Tesi di Laurea

Performance evaluation of SAR image compression techniques: application to COSMO-SkyMed data

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If the numbers are boring, then you’ve got the wrong numbers
Edward Tufte, Envisioning Information
Introduction

The needs of remotely-sensed information in the military field date back to ancient times; at the beginning men began to control enemies and their activities from a mountain, then from dirigibles and airplanes. Following the advent of rockets and satellites, observation from the space of both military and political activities taking place on the ground became feasible. Thus, since the beginning of the space exploration, hundreds of satellites have been launched, allowing to integrate the surveillance activities of military intelligence units. For their various potentialities, satellites can now assist in other areas as well as the military one - including communications, meteorology, oceanography, locations and Early Warning. Until nowadays, many satellites have been developed for governmental purpose, supporting scientific researches and environmental monitoring.

Each day the Earth is portrayed by many constellations of remote sensing satellite systems. Built and launched by a variety of international agencies, these satellites have their own specific imaging sensors, which make use of the visible, infrared, microwave and other part of the electromagnetic spectrum. The choice of the frequency range depends on what we want to investigate; for example, the IR range is very useful for studying images of the sea surface, while the analysis of urban areas images require the use of multispectral data.

In this thesis work, the focus is on active sensors; in particular the thesis is based on the analysis of SAR (Synthetic Aperture Radar) systems. The imagery satellites make use of the radar principles to form an image by using the time delay of backscattered signals: these sensors send out short pulses of microwave energy and then record the returns to obtain, by means of complex signal processing steps, a readable image of the surface. SAR images are in
digital form, so they are characterized by picture elements; these are measures referred to the radar backscattered of the ground, whose intensity determines the grey level of the pixel: roads, geological lineaments, field boundaries and forest shadows are detected through the presence of brightness variations.

Nowadays, the exploitation of remote sensing imagery, whether for military or civil applications, always requires human image interpretation. For this reason, in case of operation outside the national borders, it could be useful to dislocate capabilities of remote sensing data analysis (mobile acquisition and processing stations, imagery analysis tools, imagery analysts and data) in the operating theatre, in order to adequately support the decision makers. However, because the covered region is large and image resolution is relatively high, the amount of recorded data is huge and after the necessary processing step (creating useful images from the raw data) the required memory size is often not available. Referring to the high resolution Italian space system COSMO-SkyMed, whose actual products are used in this thesis work, memory size is measured in Gigabytes: this leads to the need to transmit a huge amount of data via ordinary digital communication channels. Compressing the images before transmitting them to the operating theatre could allow to reduce significantly memory size and hence transmission time. If data must be transmitted in near realtime to the operating theatre, compression becomes practically unavoidable.

This thesis work focuses on the performance evaluation of SAR image compression techniques and is divided in two parts:

- In the first part of the work, the topics regarding SAR imagery and data compression have been analyzed:
  - The first chapter deals with on SAR imagery. After describing the general principles and the limits of the traditional RADAR imagery, SAR system and its characteristics are analyzed, focusing on the Italian SAR system COSMO-SkyMed and on the U.S. Sandia National Laboratories researches, whose images are used in the experiments.
  - The second chapter deals with on Image compression. The prin-
ciples of data compression are first described. In particular, concerning the lossy compression techniques, the attention is focused on transform coding, which exploits the limitations of the human visual system. Finally two image compression standards are described: JPEG, based on the Discrete Cosine Transform, and JPEG 2000, based on the Wavelet transform.

– The first half of the third chapter describes how to evaluate image compression. The assessment of the performance of SAR image compression is made by objective and subjective parameters, the former (MSE, SNR, PSNR) used in the scientific field, the latter for operative exploitation, typical of military imagery analysts.

• The second part of the work (second half of the third chapter) applies the acquired knowledge to case-study. The research activity is divided into four steps. First of all, a set of images, which show typical military targets (aircrafts, buildings, airfield facilities, tanks, etc.), has been selected; this step has been conducted jointly with military imagery analysts. Then, the set has been processed by applying image compression techniques. In the third step, the images have been evaluated qualitatively by military imagery analysts, in order to establish the impact of the different techniques on compressed image interpretability. At the end, a quantitative evaluation of compressed images has been performed.

The processing and final evaluation activity was performed at C.I.T.S. (Centro Interforze di Telerilevamento Satellitare) of Pratica di Mare, with a the strict interaction with technical and imagery analyst staff.

The peculiarity of this work consists in measuring the technique quality by objective and subjective metrics: the former characterizes the scientific/quantitative method, while the latter the operative interpreters’ one. In the scientific literature there are a few similar analysis: one of this was published by Jet Propulsion Laboratory and its methodological approach has been taken into account in developing this work of thesis.
This work can be considered as the basis for future developments aiming at the evaluation of the compression technique applicability on recent and future Defense systems, as SICRAL, Storm Shadow, RECCELITE, etc.
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Chapter 1

SAR Images

SAR images are very important for both civil research and military operations. After describing the general principles and the limits of the traditional RADAR imagery, SAR system and its characteristics are analyzed, focusing the attention on the Italian SAR system COSMO-SkyMed and on the U.S. Sandia National Laboratories researches, whose images are used for this thesis work.

1.1 Introduction

The knowledge of the Earth’s surface has always been one of the most interesting topics for human beings. In fact the possibility of investigating the surroundings allows to control natural phenomena and to improve life conditions. Many branches of science, like geology, oceanography, vulcanology, aim at investigating the natural surfaces, seabed and volcanic behavior.

Since the end of the last century, it is possible to acquire information about a region of interest by measuring physical quantities through airplane or satellite-mounted sensors: so it is possible to explore inaccessible zones of the Earth or heavenly bodies.

Remote sensing is the discipline concerned with data capture of an object or phenomenon on planetary surface by the use of sensing devices that are not in direct contact. The aerial photography was developed for military
surveillance and reconnaissance during the World War I and the Cold War. In the latter half of the twentieth century the technology progress took remote sensing research to Space: its importance increased significantly and its sphere of interest extended to the civil ambit (studies about atmosphere, Earth’s surface, ...). Satellite instrumentation (the first was Landsat-1, put into orbit in 1972) provides global measurement of various data both for civil research and military purpose.

There are two basic type of sensors:

**Passive sensors** record radiation reflected by Earth’s surface and generated by natural source (mainly by solar energy). It is the case of electro-optical, infrared, etc, ones.

**Active sensors** are equipped with a transmitting system and receive the signal backscattered from the illuminated surface. It is the case of laser and radar ones.

Active sensors are mostly realized by radar systems operating in the microwaves region of the electromagnetic spectrum [1], in order to work all-weather and all-time conditions and with wavelength dimensions comparable to objects of interests. However the difference is not only in the acquisition way, since *instead of a camera lens and film, a radar uses an antenna and digital computer tapes to record its images* [22] but especially into theirs capacities. Active sensors were created in order to overcome the limits of the passive ones, such as the lack of an independent source of radiation and the presence of clouds or fog covering the area of interest.

RADAR (RAdio Detection And Ranging) systems are designed to measure the strength and round-trip time of the microwave signals emitted by an antenna and reflected on a distant surface or object. A radar antenna allows to transmit and receive a signal at different wavelengths, power and polarization. Echoes are converted to digital data and passed to a data recorder for later processing and then displayed as an image. This means that the active operating mode allows remote sensing system to be independent from
external source (i.e sunlight) and to reduce the impact of weather effect on the obtained images (day and night and all-weather imaging [1]).

Operating in the microwaves region allows to penetrate not only clouds, but also soil and vegetation: scientific research can be extended to the study of geometric and dielectric properties of surfaces (soil or ocean), not achievable by means of optical images.

Information acquired by satellites have many applications and are used in various sectors, such as optimization of the production of natural resources, study of the environment, prediction and monitoring of natural disasters, etc. Remote sensing represents a very effective tool, useful to monitor and keep a check on natural phenomena, because it offers a complete real-time description: for example, it allows to plan and get off the civil protection services.

A fundamental parameter of the radar system quality is the geometric resolution, which expresses the ability of the system to distinguish two near objects as separate entities; it is deeply linked to the frequency band and the antenna characteristics.

The main active sensor limit is the poor resolution achievable with the operating wavelength of the basic configuration, usually referred to Real Aperture Radar (RAR): if the sensor is located at a distance of 800 km and the operating frequency is 1 GHz, we should use a more 10 km long antenna to achieve a 10 meter resolution.

To overcome this limit it is possible to synthesize a very long antenna by moving a small one along a convenient path and then properly processing the received signals. We refer to this system as Synthetic Aperture Radar (SAR).

1.2 Radar Imagery

A transmitting RADAR system consists of an antenna which intercepts remote obstacles (detection) and estimates the distance (ranging). The RAR system generates a microwave impulse and records the backscattered echo. The amount of scattering marks the target and contributes to the reflectivity
1.2 Radar Imagery

Figure 1.1: Radar imaging data capture geometry

valuation of the surface scattering points.

1.2.1 Geometric configuration

The configuration of any imaging radar system is shown in Figure 1.1. The antenna is typically mounted on aircraft or satellite platforms at the altitude $h$ and flies at the speed $v$ along the flight direction. The cylindrical coordinates $(x, r, \gamma)$ are referred to as azimuth, slant range and look angle respectively. This is the coordinates system that naturally matches side-looking radar operation: this configuration is necessary to eliminate right-left ambiguities from two symmetric equidistant point. The platform trajectory, assumed as a straight line, is coincident whit the azimuth axis $x$; the antenna is oriented along the range axis $r$, pointing toward the scene.
Finally, \( \gamma \) is the polar angle in the plane orthogonal to \( x \)- and containing the \( r \)-axis.

With respect to the flight platform path, the radar antenna illuminates a region of the surface, limited in the across track (range), but not in the along track (azimuth) direction. All the points, which belong to the illuminated region and consequently contribute to the backscattered signal, constitute the footprint, which is ellipse-shaped[4].

The sensor transmits and receive impulse with a frequency PRF (Pulse Repetition Frequency) to cover continuously the region of interest. Its inverse, \( T = \frac{1}{PRF} \), represents the delay between two following impulses in order to avoid theirs backscattered echoes to overlap. An impulse can be transmitted from the position \( vT \) only if the time \( \tau = \frac{2\gamma}{c} \) passed between two pulses, where the factor 2 indicates the round-trip time and \( c \) is the speed of propagation.

### 1.2.2 Geometric resolution

*Geometric resolution* is the ability of the system to localize nearby objects. To be more precise, the resolution length is the minimum spacing between two objects that are detected as separate entities and are therefore resolved[1]. The scientific literature refers to a *resolution cell* in two dimensions as the rectangle whose sides are the azimuth (\( \Delta z \)) and range (\( \Delta r \)) resolution.

**Geometric resolution: range**

The geometric configuration considered to calculate range resolution is shown in Figure 1.2, where:

- \( W \) is the projection of the antenna on the plane perpendicular to the look direction
- \( \theta \) is the *look angle*
- \( \Delta \theta \) is the illuminated angular sector. It is assumed that \( \Delta \theta \ll 1 \), i.e. Earth’s curvature it is not taken into account.
In order to estimate the minimum distance between two objects resolved by the system, it is convenient to consider two points (two point objects) A and B in the illuminated region: $r_A$ e $r_B$ are the respective range distance (radar-object distance). If the transmitted signal is an impulse, whose length is $\tau$, the objects are resolved if the backscattered echoes (whose length is still $\tau$, because of the hypothesis of point objects) don’t overlap. If $r_A < r_B$, the signals backscattered by the points A and B are received respectively after a time $\frac{2r_A}{c}$ and $\frac{2r_B}{c}$. The hypothesis of considering backscattered signals separated can be translated in formula as:

$$\frac{2r_A}{c} + \tau \leq \frac{2r_B}{c}$$

(1.1)

So, the smallest distance $\Delta r$ that the system can evaluate, i.e. the range resolution, is:

$$\Delta r = |r_B - r_A| = \frac{c\tau}{2}$$

(1.2)

As shown in Figure 1.3, the distance between two objects on the surface is the projection on the horizontal axis of the range resolution and it is called ground range:

$$X_r = \frac{\Delta r}{\sin \theta} = \frac{c\tau}{2\sin \theta}$$

(1.3)

that is a function of $\theta$, equal to the angle of incidence, from $\theta_{\text{min}}$ to $\theta_{\text{max}}$. 

Figure 1.2: Geometry in the range plane
1.2 Radar Imagery

From expressions (1.2) and (1.3) it is clear that as smaller is \( \theta \), better are range resolution \( \Delta r \) and ground range \( X_r \). At first sight it might be thought to decrease plenty the length of the impulse (\( \tau \)): theoretically, with narrower impulses even very near objects could be resolved.

The choice of \( \tau \) is linked to two requirements:

- If \( \tau \to 0 \), since \( \tau \propto \frac{1}{\Delta f} \), the impulse band (\( \Delta f \)) increases and there are many problems with the antenna realization. As well, using narrow band signal, in order to avoid leakage effects, with small band lengths it is necessary to use very high values of carrier [5].

- The energy of an impulse is \( E = P\tau \), where \( P \) is the transmitting power, and it expresses the sensor capability of detecting: so it is important to transmit an impulse with high energy. Since the maximum power is limited by radar hardware, it is necessary to increase its length \( \tau \).

In order to have high detection capability (high \( E \)) and high resolution (high \( B \)) it is necessary that both \( \tau \) and \( B \) assume a high value, but this condition is impossible with a simple continuous wave impulse considered until now.

A way to meet these contrasting requirements is to substitute the short pulse by modulated long ones, provided that they are followed by a processing step (usually referred to as pulse compression). The most popular waveform
1.2 Radar Imagery

is the *chirp* pulse[1] whose plot is shown in Figure 1.4, it is a linearly frequency modulated signal, mathematically expressed as:

\[
x(t) = \cos \left( 2\pi f_0 t + \frac{\alpha t^2}{2} \right) \text{rect} \left[ \frac{t}{\tau} \right]
\]  

where \( f_0 \) is the carrier frequency and \( \alpha \) is called *chirp rate*. Here and in the following the amplitude information, taken unitary, is suppressed, because it does not play any role in the subsequent analysis.

![Chirp impulse](image)

**Figure 1.4: Chirp impulse**

The instant phase of the chirp signal is:

\[
\varphi(t) = 2\pi f_0 t + \frac{\alpha t^2}{2}
\]  

whereas the instant frequency, defined as \( f(t) = f_0 + \frac{1}{2\pi} \frac{d\varphi(t)}{dt} \), is

\[
f(t) = f_0 + \frac{\alpha t}{2\pi} \quad -\frac{T_c}{2} \leq t \leq \frac{T_c}{2}
\]  

Differently from a continuous wave impulse, the chirp instant frequency is proportional to time length \( \tau \); in particular it increases if \( \alpha > 0 \) and decreases otherwise. Since \( t \in \left[ -\frac{T_c}{2}, \frac{T_c}{2} \right] \) and with the hypothesis that \( \alpha > 0 \), the instant frequency varies in the interval:

\[
f_0 - \frac{\alpha T_c}{2\pi} \leq f(t) \leq f_0 + \frac{\alpha T_c}{2\pi}
\]  

i.e., in the interval considered, the instant frequency variation is:

\[
\Delta f = \frac{\alpha T_c}{2\pi}
\]

[1]The word *chirp* refers to the short high sounds made by small birds
In conclusion, a chirp impulse is characterized by an instant frequency variation proportional to time length, that is

\[ \Delta f \propto \tau_c \]  
(1.9)

And its band can be approximated by this value, i.e.:

\[ B_c \equiv \Delta f \propto \tau_c \]  
(1.10)

So the chirp impulse is important because its band is proportional to its time length. A chirp impulse with a long time length (high energy) can assure high resolution (achievable with a narrow impulse) because, during the receiving period, the different signal components (each one at a different frequency) are delayed. For this reason, two echoes backscattered from nearby objects are overlapped in the received signal, but the instant frequency \( f(t) = f_0 + \frac{\Delta f}{\tau} t \) is different for each echo at each instant. So it is possible to separate echoes but they need a following processing in order to obtain again the expression \( B = \frac{1}{\tau'} \), where \( \tau' \) is the time length of the compressed impulse: this is an adaptive filtering of the transmitted signal\[4\].

Replacing \( \tau \) with \( \frac{1}{B_c} \), the expression (1.3) can be written as:

\[ X_r = \frac{c}{2\Delta f \sin \theta} \]  
(1.11)

i.e. the band of the impulse must be raised in order to improve the resolution.

Furthermore, using a chirp signal, if we increase \( B_c \) then \( \tau \) increases and, consequently, also the transmitted power.

**Geometric resolution: azimuth**

The platform is considered carrying the radar system and moving along the azimuth direction; as for the range case, amplitude factors are neglected. Azimuth resolution explains the capability of an imaging radar to distinguish two points at the same range distance in the direction parallel to the flight direction. A RAR system can resolve two points in the azimuth direction
only if they are not within the radar beam at the same time, i.e. the distance is greater than the footprint. It implies that the azimuth resolution is independent of the impulse properties, but not of transmitting system characteristics, because points are not resolved in the footprint. So the azimuth resolution is given by the footprint width (in the azimuth direction):

\[ X_a = r \theta_a \simeq r \frac{\lambda}{L} \]  

(1.12)

where:

• \( L \) is the seeming dimension of the antenna in the azimuth direction

• \( \theta_a \) is the beam width, in radiant, as shown in Figure 1.5

![Figure 1.5: Geometry in the azimuth plane](image)

The beam width is expressed by:

\[ \theta_a \simeq \frac{\lambda}{L} \]  

(1.13)

with the hypothesis that \( \theta_a \ll 1 \), always valid because of the condition \( \lambda \ll L \) necessary for the antenna projection.
To have an idea of the achievable azimuth resolution, the expression \((1.13)\) can be applied to the COSMO-SkyMed sensors parameters: at the range distance of \(r = 900 \text{ km}\) (i.e. at the altitude of \(600 \text{ km}\) about), with a wavelength of the frequency carrier of \(\lambda = 3 \text{ cm}\) about and an antenna length of \(L = 6 \text{ m}\) it is possible to have an azimuth resolution:

\[
X_a = 6 \times 10^5 \times 3 \times 10^{-2} \times 6 \simeq 100 \text{ km}
\]

This value is of the order of kilometers and this is not acceptable for most applications.

So it is evident that a RAR system does not assure good resolution in case of high orbital altitude, aside from its other characteristics. For a RAR system, the azimuth resolution can be improved:

- increasing the antenna dimension
- decreasing the wavelength of the carrier frequency
- decreasing orbital altitude

However, since it is necessary to have high orbital altitude, in order to illuminate an extensive region, microwaves are necessary to penetrate the atmosphere and the antenna size cannot exceed tens meters, it is not possible to improve azimuth resolution of a RAR system.

### 1.3 SAR Sensors

In order to improve azimuth resolution (Equation \((1.13)\)), using microwaves frequency, it is necessary to increase the antenna dimensions: its directivity will be greater and the footprint smaller. The impossibility of realizing and putting into orbit a very large antenna is circumvented by synthesizing it by moving along a reference path a real one of limited dimensions: this system is called *Synthetic Aperture Radar* (SAR). The first operational SAR system was believed to be the X-band one built in 1957 by Willow Run Laboratories of the University of Michigan (currently *Environmental Research Institute of*
Michigan ERIM) for the U.S. Department of Defense (DoD). ERIM and JPL (Jet Propulsion Laboratory) jointly conducted the Apollo Lunar Sounder experiment, which successfully flew onboard the Apollo 17 lunar orbiter in 1972 [1]. This is the first use of SAR system.

### 1.3.1 Principles

SAR functioning is based on the platform movement along its flight direction: with the hypothesis of constant speed $v$, a target point on the surface is illuminated while the space covered by the sensor is $X$. As shown in Figure 1.6, called $x_1$ the first position and $x_n$ the last position for which the sensor detects the target point, the distance between $x_1$ and $x_n$ is $X$.

![SAR system data capture geometry](image)

Figure 1.6: SAR system data capture geometry

The antenna is synthesized by moving a small antenna along its track, not continuously, and it can be thought as an antenna array, whose length is $X$. While the antenna covers a space $X$, it receives many backscatter echoes from a target point: after processing these echoes the azimuth resolution is improved. It is important to underline that a single echo, backscattered from a target point, change their wavelength: this effect, called Doppler effect, is used for the image focusing. It concerns the change in frequency
and wavelength of a wave for an observer P moving relative to the source of the waves S. In particular, the frequency transmitted by S increases, if the source moves near the observer, and decreases otherwise.

Backscattered echoes are recorded and the Doppler history, or phase history, is a curve which describes them. For a target point, the received signal is characterized by a quadratic instant phase: it is necessary to consider the effect of range migration, as analyzed in [4]. During the synthesizing of the antenna, the range distance varies\(^2\)

\[
r(x) = \sqrt{r_0^2 + x^2} \simeq r_0 + \frac{x^2}{2r_0}
\]

The phase difference between the transmitted and received signals, proportional to the sensor-target distance, is expressed as \(\phi = 2\pi f_0 \frac{2r}{c}\). So, the phase variation is:

\[
\Delta \phi(x) = \frac{4f_0}{c} \frac{x^2}{2r_0} = \frac{2\pi x^2}{\lambda r_0}
\]

Since \(x = vt\), the azimuth frequency is proportional to \(t\):

\[
\Delta f = \frac{1}{2\pi} \frac{d(\Delta \phi(t))}{dt} = \frac{2v^2 t}{\lambda r_0}
\]

Where \(\Delta f\) is the Doppler frequency, i.e. the difference between the frequency of the transmitted and the received signal, due to the relative movement. The received signal band is:

\[
B_a = \frac{2v^2 T_a}{\lambda r_0} = \frac{2v}{L}
\]

The Doppler frequency has the same expression of the chirp band. Therefore, as in the range plane two points are resolved if the time distance is \(\Delta t = \frac{1}{B_c}\), in the azimuth they are resolved if \(\Delta t = \frac{1}{B_a}\). Concerning space variables, the distance must be:

\[
X_a = v\Delta t = v \frac{1}{B_a} = \frac{L}{2}
\]

Unlike conventional radar systems, the resolution is constant for all the

\(^2\)Taylor cut series, with \(x \ll r_0\)
illuminated points of a swath. Moreover the number of received samples and the length of the antenna is function of the range distance: as shown in Figure 1.7, the point \( P' \), in the far range, is illuminated by an antenna longer than in the range case, point \( P \). Consequently the resolution is not function of the distance sensor-target point: if the distance increases, the resolution decreases, but the antenna length increases and it receives more echoes.

![Figure 1.7: Near and far range](image)

Reading Expression (1.19), it seems that the resolution can be increased by using a smaller antenna; however, by doing so, there are many energy problems.

### 1.3.2 SAR Image characteristics

SAR images are in digital form, so they are characterized by picture elements (pixel). Each pixel refers to the radar backscatterer on the ground and the amount of the backscattering determines the grey-level (tones) of object: for example, water produces a relatively dark tone since it produces little backscatter toward the radar, trees give medium tone and buildings correspond to light tones. In general bright features mean that a large fraction of the radar energy was reflected back to the radar, while dark features
1.3 SAR Sensors

imply that very little energy was reflected.

The amount of the backscatter echoes is function of many terms, as wavelength, size of the scatter point, moisture content of the illuminated area, polarization of the transmitted pulse, observation angles.

In Figure 1.8 are shown many examples of illuminated surfaces.

![Examples of illuminated surfaces](image)

Figure 1.8: Examples of illuminated surfaces

1.3.3 SAR Image structure

A SAR image can be modeled as a sum of four components, as analyzed in [13] and [23]:

- the *micro-texture* appears as randomly placed bright spots, the same size or a little larger than the resolution cell.

  It is also called *speckle*.

- the *meso-texture*, also called *scene texture*, is the variation of backscatter due to the material and geometry of the objects. These elements are necessary for image interpretation, because they are characterized by an elementary unit covering several resolution cell.

---

[Textural element]: i.e. the texture elementary unit, smallest homogeneous element of the same radiometry constituting the texture
1.3 SAR Sensors

- the *macro-texture* are present when radar brightness variations are larger than many resolution cell, because of the presence of roads, geological lineaments, field boundaries and forest shadow.

- *homogeneous regions* characterized by the mean backscattering of homogeneous areas.

1.3.4 Speckle

Until now SAR signals have been considered to be deterministic variables, but this is not the real case, because it is necessary to consider the scattering properties of the illuminated scene. The roughness of the scene (for the surface scattering) and the density of the scatterers (for the volume scattering) can only be described in terms of statistical parameters, thus rendering the scattered field (the SAR raw signal) a random process.

In this case it is not important to characterize analytically it, but it is sufficient to explain the result of considering real surfaces. In fact a SAR resolution cell is very large when compared to the wavelength of the illuminating electromagnetic wave; in addition, a large number of scatterers are generally present within each cell, due to roughness of the surface and/or inhomogeneities of the scattering volume [1]. The received echo is the result of the coherent summation of all the returns due to the single scatterers, as shown in Figure 1.9.

![Figure 1.9: Speckle: coherent summation of echoes](image)

While the sensors moves, these contributions change with time and the received signal changes accordingly. This fluctuation in the received signal
causes on SAR imagery a grainy appearance, referred to as *speckle*.

**Radiometric resolution**

While the pixel size gives information about the spatial structure of an image, the *radiometric* characteristics describe the actual information content in an image. The *radiometric resolution* is a measure of the ability of the system to discriminate, or resolve, areas of different scattering properties [1], that are described by the reflectivity pattern $\gamma(x,r)$ of the illuminated surface. These properties change because of macroscopic and microscopic variations.

Since the shape of the surface and its electrical properties are function of the space coordinates, $\gamma(x,r)$ change with a rate that does not exceed the geometric resolution (*macroscopic changes*); its intensity competes with thermal noise. Moreover *microscopic changes* are due to the roughness of the surface and influence the phase, on a scale much shorter that the geometric resolution, statistically in nature. The ability of the system to retrieve this value is related to the speckle. So the radiometric resolution is dependent on both signal, speckle and thermal noise intensities.

Concerning the sensor ability of detecting, the radiometric resolution of an imaging system describes its ability to discriminate very slight differences in energy: the finer the radiometric resolution of a sensor, the more sensitive it is detecting small differences in reflected or emitted energy.

**Removing speckle**

Considering speckle as noise, it is possible to *denoise* the image by:

- Filtering techniques, using a moving windows filter that changes the intensity of the central pixel, depending on the intensities of all the pixels within the window [23]. Algorithms differ in the shape of the impulse response of the filter.

- Multilook, based on the averaging of independent measurements of the same target, called *looks*: they are averaged in order to reduce the grey level random variations, provoked by speckle. As explained in
multilook differ in the averaging domain: in one look, averaging of adjacent pixels, otherwise time, space and frequency.

1.3.5 Geo-referencing

Since most applications require localization of features within the image, it is necessary to geo-refer SAR data: referencing data to a coordinate system allow to analyze data taken using different sensors and imaging geometries and combining with other raster and vector format data [14].

The natural SAR image coordinates are offered by the along-track position of the platform, slant range and Doppler processing parameters: in fact these parameters are stored with image data, as ancillary information.

Geographic map coordinates are specified in terms of the projection parameters, ellipsoid and datum. The transformation of data in SAR coordinate into an orthogonal geographic map projection introduce spatial shifts on the original image in order to have a correspondance between the position of points on the final image and their location in a given cartographic projection.

Moreover SAR data geocoding is a very important step for many users because SAR data should be geometrically correct. As analyzed in [3], the most important and well known local image distortions are foreshortening, layover, and shadow (Figure 1.10). The radar sensor doesn’t see the area on the ground, but it consider the range distance: this causes that in the range elevated features are mapped in false range position.

Figure 1.10: Image distortions
These effects as well as the varying ground resolution caused by different slopes can be corrected using a digital elevation model (DEM), i.e. a digital representation of ground surface topography or terrain.

1.4 Analytical characterization

SAR Images can be achievable as a matrix, whose pixels are the samples of the $2-D$ impulse response in the range and azimuth planes. Generally this processing operation is performed in the transformed domain, using the Discrete Fourier Transform (DFT).

1.4.1 Impulse response in range plane

In the assumed cylindrical coordinate system shown in Figure($T = (x, r, \theta)$), the radar platform moves along the x-axis.

At first, it is assumed that $x = 0$, i.e. it is considered a plane orthogonal to the flight direction. An object, referred to $T = (0, r, \theta)$ lies in this plane. With the hypothesis that the target is a point, the backscattered signal is a translated version of the chirp signal (expressed by the Equation (1.4) and shown in Figure 1.4:

$$f \left( t - \frac{2r}{c} \right) = \exp \left[ j \left( t - \frac{2r}{c} \right) + j \alpha \frac{2}{c} \left( t - \frac{2r}{c} \right)^2 \right] \operatorname{rect} \left[ \frac{t - 2r/c}{\tau} \right] \quad (1.20)$$

After the heterodyne operation and the passage to space coordinates:

$$\begin{cases} r_N' \rightarrow \frac{r'}{c} \\ r_N \rightarrow \frac{r}{c} \end{cases} \quad (1.21)$$

the Equation (1.20) transforms as:

$$f(r' - r) = \exp \left[ -j\omega \tau r + j\alpha \tau^2 \frac{1}{2} (r' - r)^2 \right] \operatorname{rect}[r' - r] \quad (1.22)$$

---

4The passage to space variables consist of changing $t \leftrightarrow \frac{2r'}{c}$ and normalizing to the $\frac{c}{\tau}$.

5The pedix $N$ is omitted.
This is the received signal.

This signal must be processed with the range reference function:

\[
g(r' - r) = \exp \left[ -\frac{j \alpha}{2} \tau^2 (r' - r)^2 \right] \text{rect}[r' - r] \tag{1.23}
\]

The processed signal \( \hat{f}(r' - r) \) in unnormalized units is:

\[
\hat{f}(r' - r) = f(r' - r) \otimes g(r' - r) = ... \simeq e^{-j\omega \tau r} \text{sinc} \left[ \frac{\pi}{\Delta r} (r' - r) \right] \tag{1.24}
\]

where it is demonstrated that the range resolution \( \Delta r = \frac{\nu}{2\Delta f} \) is:

- the normalized effective range dimension of the target image
- the distance between the \( \approx -3 \) decibel points and the maximum of \( \hat{f}(r') \).

Figure 1.11: Point target processed signal in range plane

In the real situation of a continuous distribution of scatterers points described by a reflectivity pattern \( \gamma(r) \), proportional to the ratio between backscattered and incident field \[ \Pi \], the processed signal is obtained by superposition:

\[
\hat{\gamma}(r') = \int \gamma(r) \hat{f}(r' - r) dr = \int \gamma(r) \exp(-j\omega \tau r) \text{sinc} \left[ \frac{\pi}{\Delta r} (r' - r) \right] dr \tag{1.25}
\]
1.4 Analytical characterization

1.4.2 Impulse response in azimuth plane

In the azimuth dimension, the geometric configuration considered is shown in Figure 1.6.

The real antenna transmission/reception is not continue, but takes place at \((2N + 1)\) equally spaced positions. Considered a point target \(T \equiv (0, r, \theta)\) (where \(x = 0\) refers the center of the scene), the antenna illuminates it at positions \(S \equiv (x' = n'd, r = 0)\), with \(n' \in [-N, N]\).

About the antenna, it is assumed that its radiation is isotropic within its beam width and the illuminated surface is expressed by the Equation (1.12). Neglecting amplitude factors, after the heterodyne process, the signal backscattered is:

\[
f(n'd) = \exp \left(-j\omega \frac{2R}{c} \right) \approx \exp \left[-j\omega \frac{2r}{c} - j\frac{2\pi}{\lambda r}(n'd)^2\right]
\]

where:

- \(R = \sqrt{r^2 + (n'd)^2} \approx r + \frac{(n'd)^2}{2r}\) \[^6\]
- \((n'd)\), with \(n' \in [-N, N]\), is the discrete abscissa of the sensor along its path \(x\).

Neglecting the phase term \(\exp \left(-j\omega \frac{2r}{c}\right)\), because it is independend of sensor position, the Equation (1.26) becomes:

\[
f(n'd) = \exp \left[-j\frac{2\pi}{\lambda r}(n'd)^2\right] \quad n' \in [-N, N] \quad (1.27)
\]

Once recorded, the signal must be processed \[^7\] convoluting with the azimuth reference function:

\[
g(n'd) = \exp \left[j\frac{2\pi}{\lambda r}(n'd)^2\right] \quad n' \in [-N, N] \quad (1.28)
\]

\[^6\] Taylor cut series

\[^7\] This processing operation corresponds to synthesize an antenna of length \(2Nd = X\).
\[ \hat{f}(n'd) = f(n'd) \otimes g(n'd) = \ldots \approx \frac{\sin \left[ \frac{2\pi}{N} (2Nd) \right]}{N} \quad n' \in [-N, N] \] (1.29)

Operating with continuous variables \((n'd \rightarrow x')\) and normalizing \((x'_N = \frac{x'}{N}, x'_n \rightarrow x')\), in the neighbors of the target position \(x = 0\), the Equation (1.29) becomes:

\[ \hat{f}(n'd) = \text{sinc} \left[ \frac{\pi}{\Delta x} (x - x') \right] \quad x' \approx x \] (1.30)

where the azimuth resolution \(\Delta x\) is the homologous of \(\Delta r\) (about the size of the \(\text{sinc}(\cdot)\) function).

As in the case of range processing, in view of the linearity, distributed targets are accounted for by superposition and the estimated reflectivity is given by:

\[ \hat{\gamma}(n'd) = \int \gamma(x) \hat{f}(n'd - r) dx = \int \gamma(x) \text{sinc} \left[ \frac{\pi}{\Delta x} (n'd - x) \right] dx \] (1.31)

Since the spatial bandwidth of \(\hat{\gamma}(\cdot)\) is determined by the \(\text{sinc}(\cdot)\) function and equals \(\frac{1}{\Delta x}\), the processed signal for any continuous abscissa value \(x'\) can be exactly reconstructed via sampling interpolation:

\[ \hat{\gamma}(x') = \sum_{n'} \hat{\gamma}(n'd) \text{sinc} \left[ \frac{\pi}{\Delta x} (x' - n'd) \right] = \ldots = \int \gamma(x) \text{sinc} \left[ \frac{\pi}{\Delta x} (x' - x) \right] dx \] (1.32)

### 1.4.3 Estimated reflectivity of the scene

By combining the Equations (1.25) and (1.32), the overall SAR image expression is:

\[ \hat{\gamma}(x', r') = \int \int \gamma(x, r) \text{sinc} \left[ \frac{\pi}{\Delta x} (x' - x) \right] \text{sinc} \left[ \frac{\pi}{\Delta r} (r' - r) \right] e^{-j\omega \tau r} dxdr \] (1.33)

\(^8\)Whittaker–Shannon interpolation formula
where $\hat{\gamma}(x, r)$ represents the two-dimensional reflectivity pattern of the scene.

1.5 Remote sensing Systems

The Earth is being imaged each day by many constellations of remote sensing satellite systems. Built and launched by a variety of international agencies, these satellites have their own special systems of imaging sensors, which make use of the visible, infrared, microwave and other part of the electromagnetic spectrum. In this thesis work, the analysis is based on the Italian space system COSMO-SkyMed and on the U.S. DoD Sandia National Laboratories researches about U.A.V. (Unmanned Aerial Vehicle) SAR sensors.

1.5.1 COSMO-SkyMed

COSMO-SkyMed is the first example of Dual-Use (civil and military) remote sensing system, conceived and designed in order to create a global service supplying provision of data, products and services compliant with well-established international standards and relevant to a wide range of applications, such as Risk Management, Scientific and Commercial Applications and Defense/Intelligence Applications [20].

This system, funded by ASI (Italian Space Agency) and Italian MoD (Ministry of Defense), consists of a constellation of four mid-sized satellite, in low Earth orbit, each equipped with a multi-mode high-resolution SAR operating at X-band. Ground infrastructures are full dedicated for managing the constellation and assure the collection, archiving and distribution of acquired data.

The set of requirements imposed at highest level has brought to the following needed performances [20]:

- Large amount of daily acquired images,
- Satellites worldwide accessibility,
- All weather and Day/Night acquisition capabilities,
• Very short interval between the finalization of the user request for the acquisition of a certain geographic area and the release of the remote sensing product (System Response Time)

• Very fine image quality (e.g. spatial and radiometric resolution)

• Possibility of image spatial resolution trade-off with size, at most possible extent and including sub-meter resolution;

• Capability to be a cooperating, interoperable, expandable to other EO (Earth Observation) missions, multimissionborne element providing EO integrated services to large User Communities on a worldwide scale.

Since these requirements need many combinations between size and spatial resolution, the SAR was chosen as a multimode sensor, as shown in Figure [1.12] operating in:

• **Spotlight mode**, for metric resolutions over small images ($10km \times 10km$).

  In order to illuminate the scene for a time period longer than the one of the standard strip, during the acquisition time, the antenna is steered both in the azimuth and the elevation plane, increasing the length of the synthetic antenna and therefore the azimuth resolution. The acquisition is performed in frame mode and is limited in the azimuth direction, because of the antenna pointing.

  There are two CSK Spotlight modes, whose one (*Spotlight-2*) is only for military operations.

• **Stripmap mode**, for metric resolutions ($3 – 15m$) over tenth of km images ($40km \times 40km$).

  It is the most common imaging mode, obtained by pointing the antenna along a fixed direction with respect to the flight platform path. The antenna footprint covers a strip on the illuminated surfaces as the platform moves and the system operates.
There are two CSK Stripmap modes: the *Himage* and the *PingPong*. The latter implements a strip acquisition by alternating a pair of Tx/Rx polarization across bursts (crosspolarization).

- **Scansar mode** for medium to coarse (100 m) resolution over large swath.

There are two different implementation for CSK Seasar mode: *WideRegion* and *HugeRegion*, achievable by grouping of acquisition over few subsawths.

<table>
<thead>
<tr>
<th>Product</th>
<th>Swath width</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spotlight-2</td>
<td>10km × 10km</td>
<td>under 1m</td>
</tr>
<tr>
<td>Himage</td>
<td>40km</td>
<td>under 3-15m</td>
</tr>
<tr>
<td>WideRegion</td>
<td>100km</td>
<td>under 30m</td>
</tr>
<tr>
<td>HugeRegion</td>
<td>200km</td>
<td>under 100m</td>
</tr>
<tr>
<td>Ping Pong</td>
<td>30km</td>
<td>under 15m</td>
</tr>
</tbody>
</table>

Table 1.1: CSK SAR Products main characteristics
1.5 Remote sensing Systems

COSMO-SkyMed SAR Products

The COSMO-SkyMed products are divided in three classes: Standard products, Higher level products (for mid or even high level remote sensing applications) and Service products (for internal use only).

The SAR Standard products are the basic image products of the system, whose some examples are shown in Figure 1.14 and can be divided into 4 typologies:

Figure 1.13: The 5 types of COSMO-SkyMed Standard Products (examples from ERS1)

**Level 0 RAW data:** this data consist of time ordered echo data, obtained after decryption and decompression and after applying internal calibration and error compensation; it include all the auxiliary data required to produce the other basic and intermediate products

**Level 1A, Single-look Complex Slant product,** RAW data focused in slant range-azimuth projection, that is the sensor natural acquisition projection

**Level 1B, Detected Ground Multi-look product,** obtained detecting, multilooking and projecting the Single-look Complex Slant data onto a grid regular in ground. It is important to underline that Spotlight Mode products are not multilooked
1.5 Remote sensing Systems

**Level 1C/1D**, Geocoded product GEC (1C level product) and GTC (1D level product), obtained projecting the 1A product onto a regular grid in a chosen cartographic reference system. In case of Lev 1C the surface is the earth ellipsoid while for the Lev 1D a DEM (Digital Elevation Model) is used to approximate the real earth surface. In Lev 1D data is constituted by the Backscattering coefficient of the observed scene, multilooked (except for Spotlight Mode), including the annexed the Incidence Angles Mask.

For example, in accordance with the image used for this research, the Stripmap-Himage and Spotlight-2 product characteristics are:

For standard use, the format adopted for products distribution is HDF5, which allow to store image layers and the ancillary information.
1.5 Remote sensing Systems

The HDF5 (Hierarchical Data Format) format and software was developed and supported by NCSA (National Centre for Supercomputing Applications University of Illinois) since 1988 and is freely available. It is used worldwide in many fields (including environmental science, the study of neutron scattering, nondestructive testing and aerospace research), NASA’s EO System and the Department of Energy’s Accelerated Strategic Computing Initiative.

HDF5 files are organized in a hierarchical structure, as shown in Figure 1.14(a), with two primary structures, groups and datasets.

![HDF5 hierarchical organization and the application of HDF structure to EO images](image)

Figure 1.14: HDF5 hierarchical organization and the application of HDF structure to EO images

This description refers to [21].

1.5.2 Sandia National Laboratories

Sandia National Laboratories are a government-owned/contractor operated facility for the U.S. Department of Energy’s National Nuclear Security Administration. It is Sandia’s mission to maintain the reliability and surety of nuclear weapon systems, conduct research and development in arms control
and nonproliferation technologies and investigate methods for the disposal of the US’s nuclear weapons program’s hazardous waste. Other missions include research and development in energy and environmental programs, as well as the surety of critical national infrastructures. In addition, Sandia is home to a wide variety of research including computational biology, mathematics, materials science, alternative energy, psychology, and cognitive science initiatives [25].

The analysis of this thesis is based on Sandia’s products also, free downloadable because first test images. Their characteristics are the same of SAR imagery (all-weather and all-time imaging, seeing through clouds and smoke, . . . ), but their resolution is definitely higher, because there sensors work on UAVs.

Working at 16.8 \( \text{Hz} \) (the frequency can be extended to X/Ka bands) and flying at UAVs altitude, although the stability platform problems, it is possible to achieve 4-inch (0.1m about) resolutions in spotlight mode, which allow analysis of small object [24].

Figure 1.15 shows main characteristics of sensor and images:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Notes/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>Radar electronics assembly (REA): 9lbs</td>
<td>Follow-on version will be 18lbs</td>
</tr>
<tr>
<td></td>
<td>Antenna/Global assembly (AGA): 17lbs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>System total: 27lbs with cables</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>REA: ~ 7-inch cube</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AGA: ~10-inch cube</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>16.8 GHz</td>
<td>Readily extensible to X/Ka bands</td>
</tr>
<tr>
<td>Resolution</td>
<td>4-inch resolution</td>
<td>Spotlight mode, real-time</td>
</tr>
<tr>
<td>Range</td>
<td>10 km @ 4-inch resolution</td>
<td>Other range/weight tradeoffs</td>
</tr>
<tr>
<td></td>
<td>15 km @ 1-foot resolution</td>
<td>35 km with 31.5 lb AGA</td>
</tr>
<tr>
<td></td>
<td>23 km @ 12-inch resolution</td>
<td>5 km with 7 lb AGA</td>
</tr>
<tr>
<td>Tx power</td>
<td>60 W</td>
<td></td>
</tr>
<tr>
<td>Modes</td>
<td>Spotlight</td>
<td>Stripmap, GMTI, CCD (follow-on)</td>
</tr>
</tbody>
</table>

Figure 1.15: Characteristics of Sandia National Laboratories sensor and images
Chapter 2

Image Compression

This chapter will describe the motivations and principles of data compression. In particular, concerning the lossy compression techniques, it will focus on those based on transform coding, which exploit the limitations of the human visual system. Finally two image compression standards will be described in more detail: JPEG, based on the Discrete Cosine Transform, and JPEG2000, based on the Wavelet transform.

2.1 Introduction

In the last few years, human communications have much changed and are still changing, because of the rapid development of Internet and mobile and video communications. Among the many aspects of this multimedia revolution, data compression stands out: if images, video, audio are not compressed, it is not practical to use Internet, because their dimensions have much increased, compared to a few years ago. But data compression is not important only in Internet world: for example, it allowed to improve cellular phone communication clarity and the advent of digital TV.

Data compression is no longer a prerogative of scientists and engineers, but nowadays everybody use it daily, for example making a long-distance call, using the modem or the fax, listening to music or watching a DVD film. In everyday language, without doubt everyone has heard at least sometimes the
2.1 Introduction

acronyms JPEG and MPEG, which are two examples of data compression standards, respectively for images and videos.

The need to use data compression is linked to the current trend of multimedia communications. Since data can be characters in a text file, numbers that are samples of speech or image waveforms, or sequences of numbers that are generated by other processes, the dimensions of a multimedia file can be huge. Without using compression, for example, 1 second of video needs more than 20 Megabytes, and 2 minutes of CD-quality music requires more than 10 megabytes. At this rate it is nearly preclusive to download music or videos from a website. Although data-transmission is significantly advancing, allowing the store and transmission of larger volumes of information without using compression (for example by optical fibers, Asymmetric Digital Subscriber Lines (ADSL), and cable modems), as a corollary to Parkinson’s First Law\footnote{Work expands to fill the time available.}, the need for mass storage and transmission increases at least twice as fast as storage and transmission capacities improve\cite{2}.

Concerning its use, data compression allows to reduce the number of bits required to represent an image or a video sequence or music. This is one of the alterations which are applied to a signal before its transmission. In general, in an efficient and reliable digital data transmission, the signal is always coded. There are two types of coding processes:

**Source coding**, which concerns the process of encoding information using fewer bits than an unencoded representation

**Channel coding**, whose aim is to find codes which transit quickly and to protect the transmission against errors.

This thesis will overlook the latter and will consider only the analysis of source coding and data compression.
2.2 Source coding

Source coding is the process by which data that are generated by a discrete source is represented efficiently, according to the semantic of the original data. This purpose can be achieved by exploiting the knowledge of the statistics of the source: after recognizing the redundancy in the data, this can be eliminated without degrading significantly the reproduction quality. The identification of the data statistical regularities, their description in the form of model and the extraction of all redundancies are the major steps that lead to data compression, often quite difficult to pursue.

*Morse code* and *Braille code* are early examples of data compression, the first based on the frequency of occurrence of single characters, the latter on the frequency of occurrence of words. In order to reduce the average time required to send a message, in the Morse code, developed by S. Morse, shorter sequence are assigned to letters that occur more frequently, such as e (.) and a (-.), and longer sequences to letters that occur less frequently, such as q (- . -) and j (. - - -); the Braille code, which represents text by $2 \times 3$ arrays of dots, uses a similar approach to reduce the average space occupation of about 20%.

However, in addition to the statistical ones, in the data there are other structures which can be exploited for compression; one of them refers to the characteristics of the user of the data. In the case of speech and images, the user are humans, whose perceptual abilities are limited: for example, humans cannot hear the very high frequencies that dogs can hear and the human eye is more sensitive to subtle variations in luminance than it is to variations in color. By taking advantage of the limits of the human sensory system, many algorithms are designed in order to eliminate the unperceptible components.

There are two techniques of source coding, different into purpose:

**Lossless coding**, which exploits only the statistical redundancy and involves no loss of information

**Lossy coding**, which exploits the limitations of human sensory system as well and hence involves loss of information
2.2 Source coding

For both techniques the same block diagram holds, shown in Figure 2.1 divided into two parts: a coder transforms a signal $X$, generated by an input source, into a compressed file $X_C$ and a decoder, after receiving, such a file, possibly modified because of channel losses, $\hat{X}_C$, reconstructs the original file ($Y = X$) or an approximation ($Y \neq X$).

![Block diagram for general data compression](image)

Figure 2.1: Block diagram for general data compression

A performance parameter important for both lossy and lossless coding is the Coding rate $R$, which provides the average number of bits required to represent a single sample, considering for example a pixel of an image. The average number of bits per pixel in the compressed representation is 2 than the rate will be 2 bits per pixel.

Another parameter, linked to the first, is the Compression rate $CR$, used to quantify the reduction in data-representation size produced by a data compression algorithm (it is the analogous to the physical compression rate, used to measure physical compression of substances and defined as the ratio between uncompressed and compressed size). If $n_S$ refers to number of bits required to represent the data before and $n_C$ the number of bits required to represent the data after compression, the compression rate is defined as:

$$CR = \frac{n_S}{n_C}$$  \hspace{1cm} (2.1)
If an image requires 65,536 bytes before compression and, 16,384 bytes after compression, the compression ratio will be 4:1, i.e the compressed image is reduced as a percentage of 75%. For signals of interest (like data, audio and image files), the compression rate does not exceed the value 2 if only lossless compression is used, that is, perfect reconstruction is required.

Since the aim of lossy compression is not the exact reconstruction of the image, it is possible to obtain higher compression rates: depending on the quality required for the reconstructed data, varying amounts of loss of information can be tolerated. So, concerning the evaluation of compressed data (with lossy algorithms), it is necessary to define a measure of the reconstruction quality: the difference between the original and the reconstruction is called distortion\(^2\). Graphically it is important to consider the rate-distortion curves, which plot the distortion as a function of the rate: for one value of rate, compression techniques should try to minimize distortion. It is obvious that high efficiency and high quality are not achievable together.

The Rate-Distortion Theory, created by C. Shannon, gives theoretical bounds for how much compression can be achieved using lossy compression methods, in terms of curves \( R(D) \) and \( D(R) \), for given sources and distortion measures. This task is very complex, also for simple sources, and it is impossible to consider a general model for these curves; moreover, the most difficult step is the statistical characterization of the image.

### 2.2.1 Lossy compression

The advantage of lossy methods over lossless ones is that they typically produce smaller compressed files while still meeting the requirements of the applications.

When a user acquires a lossy compressed file, the retrieved file can be quite different from the original one the bit level while being indistinguishable to the human ear or eye for most practical purposes. This loss creates skepticism in several scientific communities, like medicine or remote sens-

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\(^2\)Talking about distortion the concepts of fidelity and quality will be widely analyzed in Chapter 3.
2.2 Source coding

ing. However some loss is implicit in the analog-digital conversion, which consist on sampling and quantizing the signal, but it is tolerated because of the potential advantages of digital formats: so the actual problem is not if compress, but what is its limit [1].

Most lossy compression techniques represent source symbols using one of a small number of codewords. In general, the number of possible distinct source values is much larger than the number of codewords available to represent them: the process of representing a large-possibly infinite, set of values with a much smaller set is called quantization [2].

Although quantization is a simple process, the design of the quantizer influences significantly the amount of compression: coding performances improve if quantizer parameters are well suited to source statistics. A quantizer can be designed considering the probability distribution of the source or an empirical distribution of data: for example, if statistics change in time, it is useful to design an adaptive quantizer, whose characteristics are function of the signal statistics. However redundancy is not taken into account by means of quant. In order to exploit the statistical dependence between adjacent samples or pixel, it is possible to:

- elaborate jointly symbols which must be quantized (for example by a vector quantizer).
- decorrelate data, i.e. eliminate the linear dependence, by a prediction or a transform and then quantize.

Since it is simpler and gives good results, the latter approach is used in many standards. To understand its rationale, let us consider the following example (taken by [6]).

Let us consider an input sequence:

\[ x_n = \{9, 11, 11, 14, 13, 15, 17, 16, 17, 20, 21\} \quad 1 \leq n \leq 12 \quad (2.2) \]

Without compression, the bynary transmission needs 5 bit \( \times 12 = 60 \) bits. However, analyzing the sequence, it is clear that a linear dependence exists,
2.2 Source coding

which can be modeled as:

\[ \hat{x}_n = n + 8 \]  \hspace{1cm} (2.3)

Now, considering the sequence given by the difference between the homologous symbols, the error sequence is:

\[ e_n = x_n - \hat{x}_n = \{0, 1, 0, -1, 1, -1, 0, 1, -1, -1, 1, 1\} \]  \hspace{1cm} (2.4)

that uses only three symbols, which can be coded with only 2 bits. So the transmission needs 2 bit \(\times\)12 = 24 bits. It is obvious that the decoder must know the statistical model and the error sequence to reconstruct the signal. It is important to underline that, in the error sequence, the symbols are uncorrelated, unlike in the original one: if there is still dependence, it means that this is not the best representation. So the degree of decorrelation is an important parameter which expresses how efficiently the redundancy has been exploited: the more decorrelated are the symbols, the less data must be transmitted. The most difficult step is extracting the statistical model of the signal.

2.2.2 Transform coding

To exploit correlation between samples it is possible to transform them before quantization. The advantage is that the statistical characteristics change; in fact data transforms have two purposes:

- to decorrelate coefficients in the new space
- to concentrate most of the information (energy) in only a few coefficients.

The latter task is very important, because it allows a more efficient scalar quantization of data: the new energy distribution gives different importance to coefficients and it is possible to assign proportional bit resources and even discard coefficients which do not contain much information. Moreover transform coding is good for quantization techniques based on perceptual
Source coding criteria, because coefficients of high frequency (spatial in the case of images) can be often neglected, even when the relative energy amount is not small.

Transform coding consists of three steps, as shown in Figure 2.2 and analyzed in [2].

First, the data sequence is divided in blocks of size $N$; each block is mapped into a transform sequence, using a reversible mapping. Different elements of the transformed sequence generally have different statistical properties and energy, as already said. Then the transformed sequence is quantized, taking into account on the desired average bit rate, the statistics of the various transform coefficients and the effect of distortion of the transformed coefficients on the reconstructed sequence. Finally the quantized values need to be encoded, using some binary encoding techniques.

In this chapter, the analysis will be focused only on the linear transformations, ignoring the second and the third steps.

If $x(n)$ is a time discrete signal, whose length is $N$, the forward transform is defined as:

$$y(k) = \sum_{n=0}^{N-1} a_{k,n} x(n) \quad 0 \leq k \leq N - 1$$  \hspace{1cm} (2.5)

In order to reconstruct the original signal it is necessary to consider the inverse transform, defined as:

$$x(n) = \sum_{k=0}^{N-1} b_{k,n} y(k) \quad 0 \leq n \leq N - 1$$  \hspace{1cm} (2.6)
These expressions can be written in matricial form:

\[
\begin{align*}
\begin{cases}
y = Ax \\
x = By
\end{cases}
\end{align*}
\] (2.7)

where A and B are \(N \times N\) matrices, whose elements are \([A]_{i,j} = a_{i,j}\) and \([B]_{i,j} = b_{i,j}\). It is clear that the matrix A is the inverse of B and vice versa, i.e. \(AB = BA = I\), where I is the identity matrix.

If \(x(m, n)\) is the \((m, n)\)th pixel in an image, a general linear two-dimensional transform for a block size \(N \times N\) is given as:

\[
y(k, l) = \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} a_{k,l,m,n} x(m, n) \quad 0 \leq k, l \leq N - 1
\] (2.8)

and the inverse transform is:

\[
x(m, n) = \sum_{k=0}^{N-1} \sum_{l=0}^{N-1} b_{k,l,m,n} y(k, l) \quad 0 \leq m, n \leq N - 1
\] (2.9)

In practical use, the two-dimensional transforms are separable, that is it is possible to transform a two-dimensional block by first taking the transform along one dimension and then repeating the operation along the other direction: in terms of matrices, it is possible to transform along the rows and then column-by-column or reversing the order of the operations (along the columns and then row-by-row):

\[
\begin{align*}
\begin{cases}
Y = AXA^T \\
X = BYB^T
\end{cases}
\end{align*}
\] (2.10)

Moreover, the transforms considered are usually orthonormal, that it the inverse of the transform matrix is the transpose, because the rows of the transform matrix form an orthonormal basis set:

\[
B = A^{-1} = A^T
\] (2.11)
These transforms are energy preserving and correspond to a rotation of the \( k \)-dimensions space.

### 2.2.3 Discrete Fourier Transform

The *discrete cosine transform* (DCT) expresses a finite-length sequence in terms of a sum of cosine functions, oscillating at different frequencies. So a DCT is a Fourier-related transform similar to the discrete Fourier transform (DFT), but using only real numbers, as analyzed afterwards.

As it is a linear transform, if \( \mathbf{X} \) is the \( N \)-dimensional array which must be processed, the final one is:

\[
\mathbf{Y} = \mathbf{C} \mathbf{X}
\]  

(2.12)

that is:

\[
\begin{bmatrix}
Y_0 \\
Y_1 \\
\vdots \\
Y_{N-1}
\end{bmatrix} = 
\begin{bmatrix}
c_{0,0} & c_{0,1} & \cdots & c_{0,N-1} \\
c_{1,0} & c_{1,1} & \cdots & c_{1,N-1} \\
\vdots & \vdots & \ddots & \vdots \\
c_{N-1,0} & c_{N-1,1} & \cdots & c_{N-1,N-1}
\end{bmatrix} 
\begin{bmatrix}
X_0 \\
X_1 \\
\vdots \\
X_{N-1}
\end{bmatrix}
\]  

(2.13)

where \( \mathbf{C} \) is a \( N \times N \) matrix, whose \((k,n)\)th element is:

\[
c_{k,n} = \begin{cases} 
\sqrt{\frac{1}{N}} & k = 0 \quad n = 0, 1, \ldots, N-1 \\
\sqrt{\frac{2}{N}} \cos \left[ \frac{\pi k}{2N}(2n+1) \right] & k \neq 0 \quad n = 0, 1, \ldots, N-1
\end{cases}
\]  

(2.14)

The first row is a constant vector, while the others are sinusoids, whose frequency is a function of \( k \): as \( k \) increases, the sinusoid varies more quickly, as shown in Figure 2.3, that is the case \( N = 8 \).

Each component of the transformed array can be expressed as:

\[
Y_k = \sum_{n=0}^{N-1} c_{kn} X_n \quad k = 0, 1, \ldots, N-1
\]  

(2.15)

and corresponds to the projection of \( \mathbf{X} \) on the sinusoidal functions with fre-
2.2 Source coding

Figure 2.3: Rows of transform matrix $C$ if $N = 8$

...quencies $\frac{k}{2N}$, where $k = 0, 1, \ldots, N - 1$, that are multiple of the fundamental, like in the Fourier transform. It is clear that $Y_0$ is the continuous component (DC coefficient) of the transformed array $Y$ and the other elements $Y_1, Y_2, \ldots, Y_{N-1}$ are the AC coefficients that vary according to frequency.

Since the DCT is a separable transform, the two-dimensional extension is very simple, considering in the \((2.10)\) $A = C$ and $B = C^T$.

As shown in Figure 2.4 which is the representation of an image offered by Sandia National Laboratories in the DCT domain, the lower frequency coefficients in the top-left corner of each block have larger values than the higher frequency coefficients. In compression standard the two-dimensional DCT is used on $N \times N$ blocks of pixels; $N$ is typically 8 and the two-dimensional DCT is applied to each row and column of the block.

2.2.4 Wavelet

The greatest difficulty in compression is due to the dependence of the algorithm on the statistical characteristics of the image: it is not always possible to have its model. For example natural images can be modeled as nonstationary signal, with long-period components at low frequencies (e.g.
2.2 Source coding

Figure 2.4: Example of representation in DCT domain - Image: Sandia National Laboratories

...backgrounds), called trends, and short-period components at high frequencies (e.g. edges), called anomalies; Figure 2.5 shows how the image dynamic changes. Although the latter ones cover a limited region of the image, they contain a lot of information and so they cannot be neglected.

Figure 2.5: Example of image dynamic change - CSK StripmapHIMAGE: Nisida Island

In the DCT domain, the information relating to the anomalies is spread on a large number of coefficients and the low bit rate compression is consequently characterized by blocking artifacts. In order to overcome these
limitations, new compression techniques are based on Wavelet transform, which is characterized by:

- good **time-frequency localization**
- **multiresolution** representation
- low-complexity implementation through filter banks

In order to understand what the **time-frequency localization** is, it is necessary to consider the **Fourier** transform (**FT**):

\[
FT[x(t)] = X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft} dt
\] (2.16)

As shown in Figure 2.6, which represents the sinusoidal signal, \(x(t) = \sin(2\pi f't)\), and the **Dirac** impulse, \(x(t) = \delta(t - t')\), a sinusoid is perfectly localized in the frequency domain, because it is represented with two impulses, while the **Dirac** impulse needs all the frequency components, because it has variable time characteristics (**transitory** signal).

Figure 2.6: Sinusoidal signal and **Dirac** impulse in the **Fourier** transform domain
The time domain representation is more useful for this latter kind of signals, which are characterized by sharp discontinuities. Its expression is:

$$x(t) = \int_{-\infty}^{\infty} x(\tau) \delta(t - \tau) d\tau$$  \hspace{1cm} (2.17)

From this example it is clear that the Fourier transform has a perfect frequency localization, while the identity transform has likewise a perfect time localization.

In general, a transform $T_x(\gamma)$ is given by:

$$T_x(\gamma) = \int_{-\infty}^{\infty} x(t) \phi_\gamma^*(t) dt$$  \hspace{1cm} (2.18)

and the time-frequency localization capacity depends on the time and frequency length of the functions $\phi_\gamma(t)$. Concerning the transforms considered until now:

**Fourier transform:** the function $\phi_\gamma(t) = \phi_f(t) = e^{j2\pi ft}$ has infinite time length ($\Delta t = \infty$) and null frequency length ($\Delta f = 0$). Fourier transform has perfect frequency localization.

**Identity transform:** the function $\phi_\gamma(t) = \phi_r(t) = \delta(t - \tau)$ has null time length ($\Delta t = 0$) and infinite frequency length ($\Delta f = \infty$). Identity transform has perfect time localization.

A graphic representation of the time-frequency localization capacities of a transform is provided by the time-frequency plane: each function is represented by a resolution cell, rectangle-shaped, whose length and width are respectively the frequency and time length, as shown in Figure 2.7.

Figure 2.7 shows the resolution cell of the Short Time Fourier Transform, used to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time. Simply described, the function which must be transformed is multiplied by a window function $g(t)$, which is nonzero for only a short period of time. The transform of the resulting signal is taken as the window slides along the time axis. The Short Time Fourier Transform
2.2 Source coding

Figure 2.7: Time-frequency localization

(STFT) is expressed by:

\[ STFT[x(t)] = STFT[f, \tau] = \int_{-\infty}^{\infty} x(t) g^*(t - \tau) e^{-j2\pi ft} dt \] (2.19)

One of the downfalls of the STFT is that it has a fixed resolution. The width of the windowing function relates to how the signal is represented, because it determines whether there is good frequency resolution or good time resolution: a wide window gives good frequency resolution but poor time resolution; a narrower window gives better time resolution, but poorer frequency resolution. This is one of the reasons for the creation of the wavelet transform, which can give good time resolution for high-frequency events and good frequency resolution for low-frequency events, which is the type of analysis best suited for many real signals, like natural ones.

In order to achieve variable resolution analysis, it is necessary that the ratios \( \frac{\Delta f}{f} \) and \( \frac{\Delta t}{t} \) are constant; this can be obtained by translating and scaling a single function \( \psi(t) \), called mother wavelet, shown for example in Figure
obtaining a set of basis functions expressed by:

\[
\phi_{f^e}(t) = \psi_{ab}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t - b}{a}\right)
\] (2.20)

![Wavelet example](image)

Figure 2.8: Example of mother wavelet and its scaling

So the Continuous Wavelet Transform (CWT) is expressed by:

\[
CWT[x(t)] = CWT[a, b] = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi^\ast\left(\frac{t - b}{a}\right) dt = <x(t), \psi_{ab}(t)>
\] (2.21)

An example is the Haar wavelet, related to the piecewise constant approximation of signals. Let \(\phi_{0,k}(l)\) a function equal to 1 for \(l \in [k, k + 1]\) and 0 otherwise.

Then a general signal \(x(t)\) can be approximated as:

\[
x^{(0)}(t) = \sum_k c_{0,k} \phi_{0,k}(t)
\] (2.22)

where the coefficients \(c_{0,k}\) are:

\[
c_{0,k} = <x(t), \phi_{0,k}(t)> = \int_{-\infty}^{\infty} x(t) \phi_{0,k}(t) dt = \int_{k}^{k+1} x(t) dt
\] (2.23)

In order to have a representation at better resolution, it is possible to consider narrower basis functions: \(\phi_{1,k} = \sqrt{2} \phi(2t - k)\), leading to the approximation:

\[
x^{(1)}(t) = \sum_k c_{1,k} \phi_{1,k}(t)
\] (2.24)
where the coefficients $c_{1,k}$ now are:

$$c_{1,k} = \langle x(t), \phi_{1,k}(t) \rangle = \int_{-\infty}^{\infty} x(t) \phi_{1,k}(t) dt = \sqrt{2} \int_{-\frac{k}{2}}^{\frac{k}{2}} x(t) dt \quad (2.25)$$

In general it is possible to consider the basis set:

$$\phi_{j,k}(t) = 2^j \phi(2^j t - k) \quad (2.26)$$

where the coefficients $c_{j,k}$ are:

$$c_{j,k} = \langle x(t), \phi_{j,k}(t) \rangle = 2^j \int_{\frac{k-1}{2^j}}^{\frac{k+1}{2^j}} x(t) dt \quad (2.27)$$

The functions $\phi_{j,k}$ are called *scaling functions*, because they give different representations $x(t)$ at different resolutions, as $j$ varies. They generate redundant vector spaces, because of inclusion relations. So it is convenient to eliminate this redundancy. Indeed, it is possible to express the signal $x(t)$ by:

$$x(t) = x^{(0)}(t) + (x^{(1)}(t) - x^{(0)}(t)) = x^{(0)}(t) + D^{(0)}(t) = x^{(0)}(t) + \sum_k d_{0,k} \psi_{0,k}(t) \quad (2.28)$$

where $\psi_{0,k}(l)$ a function equal to 1 for $l \in [k, k+1]$ and 0 otherwise and is the Haar wavelet related to the selected scaling function.

In general the $j$-th scale representation is:

$$x^{(j)}(t) = x^{(0)}(t) + D^{(0)}(t) + D^{(1)}(t) + \cdots + D^{(j-1)}(t) = x^{(0)}(t) + \sum_j \sum_k d_{j-1,k} \psi_{j-1,k}(t) \quad (2.29)$$

It is possible to demonstrate that such a decomposition is a cascade of filters and downsampling operations; Figure 2.9 shows an example of two-level decomposition.

Image compression is one of the most popular applications of *Wavelet* transform: in order to perform the decomposition of the image, *JPEG2000*
standard is based on Wavelet instead of DCT. Being a separable linear transforms, two-dimensional signal can be decomposed using one-dimensional filter on the row first and then on the columns (or vice versa). Figure 2.10 shows how an image can be decomposed using this kind of decomposition.

After filtering and downsampling the $N \times M$ image, it is decomposed in four $\frac{N}{2} \times \frac{M}{2}$ subimages:

- **LL**, obtained by low-pass filtering the rows and the columns
- **LH**, obtained by low-pass filtering the rows and high-pass filtering the columns
- **HL**, obtained by high-pass filtering the rows and low-pass filtering the columns
- **HH**, obtained by high-pass filtering the rows and columns

It is possible to filter and subsample again each of these subimages in turn and this process can be continued until the desired subband structure is obtained.
2.3 Image compression Standards: JPEG and JPEG 2000

A technical standard is a states norm or requirement which establishes uniform engineering or technical criteria, methods, processes and practices. It can be developed privately or unilaterally, for example by a corporation, regulatory body, military, etc., or through the activity of national or international standards organizations. Although it can be a tedious and lengthy process, formal standard setting is essential to developing new technologies. For example, the standards created through standards organizations lead to improved product quality, ensured interoperability of competitors’ products and, especially, they provide a technological baseline for future research and product development.

In this work the analysis will concern two standards: JPEG, based on DCT, and JPEG2000, based on Wavelet transform.

The name JPEG stands for Joint Photographic Experts Group, the name of the committee that created the standard. This group was organized in
2.3 Image compression Standards: JPEG and JPEG 2000

1986, issuing a standard in 1992, which was approved in 1994 as ISO10918-1. Currently a worldwide standard for image compression, JPEG defines both lossy and lossless algorithms: in this work the latter will be neglected.

Using the DCT, JPEG lossy compression causes an irreversible mapping of the image to a compressed bit stream, but this loss of information is controlled by the algorithm. As presented in [17], its key features can be listed as follows:

1. A graceful tradeoff in bit rate and quality is offered except at very low bit rates.

2. All type of images (regardless of source, content, resolution, color format, ...) are permitted.

3. DCT coefficients can be encoded in two ways: on block-by-block basis sequential coding or by multiple scans (progressive coding).

4. A hierarchical mode, with multiple levels of resolution, is allowed.

5. Low complexity implementations, in both hardware and software.

However JPEG presents many weakness:

1. There are clear artifacts at very low bit-rate, especially a visible blokyness.

2. JPEG is very susceptible to transmission errors and small error rates degrade substantially image quality.

3. There is no universal decoder architecture, because JPEG has many modes.

4. Since it is designed for continuous-tone images, it performs badly with different images, like computer generated imagery and binary images (black/white), such as text.

5. It is difficult to apply JPEG to very large images.
The other considered standard is JPEG2000, which is wavelet-based. It was created by the Joint Photographic Experts Group committee in the year 2000 in order to supersede JPEG standard. Although part of JPEG2000 has been published as an ISO standard, ISO/IEC 15444-1:200, it is not widely supported in web browsers and hence is not generally used on the World Wide Web.

In addition to improve upon the performance of JPEG, JPEG2000 introduces features, such as scalability and editability: for example, one of the strengths is the possibility of very large range of effective bit rates and the multiresolution decomposition structure.

The key features of JPEG2000 can be listed as follows:

- the compression performance is superior, especially at very low bit rates, especially for the lack of blockiness.

- it is possible to have a multiple-resolution representation and it can be exploited for other image presentation purposes beyond compression.

- the transmission is progressive by resolution and accuracy, generally referred to as progressive decoding and signal-to-noise ratio scalability. For example, if a small part of the whole file has been already received, the viewer can see a lower quality version of the final picture and the quality the improves progressively through downloading more data bits from the source.

- compression can be lossless or lossy.

- Random access to the code-stream is allowed, leading to that is also referred Region of Interest (ROI) coding. It allows to compress different parts of the same picture using different quality.

- JPEG 2000 is robust to bit errors introduced by noisy communication channels, due to coding of data in relatively small independent blocks.

- JPEG 2000 file format is flexible and can store color-space information, metadata and other information for interactive applications.
2.3 Image compression Standards: JPEG and JPEG 2000

- unlike JPEG, JPEG 2000 allows to process large and high precision images

Moreover, for the comparison between the DCT and the wavelet transform, it is possible to consider the complexity and the performance.
Concerning the first, the hardware and software implementation of the DCT is less expensive than that of the wavelet transform. For example, the most efficient algorithm for the DCT allows to transform a $8 \times 8$ block with 54 multiplications, while the complexity of calculating the wavelet transform depends on the lengths of the filters considered, which is at least one multiplication per coefficient.
Concerning the performance, when the same quantizer (and entropy coder) is used, the wavelet transform (using the 7/9 biorthogonal wavelet filters \[19\]) gives only $0.6 \div 1.0$–dB gain over the DCT at the same bit rate. For this reason, the coefficients transformed with wavelet algorithm are coded differently.
Chapter 3

SAR Image compression evaluation

The assessment of SAR images compression is based on objective and subjective parameters, the former referred to the scientific/quantitative evaluation, the latter to the operative exploitation. After presenting the objective metrics and giving the basics about image interpretation, the dissertation will explain the methodological approach, will present the experimental instruments and will show some interesting results.

3.1 Introduction

In the scientific literature concerning SAR system, the term compression is often used to indicate the data processing which allows to focus the received echoes, as rapidly described in Chapter 1; of course, we are interested here in data compression meant as a tool to reduce the data volume to be transmitted and stored.

A further distinction exists between compression carried out on-board the platform to reduce usage of download in channel and compression carried out off-line at the base station, which can leverage on more time and computation power. We will consider here this latter situation.

In case of emergency, military or civilian, it is possible that an image is
re-transmitted in an operating theatre; in this case the most important con-
straint is quickness: the short time required by tactical use allows some loss of quality. Moreover the utility of compressed imagery has been increasing as sensors produce data at rates far surpassing the bandwidth of most radio communication channels. So image compression became an operating instrument, and military and scientific research have been investigating it since the end of the nineties: for example the United States Department of Defense commissioned a study to *Armstrong Laboratory*\(^7\)\(^8\), whose methodological approach is used for this thesis work.

Apart from these two references, all other works (\(^\[13\], \[15\], \[17\]\)) come from the scientists world and use objective SAR image quality metrics, neglecting the visual effects and the consequences on the image interpretability. This analysis is very important, because the image quality requirements are very stringent and it is important to understand in which way and how much images can be modified. In this thesis work, after considering objective metrics, the final and most important analysis will concern the impact of image compression end-users, as military imagery analysts who have received specific training on image interpretability.

3.2 Measures of performance

The assessment of the performance effects of SAR image compression is made by objective and subjective parameters. In fact, in order to evaluate compression effects, it is necessary to consider objective image fidelity as well as the performance improvement observed in the work of professional analysis.

3.2.1 Image Fidelity

As repeatedly expressed, one of the purposes of compression is storing or transmitting an image with as few bits as possible, while preserving the original information content. *Image fidelity* refers to the characterization of the distance of the compressed from the original image: so it measures the *goodness* of the compression method. However these parameters do not
3.2 Measures of performance

take into account the intelligibility of the image, because they measure the absolute change. Reference [15] is one of the most complete works on this topic, because it analyzes the common objective quality metrics and suggests new ones, based on the complex nature of SAR images, as the Complex Spatial Correlation Coefficient, the Max Intensity Error, the Max Phase Error. For this study three of the more classical image fidelity measures were chosen, the Mean Squared Error (MSE), the Signal-to-Noise Ratio (SNR) and the Peak Signal-to-Noise Ratio (PSNR).

MSE provides a pixel by pixel measure of the image change from the original to the compressed image. It is the most used image fidelity measure in the scientific literature, because of its mathematical simplicity and ease of computation. If $X_{m,n}$ is the original and $\hat{X}_{m,n}$ the reconstructed signal, the MSE is defined as:

$$MSE = E[(X_{m,n} - \hat{X}_{m,n})^2]$$  \hspace{1cm} (3.1)

If the statistical characteristics are not known, but it is possible to postulate the ergodicity, the statistical mean can be replaced by the time mean:

$$MSE = \frac{1}{N} \frac{1}{M} \sum_{m=1}^{M} \sum_{n=1}^{N} [(x(m,n) - \hat{x}(m,n))^2]$$ \hspace{1cm} (3.2)

where $M$ and $N$ are the number of rows and columns of the image. Since this measurement does not distinguish between a few large errors and many small errors, in certain instances there is a little correlation between this pixel by pixel measure and the visual perceived information content, as expressed in [7].

The SNR is less used than the MSE and closely related to it, showing again little correlation with the operator performance. The SNR is based on the assumption that the compressed image is a noisy version of the original: it can be expressed in decibel as:

$$SNR_{db} = 10\log_{10} \frac{E[(X_{m,n} - \hat{X}_{m,n})^2]}{E[(X_{m,n} - \hat{X}_{m,n})^2]} = 10\log_{10} \frac{VAR(X_n)}{MSE}$$ \hspace{1cm} (3.3)
3.2 Measures of performance

PSNR is most commonly used as a measure of quality of reconstruction in image compression and it expresses the ratio between the maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation. Since many signals have a very wide dynamic range, PSNR is also expressed in terms of the logarithmic decibel scale:

\[ PSNR_{db} = 10 \log_{10} \left( \frac{[X]_{\text{max}}^2}{MSE} \right) \]  

where \([X]_{\text{max}}^2\) is the maximum possible pixel value of the original image.

3.2.2 Image Interpretation

In [9], Colwell defined the photographic interpretation as the act of examining photographic images for the purpose of identifying objects and judging their significance. Image interpretation has been empirically developed for more than 150 years, at the beginning for military needs and later also for civil purposes. Interpretation is a kind of art, because it is based on the imagination and the experience of the operators. A well-trained interpreter analyzes an image, referring to location, size, shape, shadow, tone-color, texture, pattern, height-depth and site-situation-association, without really thinking about them and correlating the objects or the phenomena in the image.

In [10], Albertz described the image interpretation process, whose block diagram is shown in Figure 3.1. It is clear that the quality of the image interpretation is closely affected by the interpreters’ experience, especially for SAR images, whose characteristics are totally different from the usual optical images. In the scientific and technical literature, the more important parameter for SAR image interpretation is the size of ground pixel. In order to understand the close correlation between pixel size and image interpretability, it is useful to consider the NATO STANAG\(^1\) 3769 [11] which, only for optical images, describes the minimal resolution that is needed for four steps

\(^1\)STANAG is the NATO abbreviation for Standardization Agreement, which set up processes, procedures, terms, and conditions for common military or technical procedures or equipment between the member countries of the Alliance
3.2 Measures of performance

Figure 3.1: The image interpretation process

of interpretation:

**Detection**, that is the discovering of the existence of an object, without recognizing it

**Recognition**, that is the ability to classify the identity of a feature or object on imagery within a group type (i.e. tank, aircraft, etc)

**Identification**, that is the ability to single out the identity of a feature or object on imagery as a precise type (i.e. T-54 tank, MIG-21J)

**Technical analysis**, that is the ability to describe precisely a feature, object or component.

Table 3.1 shows some relevant examples. It refers to six categories of military targets showing for each one what pixel size is needed to perform a given task; *STANAG 3769* describes resolution for twenty military targets, from the lowest resolution (*Terrain*) to the highest resolution (*Rockets and Artillery vehicle*), as shown in Figure 3.2. This classification is very useful for research methodology and there are many examples, like [7] and [8], which analyze the compression performance with different images, referred to each of the twenty categories. It is important to underline that, although the
### 3.2 Measures of performance

<table>
<thead>
<tr>
<th>Object</th>
<th>Detection</th>
<th>Recognition</th>
<th>Identification</th>
<th>Tec.Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain Features</td>
<td>~ 800m</td>
<td>90m</td>
<td>3m</td>
<td>0.75 m</td>
</tr>
<tr>
<td>Urban Areas</td>
<td>60m</td>
<td>15m</td>
<td>3m</td>
<td>0.75m</td>
</tr>
<tr>
<td>Roads</td>
<td>6m</td>
<td>4.5m</td>
<td>1.5m</td>
<td>0.38m</td>
</tr>
<tr>
<td>Railroad</td>
<td>15m</td>
<td>4.5m</td>
<td>1.5m</td>
<td>0.38m</td>
</tr>
<tr>
<td>Bridges</td>
<td>6m</td>
<td>4.5m</td>
<td>1.5m</td>
<td>0.3m</td>
</tr>
<tr>
<td>Airfield Facilities</td>
<td>6m</td>
<td>4.5m</td>
<td>3m</td>
<td>0.15m</td>
</tr>
</tbody>
</table>

Table 3.1: Required ground pixel size (in meters) for optical image interpretation (*STANAG 3769*)

*STANAG* refers to optical images, this thesis work is based on its methodological approach.

Another scale used for rating the quality of imagery acquired from various types of imaging system is the National Imagery Interpretability Rating Scale (*NIIRS*), considered as a standard by most civilian imagery analyst and scientists. The *NIIRS* defines different levels of image quality-interpretability, based on the types of tasks which can performed by an analyst, that is able to perform more demanding interpretation tasks as the quality of the imagery increases. The *NIIRS* consists of 10 levels, from 0 (worst quality) to 9 (best quality). Because different types of imagery support different types of interpretation tasks, individual NIIRS has been developed for four major imaging types: Visible, Radar, Infrared and Multispectral; in Figure 3.3 is shown the Radar NIIRS.
Figure 3.2: Categories considered in *STANAG 3769*
3.2 Measures of performance

<table>
<thead>
<tr>
<th>Level 0</th>
<th>• Interpretablity of the imagery is precluded by obscuration, degradation, or very poor resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 [over 9.0 m]</td>
<td>• Detect the presence of aircraft dispersal parking areas.</td>
</tr>
<tr>
<td></td>
<td>• Detect a large cleared swath in a densely wooded area.</td>
</tr>
<tr>
<td></td>
<td>• Detect, based on presence of piers and warehouses, a port facility.</td>
</tr>
<tr>
<td></td>
<td>• Detect lines of transportation (either road or rail), but do not distinguish between</td>
</tr>
<tr>
<td></td>
<td>• Identify large phased array radars (e.g., HEN HOUSE, DOG HOUSE) by type.</td>
</tr>
<tr>
<td></td>
<td>• Detect a military installation by building pattern and site configuration.</td>
</tr>
<tr>
<td></td>
<td>• Detect road pattern, fence, and hardstand configuration at SSM launch sites (missle sites, launch control sites) within a known ICBM complex.</td>
</tr>
<tr>
<td></td>
<td>• Detect large non-combatant ships (e.g., freighters or tankers) at a known port facility.</td>
</tr>
<tr>
<td></td>
<td>• Identify athletic stadiums.</td>
</tr>
<tr>
<td>Level 2 [4.5 - 9.0 m]</td>
<td>• Detect the presence of large (e.g., BLACKJACK, FLAMIER, LOCK, 707, 747) bombers or transports.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish bow shape and length/width differences of SSNS.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between the raised helicopter deck on a KRESTA II (CG) and the helicopter deck</td>
</tr>
<tr>
<td></td>
<td>with main deck on a KRESTA I (CG).</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between small support vehicles (e.g., UAZ-69, UAZ-469) and tanks (e.g., T-72,</td>
</tr>
<tr>
<td></td>
<td>T-80).</td>
</tr>
<tr>
<td></td>
<td>• Detect the break between railcars (count railcars).</td>
</tr>
<tr>
<td></td>
<td>• Identify trucks as cab-over-engine or engine-in-front.</td>
</tr>
<tr>
<td>Level 3 [2.5 - 4.5 m]</td>
<td>• Detect medium-sized aircraft (e.g., FENCER, FLANKER, CURL, COKE, F-15).</td>
</tr>
<tr>
<td></td>
<td>• Identify an ORBITA site on the basis of a 12 meter dish antenna normally mounted on a circular</td>
</tr>
<tr>
<td></td>
<td>building.</td>
</tr>
<tr>
<td></td>
<td>• Detect vehicle revetments at a ground forces facility.</td>
</tr>
<tr>
<td></td>
<td>• Detect vehicles/pieces of equipment at a SSM, ICBM, or ABM fixed missile site.</td>
</tr>
<tr>
<td></td>
<td>• Determine the location of the superstructure (e.g., fore, amidships, aft) on a medium-sized</td>
</tr>
<tr>
<td></td>
<td>freighter.</td>
</tr>
<tr>
<td></td>
<td>• Identify a medium-sized (approx. six track) railroad classification yard.</td>
</tr>
<tr>
<td>Level 4 [1.2 - 2.5 m]</td>
<td>• Distinguish between large rotary-wing and medium fixed-wing aircraft (e.g., HALO helicopter</td>
</tr>
<tr>
<td></td>
<td>versus CRUSTY transport).</td>
</tr>
<tr>
<td></td>
<td>• Detect recent cable scars between facilities or command posts.</td>
</tr>
<tr>
<td></td>
<td>• Detect individual vehicles in a row at a known motor pool.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between open and closed sliding roof areas on a single bay garage at a mobile</td>
</tr>
<tr>
<td></td>
<td>missile base.</td>
</tr>
<tr>
<td></td>
<td>• Identify square bow shape of ROPUCHA class (LST).</td>
</tr>
<tr>
<td></td>
<td>• Detect all rail/road bridges.</td>
</tr>
<tr>
<td>Level 5 [0.75 - 1.2 m]</td>
<td>• Count all medium helicopters (e.g., HIND, HIC, HAZE,hound, PUMA, WASP).</td>
</tr>
<tr>
<td></td>
<td>• Detect deployed TWIN EAR antenna.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between river crossing equipment and medium/heavy armored vehicles by size and</td>
</tr>
<tr>
<td></td>
<td>shape (e.g., MTU-20 vs. T-62 MBT).</td>
</tr>
<tr>
<td></td>
<td>• Detect missile support equipment at an SS-25 RTP (e.g., TEL, MSV).</td>
</tr>
<tr>
<td></td>
<td>• Distinguish bow shape and length/width differences of SSNs.</td>
</tr>
<tr>
<td>Level 6 [0.4 - 0.75 m]</td>
<td>• Distinguish between variable and fixed-wing fighter aircraft (e.g., FENCER vs. FLANKER).</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between the BAR LOCK and SIDE NET antennas at a BAR LOCK/SIDE NET acquisition</td>
</tr>
<tr>
<td></td>
<td>radar site.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between small support vehicles (e.g., UCLA-69, UCLA-469) and tanks (e.g., T-72,</td>
</tr>
<tr>
<td></td>
<td>T-80).</td>
</tr>
<tr>
<td></td>
<td>• Identify SS-24 launch tripod at a known location.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between the raised helicopter deck on a KRESTA II (CG) and the helicopter deck</td>
</tr>
<tr>
<td></td>
<td>with main deck on a KRESTA I (CG).</td>
</tr>
<tr>
<td>Level 7 [0.2 - 0.4 m]</td>
<td>• Identify small fighter aircraft by type (e.g., FISHBED, FITTER, FLOGGER).</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between electronics van trailers (without tractor) and van trucks in garrison.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish, by size and configuration, between a turreted, tracked APC and a medium tank</td>
</tr>
<tr>
<td></td>
<td>(e.g., BMP-1/2 vs. T-64).</td>
</tr>
<tr>
<td></td>
<td>• Detect a missile on the launcher in an SA-2 launch revetment.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between bow mounted missile system on KRIKAVAK IIII and bow mounted gun turret on</td>
</tr>
<tr>
<td></td>
<td>KRIKAVAK III.</td>
</tr>
<tr>
<td></td>
<td>• Detect road/street lamps in an urban residential area or military complex.</td>
</tr>
<tr>
<td>Level 8 [0.1 - 0.2 m]</td>
<td>• Distinguish the fuselage difference between a HIND and a HIP helicopter.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish between the FAN SONG E missile control radar and the FAN SONG F based on the</td>
</tr>
<tr>
<td></td>
<td>number of parabolic dish antennas (three vs. one).</td>
</tr>
<tr>
<td></td>
<td>• Identify the SA-6 transloader when other SA-6 equipment is present.</td>
</tr>
<tr>
<td></td>
<td>• Distinguish limber hole shape and configuration differences between DELTA I and YANKEE I (55)</td>
</tr>
<tr>
<td></td>
<td>• Identify the dome/vent pattern on rail tank cars.</td>
</tr>
<tr>
<td>Level 9 [less than 0.1 m]</td>
<td>• Detect major modifications to large aircraft (e.g., fairings, pods, wheelgts).</td>
</tr>
<tr>
<td></td>
<td>• Identify the shape of antennas on EW/GCI/ACQ radars as parabolic, parabolic with clipped</td>
</tr>
<tr>
<td></td>
<td>corners, or rectangular.</td>
</tr>
<tr>
<td></td>
<td>• Identify, based on presence or absence of turret, size of sun tube, and chassis configuration,</td>
</tr>
<tr>
<td></td>
<td>wheeled or tracked APCs by type (e.g., BTR-80, BMP-1/2, MT-LB, MT-13).</td>
</tr>
<tr>
<td></td>
<td>• Identify the forward fins on an SA-3 missile.</td>
</tr>
<tr>
<td></td>
<td>• Identify individual hatch covers of vertically launched SA-N-6 surface-to-air system.</td>
</tr>
<tr>
<td></td>
<td>• Identify trucks as cab-over-engine or engine-in-front.</td>
</tr>
</tbody>
</table>

**Figure 3.3: Radar NIIRS**
3.3 Experimental methodology

The aim of this work consists in assessing the performance of image compression, taking into account the improving effect of data compression on transmission time needs. In fact, it is usually necessary to quickly transmit an image, for example in case of natural disaster or during a military operation, but the better is its resolution, the more memory and transmission time it needs. For example, COSMO-SkyMed spotlight products, as shown in Table 1, need about 2 GB, so it is not simple to transmit such images.

For these reasons, this work is oriented toward the operative military method: it focuses on the ability of military imagery analysts to extract intelligence value for the compressed imagery. These analysts receive specialized training in image interpretation, target detection and target identification for different classes of military targets and order of battle and for different sensors, such as SAR and electro-optical sensors. The analysts were from the Italian Joint Remote Sensing Ground Centre, where the practical part of this work was developed during a 4-week stage.

The Italian Joint Remote Sensing Ground Centre \[12\] (Centro Interforze di Telerilevamento Satellitare) was established in 1994 inside the air base of Pratica di Mare, near Rome. At first it was created to receive, store and analyze the Helios 2 imagery data; in 2002, the Italian military added access to Helios 2 satellites. In 2003, the Chief of Defense decided to realize the new COSMO-SkyMed User Ground Segment inside the Center, integrating the two different systems in the same infrastructure and exploiting the operators’ earlier experience.

The evaluation is principally based on CSK data (Spotlight – 2 for the analysis of military detailed target, Stripmap HIMAGE for the analysis of general scenes), but also on the images offered by Sandia National Laboratories, whose high resolution is comparable to that of CSK – Spotlight – 2 products.

During the stage, the activity was divided into four steps:

1. Interaction with military imagery analysts in order to learn the basic

\[2\] Advanced French optical military reconnaissance satellites
3.3 Experimental methodology

principles of the image interpretation and of the software used

2. Interaction with military image interpreters in order to single out snapshots of interest and to create two different databases, one of military detailed targets and one of general scenes

3. Application of the compression algorithms (JPEG and Wavelet-based) to the selected images and numerical evaluation of performance (objective measurements)

4. Subjective performance evaluation of the compressed images: interpreters’ analysis

The software used for this work can be divided into two categories, one for the image processing, one for the image interpretation. For image processing MATLAB and IDL were used; although MATLAB offers powerful interactive capability for mathematical computations and display, it is more oriented toward mathematical analysis than data analysis, offers fewer capabilities than IDL for image display and processing, and is less versatile for user-written programs and file I/O. In fact IDL was used to process the original images, whose acquisition is not possible in MATLAB because of dimensions and format. For image interpretation ENVI was used, a software solution based on IDL for processing and analyzing geospatial imagery, used by GIS professionals, scientists, researchers and image analysts around the world.

At first, the analysis focused all the image characteristics which refer to compression. For example, the analysis of the image histograms\(^3\) showed that most pixels are limited to 8 bits, although they are coded with 16 bits. This characteristic must be analyzed, studying and assessing image interpretability after the deletion of the latter 8 bits. Moreover an important and interesting characteristic refers to the covered area: the sensor illuminates a large scene while the region of interest (ROI) is generally small with respect to the whole image. Therefore it is possible to extract the ROI from the

\(^3\)Graphical representation of the tonal distribution in a digital image, which plots the number of pixels for each tonal value. By looking at the histogram for a specific image a viewer will be able to judge the entire tonal distribution at a glance.
3.3 Experimental methodology

whole image and compress it with a higher bit rate (ideally the most important region could be not compressed at all), creating a *compression gradient* which expresses the value of the bit rate pixel-by-pixel.

This approach amounts to create a *puzzle*: since in an image there are regions with different importance, each ROI is considered as a single wedge and a particular bit rate is associated to it.

The analysis was based on the following products:

- **COSMO-SkyMed**
  - Stripmap HIMAGE
    - * Naples
    - * Buenos Aires
    - * Others, not published
  - Spotlight-2, not published because of security and authorization reasons

- **Sandia National Laboratories - Military targets**

In order to deal with a manageable sample set and with relatively small images, in each of the scenes the interpreters singled out the region of interest, representing 10 of the 20 *STANAG 3769* target categories. The first difficulty concerned the extraction of the sub-image, because of the georeferencing, the 16bit radiometric coding, the huge dimensions, and the new *HDF5* format: it was impossible to use the traditional software of image treatment. This purpose was achieved with an ad hoc *IDL* routine

After the creation of the database, the subimages were processed with *MATLAB*. In particular each of the subimages was:

- compressed with the *JPEG* algorithm, already implemented in *MATLAB"

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4written by Lieutenant Stefano Serva, chief of the technical section *COSMO-SkyMed* of the *C.I.T.S.* and co-relator of this thesis work
3.3 Experimental methodology

- compressed with a Wavelet-based algorithm. It makes the two-dimensional Wavelet Transform, using Daubechies 9/7 bi-orthogonal filters and then a zerotree coder.

Concerning the Wavelet-based algorithm, each of the subimages was compressed with a different bit rate, in order to create a set of images to be compared with the others, compressed by the JPEG technique, on the given memory occupation.

The Wavelet-based algorithm was modified in order to meet the interpreters' needs; for example, at first the only output of the algorithm was the Rate-Distortion Curve, which is a typical scientific/quantitative metric, far from the interpreters' evaluation. The changes were:

- addition of the function for storing data into a standard format, as TIFF (Tagged Image File Format), in order to analyze the compressed image with a software for image interpretation, like ENVI. TIFF was chosen because it allows to store uncompressed image (the compression is made by Wavelet algorithm) and also geo-referring information

- creation of an interface for interpreters which allows to select regions of interest with different importance, which can consequently be compressed with different bit rates. This change spares interpreters the use MATLAB, which is a software having a logic different than operative instruments. In fact this change consist on a graphical interface which allows to transfer a map of ROI, created with ENVI, to a MATLAB matrix, as shown in Figure 3.4. Then, using MATLAB, interpreters must only associate a bit rate to each ROI, as shown in Figure 3.4.

- deletion of the code related to the resource allocation, because the aim of this preliminary thesis work is the analysis of the transform and not of the coding

\footnote{written by Prof. Giovanni Poggi and Luisa Verdoliva of the University Federico II of Naples (relators of this thesis work) and by Prof. Marco Cagnazzo of the École Nationale Supérieure des Télécommunications of Paris.}
3.4 Measurement results

Flat Analysis

This analysis is characterized by the compression of the whole image, without using ROIs. This mode allows to evaluate the compression techniques, with numerical and subjective metrics.

The analysis was made with high resolution images of COSMO-SkyMed (SpotLight-2) and with Sandia National Laboratories products (whose resolution is 4-inch about). Only the latter images will be published here, because of security and authorization reasons.

Targets were chosen according to STANAG 3769, shown in Figure 3.2. A detailed study was made for five categories:

- **Aircraft**: a four-engine aircraft with fixed wing
- **Helicopter**: four medium size helicopters
- **Tank**: two medium size tanks
- **Shelter**: an entrenched shelter
- **Motorcar parking**, whose analysis is useful to value the capability of resolving two close objects

In order to deal with images of usable size and a reasonable sample set, the analysis was based on images of $512 \times 512$ pixels.
3.4 Measurement results

For each analysis, a summary shows the differences between Wavelet-based and JPEG techniques, according to the following characteristics:

**Coding rate**, from 0 to 16 bit/pixel

**Memory**, computed as $\text{NumberOfPixels} \times \text{Codingrate}$

**NIIRS Level**, if the target is indicated

**Analysis Achievability**, according to the four tasks indicated in *STANAG 3769* (Detection, Recognition, Identification, Technical Analysis)

Images were coded at three bit rates according to the three types of achievable analysis (Detection, Recognition and Identification), as described in *STANAG 3769*.

Results show that the degrading effects of image compression on image interpretability (in terms of NIIRS rates and possible analysis) increases as the compression ratio increases, though the nature of the effect is different for each technique.

At low compression ratios (high bit, corresponding to a high quality factor for JPEG), image interpretability is the same for both techniques, although JPEG images are characterized by blocking artifacts and Wavelet ones are more smooth.

At high compression ratios (low bit rate, corresponding to a low quality factor for JPEG), image interpretability is definitely different. Except for a few examples, it is impossible to interpreter a JPEG compressed image at low bit rate, while it is almost always possible to do it with Wavelet ones.

It is very interesting to consider Tank analysis, because it is possible to notice many features of the two techniques. Since the interpretability of this target (two tanks) is based on the detection and recognition of the shadows and the barrel of tanks, it is necessary to keep theirs edges. In fact, at high compression ratio the edges of the shadow and barrels are not shaped and it is not possible to detect any tank. The medium compression ratio deserves a carefully analysis, because it is the only case where JPEG image interpretability is better. In fact, since its algorithm is based on blocks of $8 \times 8$
3.4 Measurement results

pixels, the image is less smooth than the Wavelet one, where the important barrel detail (projected on the sand and on the shadow) is not visible. This capability of highlighting shadow regions is more clear in Helicopter, Shelter and Aircraft also and it allows a weak image interpretability at low bit rate (almost Detection).

At low bit rates, the blocking effect, typical of JPEG algorithm, makes it hard to resolve two close objects, because the effective pixel size is larger than the nominal resolution, as shown in the first case (Quality factor 1) of Cars analysis.

Concerning the Wavelet-based technique, objective measures show that numerical errors (MSE) are larger in images full of details (Cars, Shelter, Helicopter), as shown in Figure 3.5. Similarly, the SNR and the PSNR increase with increasing bit rate, as shown in Figures 3.6 and 3.7.

Well, of the two techniques, at low compression ratios, Wavelet and JPEG are most similar to uncompressed imagery in terms of both subjective and objective measures of effectiveness, while at high compression ratios, Wavelet one is definitely better than JPEG. These outcomes indicate Wavelet techniques is currently a more suitable technique for SAR image compression than JPEG.
3.4 Measurement results

Figure 3.5: Objective metrics: MSE

Figure 3.6: Objective metrics: SNR

Figure 3.7: Objective metrics: PSNR
3.4 Measurement results

TARGET: AIRCRAFT (10th STANAG CATEGORY)
SANDIA NATIONAL LABORATORIES

ORIGINAL

CODING RATE: 8 bit
DIMENSIONS: 512 px x 512 px
MEMORY: 256 Kb

WAVELET

CODING RATE: 0.1 bit
MEMORY: 3.2 Kb
NIIRS LEVEL: 3
D-R

CODING RATE: 0.3 bit
MEMORY: 9.6 Kb
NIIRS LEVEL: 4
D-R-I

CODING RATE: 1 bit
MEMORY: 32 Kb
NIIRS LEVEL: 6
D-R-I

JPEG

QUALITY FACTOR: 1
MEMORY: 4 Kb
NIIRS LEVEL: 0
-

QUALITY FACTOR: 37
MEMORY: 9 Kb
NIIRS LEVEL: 3
D-R

QUALITY FACTOR: 65
MEMORY: 32 Kb
NIIRS LEVEL: 6
D-R-I

Figure 3.8: Flat Analysis: Aircraft
3.4 Measurement results

**Figure 3.9: Flat Analysis: Helicopters**

**TARGET:** Helicopter (10th STANAG Category)
**SANDIA NATIONAL LABORATORIES**

**ORIGINAL**

- **Coding Rate:** 8 bit
- **Dimensions:** 512 px x 512 px
- **Memory:** 256 Kb

**WAVELET**

- **Coding Rate:** 0.1 bit
- **Memory:** 3.2 Kb
- **NIIRS Level:** 4
- **D**

- **Coding Rate:** 0.7 bit
- **Memory:** 22.4 Kb
- **NIIRS Level:** 5
- **D-R-I**

- **Coding Rate:** 1 bit
- **Memory:** 32 Kb
- **NIIRS Level:** 5
- **D-R-I**

**JPEG**

- **Quality Factor:** 4.5
- **Memory:** 3.5 Kb
- **NIIRS Level:** 4
- **D**

- **Quality Factor:** 25
- **Memory:** 23 Kb
- **NIIRS Level:** 5
- **D-R-I**

- **Quality Factor:** 41
- **Memory:** 32 Kb
- **NIIRS Level:** 5
- **D-R-I**
3.4 Measurement results

**FLAT ANALYSIS EXAMPLE**

**TARGET: SHELTER (16th STANAG CATEGORY)**
SANDIA NATIONAL LABORATORIES

**ORIGINAL**
- **Coding Rate:** 8 bit
- **Dimensions:** 512 px x 512 px
- **Memory:** 256 Kb

**WAVELET**
- **Coding Rate:** 0.1 bit
- **Memory:** 3.2 Kb
- **D-R**

- **Coding Rate:** 0.3 bit
- **Memory:** 9.6 Kb
- **D-R-I**

- **Coding Rate:** 0.5 bit
- **Memory:** 16 Kb
- **D-R-I**

**JPEG**
- **Quality Factor:** 4
- **Memory:** 4 Kb
- **D-R**

- **Quality Factor:** 8
- **Memory:** 9 Kb
- **D-R**

- **Quality Factor:** 15
- **Memory:** 16 Kb
- **D-R-I**

Figure 3.10: Flat Analysis: Shelter
3.4 Measurement results

![Flat Analysis Example](image)

**TARGET: Tank (20th STANAG Category)**

**Sandia National Laboratories**

**ORIGINAL**

**Coding Rate:** 8 bit

**Dimensions:** 512 px x 512 px

**Memory:** 256 Kb

**WAVELET**

**Coding Rate:** 0.1 bit

**Memory:** 3.2 Kb

**NIIRS Level:** 0

**JPEG**

**Quality Factor:** 1

**Memory:** 4 Kb

**NIIRS Level:** 0

**Coding Rate:** 0.3 bit

**Memory:** 9.6 Kb

**NIIRS Level:** 2

**D**

**Coding Rate:** 0.5 bit

**Memory:** 16 Kb

**NIIRS Level:** 3

**D-R**

Figure 3.11: Flat Analysis: Tanks
3.4 Measurement results

TARGET: CARS
SANDIA NATIONAL LABORATORIES

ORIGINAL

CODING RATE: 8 bit
DIMENSIONS: 512 px x 512 px
MEMORY: 256 Kb

WAVELET

CODING RATE: 0.1 bit
MEMORY: 3.2 Kb

JPEG

CODING RATE: 0.3 bit
MEMORY: 9.6 Kb

CODING RATE: 1 bit
MEMORY: 32 Kb

D

D-R

D-R-I

QUALITY FACTOR: 1
MEMORY: 5 Kb

QUALITY FACTOR: 6
MEMORY: 9 Kb

QUALITY FACTOR: 23
MEMORY: 32 Kb

D-R-I

Figure 3.12: Flat Analysis: Cars
Shape-Adaptive Analysis

This mode refers to **operative compression**, because in a possible future theatre, interpreter can compress an image after the analysis and the detection, recognition and identification of the most important targets and use **ROIs** to significantly reduce the transmission time. The final **puzzle-image** can supply the interprets’ report, giving a visual support to the operating theatre addressees and to the decision makers. This mode stems from the assumption that in an image not all targets have the same importance and so it is possible to define different ROIs, which can be compressed with different bit rates: for example, if an important target (e.g. a port) is near to the sea, it is useless to encode the sea region with the same bit rate of ships and oil tanks!

This analysis is based on subjective metrics, because only the interpreter can detect and identify different targets and associate them with suitable bit rates.

The analysis is based on **COSMO-SkyMed Stripmap HIMAGE** images of:

- **Naples**
  - Port
  - Campi Flegrei
  - Nisida Island

- **Buenos Aires**
  - Port
  - Airport

The surprising results show that it is possible decrease remarkably memory size and transmission time by a clever **ROI**-based compression of the images without affecting their interpretability.
Figure 3.13: Shape Adaptive Analysis: Naples
TARGET: NAPLES - NISIDA ISLAND

COSMO-SkyMed: STRIPMAP HIMAGE

ROI's:
- Island (bit rate 9)
- Industry (bit rate 6)
- Urban Area (bit rate 0.5)
- Sea (bit rate 0.1)

ORIGINAL
- Coding Rate: 16 bit
- Dimensions: 1024 px x 1024 px
- Memory: 2048 Kb

AFTER SHAPE-ADAPTIVE COMPRESSION
- Memory: 324 Kb

Figure 3.14: Shape Adaptive Analysis: Naples
3.4 Measurement results

**SHAPE-ADAPTIVE ANALYSIS EXAMPLE**

**TARGET:** Naples - Harbour

**COSMO-SkyMed:** Stripmap Himage

**ROI:**
- **Harbour** (bit rate 9)
- **Urban Area** (bit rate 5)
- **Sea** (bit rate 0.1)

**ORIGINAL**
- **Coding Rate:** 16 bit
- **Dimensions:** 1024 × 1024
- **Memory:** 2048 KB

**AFTER SHAPE-ADAPTIVE COMPRESSION**
- **Memory:** 579 KB

Figure 3.15: Shape Adaptive Analysis: Naples
3.4 Measurement results

Figure 3.16: Shape Adaptive Analysis: Buenos Aires
3.4 Measurement results

Figure 3.17: Shape Adaptive Analysis: *Buenos Aires*
3.4 Measurement results

**Terrain Analysis**

It is very important to consider the first STANAG category, Terrain, because in this case compression techniques worsen the image quality, but not its interpretability. Although the hypothesis of pixel independence is not verified, the final effect is similar to multilook techniques: the interpretability improves even through the resolution decreases.

Military imagery analysts found this feature analyzing airports and desert areas images (characterized by large surfaces of sand, cement or asphalt) which are not homogeneous because of the presence of the speckle. After the compression processing, these images are clearer and it is easier to recognize the objects edges, because compression algorithms reduce the intense variability due to the speckle.

Figure 3.18 shows how the sand response changes, using both Wavelet and JPEG techniques: In both techniques, image quality increases with increasing bit rate. However at low bit rates, image compressed by Wavelet-based algorithm appear clearer, because noise is partially filtered: images are smoother and terrain is more homogeneous. The JPEG results are different, because at low bit rates the algorithm creates the so called blocking artifacts, which pixelate the image and make it almost useless. The two techniques produce instead almost equal results at high bit rates.
3.4 Measurement results

Figure 3.19 shows how cement or asphalt edges change.

Comparing the first and third snapshots respectively, it is clear that at low bit rate JPEG worsens edges, while the Wavelet-based preserves one keeps them, in addition to making the image more homogeneous. This effect is clearer in the latter couple: at the higher bit rate the edges are kept by both algorithm, but in Wavelet compressed images roughness is less marked also. This feature is very important for airfield facilities interpretation.

**Histogram Analysis**

One of the most important characteristics of CSK products is the 16 bit coding, which permits high resolution, but on the other hand causes problems with data storage and transmission. In order to understand the characteristics of 16 bit coding, the analysis focused on the image histograms: although the traditional Rayleigh shape which characterizes SAR imagery, the most of components is limited in the first 8 bits. For compression analysis, it is very important to analyze the meaning of the additional 8 bits, in order to understand if they can be deleted.

The main reason of 16 bit coding is due to radiometric needs: if in the illuminated area there is a particularly brilliant point (e.g. a corner reflector or a trasponder), the backscattered echo is very marked and the relative pixel brightness is very high: hence it will lie in the right region of the histogram. Since histograms are generally normalized according to the largest pixel value, the whole image appears very dark in such cases. The high radiometric resolution is especially exploited in interferometric studies and
to better calibrate a SAR image.

Figure 3.20: Histogram Analysis - CSK StripmapHIMAGE: Naples, Campi Flegrei

As shown in Figure 3.20, for example, CSK image histogram is characterized by few components in the right region: most of components are in the left one. In fact, without histogram stretching, it is impossible to examine images, because they are too dark. In order to interpreter images, it is enough to consider the first 8 bits of the histogram, because its analysis it is not based on the strict exploitation of radiometric values, but rather on the subjective viewer capabilities and experience. This idea was numerically verified, considering only the first 8 bits and calculating the mean squared error (MSE). Although the objective and numeric metrics show a considerable worsening of the image, the image interpretability was the same.

3.5 Future research

This thesis work is a first analysis of image compression in order to take into account a possible future application to military armament systems. Nowadays all of them are based on the Net-Centric approach and the visual
information (image and video) exchange: the capabilities and resolution improve day by day, undermining the readiness and mass storage limitations which characterize real-time applications.

Compression techniques appear as an important tool to meet time constraints, while preserving the fidelity and the interpretability of the image. In fact, as analyzed, the memory size and transmission time required for storing and sending compressed images are greatly reduced, without loosing important features of the target data.

This analysis must surely be completed by testing compression technique and perform similar evaluation on optical images. In fact there is the opportunity to participate to the Kalideos program, set by CNES (Centre National d’Etudes Spatiales) during year 2000, which aims at developing remote sensing reference database for the scientific community. It will be interesting to evaluate optical image compression performance and to analyze the differences with the case of SAR. In order to create an operative instrument for military interpreters, it is necessary to implement the proposed algorithm in IDL language and create an ENVI routine, which can be directly used as vector tool.

Finally this work can be considered as the base for future development aiming at the evaluation of the compression techniques applicability on recent and future Defense systems, as SICRAL, Storm Shadow, RECCELITE, etc.

\(^6\)French government space agency
Conclusion

The aim of this work consists in evaluating the image compression performance, taking into account the improving effect of data compression on transmission time needs. In fact, it is usually necessary to quickly transmit an image, for example in case of natural disaster or during a military operation, but better is the resolution, the more memory and transmission time it is needed. For these reasons, this work is oriented toward the operative military applications and it aims to fulfill imagery intelligence requirements and economic constraints at the same time.

Briefly, the research activity evolved according to these steps: after the selection of the images set which show typical military targets, the image compression techniques were applied on them; then, the images were evaluated qualitatively by military imagery analysts in order to establish the impact of the different techniques on image interpretability; finally, a quantitative evaluation of compressed images was performed in order to estimate the MSE, the SNR and the PSNR compared with the original images.

The experimental analysis is mainly performed on CSK data (Spotlight 2 for the analysis of military detailed target - not published here because of security and authorization reasons - and Stripmap HIMAGE for the analysis of general scenes) and on the images offered by Sandia National Laboratories. In particular, the published CSK Stripmap-HIMAGE products portray Naples and Buenos Aires, while Sandia images are used for the detailed analysis of military targets.

In order to deal with a manageable sample set and with relatively small images, in each of the scenes the interpreters have singled out the region of interest, representing 10 of the 20 of STANAG 3769 target categories. After
the creation of the database, the subimages were processed with MATLAB. In particular each of the subimages was compressed with the JPEG algorithm, already implemented in MATLAB, and with a Wavelet-based algorithm (two-dimensional Wavelet transform, using Daubechies 9/7 bi-orthogonal filters and then a zerotree coder) developed at the DIET (Dipartimento di Ingegneria Elettronica e delle Telecomunicazioni). Concerning the Wavelet-based algorithm, each of the subimages was compressed with different bit rates in order to create a set of images which have been compared with those compressed by JPEG at the same bit rates.

As an additional feature, in addition to the standard compression of the "whole image" by the same compression ratio, a puzzle algorithm has been introduced, allowing to divide the image into a set of regions of interest to be compressed independently. Considering that the sensor illuminates a large scene and that the region of interest is generally a part of it, this feature leads to a supplementary reduction in image dimension. Thus, images were processed in two different ways, in order to evaluate compression techniques on the whole undivided dataset (Flat analysis) and on the puzzle dataset (Shape-Adaptive analysis).

Flat analysis is characterized by the compression of the whole image, without using ROIs. It was carried out on high resolution images of COSMO-SkyMed (Spotlight 2) and Sandia National Laboratories products (whose resolution is about 4-inches) products. Targets were chosen according to STANAG 3769; in particular a detailed study was made for five categories (Aircraft, Helicopter, Tank, Shelter, Motorcar parking). Concerning the comparison between the two techniques, subjective analysis shows that Wavelet-based processing makes images smoother and preserves object edges, while DCT-based JPEG highlights shadow regions and creates blocking artifacts, whose pixelation effect significantly decreases resolution. At low compression ratios image interpretability is the same for both techniques, while at high compression ratios it is definitely different and Wavelet performance is surely better. In order to compare the techniques, it would be interesting to consider processing time: since both Wavelet and DCT are based on linear filtering, processing time should similar; the future code optimization will
allow this analysis.

*Shape-Adaptive Analysis* begins with the assumption that in the image not all targets have the same importance and so it is possible to identify different ROIs, which can be compressed with different bit rates. This analysis is based on subjective metrics, because only the interpreter can detect and identify different targets and associate them with suitable bit rates. The results confirm the validity of the proposed approach, because the strict image-interpretability limitations are respected even if the memory occupation is reduced and data transmission time is shorter: after compression, memory size of images can be reduced at least by factor 5, although original information content is conserved.

By analyzing images with airports and desert areas images (characterized by large surfaces of sand, concrete or asphalt), which are not clear because of the presence of the speckle, military imagery analysts found that terrain interpretability improves after compression: images are clearer and it is easier to recognize the objects edges, because compression algorithms reduce the intense variability due to the speckle.

The analysis of CSK image histograms shows that the most of components is limited in the first 8 bits, although they are 16 bit-coded. In order to interpret images, it is not necessary to consider all 16 bits of the histogram, because image analysis is not based on the strict exploitation of radiometric values, but rather on the subjective visual capabilities and experience. This hypothesis was verified, considering only the first 8 bits and calculating the mean square error: although the objective and numeric metrics show a considerable worsening of the image, the image achievable interpretability is the same.

In conclusion, the *Wavelet-based* technique, in its *Shape-adaptive* modality, allows to more cleverly compress image, by locating regions of interest with different operative importance and hence optimizing the time and the transmission modes in the operating theatre. In addition, transmission can be progressive by pixel accuracy and by image resolution or size. For example, if a small part of the whole file has been already received, the viewer can see a lower quality version of the final image and the quality improves
progressively by downloading more data bits from the source. This characteristic, exploitable for operative purposes, is more difficult to be implemented in JPEG standard.
Acknowledgment

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24 Settembre 2008

Asp. G.A.r.n. Greco Alessandro

\(^7\)Usare i Rayban alle tre di notte dopo 48 ore di MATLAB non ha prezzo!!!
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## Nomenclature

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<td>ASI</td>
<td>Italian Space Agency</td>
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<tr>
<td>CITS</td>
<td>Centro Interforze di Telerilevamento Satellitare</td>
</tr>
<tr>
<td>CNES</td>
<td>Centre National d’Etudes Spatiales</td>
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<tr>
<td>COSMOskyMed</td>
<td>COnstellation of small Satellites for Mediterranean basin Observation</td>
</tr>
<tr>
<td>CSK</td>
<td>COSMO-SkyMed</td>
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<tr>
<td>CWT</td>
<td>Continuous Wavelet Transorm</td>
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<tr>
<td>DCT</td>
<td>Discrete Cosine Transform</td>
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<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DIET</td>
<td>Dipartimento di Ingegneria Elettronica e delle Telecomunicazioni</td>
</tr>
<tr>
<td>DoD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>EO</td>
<td>Earth Observation</td>
</tr>
<tr>
<td>ERIM</td>
<td>Environmental Research Institute of Michigan</td>
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<tr>
<td>FT</td>
<td>Fourier Transform</td>
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<tr>
<td>JPEG</td>
<td>Joint Photographic Experts Group</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>MoD</td>
<td>Ministry of Defense</td>
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<tr>
<td>MPEG</td>
<td>Moving Picture Experts Group</td>
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<tr>
<td>MSE</td>
<td>Mean Squared Error</td>
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<tr>
<td>NIIRS</td>
<td>National Imagery Interpretability Rating Scale</td>
</tr>
<tr>
<td>PRF</td>
<td>Pulse Repetition Frequency</td>
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<tr>
<td>PSNR</td>
<td>Peak Signal-to-Noise Ratio</td>
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<tr>
<td>RADAR</td>
<td>RAdio Detection And Ranging</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>RAR</td>
<td>Real Aperture Radar</td>
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<tr>
<td>ROI</td>
<td>Region of Interest</td>
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<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<td>STANAG</td>
<td>Standardization Agreement</td>
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<td>STFT</td>
<td>Short Time Fourier Transform</td>
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<td>TIFF</td>
<td>Tagged Image File Format</td>
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<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
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