Data Quality Requirements for Future SAR

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Abstract

SAR users have varying data quality requirements. It is their demands, market share, and strategic importance that ultimately dictate many fundamental engineering decisions for the design of the sensor and supporting ground segment. In this paper, we outline some considerations for the overall data quality requirements for future SAR systems, assuming that these missions will include imaging capabilities for applications with polarimetric, interferometric, and more traditional SAR modes that include single channels and/or single and multiple beams. Specifically, we draw from our experience with a number of existing SARs including ERS-1, ERS-2, J-ERS-1, and RADARSAT-1 to explore basic data quality issues that affect the geometric, radiometric, and interferometric (or phase) fidelity of products, and ultimately the reliability of the information products generated from them. These observations have implications on the design of satellite and ground segment components for future SARs such as ENVISAT and RADARSAT-2.

Introduction

Data quality from Synthetic Aperture Radar (SAR) has been described in terms of an information cube [1] whose dimensions cover radiometric, geometric, and interferometric (phase) properties of the imagery created from the SAR system.

Translating image quality requirements into system performance specification is a challenge from many perspectives: first, the real data quality drivers are often not known by the user community until after the system has taken shape and is actively delivering data; second, users and system engineers do not speak the same language; and, third, data quality parameters are often coupled and involve conflicting tradeoffs.

In addition to concerns over radiometry, geometry, and phase properties of the data, other issues are important to the viability of a program, particularly when they have commercial foundations such as Canada's RADARSAT series of SARs. Consider the process of data ordering and delivery. Here, a widely varying range of possibilities presents themselves. In exchange for near-real-time delivery of products, many users are prepared to receive products with reduced quality specifications. Other users may only want to work with the highest quality data and will accept a delivery delay to achieve this. The implications for the overall system, including the sensor, data reception, processing, and delivery network are, therefore, completely coupled.

The advent of satellite repeat-pass interferometry [2] as an exciting new use of spaceborne SAR data has brought forward new issues relating to orbit maintenance, knowledge, repeatability, and revisit interval.

In this paper, we outline the overall data quality requirements for future SAR systems under the assumption that these missions will include imaging capabilities for applications with polarimetric, interferometric, as well as more traditional SAR modes that include single channels and/or single and multiple beams. We draw from our experience with a number of existing SARs including ERS-1, ERS-2, J-ERS-1, and RADARSAT-1 to explore basic data quality issues and the reliability of the information products generated from them.

Interpretation and Image Quality

Although data interpretation depends on the product of spatial and radiometric resolution [3], we will first consider these aspects independently and later attempt to bring them together in the discussion. Consider

$$I \propto \rho_a \times \rho_s \times \rho_r$$

Here I is interpretability, and ρ_a, ρ_s, ρ_r are, respectively, the azimuth, range, and radiometric resolutions.

The first level of image quality (IQ) review is to examine the image data for visual artifacts. Users can notice systematic radiometric discontinuities as small

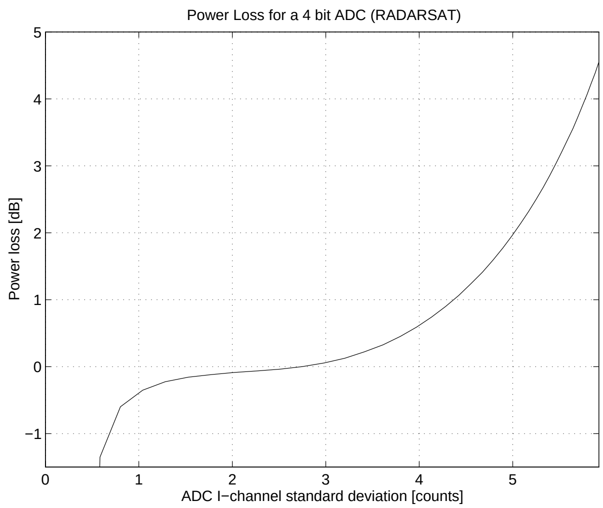

Figure 1. Power Loss Correction for RADARSAT-1's 4-bit ADC. The power loss has been calculated as a function of the corresponding RAW data I-channel variance.

as 0.3 dB relative to the average grey level of a SAR image.

Single Beam Images

Single beam imagery, despite a high percentage of relatively flawless data, sometimes exhibits serious IQ issues that include the following:

1. **Nadir ambiguities** - These are predictable lines of bright return running in azimuth that arise from the simultaneous arrival of returns from sidelobes directly below the spacecraft and from the desired swath but several pulses later. Only a few RADARSAT-1 beams are susceptible and the effect is dependent on the nature of the target in the nadir region.

2. **Saturation** - SAR data has a large dynamic range, even in its RAW form. Thus, the ADC (Analogue to Digital Converter) must be able to handle a wide range of data amplitudes. In RADARSAT-1, the use of an AGC (Automatic Gain Control) and 4-bit quantization mitigated the spatially varying nature of the target backscatter. Rapid changes in scene content or intermittent changes as are present in many coastal scenes, for instance, could not be handled adequately by this implementation. With ERS (with no AGC) and RADARSAT-1, post acquisition corrections were implemented that can improve this problem, but full compensation in a complex scene remains an issue. Fig. 1 shows the scale of this correction [4] for RADARSAT-1's 4-bit ADC.

ScanSAR Images

Although other systems have created ScanSAR imagery on an experimental basis, we focus here on RADARSAT-1. Current IQ issues for RADARSAT-1 ScanSAR include:

1. **Nadir ambiguities** - See the comments above in relation to single beams. These are particularly important in the case of ambiguities that occur near beam boundaries. Processing algorithms that use the overlap region present an interesting challenge when this occurs.

2. **Scalloping** - This is mainly a Doppler centroid estimation issue. The sensitivity [5] of IQ to Doppler processing accuracy is much higher in ScanSAR than in single beams because of the partial azimuth exposure required to allow wider swath coverage.

3. **Absolute and relative radiometric fidelity** - Because of the complexity of combining several elevation beams and the inherent processing issues, it appears that the image quality cannot be sustained to the same fidelity with ScanSAR and thus the error bars are wider.

4. **Beam boundaries** - ScanSAR operation uses several overlapping beam patterns at their edges where they are not particularly well known. Furthermore, knowledge of the satellite roll angle is critical [6] but is also not well known for RADARSAT-1.

Form of Data Product

An expectation of many new users of imaging SARs is that the products will be displayed as orthoimagery, that is, as though every pixel were imaged from a sensor looking straight down and therefore lacking any radiometric or geometric distortions. In terms of SAR, this means a geocoded or georeferenced product that is radiometrically flat across the image. For most single beam products, this means a ground range image presented in terms of β^o, σ^o, or γ^o [7]. For ScanSAR products, the wider angular range means that most distributed targets will have a significant radiometric "droop" with range, and that a range-dependent correction must be applied to obtain a pleasing and radiometrically flat displayed image.

This is a processor issue and in the RADARSAT-1 system this has been resolved by providing a set of 6 user-selected output look-up tables (LUTs): Land,

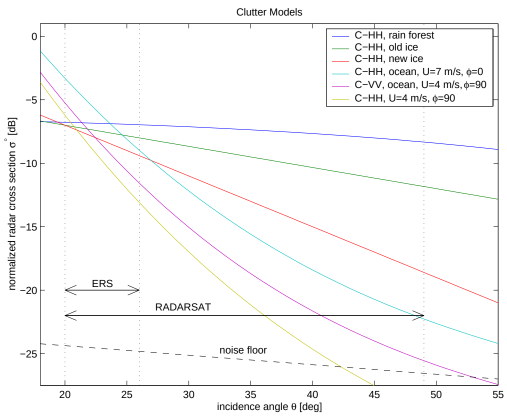

Figure 2. Illustration of the wide dynamic range of SAR imagery. In this case, we have used data from RADARSAT-1, C-HH polarization for a series of distributed targets. Point like targets will extend this range considerably.

Ocean, Ice, Mixed, Unity, and Calibration. Less obvious to the user is the advantage in use of the available dynamic range, which is a particular issue for ScanSAR with its 8-bit image products.

Appreciation for the up to 70 dB of dynamic range that might be present in a compressed SAR image is a continuing IQ issue, even if there are no saturation/underflow problems in the raw data prior to compression. The range dependence of ocean clutter, which varies dramatically with wind speed and direction, as shown in Fig. 2, means that unless a large number of bits are used for data storage, the available dynamic range of the output product will often be exceeded. Similarly, topography can introduce significant image variability that can exceed the available dynamic range.

Aside from predefined output LUTs, there are other strategies that can avoid these dynamic range problems. These include the use of a dynamic LUT (*i.e.* derived from the image data itself), and the use floating point numbers in the output products. Both of these strategies have implications on processor design as well as image product size.

Having accepted the idea that users want calibrated products and radiometrically flat images, it is clear that there must be a means to transform between these two classes of product. In the case of ERS and J-ERS, users were provided with one simple scaling factor often referred to as K, the calibration constant. In the RADARSAT-1 case, a much more complex transformation was required [8], partly because of the method used to store calibration information on the product and partly because the process is intrinsically more difficult since the application LUTs were invoked. The result of this was that only expert users could actually get to the calibrated data. A suggestion is that data suppliers provide freeware with their products to bridge this gap. For new initiates, understanding the value of SAR data to their application is challenging enough without the added frustration of data formats and data transformations.

Geometry

The term *geometry* here encompasses both the angular concepts relating illumination direction and local relief slope, and the concept of location knowledge, consistency, and accuracy.

Users of airborne SAR have long been aware of the wide changes in geometry that can occur in SAR images where incidence angles can vary in the same scene over almost 90º. The situation for spaceborne SAR in polar orbits is less spectacular; however, there can be significant angular variation across ScanSAR images and for the extended low beams of RADARSAT-1. These systematic variations mean that quantitative interpretation of the data can only be made when proper account of the geometry is taken.

The radiometric and geometric sensitivity to distortions by terrain relief also depends on viewing geometry. Fig. 3 illustrates the geometric distortion induced by relief for beam RADARSAT-1 beam S4. The effects are smaller for the beams with higher incidence angles.

In general, the smooth earth model that is used by most production SAR processors can yield data with significant radiometric and geometric distortions, requiring significant additional processing effort, as well as access to appropriate data correction algorithms. Fig. 3 shows an example from Baffin Island where relief features play significant roles not only in the geometry of the scene, but also in the radiometry and interpretation. The corresponding height image is given in Fig. 4.

Interferometry

A growing community of SAR users has demonstrated a high interest in interferometric SAR applications. In general, these fall into two groups:

1. Those who use phase related properties to characterize properties of the scene. Examples are scene coherence and speckle correlation techniques.

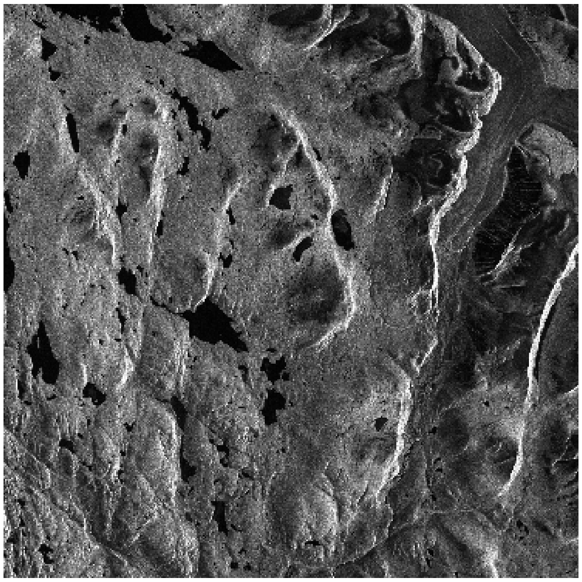

Figure 3. Example RADARSAT-1 image dominated by relief and slope induced artifacts. In this image, foreshortening of the facing slopes introduces a large geometric distortion. Related brightness modulation is also a strong feature. The ice streams in the upper right corner are glacial in nature and come from the Penny Ice cap.

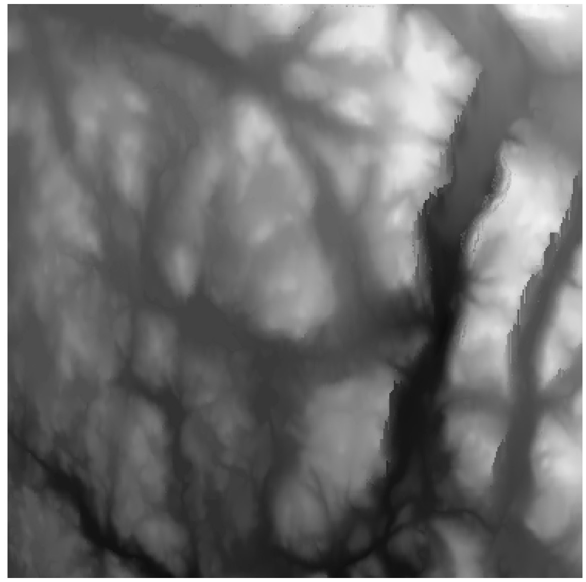

Figure 4. DEM corresponding to the image of Fig. 3. Geometric distortions in the image result from the combination of view direction and the local slope.

2. Those who use relative phase information to derive interferograms from which target height (across-track interferometry) or radial velocity (along-track interferometry) can be derived.

Pass to Pass Interferometry

In the 1970's the idea of a dual antenna interferometric SAR system was implemented and tested for the first time [9]. It became clear that this approach had great promise for DEM generation and that the technology, if implemented on future spaceborne systems, would have superior characteristics for wide-area mapping. In the 1980's Goldstein and Zebker [10] introduced the concept of using a repeated SAR acquisition to create a SAR interferogram. This allowed generation of DEMs and deformation maps using existing single antenna spaceborne SAR systems. Research and application development of this technology increased, in particular in Europe in the early 90's with the launch of ERS-1. A dedicated tandem mission of ERS-1 and the newly launched ERS-2 was executed in 1995 and 1996. It created a valuable worldwide database of data with potential for DEM generation.

ERS-1 and ERS-1/2 tandem mode were the first missions to allow routine repeat-pass interferometric measurements by satellite. The between pass coherence used to allow information extraction depends on the stability of the scattering cells (scene coherence) themselves and on the relative position (path coherence) of the satellite between the passes. In addition, there are other complicating issues related to the propagation path that come into play [11]; specifically, the stability of the local oscillator, and the system timing.

Orbit Determination and Maintenance

A basic issue for those seeking to do multiple pass interferometry is path coherence. This means that orbit knowledge and maintenance play a significant role in the exploitation of this mode. With ERS, high performance had to be achieved in both aspects since the platform carried an altimeter [12], allowing users to quickly assess the potential of the interferometric pairs and utilize the data.

In the case of RADARSAT-1, the requirements for orbit maintenance and knowledge were never intended to support this mode, but nevertheless, pass to pass interferometry has proven to be an important application of the system [13]. The utility of the data could be improved considerably if the orbit were maintained to a tighter specification.

Polarimetry

The first spaceborne SAR imagery taken in a fully polarimetric mode was from the Shuttle Imaging Radar

(SIR-C) mission. These data generated wide interest in the literature [14].

Simple geometric models were shown to provide insight to scattering mechanisms. In particular, man-made targets could be characterized by their polarization signatures, and natural targets could be discriminated as functions of the backscattering mechanisms [15].

To exploit the fully polarimetric potential of the data, pure channel polarizations (HH, HV, VH, and VV) must be extracted from the 4 distorted measurements made by the instrument [16, 17, 18]. Uncalibrated data which do not remove interchannel mixing to account for systematic phase and amplitude corrections, cannot provide any meaningful polarimetric information. The SIR-C team was careful to include a comprehensive calibration scheme to assure that the data were validated and available quickly after the mission.

The requirements identified by the JPL team[1] were for a residual like-channel imbalance which was less than 0.8 dB, with a relative phase error less than 10º, and a residual cross-talk error which was no worse than 30 dB [19]. These goals were reached in almost all cases. The high isolation of SIR-C's H and V antennas (better than 30 dB) made the calibration easier than that required for the JPL AIRSAR data. The latter system has poorer isolation (about 23 dB for AIRSAR, which is about the same as the proposed isolation of RADARSAT 2). AIRSAR calibration required the use of a uniform extended target with azimuthal symmetry along the whole swath for the removal of the cross-talk terms that vary with incidence angles. Data collected over areas with significant topographic relief could only be calibrated if a DEM was available.

If the global antenna isolation of RADARSAT 2 is worse than 30 dB, cross talk calibration might be performed using distributed targets such as the Amazon Rainforest. This approach inherently assumes that the system is stable, at least within the same orbit.

Product Delivery and Form

Each of ERS, J-ERS, and RADARSAT-1 provided primary product delivery in a format family known as CEOS [20]. This general format family allowed each sensor to be coded in a similar but sufficiently different format that special software code was required to read the product from each sensor and even from each ground station. Despite the arduous task of devising format specification, ambiguities existed in parameter definitions and their subsequent recovery. The user community has never accessed many of the fields contained in the format and large volumes were required to clearly define their use.

The next generation of satellites will likely move away from the CEOS standards and work with a new generation of product formats. It is strongly suggested that data providers also provide freeware data readers and code with functionality to deliver all of the needed parameters to describe the radiometric corrections, assumed geometry, location, orbit *etc.* Without these tools, interpretation and use are even more difficult.

Discussion and Conclusions

The above notes indicate that IQ for SAR will remain an exciting and productive activity for research and development and will lie at the core of successful applications development as we move towards automated data analysis. It is in the interest of providers to characterize their products and to monitor, maintain, and improve image quality throughout the mission lifecycle. For RADARSAT-1, IQ goals were laid out in the Mission Requirements Document [21]; however, in most instances these requirements were exceeded [22] substantially and a *de facto* performance standard was adopted. We would encourage such forward thinking since it fosters more data usage and supports a broader range of data applications.

Although polarimetric SAR has been used briefly in the SIR-C context, new challenges will face the providers of RADARSAT-2 and ENVISAT data. The calibration issues and education of users will require tools and demonstration applications that can promote acceptance and use of this new data type. Freeware with self-defining products will assist in this process, as will the availability of polarimetry modules for commercial image analysis systems.

Many users expect to use satellite imagery directly in GIS environments. Without incorporation of a DEM in the processing, many applications will be compromised in terms of their geometric and radiometric fidelity. Devising products, which incorporate these corrections implicitly, is a challenge for the next generation of processors and data providers.

Image quality in all its nuances needs to be considered as an end-to-end property that guides the SAR design from start to finish.

[1] Such requirements need validation for some applications.

References

1 Raney, RK (1998), "Radar Fundamentals: Technical Perspective", Chapter 2 in *Manual of Remote Sensing*, 3rd edition, Vol. 2, John Wiley and Sons, Inc., New York, pp 9-130.

2 Vachon, PW, D Geudtner, K Mattar, AL Gray, M Brugman, and I Cumming (1996), "Differential SAR Interferometry Measurements of Athabasca and Saskatchewan Glacier Flow Rate", *CJRS*, Vol. 22, No. 3, pp 287-296.

3 Ulaby, FT, RK Moore, and AK Fung (1981), "Microwave Remote Sensing, Active and Passive", 3 Volumes, Addison-Wesley Publishing Company, Reading, MA.

4 Vachon, PW, AL Gray, CE Livingstone, and AP Luscombe (1997), "Adaptive compensation of RADARSAT SAR analogue-to-digital converter saturation power loss", *Proc. Geomatics in the ERA of RADARSAT (GER'97)*, CD-ROM Proceedings, 27-30 May 1997, Ottawa, Ont., Canada.

5 Cumming, I, F Wong, and RK Hawkins (1999), "RADARSAT Doppler centroid estimation using phase-based estimators", to appear, *Proc. CEOS SAR Calibration Workshop*, Toulouse, France, 26-29 October 1999, 7p.

6 Hawkins, RK, (1997), "ScanSAR: where the rubber hits the road", *Proc. CEOS Workshop*, Canadian Space Agency, St Hubert.

7 Raney, RK, A Freeman, RK Hawkins, and R Bamler (1994), "A Plea for Radar Brightness", *Proc. IGARSS'94*, Pasadena, 8-12 Aug. 1994, pp 1090-1092.

8 Altrix Systems (1997), "Extraction of Beta Nought and Sigma Nought from RADARSAT CDPF Products", AS97-5001, also in *Proc. CEOS Workshop*, February, St Hubert, 1997. An update is available from: http://radarsat.space.gc.ca/, see the Application Development and Research Opportunity Program (ADRO) Tools: Tn5001r2.doc.

9 Graham, LC, (1974), "Synthetic interferometer radar for topographic mapping", *Proc. IEEE*, Vol. 62, pp 763-768.

10 Zebker, HA, and RM Goldstein (1988), "Topographic mapping from interferometric synthetic aperture radar observations", *Radio Sci.,* Vol. 23, No. 4, pp 713-720.

11 Mattar, KE, AL Gray, D Geudtner, and PW Vachon (1999), "Interferometry for DEM and Terrain Displacement: Effects of Inhomogeneous Propagation", *CJRS*, Vol. 25, No. 1, pp. 60-69.

12 Zandbergen, R, JM Dow, MR Merino, R Piriz, and FM Fadrique (1996), "ERS-1 and ERS-2 Tandem Mission: Orbit Determination, Prediction, and Maintenance", 31st COSPAR Scientific Assembly, Birmingham, 17-18 July 1996.

13 Joughin, I, AL Gray, *et al.* (1999), "Tributaries of West Antarctic ice streams revealed by RADARSAT", *Science*, Vol. 286, No. 5438, pp 283-285.

14 SIR-C/X-SAR Science Team (1995), "Special issue on SIR-C", *IEEE TGRS*, Vol. 33, No. 4.

15 Boerner, WM, *et al.* (1998), "Polarimetry in radar remote sensing: Basic and applied concepts", Chapter 5 in Manual of Remote Sensing, 3rd edition, Vol. 2, John Wiley and Sons, Inc., New York, pp 271-357.

16 Van Zyl, JJ, (1990), "A technique to calibrate polarimetric radar images using only image parameters and trihedral corner reflectors", *IEEE TGRS*, Vol. 28, No. 3, pp 337-348.

17 Freeman, A, (1990), "Polarimetric SAR calibration experiment using active radar calibrators", *IEEE TGRS*, Vol. 28, No. 2, pp 224-240.

18 Touzi, R, CE Livingstone, JRC Lafontaine, and TI Lukowski (1993), "Consideration of antenna gain and phase patterns for calibration of polarimetric SAR data", *IEEE TGRS*, Vol. 31, No. 6, pp 1132-1145.

19 Freeman, A, *et al*. (1995), "SIR-C data quality and calibration results", *IEEE TGRS*, Vol. 33, No. 4, pp 848-857.

20 See for instance: MDA (1994), "RADARSAT CDPF Product Specification", MDA document, RZ-SP-50-5313.

21 Canadian Space Agency (1991), "RADARSAT Mission Requirements Document", RS-CSA-SP0001-NC.

22 Srivastava, S, RK Hawkins, B Banik, M Adamovic, K Murnaghan, TI Lukowski, and W Jefferies (1999), "RADARSAT-1 image quality - Update", to appear, *Proc. CEOS SAR Calibration Workshop*, Toulouse, France, 26-29 October 1999, 4p.