The Radiometric Calibration Budget of RADARSAT-1

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ABSTRACT

This paper reviews the radiometric calibration budget of RADARSAT-1 using a model for the estimation of parameters used to set the calibration. The model involves all of the externally determined quantities used in the calibration together with their statistical variation including: antenna pattern determination, replica energy variation, absolute calibration using reference targets, and spacecraft attitude stability. Results from the modelling are applied to the case of standard beam S3 which may be extended to other beams without losing generality are consistent with previously reported uncertainty estimates.

INTRODUCTION

Since its launch in November 1995, RADARSAT-1 has undergone a number of stages including commissioning, qualification, calibration and maintenance phases. It was declared fully operational on April 1, 1996 and its beams have gradually been calibrated and sometimes recalibrated [1], [2], [3], [4]. During the process of estimating the RADARSAT-1 beam patterns, there is an opportunity [5] to estimate the associated radiometric errors in products generated from the Canadian Data Processing Facilities (CDPF). In this paper, we clarify the procedure and express the assumptions and limitations of that process. The absolute calibration of RADARSAT-1 is implemented in the CDPF as a product of several factors.

$$\beta^o = \frac{\sigma^o}{\sin\theta} \propto P_r \, \frac{G_{CF}^2 \times G_{\mathrm{overall}}}{\mathrm{G}_{\mathrm{ant}}^2} \qquad (1)$$

Here, β^o is the scattering brightness, σ^o is the normalized radar backscattering coefficient, P_r is the received power, G_{CF} is the Gain Correction Factor (GCF), G_{overall} is the overall gain factor determined from pulse replica power, and G_{ant}^2 is the two-way antenna pattern shape as we shall see below. The antenna shapes and the GCFs come to the CDPF through the Payload Parameter File which is updated as necessary to maintain an overall calibration accuracy.

There are four principle sources of error associated with the calibration of any product outlined and described in the subsections below. Briefly, these include antenna pattern shape and mask overlay, pulse replica power determination, external target radar cross section (RCS) and extraction of impulse response measurements from point targets, and overall system gain variation.

In addition, there are factors which relate to processor normalization and we assume that these are well understood and do not play a significant role here. In the next section, we provide a theoretical framework for the main sources of uncertainty and then go on to provide an example of overall uncertainty before drawing some conclusions.

THE APPLICATION OF THE ANTENNA PATTERN

The factor G_{ant}^2 in (1) represents the two-way relative gain of the RADARSAT-1 beam. In the current configuration of the CDPF it is placed over the image swath assuming a nominal geometry for both single beams and for ScanSAR since any attitude changes are unaccounted. Uncertainties associated with the antenna pattern can therefore be attributed to two sources: the shape of the pattern and its placement over the image. More discussion on these aspects are given in the subsections below.

The Shape of the Antenna Pattern

The antenna pattern is determined from a small set (at least 3) of Amazon rainforest measurements [6]. These are combined and contain statistical variations. Some of these are textural in nature, and some due to other causes like drainage fields and atmospheric effects. We assume that although the shape of the pattern may be stable, there may be overall gain variations (either due to the instruments on the satellite or variation in the backscatter of the rainforest) and spacecraft roll variations. These allow us to displace the individual patterns that make up the final shape both in gain and in angle in order to obtain the best overall fit [7].

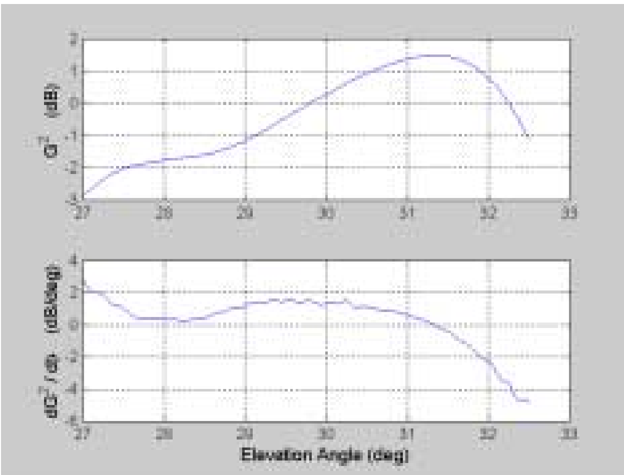

Fig 1: Roll dependence of radiometric calibration from beam S3

The error in estimating the shape itself is found from the spread in the amalgamated and shifted data from the smooth profile fitted through it and is our estimate of the uncertainty in the fitting process itself. We quantify this as $\Delta\beta_{G_{ant}}$ and it is a direct output of the antenna amalgamation software as the standard deviation of the smoothed pattern and the amalgamated data.

The Roll Variation of the Satellite

In the process of determining the amalgamated antenna pattern, the beams are shifted along the angular axis and this is attributed to roll variations in the satellite. One beam is taken as reference and the others are shifted to form the best match. The amount of the horizontal shifting is the estimated roll.

The radiometric uncertainty associated with roll is a function of the size of the roll variation encountered and the shape of the antenna pattern itself through the relation:

$$\Delta\beta^{o}_{roll} \approx -\frac{dG^2_{ant}}{d\vartheta_e}\Delta\vartheta_e \qquad (2)$$

In this equation, $\Delta\beta^{o}_{roll}$ is the change in the apparent normalized radar cross section due to an error $\Delta\vartheta_e$ in the roll angle which couples directly into the beam elevation angle associated with the two-way gain G^2_{ant}. When the antenna pattern is determined in dB, the relation provides uncertainty in dB provided the excursions are small. Fig. 1 shows the beam pattern for beam S3 from payload 16 and the derivative of the two-way pattern below it. In this figure, the effect of a 1^o roll on the radiometric accuracy is shown. Note that the overall variation in each case is about 6 dB. Within the first phase of calibration for RADARSAT, the roll error in the satellite was less than 0.3^o in the worst case. Nevertheless errors from roll uncertainty can be significant. Most transponder data takes will be in the region of the middle of the beam where the slope is approximately 1.5 dB/deg and typical roll variations are about 0.1^o. From this figure, we see that the expected errors from this source will vary from approximately 0.2 dB to –0.4 dB for this beam, presuming that roll variations are approximately 0.1 degrees. In estimating uncertainty from this source, we assume that the uncertainty of the roll is the standard deviation of the roll estimates from the antenna amalgamation process.

THE DETERMINATION OF THE REPLICA POWER

The overall gain, as it is reported in the .PRC (Processing Report Card) files from the CDPF processor [8] is determined from integration over the pulse replica and is reasonably stable. It includes any changes in the transmitted pulse energy and most of the receive path excluding the antenna and the limiter/LNA. Its function is to monitor transmitted power and any attendant receiver gains but because it does not include all parts of the link budget, we prefer to call this source of uncertainty as $\Delta\beta_{rep}$. We determine it as the standard deviation of the replica pulse energy determinations for the scene. It is listed in the standard .PRC analysis done by CCRS as illustrated in Fig. 2. In the CDPF, a single overall gain factor is determined from the average of the replica energies as follows.

$$G^2_{overall} = \frac{10^{6.5}}{< E >} \qquad (3)$$

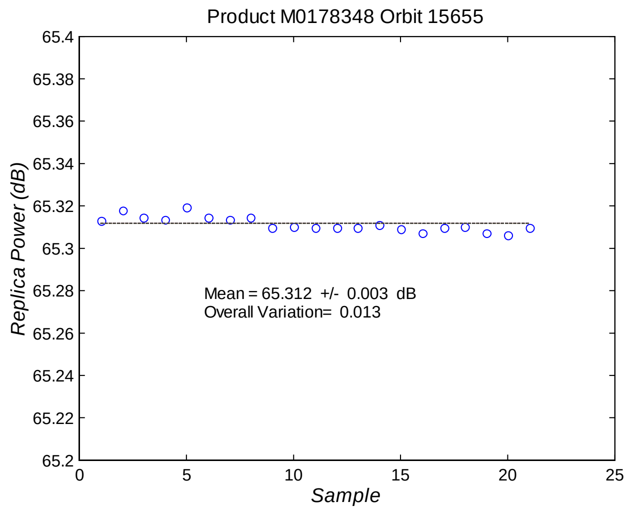

Fig. 2: Pulse replica energy from processing a scene

Here, $< E >$ is the average of the 21 replica energies normally used in the scene. The exponent of 6.5 comes from an early normalization for replica energy and which sets the reference energy as 65 dB.

There are small variations observed in the individual estimates of the replica power used in the processor and reported in the .PRC files. We use the standard deviation of this value for $\Delta\beta_{rep}$.

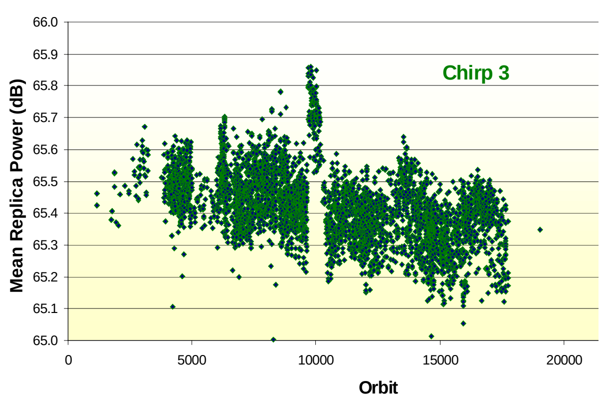

Fig. 3: Evolution of RADARSAT-1 chirp 3 energy

Fig. 3 shows the overall variation from the ensemble of chirp 3 (11.73 MHz) replica means determined since launch. We see that this systematic correction can be as much as 0.6 dB and is therefore an important systematic correction. The jump in the data near orbit 10000 relates to the Antarctic Mapping Mission in which the spacecraft was rotated to look left instead of its normal look-right geometry.

THE ESTIMATE OF THE RCS OF THE EXTERNAL CALIBRATORS

In the method used to determine absolute calibration, precision transponders [9] with known RCS are imaged and used as calibration references. Associated with this process are three related sources of uncertainty: RCS for the precision targets, impulse integrated response, and fitting error in the process of matching the target responses to the antenna pattern.

The manufacturer's specification on this was $\Delta\beta_{RCS}$ =±0.25 dB. It is expected that this estimate is actually low [10]; however, in this report, we shall assume the number is valid.

An important source of uncertainty here is fading between the clutter and the replica of the transponder return characterized by the set of Impulse Response Measurements (IRM). For the products analysed for RADARSAT-1 transponder response, the following relation can be derived [5] for the linear variance of the integrated response, ε_I^2, using the integrated signal-to-clutter ratio computed by the Image Analysis Workstation (IAW), $\left(\frac{S}{C}\right)_{iaw}$.

$$\Delta\beta_{IRM}^{o} = 10\log_{10}(1 \pm \varepsilon_I) \qquad (4)$$

$$\varepsilon_I^2 = \left[\left(\frac{S}{C}\right)_{iaw}^{-2} + 2\left(\frac{S}{C}\right)_{iaw}^{-1}\right] \times \frac{2}{76} \qquad (5)$$

Typically $\left(\frac{S}{C}\right)_{iaw}$ is in the range of 15 to 22 dB and $\Delta\beta_{IRM} \approx .12$ dB.

UNCERTAINTY MATCHING POINT TARGET AND ANTENNA PATTERN

Fig. 4 is an example of the results of a fitting process between the smoothed antenna shape and the integrated response from the precision targets for a set of data for the recalibration of beam S3. The line is the smoothed antenna pattern with its associated shape uncertainty as described above. The error bars are the estimated RCS uncertainties and do not include the contribution of the measurement of the integrated response described by (5) nor the uncertainty in the antenna pattern shape imposed on the measurements (quite apart from our determination of it) nor the uncertainty of the placement of the antenna mask at the acquisition time of the transponder data points; nor the replica power estimate. These factors *all* contribute to the scatter of the points and reflect the overall uncertainty in the region of the transponder measurements. As part of the process, three quantities are determined: the average displacement of the curve and the transponder points, $<d>$; the standard deviation of the displacement mean, $\sigma^{\mu}_{<d>}$; and, the standard deviation of the displacement, $\Delta\beta_{<d>} = \sigma_{<d>}$. The line has been displaced by all processor gains, by the expected backscatter of the Amazon (-6.5 dB) and finally adjusted by a least squares process to make a best fit with the point target results. The value of D represents this final displacement. The points represent the point target results from the five acquisitions over the RADARSAT-1 precision transponders. Their error bars are the nominal spec. on the transponder absolute accuracy of ±0.25 dB.

From the discussion above, we can estimate the contribution from unknown sources associated with the fitting, $\Delta\beta_{<d>}$, by the relation which follows.

$$\Delta\beta^2_{fit} = \Delta\beta^2_{<d>} - \Delta\beta^2_{rep} - \Delta\beta^2_{IRM} - \Delta\beta^2_{RCS} - 2\Delta\beta^2_{G_{ant}} - \Delta\beta^2_{roll} \quad \textbf{(6)}$$

Here, $\Delta\beta_{fit}$ is an unknown gain outside the mechanisms so far discussed. The antenna gain uncertainty (shape) is included twice because it appears both in the shape being fitted and the transponder data because we assume that these are approximately the same size. In the next section, we relate this to a measure of overall gain variation. Here, each of the subtracted components are evaluated in the region of the image near the IRMs. In using this relation, it is assumed that the variations are all smaller than the fitted transponder data. If this is not the case, any gain variations may be assumed to be small.

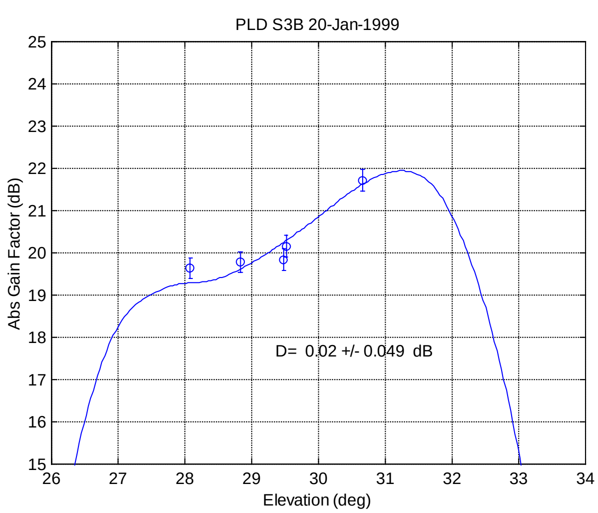

Fig. 4: Absolute recalibration of beam S3

OVERALL SYSTEM GAIN VARIATION.

In evaluating the calibration, there are several stages which the data passes through including the transmitter/receiver chain and the antenna as well as the processor before IAW work is performed. Several factors do however point to the possibility of RADARSAT-1 system gain changes:

- In reviewing the data from the Amazon rainforest [11] it is clear that there is pass to pass variation in the overall gain of the scene which does not appear to affect the shape of the extracted antenna pattern. We have no *a priori* means of telling whether this source of change is due to geophysical phenomena or gain changes in the RADARSAT-1 system.
- In some cases, similar size variations also occur in the precision transponder data that appear to be beyond the manufacturer's specification on uncertainty and again the separation of target and system is not intrinsically possible.

If we assume that both observed variations have the same system gain source and that they are random, there is an additional overall uncertainty in the absolute gain of RADARSAT-1 which can be addressed from the calibration data itself.

$\Delta\beta_{fit}$ Estimation from Precision Transponder Data

In the calibration of RADARSAT-1, we view the precision transponders as the calibration standard and the rainforest as an unknown error source. In this scenario, provided that other known sources of uncertainty are sufficiently small, we can estimate a system gain contribution.

The uncertainty in gain can then be determined from the RMS variation of the transponder integrated response fits taking into account the already included uncertainty: replica power, IRM error, antenna pattern and mask placement, and RCS uncertainties. If we assume these are in turn independent, the component associated with unaccounted overall gain variations can be determined from $\Delta\sigma_{gain} = \Delta\beta_{fit}$ using (6) to obtain $\Delta\beta_{fit}$.

Table 1 is an example of this calculation for the beam S3 recalibration. In this case, the total systematic error before inclusion of the possible gain variation exceeds $\Delta\sigma_{<d>}$. This means that we cannot find any new variation from this data set and there are no unaccounted gain variations observed in RADARSAT-1.

Table 1: Systematic error estimates from point targets

Quantity	**Standard Deviation**		**Variance**
	(dB)	**linear**	**linear**
$\Delta\beta_{rep}$	0.003	0.00	0.0000
$\Delta\beta_{IRM}$	0.12	0.03	0.0007
$\Delta\beta_{RCS}$	0.25	0.06	0.0035
$\Delta\beta_{G_{ant}}$	0.18	0.04	0.0018
$\Delta\beta_{roll}$	0.15	0.04	0.0012
Systematic total	0.39	0.10	0.01
$\Delta\beta_{<d>}$	0.25	0.06	0.0035

A similar analysis [5] carried out using the rainforest as a distributed target source leads to the same conclusion.

AMALGAMATION OF ERRORS

Each of the errors indicated in the preceding sections are statistically independent. In the RADARSAT-1 calibration, it has been traditional to talk about uncertainties in terms of three aspects:

1. The central 80% of the beam where the edges of the elevation pattern are not apparent and the slopes are more gradual.
2. The whole beam including the skirts of the beams.
3. Typical and worst case scenarios.

Returning to (1), we see that the overall uncertainty in calibrating a scene can be found from the relation

$$\Delta\beta_T = \sqrt{\Delta\beta^2_{G_{ant}} + \Delta\beta^2_{<d>} + \Delta\beta^2_{rep} + \Delta\beta^2_{roll}} \qquad (7)$$

Estimates for various error sources are indicated as per the formulae above. These results are compatible with those presented in previous summaries [4] and consistent with the Mission Requirements Document for RADARSAT-1.

Extension to More Global Statistics

The data presented so far are from a particular example for the determination of the beam pattern for beam S3. The extension to the global set of data for RADARSAT-1 will involve bringing in the larger set of data from all beams. This should provide better estimates for such quantities as the attitude variations, replica energies, rainforest variations, *et cetera*. There are no reasons in principle why these could not be jointly evaluated. Where it may not make sense to amalgamate data would be in the error due to antenna pattern roll variation which are highly dependent on the shape of the pattern itself and individual beams for this reason may have more intrinsic variation. In general, however, RADARSAT-1 calibration accuracy has been quoted globally and this would be one way of determining these statistics.

CONCLUSIONS AND RECOMMENDATIONS

In this report, we have discussed the error sources associated with the RADARSAT-1 calibration and have estimated typical and worst case overall calibration accuracy. Example data are given using recent data from the recalibration of beam S3. From these data, we conclude the errors found in the example are in line with previous estimations and appear to be fully accounted for by known systematic errors in both the transponder and rainforest data. It should be noted that all of the analysis is based on the assumption of sea level featureless terrain.

It is recommended that a full set of statistics be assembled for data from all sources to see how this analysis applies globally.

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Table 2: Summary of Uncertainties from S3 Recalibration

Aspect	Typical				Worst Case			
	Central 80%		Whole Image		Central 80%		Whole Image	
	dB	linear	dB	linear	dB	linear	dB	linear
$\Delta\sigma_{G_{ant}}$	0.18	0.04	0.12	0.03	0.54	0.13	0.36	0.09
Roll Variation (deg)	0.07		0.15					
$\Delta\sigma_{roll}$	0.14	0.03	0.60	0.15	0.42	0.10	1.8	0.51
$\Delta\sigma_{rep}$	0.03	0.01	0.05	0.01	0.09	0.02	0.15	0.04
$\Delta\sigma_{<d>}$	0.25	0.06	0.25	0.06	0.747	0.19	0.747	0.19
Total	0.33	0.08	0.65	0.16	0.98	0.25	1.92	0.55
$\Delta\sigma_{RCS}$	0.25	0.06	0.25	0.06	0.75	0.19	0.75	0.19
$\Delta\sigma_{IRM}$	0.12	0.03	0.17	0.04	0.36	0.09	0.516	0.13
$\Delta\sigma_{roll}$	0.07	0.02	0.15	0.04	0.21	0.05	0.45	0.11
$\Delta\sigma_{gain}$ from Transponders	0.00	0.00	0.00	0.00	0	0.00	0	0.00
$\Delta\sigma_{rf}$	0.1	0.02	0.1	0.02	0.3	0.07	0.3	0.07
$\Delta\sigma_{offset}$	0.09	0.02	0.34	0.08	0.27	0.06	1.02	0.26

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