detection experiment on RADARSAT-2

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Abstract. Under contract to the Canadian Space Agency and in cooperation with the Canadian Department of National Defence, MacDonald Dettwiler and Associates Ltd. will include an experimental ground moving target detection function in RADARSAT-2. The RADARSAT-2 design allows two portions of the full antenna aperture to be used independently with two separate receivers. This configuration provides a temporal (along-track) interferometer (ATI) capability. By appropriate processing of the received echo data from the two apertures, it is possible to detect targets that have a radial motion component and to measure their radial velocities. This element of the RADARSAT-2 spacecraft and ground system design is known as the moving object detection experiment (MODEX). Ongoing research into the properties of unscanned synthetic aperture radar (SAR) ground moving target indication (SAR GMTI) sensors of the RADARSAT-2 class has identified a number of features that are unique to SAR GMTI processing requirements. This paper describes the capabilities of RADARSAT-2 that are relevant to moving target detection and defines moving target detection modes of operation. Potential signal processing algorithms and issues that must be considered in the design of MODEX data processing facilities are introduced. A preliminary conceptual design for a MODEX processor is outlined.

Résumé. Sous contrat avec l’Agence spatiale canadienne et en collaboration avec le Ministère de la défense nationale du Canada, Macdonald Dettwiler and Associates Ltd. intègrera à RADARSAT-2 une fonction expérimentale de détection de cibles mobiles au sol. Le concept de RADARSAT-2 permet d’utiliser indépendamment deux portions de l’ensemble de l’antenne à ouverture synthétique à l’aide de deux receveurs distincts. Cette configuration procure une capacité d’interférométrie (ATI) temporelle (longitudinale). Par un traitement approprié des données d’échos radar captés à partir des deux ouvertures, il est possible de détecter des cibles qui ont une composante de mouvement radial et de mesurer leur vitesse radiale. Cet élément du concept de l’engin spatial RADARSAT-2 et du système terrestre constitue l’expérience MODEX (Projet de recherche sur la détection d’objets en mouvement). Des recherches en cours sur les propriétés des capteurs de radar à synthèse d’ouverture (RSO) pour l’identification des cibles mobiles au sol (RSO GMTI) du type de RADARSAT-2 ont permis d’identifier un certain nombre de caractéristiques uniques aux contraintes de traitement des données RSO GMTI. Dans cet article, on décrit les capacités de RADARSAT-2 relatives à la détection de cibles mobiles et l’on définit les modes d’opération de la détection de cibles mobiles. On présente les algorithmes de traitement de signal potentiels et les problématiques qui doivent être prises en considération dans la conception des équipements de traitement des données MODEX. On présente enfin le concept préliminaire du processeur MODEX.
[Traduit par la Rédaction]

Introduction

RADARSAT-2 includes an experimental capability for detecting ground moving targets, known as the moving object detection experiment (MODEX). The purpose of this experiment is to demonstrate moving target detection from space and evaluate and optimize the detection performance. In particular, MODEX was designed to detect moving land and sea vehicles and to measure their speed, position, radar cross section, and, for large vehicles, size. In the context of the RADARSAT-2 program, MODEX is a set of programmable operating parameters of RADARSAT-2, their possible configurations, the command process that defines them, the resulting operating modes of the radar, and the corresponding data structures that are formed from received data. In a broader sense, MODEX is a crucial component of the Canadian Department of National Defence (DND) RADARSAT-2 ground moving target indication (R2 GMTI) demonstration project and has been defined by this DND project. Project objectives include the detection of moving ground vehicles down to the size and form factor of a compact car in radar returns from modest-density urban environments and the measurement of vehicle velocity components for ground-vehicle speeds between 15 and 140 km/h. Objectives for marine environments include the detection of vessels longer than 10 m moving at speeds greater than 13 m/s in sea conditions up to sea state 4. The broad view of MODEX includes not only the radar configuration and data elements but also research and development activities that explore the

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properties and use of the data and the definition of the processing system needed to exploit MODEX measurements.

Although the MODEX radar configuration was specifically designed to partition the synthetic aperture radar (SAR) on RADARSAT-2 into two, coherent radar channels, each coupled to a different antenna aperture for motion measurements, the integration of the two-aperture configuration into the radar design has yielded a very broad, programmable, experimental capability. This paper discusses the moving object aspect of MODEX in three sections. The first section provides background information on detecting moving targets using SAR imagery. The second section describes the RADARSAT-2 MODEX, including the MODEX requirements, methods of programming MODEX acquisitions, and various MODEX operating modes. Trade-offs to be considered when setting MODEX parameters are discussed. The third section examines the processing of MODEX data. Processing algorithms and trade-offs are described and a conceptual design of a MODEX processor is presented.

Background

The detection of moving targets in radar imagery has received a lot of attention in the literature. For example, see Skolnik (1990) for an introduction. The principle of classical moving target indication (MTI) is to use the different Doppler shift for moving targets compared with that for stationary targets to detect moving targets. At its simplest, MTI consists of a filter designed to remove stationary clutter by filtering away the Doppler spectrum due to clutter. In the case of SAR, there are problems with such an approach. The high resolution of SAR is obtained by utilizing an antenna with a wide beam, providing echo returns from stationary terrain over a wide Doppler spectrum. Furthermore, in systems designed for SAR imaging, the available pulse-repetition frequency (PRF) is often not significantly higher than the processed Doppler bandwidth. This means that it is difficult to distinguish stationary targets from moving targets by filtering single-channel SAR data or imagery.

Measurement of motion by a SAR system requires that changes in a scene be measured over times shorter than the synthetic aperture formation time. In airborne radar systems this has been done by partitioning the radar and its antenna into multiple channels that make simultaneous measurements along the direction of travel of the radar. The RADARSAT-2 MODEX configuration provides two apertures displaced in the along-track direction and simultaneous data reception from both channels. As RADARSAT-2 is a SAR satellite, no azimuth scanning is used. An early look at the ground moving target indication (GMTI) potential of RADARSAT-2 (Livingstone, 1998) considered the case where the entire antenna is used for signal transmission and the two apertures simultaneously receive the radar returns. This mode of operation has been retained in the RADARSAT-2 MODEX design as the “single-transmit dual-receive” mode, and an additional capability, the “alternating-transmit dual-receive” mode, has been added. In the alternating-transmit mode, signals are alternately transmitted from the fore and aft apertures and are simultaneously received from both apertures. The dual-receive capability is used to support both MODEX and the RADARSAT-2 ultrafine mode (Morena et al., 2004; Fox et al., 2004).

RADARSAT-2 MODEX

The primary objective of MODEX is to demonstrate the feasibility of detecting ground-based moving targets with space-based SAR. Secondary objectives include developing and validating processing and detection algorithms for the resulting data, optimizing the selection of radar imaging parameters for moving target detection, and measuring moving target detection performance.

Although MODEX originated in response to interest in space-based radar measurements of moving objects on the earth’s surface, this mode allows a wide range of experimental investigations to be conducted without impinging on the commercial SAR missions. The MODEX requirements and programming descriptions provide an overview of the range of possibilities for experimental work that could yield future operating modes for purposes other than GMTI. This paper, however, is concerned with elements of MODEX that are of particular interest for GMTI measurements.

Overview of MODEX requirements

RADARSAT-2 supports the MODEX by providing the following capabilities: (*i*) operation in “dual-receive” mode; (*ii*) operation in “alternating-transmit” mode; (*iii*) onboard storage of custom beam tables, which specify individual transmit/receive (T/R) module phase and amplitude weighting on receive and phase weighting on transmit; (*iv*) onboard storage of custom phase-coded waveforms; (*v*) specifying transmitter and receiver polarizations; (*vi*) transmit and receive on a subset of the T/R module columns; (*vii*) selecting block adaptive quantization (BAQ) levels, where “no BAQ” can be selected resulting in eight-bit in-phase (I) and quadrature (Q) quantization; four-bits, three-bits, two-bits, or one-bit quantization levels are supported when BAQ is selected; (*viii*) selecting transmitted pulse bandwidth from 12 to 50 MHz (note that an effective bandwidth of 100 MHz can be achieved by combining two 50 MHz pulses for SAR imaging operations); (*ix*) controlling PRF (with an upper bound of 3800 Hz); (*x*) controlling swath width (within an overall data rate limitation of 400 Mbps); and (*xi*) uploading and storage of parameters in mode definition tables.

The definition of a specific MODEX configuration requires that custom tables and control sequences are compiled and uploaded to the satellite to form a selectable mode.

Programming of MODEX

In the RADARSAT-2 ground segment design, operating modes are specified by providing a *beam/mode definition*. All the flexibility required by MODEX is captured in parameters that can be varied in beam/mode definitions. Beam/mode definitions include references to beams and pulses via beam identifiers and pulse identifiers. The actual beams and pulses are stored in separate tables. For MODEX, space in the payload has been reserved for up to 15 custom MODEX beams. These beams can be replaced for different periods of MODEX operation, allowing a wide variety of beams to be used over the period of the mission.

The RADARSAT-2 ground segment also provides a *programming validation tool* (PVT). The purpose of the PVT is to assist in the design of beams and beam/mode definitions for MODEX. The PVT will determine if proposed parameters are within the operating envelope of the satellite and will evaluate proposed parameters by deriving performance parameters from the input parameters. Such performance parameters include signal-to-noise ratio as quantified by noise-equivalent sigma zero, data rates, and swath coverage.

For a custom configuration to be accepted, it cannot damage the spacecraft and cannot interfere with any other mode. The responsibility for custom mode performance rests with the person or group that defines it.

Considerations in selecting MODEX operating parameters

MODEX operating parameters need to be selected to optimize performance. Optimization of performance for SAR GMTI can be defined in several ways. One way is to minimize the minimum detectable velocity for given detection rates, false-alarm rates, target size, target reflectivity, and background clutter level. To select compatible MODEX operating parameters, a number of trade-offs need to be considered. This section discusses some of the trade-offs that affect the following parameters: two-way phase centre separation, azimuth beam width, incidence angle, BAQ setting, and choice of pulse bandwidth.

Two-way phase centre separation

To maximize the sensitivity of the two radar channels for low, radial, target velocities, the two-way phase centre separation on the antenna needs to be maximized. The two-way phase centre separation is increased by reducing the number of active, receiving-antenna columns to use the outer columns on each wing of the antenna. Increasing the phase centre separation reduces the blind velocities, decreases the antenna gain, increases the PRF, and decreases the radar signal-to-noise ratio. A trade-off analysis is required for detection scenarios of interest.

Azimuth beam width

To increase azimuth resolution, wider azimuth beams should be used. However, increasing the beam width requires a higher PRF, which means that the image swath is reduced because of overall data rate limitations. Furthermore, a wider beam also degrades the signal-to-noise ratio and can adversely affect the detection of weak targets.

Incidence angle

Large incidence angles result in improved ground range resolution (geometric projection effect) and better sensitivity to the ground velocities. However, higher incidence angles result in narrower ground swaths and degraded signal-to-noise ratio.

BAQ setting

Using a lower number of bits after BAQ reduces the data rate while preserving the dynamic range of the radar and increases the available swath width. However, the resulting coarsening of the sampling interval increases the digitization noise (which results in amplitude and phase errors) and decreases the radar sensitivity to slow-moving targets.

Pulse bandwidth

Higher pulse bandwidth provides better range resolution and allows range multilooking, for a given final image resolution. However, higher bandwidths increase data rate and degrade signal-to-noise ratio. Work by Chiu (2000a) indicates that high-bandwidth ATI is somewhat advantageous for detecting slow, weak, moving targets.

Potential MODEX modes

Analysis is in progress to predict the detection performance with various selections of MODEX operating parameters to explore possible radar configurations for MODEX experiments. Target detection performance (in terms of the minimum detectable velocity) depends on the selected radar configuration and on a number of external factors, including background clutter, target brightness, target density, target screening, multipath propagation, required probability of detection, and allowable false-alarm rate.

An arbitrary example set of MODEX operating parameters for dual-receive mode is given in **Table 1** to illustrate one possible radar configuration.

Other parameter sets have been used to generate the GMTI simulation results found in work by Chiu (2000a; 2000b; 2002).

MODEX T/R configurations

There are two different T/R configurations available for use in RADARSAT-2 MODEX measurements: the single-transmit dual-receive mode and the alternating-transmit dual-receive mode. Used in conjunction with the ability to define active and

Table 1. Example MODEX operating parameters.

No. of columns on receive	3 per wing
No. of columns on transmit	16 (all columns)
Two-way phase centre spacing (m)	6.1
Azimuth beam width (°)	0.25 (6 dB two-way power)
Incidence angle (°)	40
Pulse bandwidth (MHz)	50
BAQ setting (bits)	3
PRF (Hz)	1420
Ground swath width (km)	40

disabled array columns, these two modes allow a range of interferometric baselines to be synthesized for target detection studies.

Single-transmit dual-receive mode

The RADARSAT-2 antenna (**Figure 1**) is an active phased array with 512 T/R modules. These T/R modules are arranged in 16 columns of 32 modules each. The antenna itself consists of two wings: a fore wing and an aft wing. Thus each wing has eight columns of T/R modules distributed over two panels. The radar control functions include the capability to simultaneously receive data from the two apertures in two independent receive channels. A switch matrix controls the selection of these two channels. In dual-receive mode, the switch matrix is set so that the two independent receive channels correspond to the fore and aft wings at either horizontal (H) or vertical (V) linear polarization. In contrast, in dual-polarization mode, the switch matrix is set so that the two independent receive channels correspond to H and V receive polarizations, each from the full array. This means that in dual-receive mode the radar is constrained to recording one receive polarization, and the radar data in the two parallel receiving channels correspond to the fore and aft receiving apertures of the antenna.

In the single-transmit dual-receive mode, the antenna transmits on the full aperture (both wings) but receives simultaneously but separately on each wing. In terms of two-

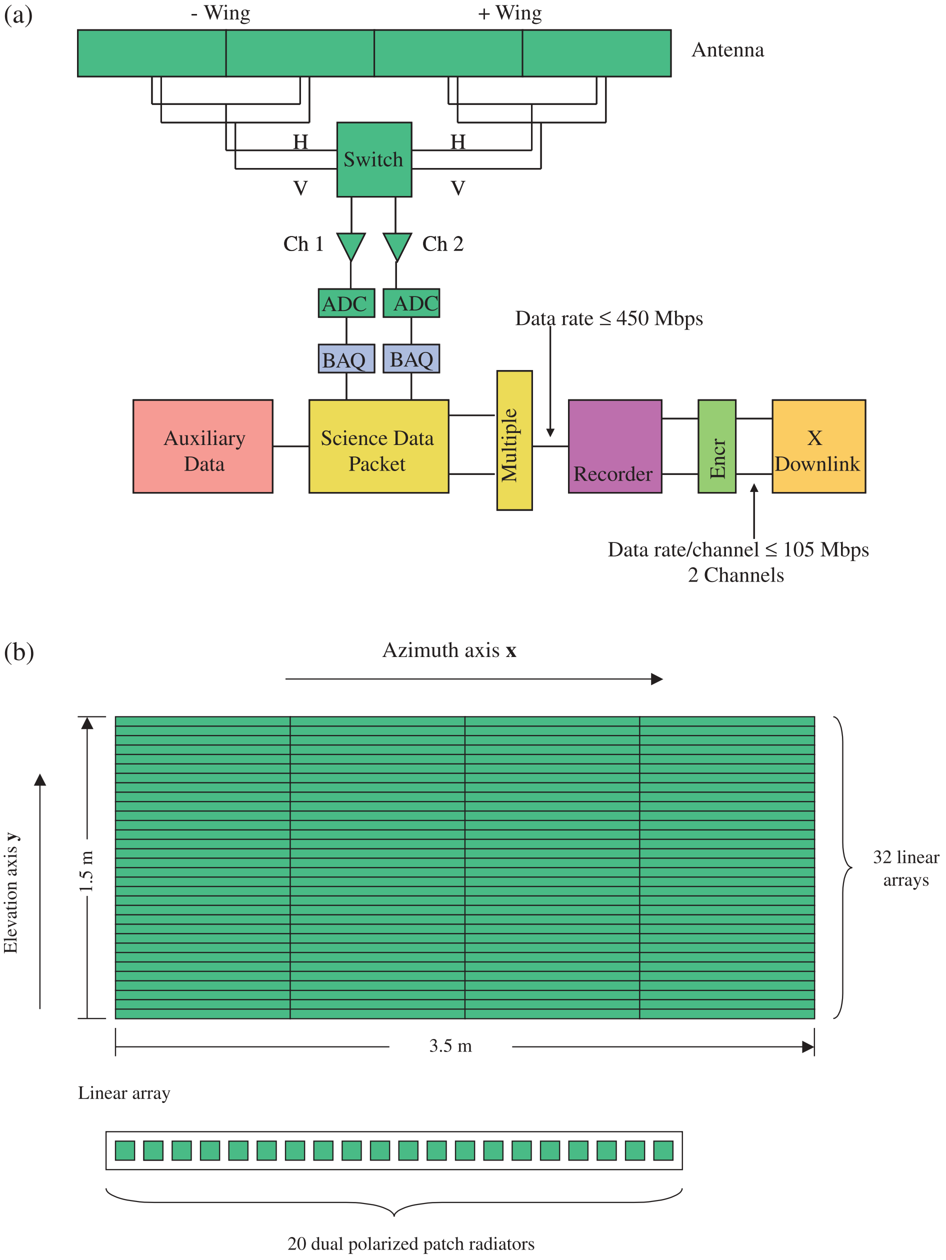

Figure 1. (a) High-level block diagram of RADARSAT-2 showing the antenna and channel architecture. (b) RADARSAT-2 antenna panel showing the T/R column structure.

way phase centres, single-transmit dual-receive mode provides two-way phase centres that are spaced apart by one half of the receive-aperture phase centre separation in the along-track direction. Control of the two-way phase centre spacing is provided by phase and amplitude aperture weighting and an additional capability to turn whole columns on and off for signal reception.

Alternating-transmit dual-receive mode

Alternating-transmit mode is a mode where the pulse transmissions alternate between wings from pulse to pulse and both wings receive signals simultaneously as two parallel channels. For each pulse transmitted, the echo collected on the same wing as that used for the pulse transmission provides greater two-way phase centre separation than in the single-transmit dual-receive mode. Since increased two-way phase centre separation can increase the sensitivity of a dual-aperture SAR to detect slow-moving targets, alternating-transmit mode is a desirable capability.

An interesting complication related to alternating-transmit mode concerns the rank. Let the rank denote the number of pulses in flight, then

$$\text{rank} = \text{floor}(2R/c\text{PRF}),$$

where R is the slant range of the swath, c is the speed of light, and PRF is the pulse-repetition frequency. Here, the PRF counts all pulse transmissions from both wings. Depending on whether the rank is even or odd, the spatial position where echoes are recorded relative to pulse transmissions is different. In the even-rank case, each echo should be recorded on the same wing as that from which the immediately preceding pulse (i.e., the pulse transmitted less than one pulse-repetition interval (PRI) prior to the recording of the current echo) was transmitted. In the odd-rank case, it is the other way around: each echo should be recorded on the opposite wing from where the immediately preceding pulse originated. When both cases are present in the data, two different aperture separations (interferometric baselines) are contained in the common dataset. The price paid for the use of the alternating-transmit configuration is a reduction of the radar signal-to-noise ratio.

Processing of MODEX data for moving target extraction

A processing system to extract moving target position and speed measurements from MODEX data differs from a standard SAR processor in the following ways:

(1) The systematic amplitude and phase properties of the two data channels must be balanced before target motion measurements are attempted.

(2) Residual, differential, earth-rotation effects must be removed from the fore and aft aperture file pairs.

(3) Deterministic range migration effects caused by spacecraft squint and range curvature must be corrected prior to target extraction.

(4) The data processing stream has two essentially parallel branches, imaging processes and non-imaging processes: (*i*) each branch contains an essentially parallel set of moving target detection functions, followed by an essentially parallel set of moving target parameter estimation functions; (*ii*) the detection function algorithms must be designed to perform at constant false-alarm rate; and (*iii*) the processor architecture needs to efficiently accommodate iterative passes through the same data in the imaging branch.

(5) At the end of the target detection process in each branch, detections must be combined to create a “best” moving target list that identifies the signal-space position of each target.

(6) At the end of the target parameter estimation process, target lists from each branch must be combined to create a “final” target list where each target in the list is associated with a target parameter vector that contains estimates of (*i*) target position, (*ii*) target velocity components, (*iii*) target cross section, and (*iv*) target dimension.

(7) In the processor output, target positions must be projected onto geographic coordinates using terrain elevation data.

(8) The processor outputs may also contain geometrically corrected images and target position maps as secondary data.

In SAR GMTI data from RADARSAT-2, moving target measurements are complicated by the almost complete overlap of moving target and stationary scene spectra in the sampled data set. This section presents a proposed processor architecture, examines factors that must be considered in defining GMTI processors for use with MODEX data, and discusses useful approaches to the detection and measurement of moving objects.

Conceptual SAR GMTI processor architecture for RADARSAT-2

At the highest level, the RADARSAT-2 GMTI processor can be modeled in terms of four blocks of processes: (*i*) a preprocessor that executes all functions common to imaging and non-imaging GMTI target detection and measurement; (*ii*) a non-imaging GMTI detection and measurement branch; (*iii*) an imaging GMTI detection and measurement branch; and (*iv*) an output module that combines the measurements from both branches to produce a master, attributed list of moving targets in the scene and projects the targets to geographic coordinates.

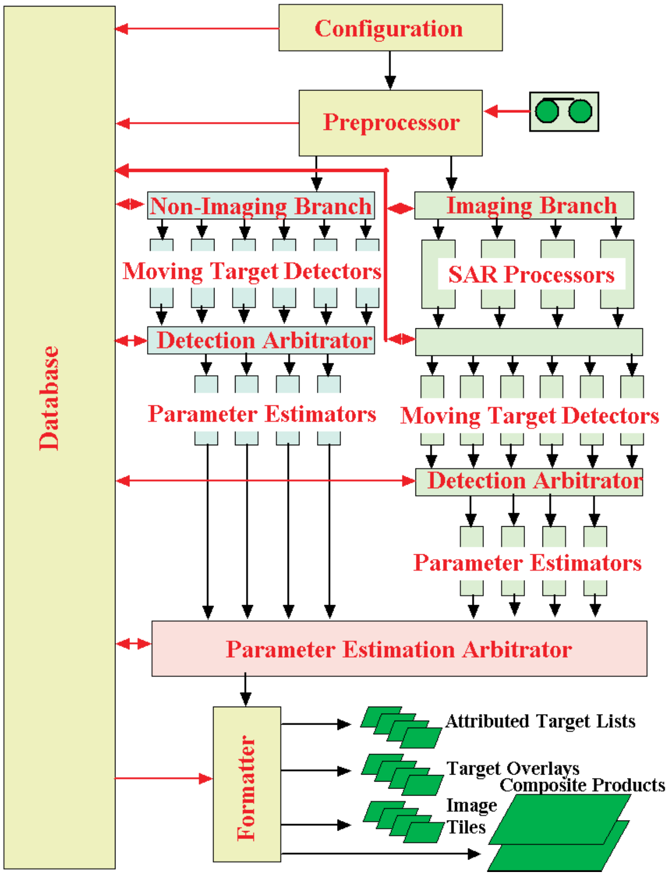

Figure 2. SAR GMTI processor conceptual design.

Figure 2 provides a conceptual view of the processor architecture discussed in this section. A range-Doppler SAR algorithm is used for image formation when this is needed. This section outlines the conceptual design for the processor and keys the design to some of the research results on which it is based. Most of the key algorithms have been tested for airborne data. The development of the RADARSAT-2 processor, based on the conceptual architecture in **Figure 2**, is in progress at the time of writing.

Preprocessor functions

Ingest

MODEX data will arrive at the GMTI processor as encrypted files in framed raw expanded data (FRED) format. These data must be decrypted to RADARSAT-2 MODEX format and then must be unpacked into header and signal data files for processing. At this point, the signal data are still compressed by the RADARSAT-2 BAQ algorithm.

Decompression

The BAQ applied to RADARSAT-2 data must be inverted before any data analysis takes place. During the quantization process, eight-bit in-phase (I) and quadrature (Q) outputs from the radar analog-to-digital converter are partitioned into blocks of 128 range samples. The statistics of each block are used to rescale the data quantization levels, and the reduced data and the scale coefficients are down-linked to the satellite receiving station. During data processing, an inverse algorithm must be applied to restore the data to its original eight-bit form. The BAQ data compression process introduces some amplitude and phase errors into the data.

BAQ inversion is specific to RADARSAT-2 and is common to both SAR and MODEX processing streams.

Range compression

Each of the fore and aft channel MODEX data streams must be range compressed and corrected for the deterministic range-cell migration effects that are generated by the radar beam squint used to provide a coarse compensation for earth rotation and by the range curvature over the radar illumination pattern on the ground. Data correction for deterministic range-cell migration is a common requirement for SAR and GMTI processing.

The range-compressed, migration-corrected fore and aft data channels form the raw input to the GMTI processing functions. Before these channels can be used for this purpose, two other compensation operations are required: channel balance and residual earth rotation compensation.

Channel balance

In any real radar system that has a number of nominally identical channels there are small amplitude and phase response differences between the channels. These differences are sufficiently large to influence the accuracy of the differential measurements between the channels that form the basis of GMTI, even for relatively stable, space-based sensors such as RADARSAT-2. The MODEX processor will need to balance the systematic amplitude and phase properties of the fore and aft data channels early in the processing chain. Investigations with an airborne, two-aperture SAR system have shown that adaptive algorithms that measure the channel amplitude and phase responses after range compression can effectively remove channel mismatches for land data (Gierull, 2003). Extensions of these algorithms to the marine case (moving scene) are under investigation. Parallel investigations have shown that model-based channel balance algorithms that used dynamically measured system parameters are equally effective.

Channel balance compensation is common to both airborne and space-based multi-aperture GMTI radars and is most accurately applied after range compression (to include range-dependent gain variations) and before azimuth processing in the data processing stream.

Residual earth rotation

The earth rotation compensation produced by the RADARSAT-2 dynamic beam squint will provide nearly perfect correction at one range in the 500-km access swath of the radar. Small residual effects will remain in the MODEX data and need to be removed to separate the residual earth rotation from true moving targets. The effects are expected to be most troublesome in urban areas where the radar scattering processes can be very inhomogeneous. GMTI processors are more sensitive to residual earth rotation components than are SAR processors.

Channel registration

The fore and aft channel data collected at any instant in time observe the world from two different points along the radar flight track. To perform the short-time change detection operations that constitute GMTI analysis, the data need to be temporally registered to correspond to the fore and aft apertures occupying the same point in space. Registration requires a combination of time shift and interpolation applied to one channel to register both.

Summary

When channel balance and earth rotation corrections have been completed, the data are ready for processing by the imaging and non-imaging GMTI processor branches. In summary, the preprocessor executes the following functions: (*i*) data decryption, (*ii*) data unpacking, (*iii*) BAQ inversion, (*iv*) range compression, (*v*) deterministic range-cell migration correction, (*vi*) channel balance, (*vii*) residual earth-rotation compensation, and (*viii*) channel registration.

Bulk scene parameters

In addition to preparing the data for moving target extraction and measurement, the MODEX preprocessor needs to generate a stationary world parameter map of the imaged scene for use with the target detection and measurement functions. The parameter map is best generated from single-look, complex, stationary world SAR images for the fore and aft radar channels. Studies of the moving target detection process for a two-aperture radar system (Gierull, 2001a; 2001b; 2002a; 2002b; Sikaneta and Gierull, 2002; Chiu, 2003) have shown that the detection of moving targets and measurement of their motion are influenced by the local, radar properties of the terrain in which they are embedded. Two-aperture SAR image properties that most strongly affect detection and measurement algorithm performance are (*i*) local, mean radar cross section (Chiu, 2003); (*ii*) local coherence (Gierull, 2001b; 2002b; Sikaneta and Gierull, 2002); (*iii*) interferometric "number of looks" (INL) (Gierull, 2001a; 2002a); and (*iv*) local inhomogeneity (Gierull, 2001a; 2002b). All of these parameters can be estimated from single-look fore and aft MODEX image pairs and, when computed as maps (at grid spacings that depend on the estimated parameter) over the image space, can be represented as a grid of four-dimensional scene parameter vectors (SPVs) that is coupled to the image coordinates. The preprocessor module that generates this map is called the bulk-parameter estimator.

Non-imaging moving target detection and measurement

The extraction and measurement of moving targets from a SAR GMTI scene is not, inherently, an imaging process (Gierull and Sikaneta, 2003). The primary output of the processor is an attributed list of all moving objects found in the scene that provides their locations and parametric descriptions. There are a number of algorithms that can detect targets and measure their motion and position from range-compressed, two-aperture, and SAR data without ever forming a SAR image (Sikaneta et al., 2003; Sikaneta and Gierull, 2004). Not forming SAR images decreases processing overhead and processing time at the cost of missing some of the weaker targets but with the advantage that defocusing caused by target motion is not an issue.

In the non-imaging branch of the processor, range-compressed data, from the preprocessor, are directly analyzed by a bank of detection algorithms to detect moving targets. Motion parameters and positions of the detected targets are then estimated by further analysis of data blocks that contain the target information.

As illustrated in **Figure 2**, several detection algorithms are run in parallel to maximize target detection and minimize false alarms. Individual detectors either apply subtractive (displaced phase centre analysis (DPCA)) or correlation (along-track interferometry (ATI) phase and (or) covariance Eigen decomposition; Gierull and Sikaneta, 2003; Sikaneta et al., 2003; Sikaneta and Gierull, 2004) operations to the fore and aft data files to isolate potential moving targets from the stationary world. The parameter (SPV) map generated by the preprocessor bulk-parameter estimator is used to set appropriate, local constant false-alarm rate (CFAR) detection thresholds for each detector. Local scene magnitude, coherence, INL, and heterogeneity estimates from the SPV map are used in rule-based algorithms to combine the detector outputs into a single target list that identifies the data domain for each target. For example, DPCA detectors work best when the local terrain is homogeneous (fields, forests, etc.), the hyperbolic detector described in Sikaneta and Gierull (2004) has superior performance in heterogeneous terrain (urban), and ATI phase measurements are robust under scene heterogeneity when the local coherence and INL are known (Gierull, 2001a; 2002c; Sikaneta and Gierull, 2002).

Targets detected in the detector bank are isolated as small data blocks that are then processed by the parameter estimation software to extract target velocity components V_y and V_x normal and parallel to the radar flight track, respectively. For the non-imaging branch of the processor, variations in time–frequency analysis are used to provide best estimates of target velocity components and target position in image space (range–azimuth position). One analysis approach (Gierull and Sikaneta, 2003; 2004) partitions the time history of the target signal data into short time segments (each approximately 10% of the target illumination time), computing the spectrum of each segment and viewing the target response in the time–frequency plane we have target tracks of in the form shown in **Figure 3** (global positioning system (GPS) monitored pickup truck in the 1999 Petawawa experiment described in Livingstone et al., 2002). The time–frequency target data are iteratively processed by azimuth (slow time) matched filters with varying V_x and V_y to obtain the best possible velocity component estimates. The

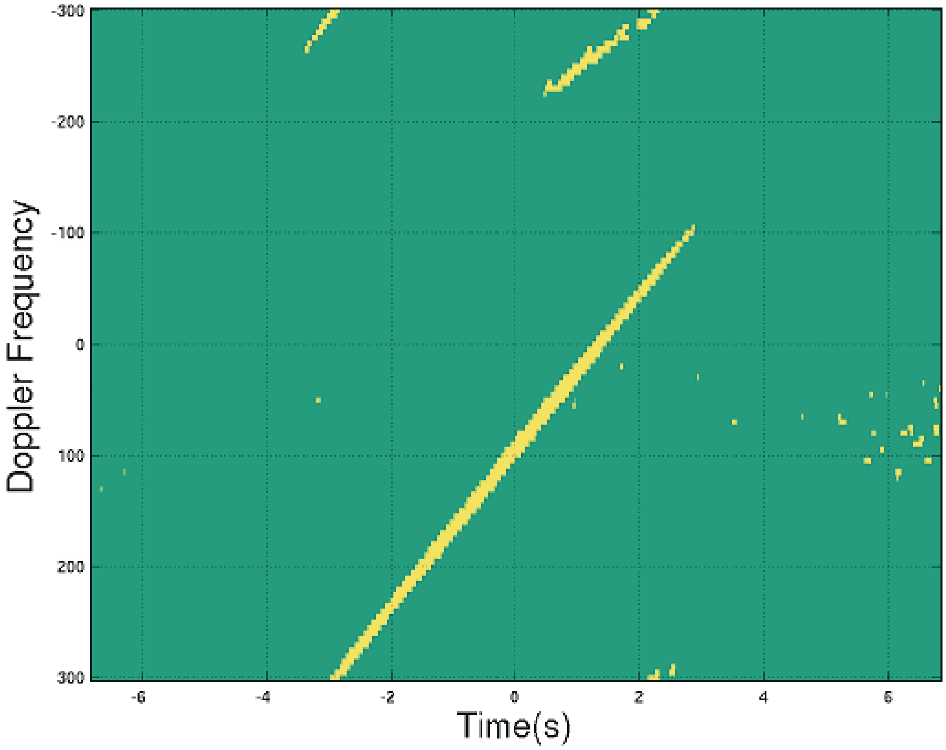

Figure 3. Time–frequency decomposition of a moving pickup truck. The target track at the upper left (near coordinates (–3, –300)) is the main target history wrapped by the signal sampling frequency. The track segment in the vicinity of coordinates (1, –250) is part of the return from another target, moving at a different speed. The scattered points in this figure are false alarms from stationary world features that survived DPCA background suppression processing. Figure courtesy of I. Sikaneta.

iterative process separates multiple, clustered targets into independent entities and identifies single targets that occupy several resolution cells. ATI phase is used to cross check V_y estimates. The best, obtainable velocity estimates are used to estimate the "true" image position of the target in range–azimuth image space. Position estimate accuracy is constrained by velocity estimation accuracy, which is in turn limited by uncompensated target acceleration (Sharma and Collins, 2004) and, for weak targets, by background clutter contamination of the target signal (Chiu, 2003).

A second time–frequency analysis approach, the fractional Fourier transform (Chiu and Sikaneta, 2004), rotates the time–frequency coordinate system through an angle α to find the angle that maximizes the target energy (**Figure 4**). The ATI phase of the maximized target is used to estimate V_y, and the equation for the angle α is inverted to estimate V_x. In the fractional Fourier transform approach, α replaces (and can be mathematically linked to) the pair of matched filters in the previous discussion of time–frequency analysis. Target acceleration is not accounted for in the mathematical models and yields residual errors as do target–clutter interactions (Chiu, 2003).

Each detected target is individually processed and the target list is refined to provide its velocity and stationary world position and a best estimate of target strength is added to the list. Where multicell target signatures are detected, estimated dimensions are appended to the target attribute list.

Imaging moving target detection and measurement

The imaging branch of the GMTI processor applies moving target, azimuth matched filters to fore and aft channel data to localize and enhance signal returns from moving targets against the stationary world background. This is particularly advantageous for capturing and measuring slow, weak targets (Gierull and Sikaneta, 2004). The SAR image formation process is necessarily iterative to minimize target loss to filter mismatches because of target energy spreading in the resulting images. When the ratio of target speed to radar platform speed is large (airborne case) (Livingstone et al., 2002), a large number of iterations are needed to scan the signal space. For RADARSAT-2, the target velocity is a small fraction of the platform velocity, and a much smaller number of iterations are required to capture all targets in the scene.

The matched filter required to focus any SAR image is the time-reversed phase history (φ) of each point in the matched terrain. This is a simple, range-dependent function. When the point(s) of interest is (are) a moving target, the SAR phase history of the target tracks its motion and has the form

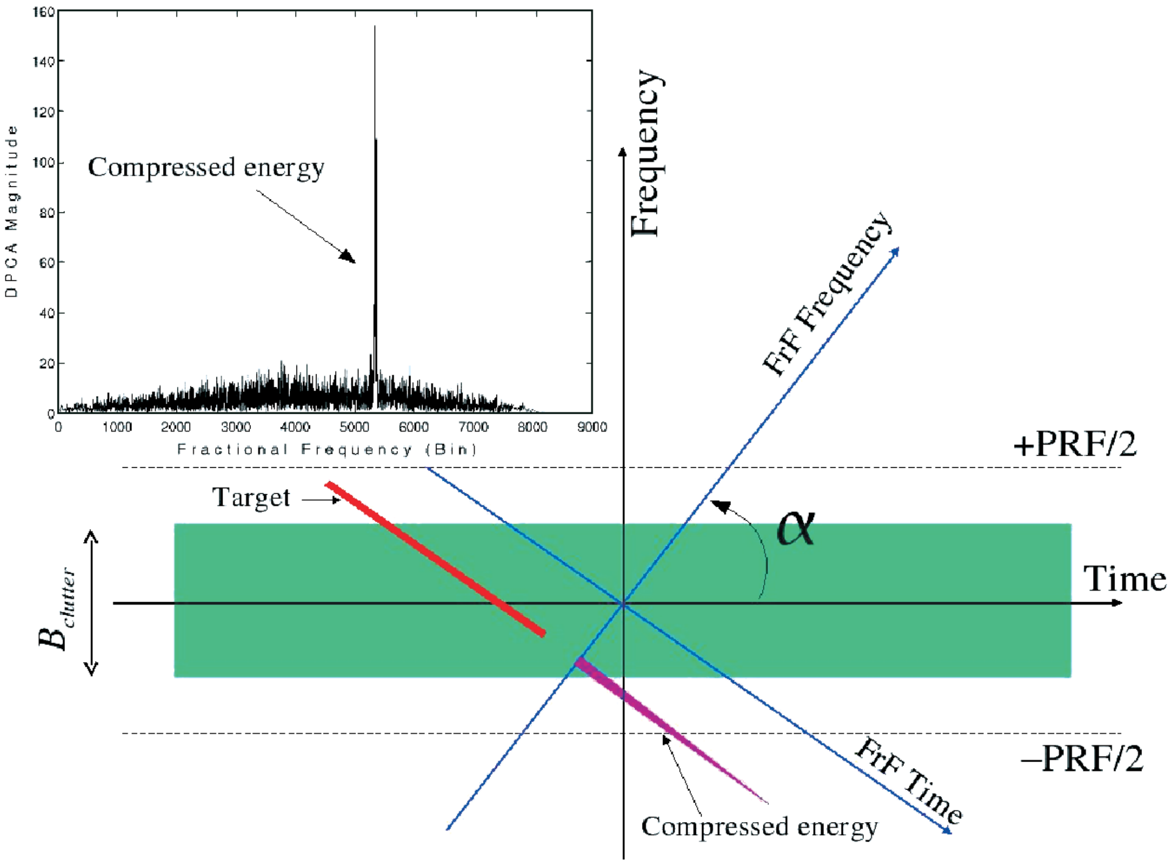

Figure 4. The fractional Fourier (FrF) transform operates in time and frequency axes rotated through an angle α. When the axes align with the time–frequency trajectory of a moving target, the target energy, and thus its contrast to the background radar returns, is maximized. Figure courtesy of S. Chiu.

$$\varphi = \frac{4\pi}{\lambda}\left[\,|\vec{\boldsymbol{R}}(t) - \vec{\boldsymbol{V}}_{\mathrm{T}}t| - |\vec{\boldsymbol{R}}_0|\,\right]$$

where $\vec{\boldsymbol{R}}(t)$ is the range history of the point that the target occupied at the centre of the synthetic aperture, $\vec{\boldsymbol{R}}_0$ is the range vector from the satellite to the target point when the satellite is at the centre of its target observation window, $\vec{\boldsymbol{V}}_{\mathrm{T}}$ is the target velocity vector on the earth's surface, and λ is the radar wavelength.

Normalizing the hyperbolic phase history to R_0 and expanding the square root in the normal way, we have the quadratic approximation

$$\varphi \approx \frac{2\pi}{\lambda R_0}(V_{\mathrm{S}}'^2 - 2V_{\mathrm{S}}'V_{\mathrm{T}x} + V_{\mathrm{T}x}^2 + V_{\mathrm{T}y}^2)t^2 + \frac{4\pi V_{\mathrm{T}y}y_0'}{\lambda R_0}t - \frac{2\pi R_0}{\lambda}$$

where t is time, V_{S}' is the effective (ground projected) satellite velocity, $V_{\mathrm{T}x}$ is the target velocity component parallel to the radar motion, $V_{\mathrm{T}y}$ is the target velocity component transverse to the radar motion, and y_0 is the target transverse position at the center of the radar beam.

The coefficient of t^2 determines the SAR focus, and the coefficient of t determines the azimuth displacement of the moving target in the processed image. The FM rate error (focus error parameter) for the moving target with respect to the stationary world is

$$\mathrm{d}r_{\mathrm{FM}} = \frac{V_{\mathrm{T}x}^2 + V_{\mathrm{T}y}^2 - 2V_{\mathrm{S}}'V_{\mathrm{T}x}}{V_{\mathrm{S}}'^2}$$

For 6 m azimuth resolution, an FM rate error of ~2.6% will reduce the impulse response height by 3 dB through defocusing (**Figure 5**). For RADARSAT-2, $V_{\mathrm{S}} \approx 7500$ m/s, $V_{\mathrm{S}}' \approx 6700$ m/s, and setting $V_{\mathrm{T}y} = 0$ we find that motion parallel to the satellite track will cause 3 dB defocusing at $V_{\mathrm{T}x} \approx 33.3$ m/s. Defocusing is significant at the upper part of the speed range that is of interest for GMTI. Setting $V_{\mathrm{T}x} = 0$ and estimating the impact of transverse motion on SAR focus, 3 dB defocusing occurs at $V_{\mathrm{T}y} \approx 670$ m/s. This is outside of the GMTI range-of-interest. For target detection purposes, three matched filters corresponding to along-track velocities 30, 0, and –30 m/s should suffice for ground targets.

The coefficient of t in the matched filter expansion determines the Doppler shift and thus the azimuth displacement of a radially moving target. For the local, Cartesian coordinate system used, $y_0'/R_0 = \cos(\theta)$, where θ is the target incidence

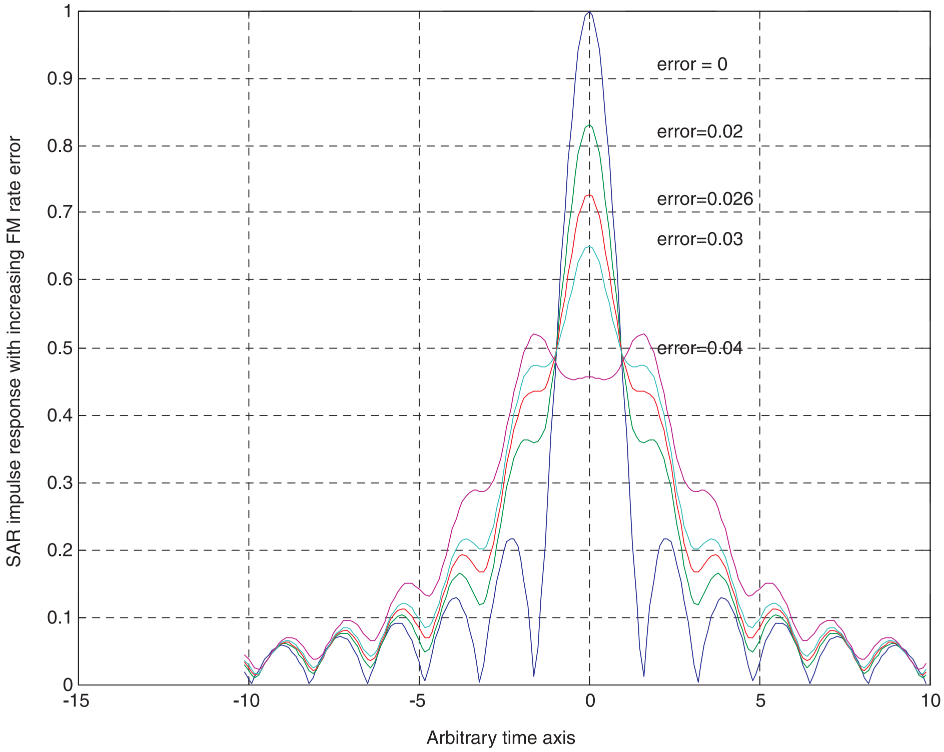

Figure 5. Model calculation showing the degradation of SAR impulse height with increasing FM rate error in the SAR matched filter.

angle. The along-track (azimuth) displacement (X) of the moving target in the SAR image is (Livingstone et al., 2002)

$$X = R_0 \frac{V_{\mathrm{Ty}}}{V_{\mathrm{S}}'} \cos(\theta)$$

For RADARSAT-2 values $R_0 = 10^6$ m, $\theta = 45°$, $V_{\mathrm{S}}' = 6700$ m/s, and $V_{\mathrm{Ty}} = 10$ m/s, the moving target azimuth shift is $X \approx 1055$ m. As the target velocity to position scale factor is quite large, 149/s in this case, small errors in target y velocity estimates will yield significant target position errors.

As opposed to conventional, image-generation SAR processors, which employ significant amplitude weighting and spectral guard bands to minimize the presence of sampling ambiguities in the output images (normally 50%–70% of the available data is processed), GMTI SAR processors are constrained to process the full signal bandwidth with minimal weighting so that velocity-shifted moving target returns are not lost to “out-of-band shifting”. The stationary world ambiguities do not compromise moving target detection.

Time spent processing a scene for two apertures and a number of matched filters can be mitigated by performing a number of processing operations in parallel, as is suggested in the conceptual architecture in **Figure 2**.

As was the case for the non-imaging target detection, the imaging branch of the GMTI processor uses a number of detector algorithms to operate on the same fore and aft aperture image pair to generate lists of detected targets. As the image formation process is linear, all detection algorithms that can be used on the non-imaging branch also apply to the imaging branch of the processor (Sikaneta and Gierull, 2004). In addition, image-specific algorithms of the form proposed by Chiu (2002) can also be employed. As was the case for the non-imaging branch detectors, elements of the SPV map that are proximate to the image positions of the detected targets can be used to set CFAR thresholds for the detectors. The relative performance of detector classes in the image domain is the same as that in the non-imaging domain. For inhomogeneous terrain such as the urban scene shown in **Figure 6a**, the scene residuals in the DPCA-cancelled stationary world returns (**Figure 6b**) make the definition of a target detection threshold very unreliable, and the DPCA moving target detector performs poorly in the urban area but does find the highway targets in the relatively homogeneous region beside it. ATI phase measurements on the same scene (**Figure 6c**) provide a robust moving target detection threshold, and moving target signatures are clearly seen beside the stationary world returns. The hyperbolic detector (results shown in **Figure 6a**) performs better in urban (inhomogeneous) areas than all others tested (Sikaneta and Gierull, 2004; Gierull and Sikaneta, 2004).

The outputs from the detector array are target lists that identify the image position of each detected target. The target lists are combined in a rule-based arbitration module that minimizes false alarms and maximizes the number of reported detections by using known relationships between local scene magnitude and heterogeneity and detector performance. The resulting master list forms an input to the target parameter estimation process.

In the estimation process, small domains in the vicinity of each target are independently processed by a number of algorithms to provide estimates of (*i*) target “*y*” velocity (ATI phase), (*ii*) target “*x*” velocity (iterated focus), (*iii*) the presence of target acceleration (iterated focus), (*iv*) “stationary world” target coordinates (range and azimuth position), (*v*) target strength, (*vi*) target size (in resolution cells), and (*vii*) velocity ambiguities (range displacement between filtered fore and aft sub-beams for each aperture).

Owing to Doppler shifts produced by target motion towards or away from the radar, all targets are detected in their azimuth-shifted positions. The azimuth position of the targets in the stationary world is a derived parameter and is subject to errors arising from velocity estimation limitations.

The calculated attribute list for each target is appended to the target location as an attribute vector. If both the non-imaging and imaging GMTI processor branches are active for the same

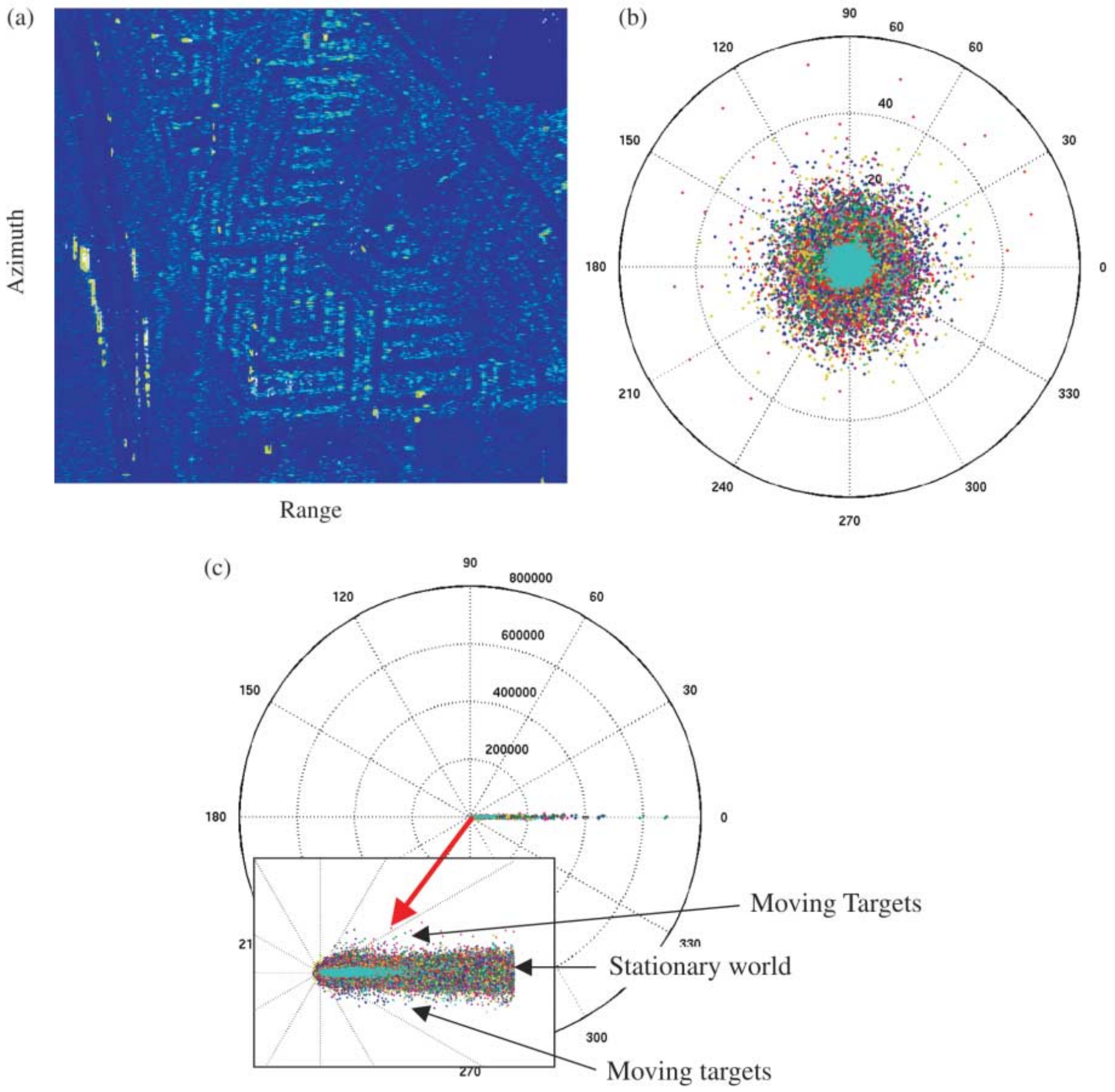

Figure 6. (a) A 1 km × 1 km segment of a single-look SAR scene showing a residential area in Ottawa with a major highway on the left side of the figure. Hyperbolic detector outputs for moving vehicles in the scene are highlighted in yellow. Targets are shown in their velocity-displaced position. The DPCA detector finds most of the highway moving targets but misses most of those in the residential area. (b) The DPCA image for **Figure 6a** is shown projected onto the complex plane prior to threshold application. The detected moving targets are found in the outliers of the central cluster (as are several buildings). (c) The fore–aft channel interferometric SAR scene corresponding to **Figure 6a** is projected onto the complex plane. The stationary world returns, spread by radar phase noise, lie along the positive real axis. The points seen above and below the magnified portion come from moving targets in the scene. There are normally several points along a phase radial for each moving target.

data, the attributed target lists are combined in a second, rule-based arbitration module to form the GMTI processor output.

Output module

The output module of the GMTI processor accepts the attributed target list from the final arbitration process as its primary input. A secondary, image input can be generated, if desired, by applying a windowed stationary world matched filter in the SAR azimuth processor module. Both inputs are defined in radar slant range. The output processor projects the slant-range image data to geographic position by using satellite position information that has been received with the signal data and a digital elevation model that has been previously registered to the imaged scene. The GPS satellite position and imaging geometry parameters for RADARSAT-2 are contained in the signal data headers.

The output module (*i*) maps the image slant-range coordinates to geographic coordinates, (*ii*) assigns geographic positions to each target in the target list, (*iii*) constructs a geographic image overlay showing estimated target positions, (*iv*) projects the slant range image to the earth's surface, and (*v*) formats the computed data for output as NATO 4607 and ASCII formats for target list data or NATO (TBD) and GeoTIFF formats for image data. The details of the output formats are being defined at the time of writing.

MODEX processor design issues

As the MODEX GMTI processor is designed to measure moving objects, a number of issues arise that are not of significance in conventional SAR processors.

Range migration

It was previously noted that deterministic range migration corrections need to be applied in the preprocessor stage to remove artifacts caused by the radar squint and range curvature. These corrections are specific to the radar system and apply equally to image formation and MODEX processing. For moving targets, the target displacement over the radar observation period can create target detection problems for targets with a low cross section in high-return backgrounds.

Assuming a processed beam width of 0.25°, a slant range of 1000 km, and a satellite speed of 7500 m/s, the synthetic aperture time is 0.6 s. Assuming a range transmit bandwidth of 50 MHz and a range sampling frequency of 56.3 MHz, the range resolution is 3 m and the slant-range sample spacing is 2.7 m. We will define range migration of one half of a sample as significant. With these assumptions, radial velocities of 2.3 m/s (or cross-track ground velocities greater than 3.6 m/s at 50° incidence) or higher cause detectable range cell migration (RCM) differences when compared with that of stationary targets. Target range migration becomes a detection problem for targets with a low cross section when the target energy in any range cell decreases by ~5 dB. Target migration through three range cells (9 m or 3.3 samples) over an illumination period yields approximately 5 dB signal loss per range cell and corresponds to a target radial velocity of 15 m/s.

Mitigation of target range walk effects can take three forms:

(1) Process data to coarser range resolution by range averaging (this applies to both imaging and non-imaging processor branches) and measure the velocity of the enhanced target.

(2) Combine range averaging with the formation of fore and aft azimuth sub-beams in the imaging mode. This corresponds to the classical two-look filter and is applied to each of the fore and aft aperture data. The target displacement between the two sub-beams provides a check on the y velocity estimated from phase measurements.

(3) Search neighboring range cells for target fragments and test for velocity consistency.

Once an estimate of the target motion is known, the range cell migration of the moving targets can be properly compensated.

Range migration effects are present in all GMTI radar systems and are most troublesome in those that have fine range resolution. Range migration mitigation functions need to be included in the MODEX processor detector module design.

Sampling ambiguities

RADARSAT-2 has been designed to minimize the presence of range ambiguities, and only azimuth ambiguities arising from target motion need be considered. As the full, sampled spectrum of the radar signal is used in the processor, signal frequency shift due to target motion will cause the tail of the target spectrum to wrap to the opposite side of the spectrum at the sampling frequency, as shown in **Figure 3**. The wrapped signal represents a "target" moving in the opposite direction to the true target. For non-imaging processors, this spectral shift is easily detected and a corrected y velocity estimate is easily obtained. For imaging processors, filtering the signal spectrum to create fore and aft sub-beams, as noted in the section titled Range migration, yields a technique for resolving which is the ambiguous target by using displacement between the target position at the sub-beam centres to determine the true sign of the ATI phase estimate for both parts. Once an ambiguous target has been detected, it is easily associated with the true target and a corrected velocity estimate can be generated.

Weak target effects

Focused moving targets are spectrally superimposed on azimuth-displaced returns from stationary terrain, causing target–clutter interaction effects to appear in the complex data used to measure target speed. Results obtained by Chiu (2003) and Gierull (2002c) have shown that signal-to-clutter ratios smaller that 10 dB will bias the measured target speeds to lower values. Knowledge of the local signal-to-clutter ratio can be used to roughly correct target speed estimates. Terrain clutter interference effects will be significant in the processing chain for both weak, slow targets and strong, fast targets that have significant range walk. In the former case, the target strength will measurably impact the minimum detectable velocity of the radar. In the latter case, range migration correction will correct the speed measurement error.

Blind velocities and directional ambiguities

Blind velocities occur when the phase estimation removes the moving target owing to ATI phase wrapping effects. To be in a blind spot, a moving target would have to have a similar (wrapped) phase in both apertures. This means

$$n2\pi = (-4\pi/\lambda)\Delta R$$

where ΔR is the change in range of the target between apertures, and n is an integer. Thus

$$\Delta R = d\nu_{\mathrm{radial}}/\nu_{\mathrm{sat}}$$

where d is the spacing between two-way phase centres, ν_{sat} is the satellite speed, and ν_{radial} is the target radial velocity.

Thus the blind velocities are at

$$\nu_{\mathrm{radial}} = n\lambda\ \nu_{\mathrm{sat}}/(2d).$$

For our numbers, these are at all integer multiples of 55.5 m/s, assuming $d = 3.75$ m.

The blind spots have width equal to twice the minimum detectable velocity and are generally not a serious problem except at the high-speed end of the GMTI speed range. The use of the filtered sub-beams discussed previously provides a means to detect targets moving near the blind speed by looking for displacement effects in the combined data when the ATI phase lies in the indeterminate range near 0°.

When ATI is used to estimate target speeds, a directional ambiguity (ambiguity in target motion direction) occurs at half of the blind speed. The ambiguity can be resolved by displacement estimates between the fore and aft sub-beams in the imaging branch of the processor.

Conclusion

RADARSAT-2 includes an experimental moving target detection capability known as MODEX. This capability is based on the division of the radar aperture into two separate and independent apertures in the along-track direction and on user definition/selection of radar operating parameters. Elements of possible MODEX radar configurations are presented and discussed. The RADARSAT-2 mission will support MODEX by providing the capability to program custom beams and modes that are optimized for moving target detection.

Processing of the MODEX data will apply both imaging and non-imaging GMTI algorithms to detect moving targets in the received data and to measure their properties. Research results, based on airborne data, point to a processor design that operates several moving target detectors in parallel, guides the detection process by means of two-aperture, stationary scene parameters from the radar returns containing the targets, and individually estimates a target parameter set for each detected target. Some of the moving target detection and estimation processes are inherently iterative. The conceptual architecture that is being used to develop a MODEX GMTI processor for RADARSAT-2 is presented and discussed.

Processing issues that need to be addressed in the development of a MODEX GMTI processor are presented and discussed in the light of current understanding of the processor problem. Research results to date indicate that the detection, measurement, and arbitration operations within the processor can be automated.

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