In-Orbit Characterisation of the RADARSAT-2 Antenna

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INTRODUCTION

The RADARSAT-2 antenna is an active phased array which uses two-dimensional beamforming and beamsteering to produce the many (over 200) different beams required for the RADARSAT-2 imaging modes. For calibration purposes, it is necessary to have a means for obtaining information about the characteristics of the array in-orbit. This paper is concerned with the in-orbit measurement operations that are planned for characterisation of the antenna. These operations do not involve any interaction with any hardware units on the ground, and so they can be performed at any point in the orbit where the ground has the required backscatter characteristics.

The purpose of these operations and the information that is to be obtained is described in this paper, followed by assessment of the accuracy of the information. The set of measurements described use special sequences involving transmissions or receptions with individual Transmit Receive Modules (TRMs), rows or columns or subsets of the TRMs, rows or columns. An outline description of the operations, the required spacecraft and ground resources required, and the accuracy of the derived data is then presented.

Analysis and simulation have shown that all the test and measurement accuracy goals can be met with data from a single cycle of each of the test sequences, but provision has been made for multiple successive cycles to be performed to increase accuracy if required.

RADARSAT-2 ANTENNA

The RADARSAT-2 Synthetic Aperture Radar is required to generate a wider range of data products than any other preceding civilian satellite SAR. To achieve the required flexibility the RADARSAT-2 antenna is a fully active phased array which provides two-dimensional beamforming and beamsteering. The antenna (see block diagram in Fig. 1) contains 512 Transmit/Receive Modules (TRMs), arranged in an array of 16 elements along the length of 15 m by 32 elements across the width of about 1.5 m.

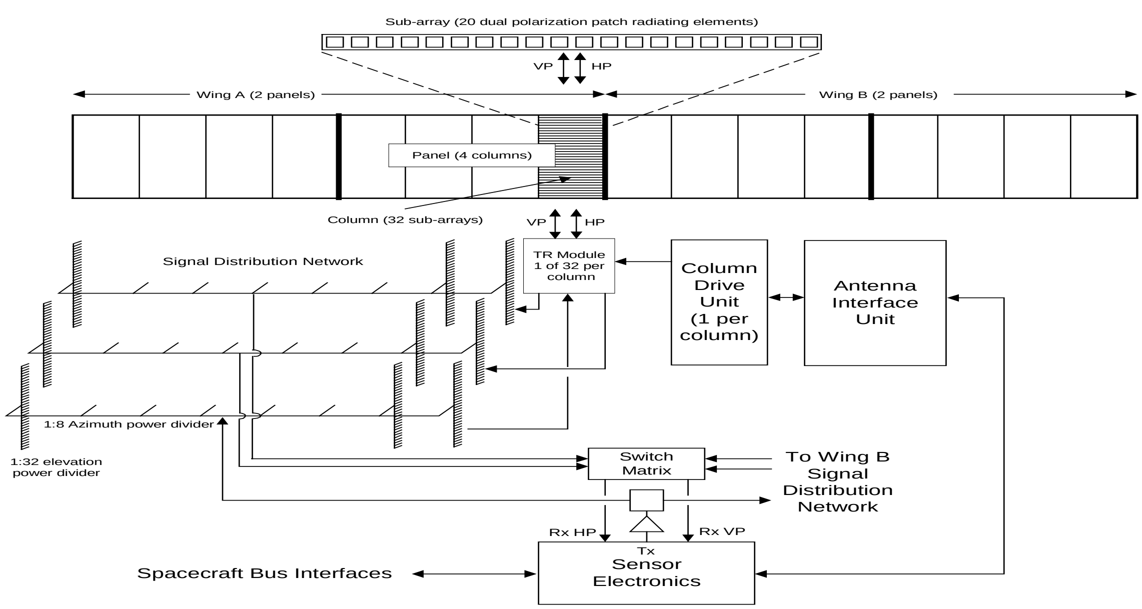

Fig. 1. RADARSAT-2 SAR Payload Block Diagram

PURPOSE OF DIAGNOSTIC/CALIBRATION OPERATIONS

The diagnostic/calibration operations are designed to provide the following information on the RADARSAT-2 antenna while on orbit:

- Whether each TRM is functional for transmit and receive for each polarization
- The relative mean phases of the 16 columns and 32 rows of TRMs for transmit and receive
- Whether each bit of the receive amplitude control is functioning for each antenna row or column
- The relative phases of the 16 individual TRMs along a selected row for transmit and receive
- Whether each bit of the receive amplitude control is functioning for each TRMs along a selected row

This information will be used for the following purposes:

- Identification and characterization of any systematic mechanical distortions across the antenna array
  If there is a significant physical distortion of the antenna plane, this will be revealed by the pattern of phase errors across one or other dimension of the antenna.
- Aiding radiometric calibration and image quality optimisation
  The radiometric calibration of the RADARSAT-2 products depends on determination of the elevation gain patterns for the various beams. A significant factor in any distortions of these patterns is due to errors in the relative phases of the antenna rows on transmit or receive. The measured data will be an input to the antenna model used to generate beam patterns.
  The information on the relative phases of different antenna columns will be used to support determination of the azimuth beam pattern. The information derived from the column tests will be useful in determining the form of any distortion observed in the azimuth patterns for these beams. Accurate determination of the actual beam supported by this data will help achieve optimization of the azimuth impulse response.
- TRM fault detection and characterization.
  These tests allow individual TRM faults or failures to be tracked and diagnosed.
- As input to any required beam resynthesis
  If the distortions of the beam patterns are large enough that effective compensation cannot be performed during processing, new sets of TRM coefficients will be generated for some or all of the beams. In this event, the information on the phase characteristics across the array will be a primary input in determining the adjustments to be made to the TRM settings.

DIAGNOSTIC/CALIBRATION ACCURACY REQUIREMENTS

The performance requirements for amplitude control and TRM functionality tests are given in terms of the probability that a test gives a false result: for example, that a TRM failure is indicated when no failure has actually occurred. The performance requirements for phase measurements are given in terms of phase accuracy (1σ degrees).

The following performance requirements have been established for the tests:

- For tests that individual TRMs are functioning (referred to as “TRM Go/NoGo Tests”), the goal is that a false result should occur less than once in every 10,000 tests. Thus an error should occur less than once in every ten series of tests, each covering all 512 TRMs on transmit and receive. This relatively high error rate is acceptable since the apparent failure of one TRM will not require any immediate action, and any false results will be uncovered on the next series of tests. This level of false result therefore causes no significant additional work. The minimum acceptable performance is one false result in every 1000 tests.
- For measurements of relative phases of different antenna rows or columns, the goal is to achieve a 1σ-accuracy of better than 6°. This corresponds approximately to one bit in the phase control, and random errors of this magnitude across one dimension of the antenna are small enough to cause negligible change to the beam pattern. The minimum acceptable performance is a 1σ-accuracy of about 10°. At this level, the test will be sufficient to reveal major systematic errors, but multiple measurements will be required for good characterisation.
- For tests of row and column amplitude control bits, the goal is that an error occurs less than once in every 1000 tests for any of the most significant four bits. This would mean that an error occurs for one of the top four bits no more than once in every 8 series of row amplitude tests, and no more than once in every 16 series of column tests. A failure in one of the least significant bits for one row or column has minimal impact on beam patterns, and so higher false result rates can be accepted. A false result for any bit will generally be uncovered with a repeat test. The minimum acceptable performance for one of the four most significant bits is one false result in every 100 tests.

- For measurements of relative phases of different TRMs in a row of the antenna array, the goal is to achieve a 1σ-accuracy of better than 6°. The minimum acceptable performance is a 1σ-accuracy of about 20°.
- For tests of TRM amplitude control bits, the goal is that an error occurs less than once in every 1000 tests for any of the most significant three bits. For the other bits, a means for testing should be provided, but higher error rates can be accepted. The minimum acceptable performance for one of the three most significant bits is one false result in every 100 tests.

DIAGNOSTIC/CALIBRATION MEASUREMENTS OPERATION

Seven different types of measurement operation are planned, but all use the same basic approach:

- A focused beam from the full aperture is used for one direction of the signal path (transmission towards the ground, or reception of returns back from the ground).
- A subset of the antenna is used for the other direction. This subset could be one row or a subset of the rows, one column or a subset of the columns, a single TRM or a subset of the TRMs in one row.
- For each type of test, the size of the subset of the antenna, the direction of the beam and the surface type are selected so as to provide sufficient received signal to allow good measurement. (For subsets of rows and columns, the beams are pointed perpendicular to the antenna plane: i.e. at an angle of 29.8° from the nadir direction. For subsets of TRMs or a single TRM, the beams are pointed towards nadir to increase the level of the return signal.)
- A sequence of different subsets are used to allow relative measurements between different items of the same type (rows, columns or TRMs). A relative measurement between one item and another is obtained by replacing the first item in the subset used for one operation by the other, and performing the same operation.
- Phase information for an item (row, column or TRM) is obtained using a subset consisting of a reference set of items (rows, columns or TRMs) plus the item to be measured. Data are collected using a series of different phase settings for that item covering the full 360 degree range, and the signal level variations with phase setting are used to determine when the item is in phase with the reference set.
- Amplitude tests are intended to test that individual bits in the amplitude setting are functioning. Tests for a row, column or TRM are performed by operating that item using a series of different amplitude settings. The reference setting used for the tests is with all amplitude bits being set to 1. All other settings are with one bit set to 0, and all others to 1. A reduction in the signal level indicates that the bit set to 0 is functioning. Since the TRM amplitude can only be set for receive, measurements of this type only apply in one direction.

TEST SEQUENCES

The full set of tests has been split into seven sequences.

1. Row Phase (Transmit and Receive)
2. Row Amplitude (Receive)
3. Column Phase (Transmit and Receive)
4. Column Amplitude (Receive)
5. TRM Phase (Transmit and Receive)
6. TRM Amplitude (Receive)
7. Go/NoGo Tests (Individual TRM functional)

Only the Row Phase Measurement is described in detail, the others are similar mutatis mutandi:

ROW PHASE MEASUREMENTS

These tests provide measurements of the relative phases of the 32 rows of the antenna. Separate portions of the test sequence cover the phases for transmit and receive. The same approach is used for both, but in one case signals are transmitted by a subset of rows and received by the full antenna, and in the other transmitted by the full antenna and received by a subset of rows. The beams used for these measurements are pointed in a direction normal to the antenna plane (i.e. at an elevation angle of 29.8° from the nadir direction) and areas of reasonably uniform and moderately high backscatter are optimum.

Three different reference groups of rows are used for the tests, each group consisting of 8 rows spread across the antenna width. In each measurement, a reference group is used in combination with the row that is being measured.

To obtain phase information for the row, the phase settings for the row under test are cycled around a full 360° over a series of pulses. The received data are analysed to determine the variation of the signal level at the beam boresight direction in elevation. The peak of this cyclic variation corresponds to the phase setting when the row under measurement is in phase with the reference group of rows.

Each of the three reference groups of rows is used for measurements with 16 other rows, giving information on the relative phases of these 16 rows. Sixteen of the rows are covered with two different reference groups, allowing the relative phases of all 32 rows to be determined.

Fig. 2 illustrates the reference groups of rows, together with the test rows that are measured in combination with each reference group. There are three different references groups, each containing one row from each successive set of four rows across the antenna width. Each reference group is used with one of 16 different test rows in turn, indicated in the second column for each reference. Each row is measured with either one reference (indicated in blue, the darker shading) or with two different references (in yellow, the lighter shading). The rows measured with multiple references are used as tie-points to relate phase measurements with different references to one another.

The effect of mutual coupling from one row to another is predicted to be very small. To provide a check that this is the case, the test sequence includes pairs of measurements with eight of the rows, one when an adjacent row is also active (indicated by 'T') and the other when there is no active adjacent row (indicated by 't').

The following is a summary of the sequence of measurement pulses used to generate one set of information (transmit phase or receive phase. This sequence provides two pulse returns for each setting, and can be repeated a number of times to generate more data as needed to improve accuracy.

For Reference Group A:

- Collect a series of pulses with a focused beam
- For Row 1 tested with this reference:
  - Collect two pulses with test row set at phase 1
  - Collect two pulses with test row set at phase 2
  - ……
  - Collect two pulses with test row set at phase 11
- Repeat for Rows 2-16 tested with this reference
- Repeat for Reference Groups B and C

With this sequence, the full set of data with 11 phase settings for one test row is collected in about 0.02 seconds. This means that over 95% of the beam footprint is the same for the full set of data, so that the effect of any backscatter variation on the measurement is negligible.

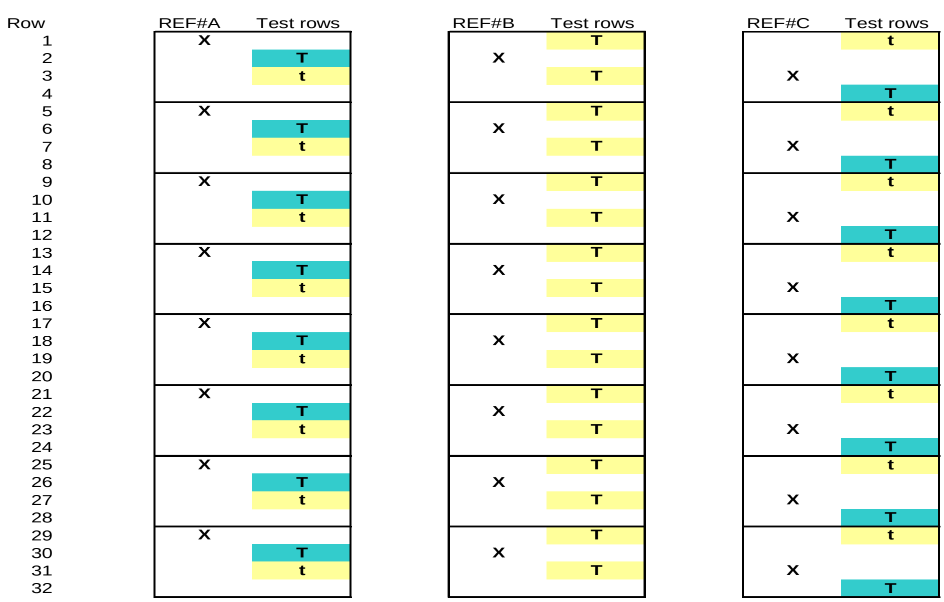

Fig. 2 Reference and Test Rows for Row Phase Measurements

OPERATIONS AND RESOURCES

Some of the principal factors taken into account when defining the sets of antenna diagnostic/characterization measurements are;

- Use of the full focused antenna for one direction of measurement (i.e. receive beam for transmit measurements, and vice versa) to maximise the signal level and the signal-to-noise.
- Direction of pointing. The first choice of pointing direction is normal to the plane of the antenna. For tests using single TRMs or small groups of TRMs, the signal return will not be sufficient from this direction. For these tests, the beam is pointed towards nadir, where the backscatter coefficient is higher, and a large area contributes within a very limited slant range interval.
- Use of individual rows, columns and TRMs for amplitude and Go/NoGo tests. These tests all involve detection of signal level changes. For the Go/NoGo test the change is between signals collected with a TRM on and off. For amplitude tests, it is between signals collected with a row, column or TRM amplitude bit on and off. Each of the measurements is subject to statistical uncertainty (similar to image speckle). This uncertainty is reduced by multi-looking and averaging of independent data samples. Individual rows, columns and TRMs are used for these measurements in order to increase the contrast between the two levels being measured.
- Use of reference groups of rows, columns and TRMs for phase measurements. For all measurements of relative phases, a reference group of rows, columns or TRMs (as applicable) is used in combination with the item (row, column or TRM) being measured, and the same reference group is used with a set of different such items. At least two reference groups are used to allow measurement of all items, and at least four items measured with one reference are also measured with another reference. This ensures that the measurements with different references are accurately related, and provides a check of the validity of the measurements.
- Choice of reference group size. These have been chosen as a compromise between two opposing considerations. A larger group will give a higher signal level and improved signal-to-noise, and therefore reduce the random variation in the measurements. A smaller group will give improved sensitivity to the item being measured as its phase is systematically changed.
- Choice of reference group distribution. All reference groups have been chosen to be fairly uniformly spaced across nearly the full dimension of the antenna (e.g. Ref A Rows are 1, 5, 9, 13, 17, 21, 25 and 29 from the full set of 32). This approach was taken because the resulting beam mainlobe remains as a simple unimodal pattern when the phase of the test item is cycled through 360°, allowing the level variations at the centre to be more easily measured. The pattern is illustrated in Fig. 3. Note that the high sidelobe in the Receive pattern is suppressed by a null in the Transmit pattern. For a reference group of closely-spaced items, the mainlobe would be broader and can become severely distorted for a test item which is not very close to this group. This option has therefore been rejected.

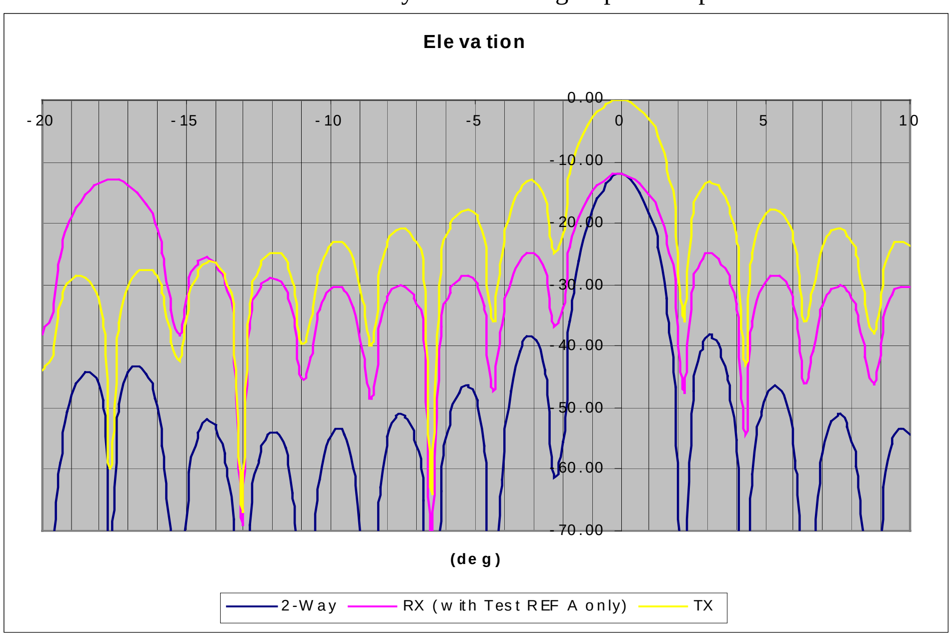

Fig. 3: Elevation Pattern with Reference Rows

DIAGNOSTIC/CALIBRATION MEASUREMENT PERFORMANCE AND CONCLUSION

Monte Carlo simulations with 10,000 runs were performed for the various types of antenna measurement, and the statistics of the estimated performance were determined. Amplitude performance is not presented.

The results for the proposed antenna phase measurements are given in Table 1. These results are for measurements using just one cycle of each test sequence, and the accuracies can be improved further by performing multiple cycles. This table contains the basic information about each of the measurements, including the values of two key parameters: max/min and s.d./mean ratios.

- Max-to-min is the ratio of the maximum and minimum mean powers around the cycle of 360° in phase settings. This ratio is determined by the number of rows, columns or TRMs in the reference and by the noise level. The maximum corresponds to a coherent sum of the reference and the test item plus noise. The minimum corresponds to coherent sum of the reference and the test item in anti-phase, plus noise.
- The “signal-to-noise” corresponds to the signal from the reference only, and is therefore approximately the average value across the series of phase settings. The values of standard deviation to mean ratio for the power level measurements are based on calculations using two range lines per setting (i.e. the data from one cycle of the sequence).

For row and column measurements, which use signals from the antenna boresight direction to the side of the satellite, the spatial averaging over the beam footprint provides an effect equivalent to 1000 looks. For TRM measurements, which use signals from nadir, various amount of range multi-looking are included, and the effect on signal-to-noise is taken into account.

Table 1. Phase Measurement Accuracy from One Cycle of Test Sequence

Test	**Reference**	**No. of range looks**	**Signal-to-noise**	**Max-to-min ratio**	**Standard deviation/ mean**	**Rms phase error**
Row Tx	8 rows	-	14 dB	1.62 = 2.1 dB	0.022	2.3°
Row Rx	8 rows	-	19 dB	1.64 = 2.2 dB	0.022	2.2°
Column Tx	4 columns	-	14 dB	2.65 = 4.2 dB	0.022	1.2°
Column Rx	4 columns	-	18.5 dB	2.73 = 4.4 dB	0.022	1.2°
TRM Tx	4 TRMs	4	20 dB	2.75 = 4.4 dB	0.352	21.3°
		10	18 dB	2.73 = 4.4 dB	0.224	12.6°
		50	14 dB	2.67 = 4.3 dB	0.100	5.6°
TRM Rx	4 TRMs	4	35 dB	2.78 =4.4 dB	0.352	21.6°
		10	33 dB	2.78 =4.4 dB	0.224	12.6°
		50	29 dB	2.77 =4.4 dB	0.100	5.3°

These results are all estimates of the accuracy of measurements obtained with one cycle of the test sequence. The accuracies can be improved by running the sequence multiple times to allow more averaging in the power level measurements.

For the row and column phase measurements, the accuracies from one cycle meet requirements. For the TRM measurements, the performance depends on the amount of range multi-looking performed.

The analysis and simulation have shown that all the test and measurement accuracy goals can be met with data from a single cycle of each of the test sequences, and the design of the tests has allowed them to be implemented within the memory space and time constraints.

Finally, the tests have the advantage that they do not have to be performed over one specific geographical location, and they do not require transponders or similar ground infrastructure.