SYNTHETIC APERTURE RADAR IMAGE QUALITY AND MEASUREMENT

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Abstract

The Remote Sensing Group at Marconi Research Centre (MRC), GEC Research Laboratories, is performing various studies for the European Space Agency (ESA) related to performance and image quality for Synthetic Aperture Radar (SAR), in particular the system proposed for the ESA Remote-sensing Satellite, ERS-1. ESA have described the required image in terms of a set of image quality specifications which includes standard measures such as spatial resolution and radiometric accuracy, as well as some specially defined measures such as 'energy distribution' and 'image contrast'. MRC has developed methods for analysing performance in terms of these measures, including analysis of the effects from phase and amplitude errors and of such features as range and azimuth ambiguities, as part of the ERS-1 Phase B Study.

This theoretical analysis is complemented by two studies undertaken for ESRIN which are concerned with evaluation of images and processor performance. The first of these studies was for development of algorithms designed to extract measures of performance from real images. The second is a review of current SAR simulation programs and processor test procedures and a consideration of any additional tools needed for the ERS-1 project.

The performance measurements which can be made are not precisely those covered by the ESA specifications and a consistent approach must be found to enable the performance of the system to be verified in operation.

Introduction

The Remote Sensing Group at the Marconi Research Centre has undertaken several studies for the European Space Agency in the general area of SAR performance and image quality. These studies approach the subject from different directions and analyse performance of different parts of the complete SAR system. The three aspects discussed below in more detail are:

i) Theoretical analysis. Development of methods for analysing performance in terms of the measures defined in the ESA SAR image specification.

ii) Image assessment. Development of algorithms to make measurements of performance from general images; either real images from other systems or simulations for the ERS-1 system.

iii) SAR simulation. Review of available SAR simulation tools and processor test procedures. Specification of additional data sets needed to test processors fully.

All three were conducted as part of the programme of studies leading up to the ERS-1 satellite launch in 1988, but are applicable to other SAR systems. At present the image measures used by groups working in the three areas are not the same, although in many cases they are closely related : for example, some image quality specifications refer to target types which are not encountered in practice and which may not be easy to simulate. Some rationalisation of the performance measures is needed if the theoretical analysis is to be related to the final image products and, in particular, if the complete SAR system performance is to be verified when operational.

1. Theoretical Image Quality Analysis

The image requirement for the ERS-1 SAR system is given in terms of a set of image specifications as, for example, in Table 1 taken from the System and Satellite Requirements document [1]. Some of the parameters in this table are standard measures, whilst some have been devised and defined specifically for this mission.

An outline of some of these measures and the methods developed for theoretical analysis are given below [2].

a. Spatial resolution. Distance between points in the impulse response function 3dB below the peak. Analysis takes into account the effects of weighting functions, phase and amplitude errors, misregistration between looks.

b. Radiometric resolution. Defined as the difference in power between the mean level in the image distribution for an area of distributed target and a level one standard deviation above. This definition leads to a formula in which radiometric resolution is a function of minimum signal-to-noise ratio and number of independent looks.

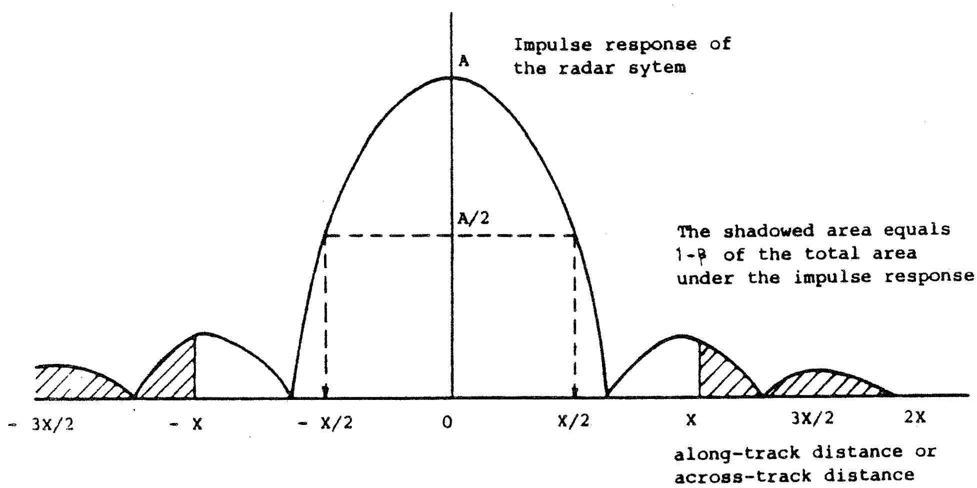
c. Energy distribution. Defined as the percentage of the total energy from a point target which falls in the central square of side 2X of the response function, where X is the nominal spatial resolution. Analysis takes into account the same factors as a above. (Figure 1).

d. Image contrast. The average level in the central 4X square of an image of a square area of side 5X of zero reflectivity surrounded by an infinite area of uniform distributed target. This measure is given as a level relative to the image of the surrounding area and takes into account such effects as range and azimuth ambiguities, spread of energy in the response function, phase and amplitude errors. (Figure 2).

SPATIAL RESOLUTION, X (3 dB width)	30 M	100 M
ENERGY DISTRIBUTION (Energy in central 2X x 2X)	81%	90%
IMAGE CONTRAST (Mean level in 4S square well)	- 5dB*	- 8dB
RADIOMETRIC RESOLUTION (Difference between σ_o and σ_o + SD in image distribution)	2.5dB	1
RADIOMETRIC ACCURACY	3 dB MEAN	1dB S.D.
IMAGE LOCALISATION	1KM	
DYNAMIC RANGE	Distributed and man-made targets	σ_o - 18 dB to + 10 dB
	Point targets	σ < 50 dB.M^2
GEOMETRIC DISTORTION,	< ½ PIXEL DISCONTINUITIES	
OUTPUT MAP FIDELITY,	80 KM. SQUARE IMAGE (MIN.)	
IMAGE FORMAT	MAX. PIXEL SIZE < X/2.	

Table 1 - ERS-1 Image Specification

Each of the specifications is intended to reflect some characteristic of the final image which is relevant to a potential user: spatial resolution is a measure of minimum distance between distinguishable features; radiometric resolution is a measure of minimum difference in σ_o (normalised scattering cross-section) between distinguishable areas of distributed target; energy distribution and



FRACTION OF TOTAL ENERGY IN CENTRAL 2X x 2X
SQUARE OF RESPONSE FUNCTION = PRODUCT OF
FRACTIONAL ENERGY IN 2X INTERVAL OF 1-D FUNCTIONS; I.E. β, β,

Figure 1 - Energy Distribution

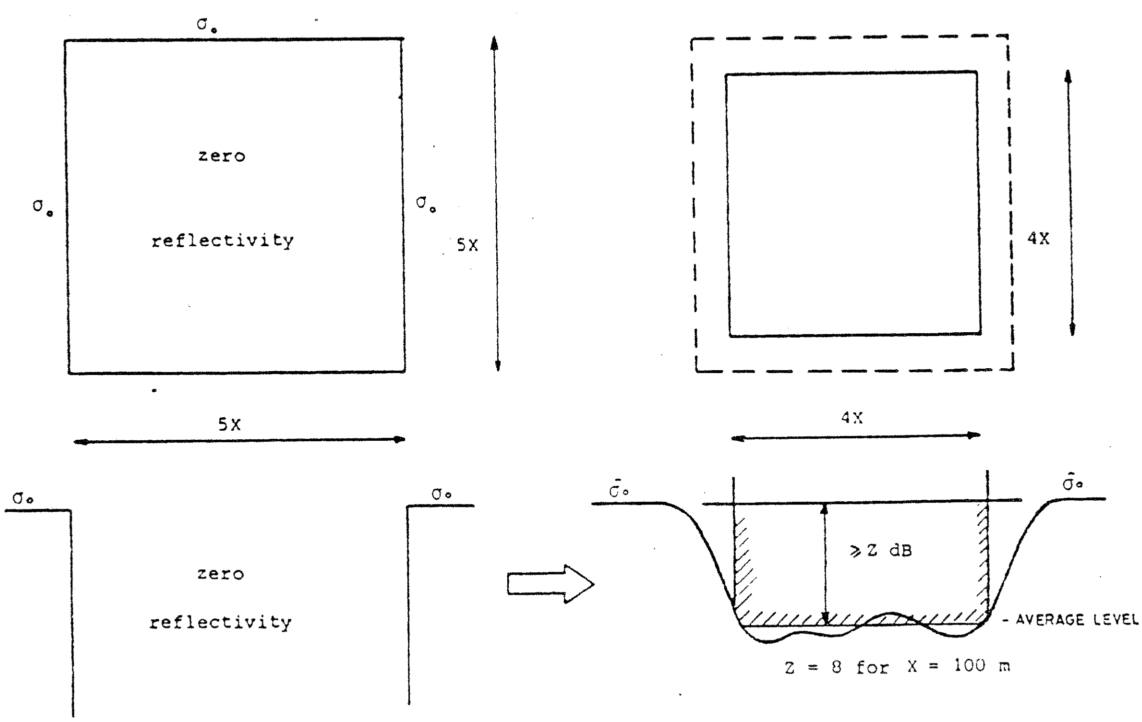


Figure 2 - Image Contrast

image contrast indicate the spread of energy from point targets and areas of distributed target. Although these parameters are related to the image they are not necessarily measurable from a general image or even from images of specially selected sites. Spatial and radiometric resolutions can be measured to some extent from images of point targets and distributed target respectively (see Section 2) and energy distribution could be estimated from an image of a corner reflector erected in an area of very low backscatter. The image contrast specification, however, is virtually impossible to verify because even if a square area of zero reflectivity could be constructed it would be unlikely to extend as far out as the first ambiguity positions. A partial measurement could be made by the simulation of signal from the required area, but this would only take into account processor effects, and not effects from other parts of the system (e.g. phase and amplitude errors): the current simulation programs do not seem to model even ambiguity effects accurately (see Section 3). Other partial measures of image contrast (i.e. measures of effects which contribute to the total image level within the central 'square well' of the definition) could be made from images of sharp transitions between areas of distributed target of different σ_o, or from images of ambiguities arising from strong features. This specification does correspond to a real characteristic of the image but remains an image quality measure which can only be assessed theoretically.

2. Image Assessment

The major work performed by MRC in this category has been in contracts for the Earthnet Programme Office (EPO) of the European Space Agency (ESA) [3]. The aim has been to devise algorithms to make measurements of image quality from real images stored in digital form. The algorithms are equally valid for use with images generated by a simulation of a SAR system (see Section 3), although image assessment is much easier to make with such images because specific target types can be set up for the purpose.

For a general real scene two distinct types of measure are to be made : those involving point targets (e.g. spatial resolution) and those with distributed target (e.g. radiometric resolution). The first stage in any procedure is, therefore, to locate suitable features and areas in the given image - assuming there are some. Validation tests have been written for each target type and although these could be used to search the image for the required types of area it has proved to be much more convenient to make a preliminary visual search and to apply the tests to selected areas.

If and when a point target has been identified and accepted the following measurements can be made:

i) location of peak of the response function by interpolation across a block of pixels.

ii) 3dB widths of the response function in each dimension of the image

iii) ratio of peak to background level

For an area of distributed target the following can be calculated:

i) mean and standard deviation of image pixel distribution

ii) histogram of pixel distribution

These measurements are related to the radiometric resolution specification (see Section 1), but a direct measurement cannot be made unless an area of distributed target of the minimum specified scattering cross-section can be identified, since the radiometric resolution as defined is dependent on the signal-to-noise ratio.

Although measurements of energy distribution and image contrast (see Section 1 for definitions) could be made if ideal targets (point target on very weak background and 'square well' of zero reflectivity in uniform target area) occurred in the image, in practice such measurements are not possible for images produced from real data (as opposed to simulated data).

The point target measurements have demonstrated clear differences in the performances of processors which produce images of nominally the same specifications [11]. The results from the distributed target algorithms have not shown such significant variations in performance, perhaps because the radiometric resolution is principally dependent on the number of independent looks and is not significantly affected by errors such as defocusing or misregistration in the processing.

An additional measurement of image quality which has been made, but which, unlike those described above, requires a large amount of human supervision, is in measurement of geometric distortion. Until such time as automatic ground control point identification can be performed (an operation which is particularly difficult for SAR because of the speckle effects) these measurements will remain very time consuming.

Two further types of SAR data analysis have been implemented for ESA:

- raw SAR data analysis, including statistical measures, histograms and spectral analysis which have revealed some unexpected anomalies in the Seasat data, and

- processing of SAR images of the sea to try to extract a representation of the sea surface by filtering of the signal in the spectral domain ([4] and [5]).

In summary, therefore, of the image assessment studies it has been found that, although measurements of the precise image quality parameters specified by ESA cannot be made automatically from a general image, measurements can be made which enable the variations in the product from one particular processor to be monitored and which enables products from different processors to be compared.

3. SAR Simulation

MRC are studying for ESA of SAR simulation experiments. A number of establishments have produced simulations of part or all of a SAR system and the study is intended to be a review of the current simulation programs and an evaluation of such programs for the purposes of generating data which can be used to test processors and other ground facilities (e.g. dissemination networks, storage media, auxiliary data processing). Current procedures for testing SAR processors cover many, but not all, aspects of their performance, and these procedures are being reviewed to enable a comprehensive test program to be specified. The simulated data sets needed for such tests are being defined and, when the data cannot be produced by available simulation programs, methods for generating them are proposed.

Two distinct types of SAR simulation have been identified:

i) Simulation of a radar image of a given area of terrain.

The most widely publicised program of this type is that produced by the University of Kansas [6,7,8]0, which incorporates simulation of various reflectivity categories and terrain elevation effects, and takes into account system parameters such as incidence angle and radar wavelength. Although useful for testing simple observational hypotheses, such as optimal incidence angle for a particular purpose, image simulation is not of use for testing processor operation.

ii) Simulation of the complete SAR process and in particular the generation of raw signal from different image features. The simulation model at the University of Texas comes into this category; enabling simple terrain types such as single discrete targets and uniform distributed target (modelled by a number of point targets within each cell) to be simulated. Although the test case reported in [9] involves several simplifications (for example in the modelling of the antenna beam) this type of program should be capable of producing data sets to test most aspects of a processor. ESA SARSIM is also of this type.

The processor acceptance test procedures which have been used as a starting point for the study are those devised by MacDonald Dettwiler for the processor commissioned by ESA [10]. These tests consist largely of measurements made from images of simulated point targets; covering characteristics such as spatial resolution, peak sidelobe level, radiometric accuracy, geometric distortion and localisation. The measurements are not particularly tied to parameters given by ESA in the ERS-1 SAR image specification [1], although some are closely related: for example, the integrated sidelobe ratio (ISLR) measurement is similar to the 'energy distribution' of the specification.

In the present study a number of other aspects of the processor have been identified as needing to be tested; some of which could be examined with the point target data sets, but some which would require the simulation of more complex targets or modelling of other system effects. The following are given as examples of additional tests:

i) Flexibility of processing operations; e.g. weighting functions, number and length of looks, etc.

ii) Ability to handle data with maximum pointing variations within the specified range; i.e. maximum update of reference patterns.

iii) Handling and throughput of a full scene rather than just a limited area.

iv) Correct arrangement and alignment of image areas produced by successive period of block processing.

Other tests which have been considered are only relevant when the processor specification includes certain additional functions such as image rotation or resampling. If the processor is intended to perform auxiliary data processing to generate information about the Doppler centre frequency (Doppler tracking) and/or the Doppler FM rate (autofocus) these algorithms should also be tested with suitable data sets, preferably not just point targets or uniform distributed target.

Some basic terrain types (such as point targets, finite areas of distributed target and infinite full- or half-plane areas of distributed target) have been considered as possible features for simulation and the aspects of the processor which can be examined with each have been examined. The general conclusion is that there is no need to simulate more complex terrain patterns (e.g. chequerboard, ramp function, sinusoidal variation, square well) in order to test all features of the processor.

The use of real scenes in test procedures provides an output which might be appreciated by potential users but is not essential as a test. Artificial test patterns (incorporating, for example, the characters ERS-1 are not of value.

4. Summary of Performance Assessment Methods

The three previous sections have each considered a different approach to the assessment of the performance of a SAR system. Each tests a different part of the end-to-end system and makes different assumptions about the available data, as summarised in Table 2. For example, although the theoretical analysis can cover the complete system (i.e. both the on-board hardware and the processing) the results are dependent on accurate error specifications (e.g. phase and amplitude errors, attitude control) and on realistic analytical models. Simulated data sets from specific target types provide a good test of the processor performance which can be extended to a full system assessment if error effects are modelled, although again the validity will depend on the accuracy of the error specification. The image assessment algorithms described in Section 2 are intended principally for use with a general SAR image and so, although they give valuable measures of relative performance (between different processors or for the same processor at different times), they cannot be expected to give a precise measure of performance in terms of the standard image quality parameters. However, if these algorithms are used with images of specially constructed 'verification sites', containing for example corner reflectors

METHOD	TESTING	INPUTS	ASSUMPTIONS	MEASURES
Theoretical analysis	Full system	System parameters Error specifications	Relatively simple analytical models	Spatial resolution Radiometric resolution Energy distribution Image contrast
Image assessment	Relative processor performance	Image of general area	Presence of genuine point target or distributed target	Spatial resolution Radiometric Resolution
Simulation	Processor	Simulated data for special target types	Accurately simulated radar system	Spatial resolution Radiometric resolution Energy distribution Image contrast
Verification Procedures	Full system	Real image of special targets (verification sites)	Perfect Target types	Spatial resolution Radiometric resolution Energy distribution

Table 2 : Summary of performance assessment methods

on very weak background and areas of uniform distributed target, then more precise measurements are possible and an accurate assessment of the system can be made. In Table 2 the various methods are summarised in terms of their assumptions, input requirements and possible measurements (restricted to the set defined in Section 1).

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