MASTER IN EMERGENCY EARLY WARNING AND RESPONSE SPACE APPLICATIONS

SAR IMAGE QUALITY ASSESSMENT

SEMINAR FINAL REPORT

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ABSTRACT

Quality analysis is an important task in the development of SAR image digital processing methods. In this work the methodology for the analysis of both, point and extended targets in SAR images is presented. The methodology is demonstrated in the study of the correct focusing of images.

Key words: SAR processing, quality assessment
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During the last few years the increasing interest of the Remote Sensing Community on Synthetic Aperture Radar (SAR) images has made Digital SAR Data Processing an active field of research.

In contrast to optical imagery, SAR data have to be pre-processed in order to obtain an image. The focusing of SAR raw data is essentially a two dimensional problem. The reference function of this correlation is the Impulse Response Function (IRF) of the SAR system.

Mainly the SAR image quality assessment involves the post-processing quality control. Martinez and Marchand in 1993 [1] established that the main objective of the SAR quality analysis methods is to provide a tool for the study of the focusing performance of different processing algorithms and the influence of key parameters in the quality of the final image. But it should be noticed that to carry out a complete quality evaluation it must be checked first if the RAW data satisfies a number of items that determine its goodness.

The set of parameters and relevant measurements to calculate the image quality should be studied to meet the demand of SAR image quality evaluation. In this work the image quality assessment is studied without making focus on the calibration procedures of the SAR instruments, but it should be taken into account that the SAR image quality comprises also (and mainly) the evaluation systems for SAR image calibration or validation of a designed SAR system. In this case the image quality evaluation should also match with the post-processing requirements that come from the rapid increasing need of SAR image applications [2].

Image quality assessment involves also the radiometric analysis using distributed targets by means of statistical information obtained from distributed targets. In this work the methodology for the analysis of the SAR RAW data, SAR focusing performance and radiometric quality of the image is presented.
The generation of any value added SAR product starts with a level 0 one, called RAW data. This is exactly what the sensor acquires and transmits to the ground stations where it shall be processed. So, the first step measuring the image quality must be the analysis of this data.

The level 0 products have to be in line with their specification and they should not show any systematic deficiencies. This is the major task of the level 0 product validation activity [3].

In the SAR RAW data, the signal energy from a point target is spread in range and azimuth, and the purpose of SAR focussing is to collect this dispersed energy into a single pixel in the output image. In range, the signal is spread by duration the linear FM transmitted pulse. In azimuth, the signal is spread by the duration it is illuminated by the antenna beam, or the synthetic aperture [4].

Gaussian scattering occurs when the reflectivity observed is the result of a coherent sum of many individual statistically independent reflections from within a given resolution cell [5]. So, since RAW data is obtained through a coherent recording of a huge number of independent echoes, the RAW signal is (and should be) gaussian noise. The related quality is hence related to measure the closeness of the RAW signal statistical distribution to a zero average Gaussian distribution.

The measures of the quality of RAW data is based on the following RAW data statistics analyses:

- I,Q means and I,Q gain imbalance (ratio of the I and Q Standard Deviations)
- I,Q non-orthogonality (arc cosine of the correlation coefficient between I and Q)
- RAW phase statistical distribution (should be uniform in $[0 − 2\pi]$)
• non-gaussian distribution test (e.g. chi-square test measuring the similarity with a gaussian distribution)

• Missing lines (should be very low, $0.0 \approx 0.5\%$ of the data in one image)

• Replica quality (including phase and amplitude analysis, autocorrelation width)

• Ancillary data accuracy & correctness (including internal calibration data, swath width, corner localization, range line datation, image sizes, etc.)
Image quality refers both to the impulse response properties of a radar/processor combination, and to the response of the system to distributed scatterers. In this chapter both of them shall be detailed.

The SAR response to a point target, assuming negligible background reflectivity and thermal noise, is commonly referred to IRF. The analysis of the signature of a point target in a SAR image allows the determination of several parameters that are related to the SAR spatial resolution and the presence and importance of undesired, but inevitable, side lobe peaks [1].

Figure 3.1: Graphical representation of a SAR point target response showing several quality parameters.

Figure 3.1 shows the IRF of an isolated point target. The Impulse Response Function is a sinc function with a mainlobe and many secondary lobes. The figure shows a one dimensional cut of the IRF in the azimuth direction (spacecraft velocity direction) and two quality parameters measured from it (spatial resolution and PSLR). These parameters shall
be described in the following sections.

A SAR image is the result of coherently processing returned echo signals; thus, the pixel values are complex quantities. For most applications, representation of the magnitude of the image is enough. It is possible to use the modulus of the complex pixel (amplitude) as well as the squared modulus (intensity). The peak intensity is the maximum pixel value in the main lobe of the impulse response function [1].

### 3.1 Spatial resolution

The spatial resolution is the distance between two objects on the ground at which the images of the objects appear distinct and separate. The ideal spatial resolution of a SAR system can be computed from theory and then compared with that obtained from the IRF analysis. The spatial resolutions in range and azimuth are obtained from theory [6]:

**Slant range resolution:**

$$\rho_{rs} = \frac{c}{2B} \tag{3.1}$$

where \(c\) the speed of the light and \(B\) the chirp bandwidth.

**Ground range resolution:**

$$\rho_{rg} = \frac{\rho_{rs}}{\sin \phi} \tag{3.2}$$

where \(\phi\) is the local incidence angle.

**Azimuth resolution:**

$$\rho_{az} = \frac{L}{2} \tag{3.3}$$

where \(L\) is the antenna length in azimuth direction.

In SAR images, the spatial resolution is measured as the distance between the points with intensities 3 dB below the maximum intensity of the main lobe peak in the azimuth and range directions [1]. Figure 3.2 shows the IRF of a point target and the points 3dB below the maximum intensity.

To determine these resolutions it is necessary to calculate previously the pixel and line spacings\(^1\) (range and azimuth spacing, respectively). These values are calculated as:

$$Sp_r = \frac{c}{2F_s} \tag{3.4}$$

where \(Sp_r\) is the pixel spacing (i.e. the range spacing) and \(F_s\) is the sampling frequency.

---

\(^1\) **Pixel spacing** represents how much area each pixel covers, while **resolution** indicates the smallest object you could pick out in an image [7]. **Pixel spacing** is commonly used to express the spacing in range while **line spacing** is used to express the azimuth spacing.
3.2 Peak side lobe ratio

The peak side lobe ratio (PSLR) is defined by the ratio of the largest level of sidelobes to the peak level of mainlobe [9]. It represents the ability of the SAR to identify a weak target from a nearby strong one [2].

The PSLR is calculated as [2]

$$PSLR = 10 \log_{10} \frac{I_s}{I_m}$$ (3.6)

where $I_s$ stands for the peak intensity of the most intense sidelobe and $I_m$ stands for the peak intensity of the main lobe\(^2\). Both values are shown in Figure 3.2.

\(^2\)The PSLR as other quality parameters exposed in this work are expressed in decibels. The decibel (dB) is a logarithmic unit that indicates the ratio of a physical quantity (usually power or intensity) relative to a specified or implied reference level. A ratio in decibels is ten times the logarithm to base 10 of the ratio of two power quantities [10].

---

Figure 3.2: IRF and point target evaluation parameters

$$Sp_a = \frac{V_{st}}{PRF}$$ (3.5)

where $Sp_a$ is the line spacing (i.e. the azimuth spacing), $V_{st}$ is the sensor-target mutual velocity and $PRF$ is the pulse repetition frequency.

These values are very close to those of the range and azimuth resolutions. It means that the mainlobe of the IRF is contained just in one pixel and it becomes impossible to determine the distance between the -3dB points. So, an interpolation is needed by a factor of at least 8 [8] to make the measurement possible. In the next Chapter, the methodology for the point targets extraction and the way to interpolate them are detailed.
The PSLR may be improved by mean of a sidelobe clutter and noise minimization with multiple-aperture SAR, which considerably improves the quality of SAR image [11].

### 3.3 Integrated side lobe ratio

The integrated side lobe ratio (ISLR) is the ratio of the power (energy) in the main lobe to the total power in all the side lobes (or vice versa depending on definition) [1]. It characterizes the ability to detect weak targets in the neighbourhood of bright targets. As the PSLR, the ISLR is a measurement of the relative importance of the side lobes with respect to the main lobe.

The mathematical formal definition given by [2] is:

\[
ISLR = 10 \log_{10} \frac{\int_a^b |h(\tau)|^2 d\tau + \int_0^\infty |h(\tau)|^2 d\tau}{\int_a^b |h(\tau)|^2 d\tau}
\]  

(3.7)

where \(h(\tau)\) stands for the IRF in azimuth or range direction and \([a, b]\) stands for the range of main lobe at 3dB below the maximum intensity peak. These values are shown on Figure 3.2.

There are several different ways for calculating the ISLR proposed by many authors in the literature, with differences in the adoption of the areas in which the energy is integrated:

Sanchez [12] defined the ISLR as the ratio of the energy inside a rectangle centred on the maximum of the main lobe and side length equal to the \(-3dB\) width of the IRF to the rest of the energy of the IRF. In this definition, only one resolution cell is considered to have the energy in the main lobe.

\[
ISLR = 10 \log_{10} \frac{\int_{-3dB} Idxdy}{\int_{-\infty}^{+\infty} Idxdy - \int_{-3dB} Idxdy}
\]  

(3.8)

Franceschetti et al. [13] defined the normalized integrated side lobe ratio, NISLR, as follows:

\[
NISLR = I_{max} 10 \log_{10} \frac{\int_{-\infty}^{+\infty} Idxdy}{\int_{-\infty}^{+\infty} Idxdy - \int_{-3dB} Idxdy}
\]  

(3.9)

Guignard [14] proposed that there are different regions in the IRF: the main beam area, which is 3 by 3 pixels centred on the maximum; the guard band, which is formed by the 26 pixels surrounding the main beam area; and the side lobe area, formed by a square of 99 pixels side, disregarding the inner 5 by 5 window.

\[
ISLR = 10 \log_{10} \frac{\int_{99 \times 99} Idxdy - \int_{5 \times 5} Idxdy}{\int_{3 \times 3} Idxdy}
\]  

(3.10)
Holm et al. [15] established the ISLR is the ratio of the power within a square centred on the maximum and twenty by twenty resolution cells, without considering an inner window of three resolution cells side and the power in the second window.

\[
ISLR = 10 \log_{10} \frac{\int_{20 \times 20} I \, dx \, dy - \int_{3 \times 3} I \, dx \, dy}{\int_{3 \times 3} I \, dx \, dy} \tag{3.11}
\]

The European Space Agency (ESA) [16, 17] established the ISLR as the ratio of the power within a square centred on the maximum and ten resolution cells side, without considering an inner window of two resolution cells side and the power in the second window.

\[
ISLR = 10 \log_{10} \frac{\int_{10 \times 10} I \, dx \, dy - \int_{2 \times 2} I \, dx \, dy}{\int_{2 \times 2} I \, dx \, dy} \tag{3.12}
\]

Martinez and Marchand [1] proposed to work with the normalized form of the ESA’s definition:

\[
\text{normISLR} = 10 \log_{10} \frac{\frac{1}{96} (\int_{10 \times 10} I \, dx \, dy - \int_{2 \times 2} I \, dx \, dy)}{\frac{1}{4} \int_{2 \times 2} I \, dx \, dy} \tag{3.13}
\]

## 3.4 Radiometric resolution

The radiometric resolution is a measure of the ability of the system to discriminate, or resolve, areas of different scattering properties. Meanwhile the geometric resolution is a quantitative measure of the ability of the system to discriminate different objects in space, the meaning of radiometric resolution is to quantify the minimum distance between two reflectivity levels (in a homogeneous zone) which can be separated by the radar [6].

The radiometric analysis is the counterpart in the frequency domain of the IRF analysis. The targets of investigation are uniform, extended regions, which ideally have a point-like signature in the frequency domain. In fact, the radiometric resolution quantifies “the ability to distinguish between uniformly distributed targets with different backscattering coefficients”. This ability is strongly related to the phenomenon of speckle and therefore to the image multi-looking [18].

Sources of radiometric anomalies are:

- sensor electronics failures,
- antenna array distortion due to large temperature variations,
- atmospheric propagation attenuation,
3.4 Radiometric resolution

- platform stability (influence on Doppler parameter estimation),
- focusing processor.

The radiometric resolution is dependent on both signal, speckle, and thermal noise intensities [6]. A conventional definition for the radiometric resolution is [19]:

$$\gamma = 10 \log_{10} \left( 1 + \frac{\sigma}{\mu} \right)$$  \hspace{1cm} (3.14)

where $\mu$ and $\sigma$ are the mean value and standard deviation of the distributed target intensity values.

3.4.1 Equivalent Number of Looks (ENL)

As said, the radiometric resolution is related to the speckle noise and therefore to the image multi-looking. Image speckle may be reduced by averaging over different sub-images of the same scene. Look$$s$$ are the sub-images formed during SAR processing. The image speckle variance is reduced by the number of statistically independent sub-images used in the average [5].

Usually, sub-images are extracted from the available data by partitioning the spectra in the azimuth frequency domain. Frequency partitioning to generate looks is logically equivalent to a linear filter applied to smooth the image data after detection [5]. Figure 3.3 shows the idea of partitioning the azimuth spectra.

![Figure 3.3: Multilooking with 3 looks: partitioning the azimuth spectra in three different looks](image)

The multilook technique consists of first dividing and then separately processing $N$ overlapped portions of the SAR bandwidth. The incoherent average of the so obtained
3.5 Dynamic Range

$N$ SAR images improves the radiometric resolution by a factor of $N$. However, antenna pattern spectral modulation, aliasing, etc. render this improvement only an upper bound. Its effective value can be quantified in terms of an equivalent number $N' \leq N$ of uncorrelated samples; this number is usually referred to as equivalent number of looks (ENL) [6], which is the look parameter of importance in applications [5].

On the other hand, a reduction of the geometric resolution by the same factor $N$ must be tolerated due to the reduction of the processed bandwidth. A trade-off between geometric resolution and speckle reduction must be considered [6].

![Figure 3.4: Spatial and Radiometric resolutions vs ENL](image)

The ENL for an homogeneous region of an image is defined to be the ratio between the mean squared to the variance, both estimated using image data expressed in power ($\sigma^0$) radiometrics [5]. The mathematical definition of the ENL is [6]:

$$ENL = \left( \frac{\mu}{\sigma} \right)^2$$  \hspace{1cm} (3.15)

The ENL is equivalent to the number of independent intensity values averaged per pixel. It is often applied not just to describe the original data but also to characterize the smoothing effects of post-processing operations such image filtering [20].

3.5 Dynamic Range

The dynamic range describes the range of radar backscatter coefficient when radiometric resolution value fit the system design [2]. It is calculated as
3.6 Ambiguities and Ghosts in SAR images

Ambiguities are the manifestation of ‘ghosts’ (undesired) targets in the SAR images inherent to pulsed radar systems [21]. They are intrinsic effects of a SAR system, both in azimuth and range.

There are two types of ambiguities in SAR: the range ambiguities, and the azimuth ambiguities. The range ambiguities arise when different backscattered echoes, one related to a transmitted pulse and the other due to a previous transmission, temporarily overlap during the receiving operation (See Figure 3.5). In this case the range information contained in the echo delay becomes ambiguous because it cannot be directly related to a single transmitted pulse. This effect is particularly relevant for spaceborne sensors due to the relatively large target-sensor range [13]. As the range ambiguities result from simultaneous arrival of different pulses at the antenna, they are controlled via the PRF (Pulse Repetition Frequency) selection [1]. An upper limit to the PRF is set by the necessity to avoid that successive echoes backscattered by the illuminated scene are received simultaneously. This is achieved if the time extension of each echo is smaller than the interval between two successive pulses [13].

Furthermore, as every antenna pattern, the range direction has sidelobes. Such lobes can allow (when in presence of special combination of sidelobes position and reception window) the reception of echoes coming from portions of the earth outside the range (with the creation of range ghosts) [6] (See Figure 3.6). Such phenomenon can be avoided with a proper selection of the antenna and reception window parameters [1].

The azimuth ambiguities are caused by the aliasing of the Doppler phase history of each target, that is sampled according to the sensor azimuth sampling frequency, $f_{sa}$, which equals the Pulse Repetition Frequency (PRF). Usually, such ambiguities are kept below a reasonable level by exploiting the Azimuth Antenna Pattern (AAP), that acts as a sort of anti-alias pre-filter, by illuminating ground patches in the direction of the desired contributions and blocking returns from “interfering” angles [22]. These ambiguities appear because of the sidelobes of the antenna pattern in azimuth direction. This effect is particularly relevant for high reflectivity objects that appear in the SAR image as ghosts targets inside low reflectivity areas [6].

\[ D = 10 \log_{10} \frac{I_{\text{max}}}{I_{\text{min}}} \]

where $I_{\text{max}}$ and $I_{\text{min}}$ stand for the maximum and minimum intensity of the SAR image.

It describes the span of useful levels of a signal. Most modern SAR image processing systems use floating-point arithmetic to accommodate large dynamic range. Image files are routinely produced in amplitude format reducing the need for excessively large image dynamic range [5].
3.6 Ambiguities and Ghosts in SAR Images

In normal conditions, the azimuth sidelobes are low enough (-13 dB) to maintain such aliasing signal at a low level. But when there is a scene in which a high reflectivity zone is adjacent and followed (in the velocity direction) by a low reflectivity one, the signal coming from sidelobes can be even higher than the one from mainlobe and ghost images appear called azimuth ambiguities. Figure 3.7 explains the situation which causes such effect and Figure 3.8 shows the presence of ghosts on a SEASAT image.

Martinez and Marchand [1] examined the effect of the processed azimuth bandwidth on the point target response. The two compared ERS-1 images were taken from a region around a transponder near the sea. The first image was processed using the full azimuth bandwidth (1678.712 Hz) while in the second only 1000 Hz were used. All other parameters were kept constant.

The results shown that in the image processed using the full azimuth bandwidth appear bright points in the water area. In the processing of the 1000 Hz image, the higher frequency contents were ignored, producing lower ambiguity in the azimuth direction. But, it should be noticed that processing a reduced bandwidth has negative effects on the point target
3.6 Ambiguities and Ghosts in SAR Images

Figure 3.7: Cause of ghosts presence over low reflectivity areas because of azimuth sidelobes

Figure 3.8: Azimuth ambiguities in a New Orleans image acquired by SEASAT

response (e.g. decreasing of azimuth resolution and worst PSLR values)

The ambiguity level is obtained from the difference of the energy (intensity) in the point target and in the ghosts [1]. As broader the processed bandwidth the higher the ambiguity level.

3.6.1 Ambiguity level (ratio)

The ambiguity level is the ratio of the energy in the ghosts to that in the main lobe, and is expressed in dB [1]. Curlander and McDonough [18] defined the same concept as the ambiguity to signal ratio (ASR).

\[ ASR = 10 \log_{10} \left( \frac{\text{Ambiguity}}{\text{Point Target}} \right) \]  

(3.17)

where Ambiguity and Point Target are the peak power of the ghost and of the actual
3.6 Ambiguities and Ghosts in SAR Images

target, respectively.

The antenna and the PRF shall be designed in such a way to minimize the ASR. The
tenna must have low (elevation/azimuth) side-lobes reduce the (range/azimuth) ambigu-
ities. Reducing the PRF, the range ambiguities decrease but the azimuth ones increase. So,
the PRF must satisfy some restrictions to control both, range and azimuth ambiguities.

To control the range ambiguities it is needed to respect the following inequality [23]:

\[ PRF < \frac{c}{2R_{\text{max}}} \]  

(3.18)

where \( c \) is the speed of the light and \( R_{\text{max}} \) (the maximum unambiguous range) is the
longest range to which a transmitted pulse can travel and return to the radar before the next
pulse is transmitted.

To avoid the azimuth ambiguities the PRF is constrained to [21]:

\[ PRF > B_D \]  

(3.19)

where \( B_D \) is the Doppler Bandwidth which is the range of Doppler frequencies extend-
ings across the antenna footprint.

Assuming the generally valid condition for most SAR systems of negligible coupling
between azimuth and range ambiguities we can distinguish between Azimuth Ambiguity
to Signal Ratio (AASR) and Range Ambiguity to Signal Ratio (RASR).

A typical design value is (A/R)ASR \( \leq -20 \) dB. Ambiguous signals can be detected in
images that have very bright targets (urban area) near dark ones (calm lake). In such case:
(A/R)ASR \( \approx -10 \) dB.

To calculate the ambiguity level, the ghost images of a given target must be found.
They are displaced with respect to the actual target and this offset can be calculated. Next
sections explain how to calculate it.

3.6.2 Azimuth ambiguity offset

Azimuth ambiguities are displaced with respect to the “true” target in the azimuth direction
by [8]:

\[ \Delta AzAmb = \frac{\lambda}{V_st} R_{st} \frac{PRF}{2} \]  

(3.20)

where:

- \( \Delta AzAmb \) is the azimuth offset
3.6 AMBIGUITIES AND GHOSTS IN SAR IMAGES

- \( \lambda \) the SAR wavelength
- \( V_{st} \) is the sensor-target relative speed
- \( R_{sr} \) is the Slant range point target distance

### 3.6.3 Range ambiguity offset

Range ambiguities show a displacement in the range direction, expressed by [8]:

\[
\Delta \text{SlantRange} \approx \frac{mc}{2PRF} \quad (3.21)
\]

where \( \Delta \text{SlantRange} \) is the slant range offset, \( c \) the speed of the light and \( m \) the ambiguity level. The ambiguity level calculation shall be explained in next subsection.

The calculus of the ground range ambiguity offset is a little bit more complicated:

\[
\Delta \text{GroundRange} \approx G(R_{sr} + \Delta \text{SlantRange}) - G(R_{sr}) \quad (3.22)
\]

where function \( G \) is defined as

\[
G(R) = R_T \cos^{-1} \left( \frac{R_S^2 + R_T^2 - R^2}{2R_SR_T} \right) \quad (3.23)
\]

\( R_T \) and \( R_S \) are the Earth and spacecraft orbit radius, respectively, and \( R \) is the slant range distance.
Two different kinds of measures were presented in Chapter 3, the first one refers to the impulse response properties of a radar/processor combination which includes the analysis of spatial resolution, PSLR, ISLR, ambiguities, etc. The second refers to the response of the system to distributed scatterers and involves the study of the radiometric resolution.

The measurement of the radiometric resolution is easily performed by extracting an homogeneous area from the original SAR image and calculating its statistics [1]. It shall not be studied more deeply in this chapter.

On the other hand, the procedure for the analysis of point targets is somehow more elaborate because it requires several steps before the analysis can be done. The whole process to perform the extraction of point targets, needed to carry out the IRF analysis, is described in the next sections.

### 4.1 Extraction of point targets

The calculation of the quality parameters of an image is not a straight forward task, at least in the case of point targets [1]. Figure 4.1 shows the procedure for the analysis of point targets.

First of all, the target has to be extracted from the rest of the image before any analysis. This is to avoid spurious influences of the surrounding environment [1]. The point target must be as bright as possible. Most of the image quality controls are performed on images of “well known” targets. Examples of these targets are the man made ones such as corner reflectors and active transponders.

**Corner reflector:** passive device which reflects the SAR signal. The most popular is the
triangular trihedral. Cross section \( \approx \frac{4\pi l^4}{\lambda^2} \) (\( l \) = side length, \( \lambda \) = radar wavelength) [24]

**Active transponder:** active reflector. Advantage: increases the signal strength by electronic amplification. Cross section \( \approx \frac{\lambda^2}{4\pi}G_rG_eG_t \) (where the \( G \) terms are the reception, electronic and transmission gains, respectively) [25].

These artifacts are preferable, but they are not available in most of the images; in such situation, opportunity targets can be used [1, 2].

### 4.2 Interpolation

When analyzing a point target for impulse response function parameters determination, it is desirable to have an interpolated image to perform the calculations. In this way, the obtained parameters will be more accurate than in the case when no interpolation is done. The interpolation is made via a FFT zooming method with complex data [26].

After the extraction (zooming) of the *interest area* a Hamming window filtering must be applied to the input image in order to prevent side effects in the Fourier transforms. Then the two-dimensional FFT of the filtered image is performed to obtain the point target spectrum [1].

In the next step the Fourier spectrum is divided in four equal quadrants. These quadrants are put in the corners of a bigger spectrum, with the size of the desired interpolated image by padding with zeros the central area. At this point the inverse FFT is calculated. The last step in the formation of the interpolated image it to remove the effects of the Hamming window filtering, although it is not necessary [1].
4.3 Evaluation of quality parameters

Once the interpolated image is available the quality parameters can be calculated. The search for secondary lobes may not be restricted to the range and azimuth directions alone. Additionally, the position of both the first secondary lobes (those closest to the main peak) and the absolute ones in the extracted image have to be obtained. The accuracy of the spatial resolution is improved by using linear interpolation of the pixel values; in this way, subpixel precision can be achieved [1].

4.4 An example of point target extraction

As an example of the exposed methodology for point target extraction few IDL functions were developed to apply the steps proposed by [1]. It was also used the software ENVI® to cut the 128 by 128 pixels of the original image according to [8] and to visualize the interpolated image.

To carry out the test, it was used a single look complex (SLC) image focused using my own implementation of the Range-Doppler Algorithm (RDA) applied to an ERS-1 RAW belonging to the Deutsch zone of Fleavoland where ESA has three active transponders. Figure 4.2 shows the focused image before the PT extraction.

![Figure 4.2: ERS’ SLC image of the Fleavoland area. The response of the active transponder is easily observed. An ENVI window shows it marking the PT with a red box around it.](image)

The extracted point target is shown in Figure 4.3, meanwhile the scaled point target (by a factor of four) is shown in Figure 4.4. Both images are in scale 1:1 of the ENVI window on the screen.
4.4 An example of point target extraction

Figure 4.3: Extracted point target.

Figure 4.4: Scaled point target using FFT interpolation.
4.4 AN EXAMPLE OF POINT TARGET EXTRACTION

As the methodology propose, after the PT extraction the sub-image was filtered by means of a Hamming filter [27]:

\[
w(n) = 0.54 + 0.46 \cos \left( \frac{2\pi n}{N-1} \right)\] (4.1)

A filter was created in each direction (rows and columns) and then a 2D filter was generated. The IDL source code used to generate the filter is the following:

```idl
function hammingfilter, size
    ; creating a temporal vector using the given size
    temp = findgen(size)

    ; creating the Hamming Filter
    filter = 0.54 + 0.46 * cos(!pi*(temp-(size/2.))/float(size-1))

    ; creating the output matrix for the 2D Filter
    mat = fltarr(size, size)

    ; filling the matrix with the product row * column
    for i=0, size-1 do begin
        for j=0, size-1 do begin
            mat[j,i] = filter[j] * filter[i]
        endfor
    endfor
    return, mat
end
```

The image shown in Figure 4.4 was interpolated in the frequencies domain using the following function developed in IDL:

```idl
function scaling, image, factor
    ; transform the data into the 2D frequency domain
    spectra = fft(image)

    ; make the computations dependent of the given image size
    tam = size(image)
    ncols = tam[1]
    nrows = tam[2]

    ; create a scaled matrix by the given factor
    columns = ncols * factor
    rows = nrows * factor

    ; create a new spectra filled with zeros
    scaledspectra = complexarr(columns, rows)

    ; complete the corners with the original data spectra
```

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4.4 AN EXAMPLE OF POINT TARGET EXTRACTION

scaledspectra[:,0:(ncols/2-1)] = $
spectra[:,0:(ncols/2-1)]
scaledspectra[:,ncols-(ncols/2+1):(cols-1),0:(ncols/2-1)] = $
spectra[ncols-(ncols/2+1):(cols-1),0:(ncols/2-1)]
scaledspectra[0:(ncols/2-1),0:(rows-(ncols/2+1):rows-1)] = $
spectra[0:(ncols/2-1),rows-(ncols/2+1):rows-1]
scaledspectra[:,columns-(ncols/2+1):columns-1,0:(ncols/2-1)] = $
spectra[columns-(ncols/2+1):columns-1,0:(ncols/2-1)]
scaledspectra[:,ncols-(ncols/2+1):ncols-1,0:(rows-(ncols/2+1):rows-1)] = $
spectra[ncols-(ncols/2+1):ncols-1,0:(rows-(ncols/2+1):rows-1)]

; convert the data back into the SAR signal domain
scaled = fft(scaledspectra,/inv)
return,scaled
end
As seen in Chapters 3 and 4 one of the main tasks in the SAR image quality assessment is the IRF analysis. Furthermore, the use of this analysis is also needed to test the performance of the SAR systems by the evaluation of the final SAR images obtained from a ground test site [28].

A point target analysis model is commonly used to predict the basic system performance in initial design stage, but actually, it may not reflect an influence of the realistic environments because this ideal case does not take into account the clutter and noisy background from the real environment [9]. In practical situation, the response of a point scatterer is usually obtained from corner reflectors or active transponders on the ground test site, and thus the realistic data always contains the noisy clutter from the backscatters [29].

One way to approach this problem is to estimate the clutter effect by establishing a stochastic model. The study on the estimation method of IRF taking into account a clutter environment has been reported [30] which is detailed in 5.1.

In 2008 Jung et. al [9] proposed a new technique for IRF analysis by considering clutter background obtained directly from an actual SAR image. In order to give the realistic effects of clutter environment, the ideal impulse response is corrupted with the extracted clutter data, see 5.2.

The ASAR Calibration and Validation Team proposed a noise removal before the IRF measurements [8]. The method proposed by ESA is exposed in section 5.3.
5.1 IRF Analysis Based on Stochastic Model

The best way of approaching the clutter problem is actually to examine the real clutter, which surrounds a physical reference reflector on the ground, through a flight test. In order to obtain a wide variety of clutter distribution and inspect the influence of the measured clutter on impulse response, it is necessary to observe the various clutter regions surrounding a number of reference reflectors deployed. This has a very large cost and time requirements for data collection through the flight test [31].

5.1.1 Signal to Clutter Ratio

In 4.1 was exposed the way the measure of the SAR image quality is performed through the impulse response obtained from corners reflectors or active transponders.

Due to the clutter and noisy environment on the ground, the clutter contribution adjacent to ground-fixed reference target should be taken into account for the performance estimation. Representative parameter describing the degree of clutter contribution is signal-to-clutter ratio (SCR) [31]:

$$SCR = \frac{\sigma_P}{\sigma_0A_{res}}$$  \hspace{1cm} (5.1)

where $\sigma_P$ is the backscattered energy of a reference point target and $\sigma_0A_{res}$ represents the mean backscattered energy of the clutter within a resolution cell, $A_{res}$.

5.1.2 PSLR estimation considering background

Since the amplitude of clutter background is very dynamically fluctuated, PSLR depending on the peak of IRF has a serious effect [31]. A deterministic-statistical model of PSLR error is suggested as follows by [30]:

$$PSLR_C = \left| \frac{U_{SL,C}}{U_{ML,C}} \right| = \left| \frac{U_{SL} + \Delta U_{SL}}{U_{ML} + \Delta U_{ML}} \right|$$  \hspace{1cm} (5.2)

where $PSLR_C$ is clutter-affected PSLR. $U_{ML} = I_{ML} + Q_{ML}$ and $U_{SL} = I_{SL} + Q_{SL}$ are the complex-deterministic amplitude of mainlobe and sidelobe, respectively. $\Delta U_{ML}$ and $\Delta U_{SL}$ represent the clutter-affected amplitude of mainlobe and sidelobe, respectively. Based on this model, the error of PSLR is derived as [31]:

$$PSLR_C = PSLR \pm \sqrt{\frac{E_t}{E_p}} \left( 1 - PSLR \right) \left( \frac{k}{\sqrt{SCR}} \right)$$  \hspace{1cm} (5.3)
where $k$ is a coefficient to expand the confidence interval of the error estimation, $E_t/E_p$ is quality measurement for signal focusing and $SCR$ is energy based signal-to-clutter ratio.

![Figure 5.1: Error bounds of PSLR for a fixed $E_t/E_p = 2$](image)

### 5.2 IRF Analysis using Real Background Data

In this technique for IRF analysis it is considered a clutter background obtained directly from an actual SAR image, not from the statistical model, nor from the corner reflector. This approach needs to generate the ideal impulse response and extract the clutter patches from the real SAR image. In order to give the realistic effects of clutter environment, the ideal impulse response is corrupted with the extracted clutter data [31]. Since the extracted data from the actual SAR image contains not only the surface reflectivity on the ground but also the receiver noise induced from actual SAR subsystems, the extracted data can be regarded as an appropriate signal model of the clutter background surrounding the point scatterer [9].

Since the SAR image is composed of digital number data, the extracted clutter data needs to be converted to SCR level before applying the clutter background to the ideal IRF [9].

#### 5.2.1 Procedure for IRF analysis

The procedure proposed by [9] is composed mainly of four steps:

1. A hypothetical point scatterer is modelled and generated as an ideal reference target
2. The clutter patches from various areas of interest are carefully extracted from the SAR image.
3. The generated point response and the extracted clutter patches are expanded by interpolation process for detailed analysis and then, the point target response is overlaid with these extracted clutter patches.

4. The performance of impulse response considering the real clutter background is assessed in terms of IRF.

Figure 5.2 shows the flow diagram of the overall procedure.

![Flow diagram of IRF](image)

The results obtained by Jung et. al [9] shown how the ideal response of a point target is affected by the clutter background. An ideal point target was simulated using the parameters (platform velocity, center frequency, range bandwidth, Doppler bandwidth, PRF, etc) of RADARSAT-1, and the clutter patches were obtained from an image of Vancouver of the same sensor. Figure 5.3 shows the simulated point target (Fig. 5.3 a)) and the clutter affected impulse response (Fig. 5.3 b)) using an actual SAR image patch. Figures 5.3 c) and 5.3 d) show the ideal impulse responses in range and azimuth, respectively, both superimposed with doted lines showing the clutter affected IRF.

Using this technique it is possible to estimate the PSLR performance in realistic environment as well as to determine the SCR level of actual reference point scatterer to minimize the clutter effect on PSLR performance.

### 5.3 Background removal and image interpolation

The methodology described in [8] was defined by the ASAR Calibration and Validation Team for deriving all the quality parameters during the ENVISAT Commissioning Phase. The same methodology can be applied during the IRF analysis on any image containing a well known point target.

The methodology is quite simple and aims to remove the background backscattering contribution from the image under analysis. The following pre-processing steps shall therefore be carried out [8]:

1. **Generation of point target**
2. **Extraction of clutter patch**
3. **Zero padding in spectrum domain**
4. **Inverse transform to time domain and overlaying**
5. **Performance analysis of impulse response**
5.3 BACKGROUND REMOVAL AND IMAGE INTERPOLATION

Figure 5.3: (a) Ideal impulse response expanded by factor of 8, (b) clutter containing impulse response, (c) IRF profiles in range direction, (d) IRF profiles in azimuth direction

1. extraction of a sub-image of 128 by 128 pixels around the point target  
2. conversion of pixel values to intensity ($I_{\text{int}}$) 
3. derivation of the background intensity ($I_{\text{backg}}$) by summing the pixel intensities over four square areas of $M = 10$ resolution cells, positioned around the target in such a way that they do not include samples on the range or azimuth IRF cuts or other PTs responses but mainly the clutter intensity (see Figure 5.4) 
4. subtraction of the mean background intensity ($I_{\text{backg}}$) from the intensity image ($I_{\text{int}}$) 
   \[
   I_c = I_{\text{int}} - \frac{1}{4M^2} I_{\text{backg}} 
   \] 
5. interpolation of the intensity background corrected sub-image ($I_c$) by a factor of 8 ($I_{c,\text{int}}$). IRF analysis is performed on this interpolated image as described in Chapter 4.
5.3 BACKGROUND REMOVAL AND IMAGE INTERPOLATION

Figure 5.4: Point target response area and background areas for IRF analysis
The implementation of calibration and verification concepts requires algorithms and tools to perform specific measurements and analyses. Early developments date back to the SIR-C/X-SAR missions in 1994 and have been subsequently continuously improved and extended. In 1999 a contract from ESA/ESRIN was awarded for the development of the SAR Product CONtrol Software (SARCON) for ERS and ASAR products. With BAE Systems Ltd. as software engineering partner, SARCON has been extended and improved over the last years and is currently the standard software in ESRIN’s product control service. With the growing complexity of the sensors, more sophisticated algorithms, e.g. for PN-Gating, distributed target ambiguity analysis or antenna beam pattern optimization, have been added [32]. Newer SAR systems such as TerraSAR-X and ALOS use the CALIX software for calibration and verification.

6.1 Sarcon

The SAR Product CONtrol Software (SARCON) is a cooperation between teams at BAE SYSTEMS Advance Technology Centre and DLR under contract to ESA (ESRIN). The development began in 1999. It provides a tool for measuring defined quality parameters for a range of SAR products from spaceborne SAR instruments [33].

The tool is used for the routine monitoring and analysis of SAR products and therefore SARCON is primarily designed to meet the needs of ESRIN for controlling SAR product quality.

The basic features of the SARCON software include a product reader, raw data analysis, image mode analysis and wave mode analysis. Image mode analysis includes antenna pattern estimation, point target analysis, distributed target analysis, polarimetric analysis, target detection analysis and InSAR analysis. The software is initiated under operator
control, i.e. the operator selects datasets for analysis, the required quality parameters, controls the visualization of results, etc. SARCON contains an internal database to store the derived quality parameters in order to facilitate retrospective analysis and predictions of performance [33].

6.1.1 SARCON tasks

SARCON consists of a series of analysis modules for measuring product quality parameters for a wide range of SAR products, these modules may be used in different ways for four basic types of tasks (See Figure 6.1)

- Screening Task. The screening task is performed on a regular basis for routine analysis of any product. It uses standard sets of measurements with a minimum of operator interaction. The primary aim is to characterize the product.

- Validation Task. The validation task is to make a comprehensive check of all products. The type of measurement and product are chosen for maximum sensitivity to specific imperfections. The primary aim is to confirm the correct operation of the data chain.

- Trouble Shooting Task. The trouble-shooting task is to investigate specific product imperfections. Measurements on sets of products, e.g. raw data and the processed data products, are performed. The primary aim is to help identify the source of product imperfections.

- Monitoring Task. The monitoring task is to analyze product quality parameters stored in the SARCON database. The primary purpose is to identify trends in performance changes, which may need remedial action.

<table>
<thead>
<tr>
<th>Task</th>
<th>Primary Feature</th>
<th>Type of analysis</th>
<th>Type of Sensor</th>
<th>Type of data</th>
<th>Operator interaction</th>
<th>Operator qualification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screening</td>
<td>routine characterization</td>
<td>Standard set of quality measurements</td>
<td>ASAR</td>
<td>any SAR product</td>
<td>little</td>
<td>Non-expert</td>
</tr>
<tr>
<td>Validation</td>
<td>confirm correct operation of data chain</td>
<td>Comprehensive quality measurements</td>
<td>ASAR and ERS</td>
<td>sets of all SAR products</td>
<td>medium</td>
<td>SAR expert</td>
</tr>
<tr>
<td>Trouble shooting</td>
<td>investigate product errors</td>
<td>specific quality measurements</td>
<td>ASAR and ERS</td>
<td>specific SAR products</td>
<td>low</td>
<td>SAR expert</td>
</tr>
<tr>
<td>Monitoring</td>
<td>trend analyses</td>
<td>Retrospective analyses of database parameters</td>
<td>ASAR</td>
<td>product quality parameters in database</td>
<td>low</td>
<td>SAR expert</td>
</tr>
</tbody>
</table>

Figure 6.1: SARCON Tasks and Features

6.1.2 Raw data analysis

Raw data analysis was described in Chapter 2 and SARCON allows to perform it in an automated way. It performs the evaluation of all housekeeping parameters embedded in the
telemetry and the data quality analysis of the SAR signal / echo data itself. But this module of the software provides also other tasks such as calibration pulse analysis, the derivation of the Doppler centroid value and the generation of the range-compressed data.

**Figure 6.2:** Raw Data Analysis: Doppler centroid estimation, range compressed data and replica pulse analysis

### 6.1.3 Point target

With details of known point targets inserted into the SARCON database, the location of these point targets are automatically shown on the full scene (Figure 6.3 (a)).

**Figure 6.3:** SARCON IRF automatic analysis
Once the four background boxes have been selected (Figure 6.3 (b)), the IRF parameters and radar cross-section are calculated. These results are displayed together with the interpolated image, slices in azimuth and range through the IRF (Figure 6.3 (c)), a power spectrum, slices through the power spectrum and a 3D representation of the IRF (Figure 6.3 (d)). The module also analyzes point target azimuth and range ambiguities via the derivation of the ambiguity ratio [33].

6.1.4 Distributed target analysis

For a user selected distributed target, the mean and standard deviation of the image intensities and the radiometric resolution are calculated. Furthermore the mean value is converted to the $\sigma^0$ coefficient\(^1\). If noise estimates are available and the ambiguity analysis is performed, radiometric bias and radiometric resolution including noise and ambiguity contributions will be calculated. These results are used in the applications analysis to indicate the suitability of the product for a certain applications [33].

6.1.5 Another features of SARCON

SARCON also provides tools for targets detection, polarimetric analysis, detection of possible phase anomalies caused by processing errors using the interferogram phase and the coherence.

Database querying and reporting: SARCON uses a MySQL database which allows to store data and make queries to extract required parameters from it.

6.2 Calix

The core for the calibration and verification algorithms of the DLR is the CALIX software, which was upgraded for TerraSAR-X and ALOS. A key element of CALIX is the point target analysis tool featuring measurement of impulse response function parameters, integrated point target energy (for determination of absolute calibration factors), target/clutter ratios (to weight calibration factor estimates), as well as peak phase estimates in the case of multi-channel (e.g. quad-pol) data. Figure 6.4 shows a screen-shot of this tool. Furthermore CALIX offers tools for distributed target analysis and for geometric calibration (internal delay and data accuracy for accurately surveyed targets) [32].

\(^1\sigma^0\) is the backscattering coefficient (i.e. the physical magnitude measured by the radar. The backscattering coefficient is the radar cross section by unit of area, this means that $\sigma^0$ has no dimensions)
Figure 6.4: Examples of the DLR’s Microwaves and Radar Institute calibration ground equipment using Calix Software. IRF analysis of a corner reflector with 3m leg length
CHAPTER

SEVEN

CONCLUSIONS

Image quality assessment is a key stage in the use of SAR images and nowadays it becomes even more important because of the many applications they are useful for. In this report many articles exposing SAR quality assessment techniques have been reviewed. A set of parameters that must be analyzed to qualify the SAR focusing performance as well as the radiometric properties of the images being analyzed have been studied. Methodologies proposed, for both point and distributed targets analysis, were shown. Different criteria to obtain better results analyzing these parameters which allow improved estimations of the IRF were studied and detailed. Finally, two specialized software to automatize the SAR image quality assessment were described briefly.

The RAW data and the focused image are the first two links on the SAR processing chain. So, the implications of starting with high quality products are of great impact over the whole process. Because of this, measuring the SAR image quality becomes essential. Image quality assessment can be used (and must be used) in all processes involving SAR processing for the generation of any value added products. Generally the focused images provided by the Space Agencies have already been approved by their production teams, but when someone is working on SAR image focusing the above mentioned steps must be carried out before using such images on the next steps in the processing chain (multilooking, filters, geocoding, etc).

There are new techniques proposed for the near future that aim to get better quality SAR images working with several small SAR satellites instead of just one. This idea works under the minimization of sidelobe clutter and noise using multi-aperture spaceborne radars [11]. The future needs of a continuous work over SAR quality image assessment using new technologies as this one allowing to get better and better products.
ACRONYMS

AFSCN  Amplification Factor of Sidelobe Clutter and Noise
AAP    Azimuth Antenna Pattern
AASR   Azimuth Ambiguity to Signal Ratio
ASAR   Advanced Synthetic Aperture Radar (ENVISAT’s SAR sensor)
ASR    Ambiguity to Signal Ratio (ambiguity level)
DLR    Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center)
ENL    Equivalent Number ofLooks
ESA    European Space Agency
FFT    Fast Fourier Transform
IRF    Impulse Response Function
ISLR   Integrated Side Lobe Ratio
NISLR  Normalized Integrated Side Lobe Ratio
PRF    Pulse Repetition Frequency
PSLR   Peak Side Lobe Ratio
PTs    Point Targets
RASR   Range Ambiguity to Signal Ratio
RDA    Range-Doppler Algorithm
SAR    Synthetic Aperture Radar
SARCON SAR Product Control Software
SCR    Signal to Clutter Ratio
CONCLUSIONS

SLC  Single Look Complex


