Quality Analysis of SAR Image

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Abstract: Synthetic Aperture Radar(SAR) is an active microwave instrument that performs high-resolution observation under almost all weather condition. Research and algorithms have been proposed to process radar signal and to increase the quality of SAR products. In fact, many complicated steps are involved in order to generate a SAR image product. The purpose of this paper is to derive quality assessment procedures and define important test parameters in each procedure inside a SAR processor. Thus those test parameter values indicate the quality of SAR image products and verify the processor's performance. Moreover, required procedures to correct and handle errors which are indicated during the assessment are also presented.
Keywords: SAR, Quality assessment procedures, Quality test parameters

1. Introduction

SAR systems take advantage of the long-range propagation characteristics of radar signals and the complex information processing capability of modern digital electronics to provide high-resolution imagery. Synthetic aperture radar complements photographic and other optical imaging capabilities because of the minimum constraints on time-of-day and atmospheric conditions and because of the unique responses of terrain and cultural targets to radar frequencies. Synthetic aperture radar technology is applied in many applications. It provides terrain structural information to geologists for mineral exploration, oil spill boundaries on water to environmentalists, sea state and ice hazard maps to navigators, and reconnaissance and targeting information to military operations.

SAR is a coherent radar system that generates high-resolution remote sensing imagery. Signal processing uses magnitude and phase of the received signals over successive pulses from elements of a synthetic aperture to create an image. A detailed description of the theory of operation of SAR is complex and beyond the scope of this paper. Other good explanation can be found in references[1]. Instead, this research is focused on the quality assessment procedures and test parameters which are required to verify on the quality of radar images. Our research lab has been developing a SAR processor including receiving system which is a form a part of *the National Research Laboratory (NRL) for satellite image receiving and processing* system. Certainly, assessment procedures should be defined to verify the SAR processor and its products. However, there is little comparative research and guidance showing the assessment procedures and test parameters for the SAR processor. In this paper, we define several important quality assessment procedures and their test parameters in each processing step. Quality assessment models for the SAR products and their parameters will be presented in section 2. Conclusion and future works are followed in section 3.

2. Quality Analysis Procedures

In general, SAR processor includes several complicated processing steps. It starts from onboard processing in a satellite and then digitizer in which complex signal is transformed into in-phase (I) and quadrature (Q) components. Then, several steps - range compression, range migration correction, and azimuth compression - are followed in the ground station to convert the raw signal into a single-look complex (SLC) image. By averaging over azimuth resolution cells, a multi-look image is generated. Thus, it is also necessary that the quality assessment procedures are followed by each processing steps in the SAR processor. Fig 1 shows the proposed quality assessments procedures in the SAR processor.

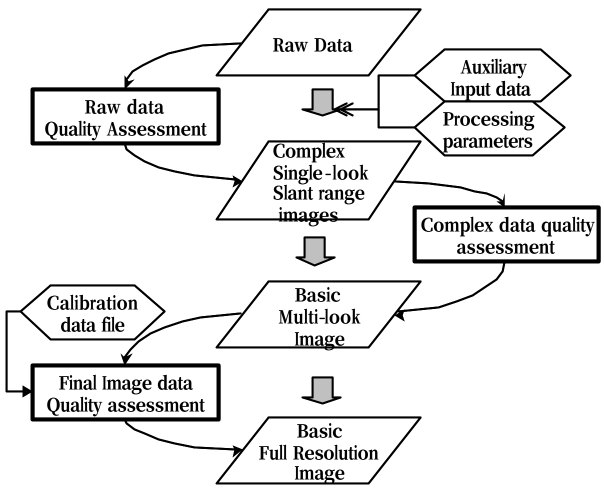

Fig. 1. The required quality assessment procedures in the SAR processor.

1) Raw data quality assessment parameters

The first quality assessment on raw signals is a well-defined and automatic procedure, and it is based on the statistical evaluations. During the assessment steps, the following test parameters are monitored to verify the quality of raw signals.

1. The number of missing and duplicated range lines
2. The I and Q channel arithmetic means and standard deviations.
3. The cross-correlation coefficients between the I and Q

4. The I and Q channel saturation levels
5. The I and Q channel normality factors
6. The I and Q channel levels with high occupancy and the associated occupancy levels
7. The phase uniformity factor
8. The number of spurious frequency terms

Because the parameters 1, 2 can be simply calculated and the application of the corresponding correction is straightforward, the detailed explanation will be skipped. The cross-correlation coefficient, ρ_{IQ}, between the I and Q channels gives the value of phase error, Φ.

$$\rho_{IQ} = \sin \Phi$$

If the cross-correlation coefficient between I and Q values of n complex samples taken from a single range line is defined by ρ_j, then an overall coefficient ρ_{IQ} is obtained by transforming ρ_j

$$Z_j = 1/2 \ln [(1+\rho_j)/(1-\rho_j)]$$

and evaluated in the follow 3 steps,

$$\rho_{IQ} = \tanh (\mu_z)$$

$$\rho_{IQ} + \sigma = \tanh (\mu_z + \sigma_z)$$

$$\rho_{IQ} - \sigma = \tanh (\mu_z - \sigma_z)$$

where μ_z, σ_z are respectively the mean and standard deviation of the Z_j values, evaluated over n range line. Because I and Q channel should be orthogonal, the ρ_{IQ} is 0. Non-orthogonality between channels is caused by the introduction of a constant phase error during I and Q generation. Usually, correction is applied on Q channel only, so that

$$\textit{corrected}\ Q_{ij} = Q_{ij}/\cos \Phi - \tan \Phi$$

Saturation parameters are defined in both channel. $S(I)_t$ or $S(Q)_t$ is the percentage of samples occupying the highest quantisation level and $S(I)_b$ or $S(Q)_b$ is the percentage of samples occupying the lowest quantisation level of I and Q, respectively. It is recommended that S_t and S_b in both channels will be less than 0.5 percentages[3]. If the raw signal fails in this criterion, the data need to be discarded for processing. The other parameters 5 ~ 7 are related to statistical distribution functions to show how the received raw signals in I and Q channels are well distributed overall. The pre-defined statistical threshold values are used to evaluate the test parameters. However, errors in these parameters might be scene-dependent, rather than system-dependent.

The phase uniformity factor is given by

$$U_\theta = X^2{}_\theta / X^2\ 0.05$$

where $X^2{}_\theta$ is the value of chi-square statistic obtained for a fit to the data of a uniform phase distribution and X^2 0.05 is the chi-square value corresponding to the fit being accepted at the five percent level of significance. The value of U_θ is expected less than 1. Error in this value implies failure of the multiplicative speckle noise model and will cause potential quality problems on SAR image products later. Finally, the spurious frequency terms are unwanted spikes in range spectra. It might be caused by interference attributable to the on-board or ground equipment. A correction is simply implemented by a notched filter of appropriate depths and frequencies in the frequency domain.

Based on the above measurements, the raw data correction should be applied sequentially: a I/Q bias removal in one of the channels, power balance in one of the channels (I/Q gain imbalance correction), and phase correction in Q channel.

2) Complex image data assessment parameters

After the first step, received signal is focused in order to generate a single-look complex image product. In a long aperture, the lines-of-sight from a particular point on the ground to each individual element of the array differ in distance. These range differences, or path length differences, of the radar signals can affect image quality. In a focused SAR image these phase errors can be compensated by applying a phase correction to the return signal at each synthetic aperture element. Focusing errors may be introduced by unknown or uncorrected platform motion.

The quality assessment of complex image data involves quality measures performed on the detected coherent correlation function (CCF) and the signal phase distribution. The detected CCF can be used to detect amplitude errors, but not phase errors. Thus, the CCF is used in conjunction with the IRF to verify the spatial characteristics of the complex data. The following test parameters need to be derived [3].

1. The detected CCF resolution width
2. The detected CCF peak sidelobe ratio
3. The detected CCF integrated sidelobe ratio
4. The phase uniformity factor within one or more uniform regions

In order to derive the detected CCF, FFT and square-law detect is applied to obtain power spectrum, and finally, inverse FFT is performed to obtain square-law detect in the time domain. Test parameters 1 ~ 3 are related with the spatial characteristic of the data via measurements performed on the detected CCF, while parameter 4 tests the distribution of the phase. However, the parameters, 2 and 3 related to sidelobe ratio require certain calibrated targets in the case of conjunction with IRF because the expected values of the various detected CCF test parameters can be calculated by deriving the detected CCF corresponding to the ideal IRF. In addition, the range and azimuth coefficients of the detected CCF may be indicative of possible over or under-sampling of the data. Over-sampling can be corrected by appropriate resampling, while under-sampling of complex data less than the Nyquist rate cannot be corrected.

The phase uniformity factor must be measured in regions in the complex image which have been identified as uniform by uniformity test. For the uniformity test, the 2-dimensional detected CCF is derived for different, totally exclusive areas in the final detected image, the areas being selected at random from the complex image data. Each of the selected regions is square-law detected and the 2-d intensity correlation function (ICF) is derived. The residue, a difference between ICF and CCF, is calculated by the following equation,

$$\text{Residual} = \text{ICF} - 1 - |\text{CCF}|^2$$

where ICF is also derived by square-law detect of the complex data in frequency domain and a time domain. If the residue is smaller than a defined threshold, the area is accepted as uniform. The computation of phase uniformity factor is same as the number 8 in the raw data assessment parameters. Comparison of the complex data phase uniformity factor, derived from one or more uniform regions, with the raw data values can reveal whether any phase errors have been introduced by the focus processing. If the raw data satisfy this parameter requirement but the complex data fail to do so, errors introduced during processing are indicated. The causes of these errors need to be investigated by processing simulated distributed target data.

3) Final image data assessment parameters

The quality assessment of final image products consists primarily of a number of quality tests performed on the impulse response function (IRF) [2][3]. In addition, a small number of images are also used to determine the radiometric stability and accuracy and the localization accuracy of the SAR system.

1. The range and azimuth spatial resolutions
2. The range and azimuth IRF peak sidelobe ratios
3. The range and azimuth IRF integrated sidelobe ratios
4. The range and azimuth ambiguity ratios
5. The radiometric stability, accuracy
6. The range and azimuth localization accuracies

Calibrated point targets are required to estimate the above parameters. However, calibrated point targets are very expensive in measuring and keeping practically and periodically. For an alternative measurement, instead of calibrated targets, bright point targets-of-opportunity can be used in some cases. Visual inspection could be used to locate possible point targets which would be subjected to a validation test. Moreover, bright point targets can be measured automatically by using intensity threshold and segmentation techniques. The parameters 2~ 5, related to IRF, ambiguity and radiometric properties should be estimated with the well-measured calibration targets only. The spatial resolution and location accuracies can be estimated with the bright point targets-of-opportunity. In the case of location accuracies the ground (location) truth of the targets-of-opportunities are also required. In general, calibration targets are required to perform the accurate measurements needed to verify the performance of the SAR system, while target-of-opportunity can be used to verify the quality of individual images. Because the detailed measurement methods of test parameters are straightforward, explanations are skipped in this section, but we emphasize on the causes of failure and the required correction steps, instead.

Failure of the test parameters to satisfy the defined requirement can be caused by (1) phase errors, which cause mismatches in the SAR processing, leading to defocusing of the IRF, i.e. a spread of energy away from the peak of the IRF into the sidelobe region, and (2) amplitude errors, which tend to increase/decrease the effect of Hamming weighting function used in azimuth compression. In detail, possible causes of those errors in the range processing view are (i) amplitude and/or phase errors on the transmitted chirp, (ii) use of the wrong chirp replica in the processing, (iii) an incorrect range cell migration correction (RCMC), (iv) range imbalance or non-orthogonality between I and Q channels prior to range compression. In the azimuth view, possible causes are (i) use of an incorrect weighting function in processing, (ii) a mismatch between the Doppler frequency slope (Doppler FM rate) of the signal and that of the reference function used in processing, (iii) incorrect RCMC. In order to correct listed errors, the following actions can be applied: (1) examination of the chirp replica and comparison between the chirp replica autocorrelation function and the 1-d range CCF, derived from the raw data prior to azimuth compression, to determine whether the chirp used in processing was in fact matched in the signal data, (2) processing simulated point target data which will reveal whether an incorrect function or an incorrect RCMC has been used in the processing, (3) examination of the algorithm applied for autofocussing to correct errors in the Doppler FM rate.

In addition, one of the considerations that affects the image quality is signal noise that is unwanted or contaminating signal competing with the desired signal. The relative amount of additive noise is described by the signal-to-noise ratio (SNR). Signal dependent noises, such as azimuth ambiguities or quantization noise, arise from system imperfections.

3. Conclusion

Conclusively, this research proposed the quality assessment procedures and their test parameters which can be used to validate the SAR processor and it's products. Even though some of the test parameters require calibrated targets to estimate values, others can be implemented systematically in the processor systems. Depending on the parameter's characteristics the assessment procedures can be applied to the each SAR image product periodically or at all times. Currently, the defined procedures are partially implemented on the developed SAR processor. The evaluation of the developed SAR processor based on the assessment parameter values should be followed.

References

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