On the use of SAR image simulation for the validation of topographic mapping techniques

Laurent Polidori and Pierre Armand

AEROSPATIALE, BP 99, 06322 Cannes La Bocca cedex, France
Tel. : (33) 92 92 78 86 – Fax : (33) 92 92 71 60

ABSTRACT

Synthetic aperture radar is a very promising tool for topographic mapping. Several techniques have been developed for deriving 3D information from SAR images, such as stereo radargrammetry, interferometry or shape-from-shading. However, the performances and limitations of these techniques cannot be easily evaluated, essentially due to the lack of accurate reference for comparison, and because the few experiments carried out so far are closely related to a particular set of sensor parameters, illumination geometry and landscape characteristics. In order to partially solve this problem, a simulation-based validation procedure is proposed.

1. INTRODUCTION

Topographic mapping from space has become operational with the launch of SPOT in 1986, and high performance techniques based on automated stereo-matching have been used to derive DEMs (digital elevation models) in many countries of the world. However, the limitations of optical imagery, and particularly the need for a dry atmosphere, have encouraged radar mapping methods. A great amount of radar images have been provided by airborne and spaceborne SARs (synthetic aperture radars), and their increasing quality has made possible the development of different 3D mapping techniques, such as stereoradargrammetry, interferometry and shape-from-shading (Leberl 1990).

The operational use of radar for mapping is just beginning, but the launch of several spaceborne radars in the next years could stimulate the development of radar mapping facilities in a lot of public and private companies. Therefore, the quality of radar derived DEMs is going to become a crucial question (Polidori 1991). Digital elevation model quality assessment is not an easy task, since the evaluation is often limited by the lack of reference data. Moreover, the concept of data quality depends on the requirements of each user, particularly in the context of multiple user geographic information systems.

The aim of this article is to show that SAR image simulation can usefully contribute to the quality assessment of a relief mapping technique. The problem of DEM quality is briefly discussed in section 2 with emphasis on the case of radar derived DEMs. Section 3 deals with the simulation of SAR images and presents the principle of simulation-based relief mapping validation. Finally, the advantages and limitations of the simulation approach are analysed in section 4.

2. ON THE QUALITY OF RADAR DERIVED DIGITAL ELEVATION MODELS

2.1 General considerations on DEM quality

Digital terrain model quality assessment is a quantitative evaluation of the discrepancies between the DEM and the real topographic surface. This can be done in two different ways, namely, internal and external validation.

Internal validation consists in checking the consistency of the DEM with regards to some *a priori* knowledge of the surface. For instance, it can be assumed that all rivers go downhill, so that an artifact may be seen (and measured) wherever a river goes uphill over some distance. Similarly, building extraction can be internally controlled by assuming right angles and vertical walls.

On the contrary, external validation is an objective comparison with a reference data set, allowing quality measurements such as standard height error, maximum height error, or the accuracy of height derivatives (slope, aspect...).

Since a DEM is seldom elaborated when another DEM of higher accuracy already exists over the same area, external validation is generally performed using a restricted set of ground control points (GCPs).

However, the comparison of a DEM with a set of GCPs has several major limitations. First, statistical quality indicators such as RMS height error become meaningless when the number of GCPs is too low. Second, ground control points are often plotted on medium scale maps, so that they have their own error. More seriously, a reduced number of GCPs does not allow to evaluate the derivatives of height, such as slope, orientation or curvature, which are very useful in most geoscience applications. Indeed, the derivatives of height are the indicators of terrain shapes, so that they have to be carefully controlled. Indeed, the topographic surface is so familiar for us, it has so many intuitive properties, that we have far more requirements for its cartographic representation than for the representation of any other physical surface. These requirements increase the need for an internal validation.

The factors of DEM quality can be divided into two main categories, namely, those related with the computation of height and those related with resampling. The importance of the former is obvious, but the latter should not be disregarded since the resampling method (in particular the size and shape of the sampling mesh) has a great incidence on the possibility that offers the DEM to recover the real surface. These considerations have led to the development of irregular sampling methods such as triangular irregular networks or composite sampling (Burrough 1986).

2.2 Topographic mapping from SAR data

Synthetic aperture radar is very sensitive to topography, and several methods have been developpped for the extraction of 3D information from SAR images: stereoradargrammetry, interferometry and shape-from-shading. A review of these methods can be found in Polidori (1991).

Radargrammetry consists in computing elevations from parallax measurements in two overlaping radar images (Leberl *et al.* 1986a, 1986b). It has two major differences with photogrammetry. First, the geometric equations of a pixel location define a so-called range-Doppler circle instead of a perspective line. Second, SAR is an active sensor, so that illumination changes with the antenna position. This makes the stereomatching of SAR images a very difficult task compared with the stereomatching of optical images which is often successful when the surface does not change too much between the two acquisitions. A complete description of radargrammetry has been performed by Leberl (1990) and a recent state-of-the-art can be found in Kaufmann & Raggam (1993).

The aim of **interferometry** is to analyse the phase difference between the signals received at two antenna positions. Under suitable geometric conditions, the phase difference contained in the interferogram is very sensitive to terrain elevation. A digital elevation model can be derived by analytical transform provided that the 2π ambiguity can be removed (Zebker & Goldstein 1986, Gabriel & Goldstein 1988). The removal of this ambiguity, known as phase unwrapping, is one of the major challenges for automated SAR interferometry.

The relationship between image grey level and surface orientation is the basis of **shape-from-shading** (or radarclinometry). A DEM can theoretically be derived through a pixel-by-pixel integration using a backscattering model and some assumptions about the surface curvature (Wildey 1986, Guindon 1989).

The performances and limitations are briefly discussed in section 2.3.

2.3 Performances of SAR mapping techniques

Even though the accuracy of SAR mapping techniques has often been estimated from a theoretical viewpoint, the experiments carried out over the past years have led to very rough orders of magnitude concerning their real performances.

As reported by Polidori (1991) the performance of a SAR mapping technique is a user concept which depends on what is expected from the radar-derived DEM. Indeed, the different techniques do not provide the same kind of information about the topographic surface.

In radargrammetry, individual heights are computed for each pair of matched points, so that the height error cannot propagate. An accuracy of a few pixels can be achieved in range, azimuth and elevation, but the correlation noise caused by radiometric dissimilarities leads to very poor micro-relief depiction, as observed by Leberl (1990).

On the contrary, shape-from-shading is based on slope computation, so that an accurate DEM (in terms of location standard error) cannot be obtained since the error propagates during the integration process.

Interferometry also suffers from error propagation since height differences are computed between adjacent points. However, unlike shape-from-shading, the relationship between phase difference and height difference is rigorous and rather accurate. The main pitfalls are the need for phase unwrapping, which can be very difficult for particular geometrical configurations, and an uncontrolled decorrelation between the echoes, which can be caused by changes in the environment (atmosphere, vegetation...).

Since relatively few DEMs have been extracted from radar data, several basic questions still arise concerning all techniques when the problem of SAR mapping performances is addressed:

- What is the impact of the landscape on the DEM accuracy?
- What is the impact of the radar system (as compared with other existing or hypothetic system) and the acquisition conditions on the DEM accuracy?
- Can radar mapping be fully automated or will human supervision always be required?

These questions aim at evaluating the intrinsic performances of SAR mapping techniques. It is clear that these performances have to be improved, but it is also important to evaluate their limitations at any development step. The next sections will show how a simulation approach can contribute to this evaluation.

3. SAR IMAGE SIMULATION FOR EVALUATING DEM EXTRACTION TECHNIQUES

3.1 Overview of SAR image simulation

A synthetic radar image can be generated using a landscape model (DEM, land use) and a set of platform and sensor parameters. All simulation algorithms consist in computing the radar cross-section for each ground element, and representing the resulting image in the radar geometry associated with the selected system parameters and the selected DEM. Figure 1 illustrates the basic principle of SAR image simulation.

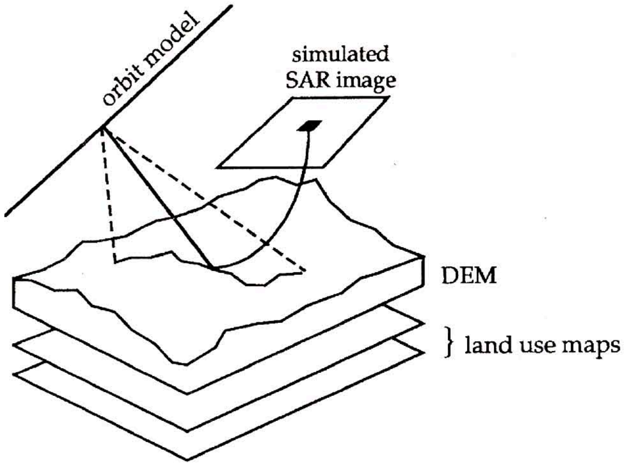

Figure 1 - Basic principle of SAR image simulation.

Using simulated data to analyse the radar imaging process is not a new idea. La Prade (1963) simulated radar images of an analytical surface including a few planimetric features, in order to demonstrate the feasibility of measuring parallax values in a radar stereopair. More recently, Kaupp *et al.* (1983) simulated spaceborne radar stereopairs in order to compare the aptitude of different viewing angles for stereo mapping. Leberl *et al.* (1985) simulated SIR-A images in order to reveal the influence of such geometric parameters as flight direction, off-nadir angle and squint angle, and therefore to improve the understanding of real images.

Geometric modelling

The acquisition geometry may be modelled either through a direct location function (i.e. in the image space) or through an inverse location function (i.e. in the object space). Since a DEM is not an analytical surface, direct location is a very tedious search procedure, while inverse location is easily performed with a slant range computation. The only drawback of inverse location may be some aliasing if the SAR image has a high resolution compared with the resolution of the landscape model.

Radiometric modelling

Several approaches may be considered for the modelling of radar backscattering and speckle noise. This radiometric information can be derived from an actual SAR image. In this case, the aim of radar simulation is to transform the actual image into another imaging geometry with unchanged radiometrical and textural properties. This can be done to simulate a satellite image from an aerial one.

More generally, the radar cross-section is computed using a backscattering model, in order to relate the backscattered power with the incidence angle and some information about the imaged target. Several backscattering models have been proposed, from the simple lambertian model (only the area effect is modelled through the cosine of local incidence angle) to more sophisticated rules based on a semi-empirical radiometric analysis of real SAR images. The incidence angle depends on the off-nadir angle and the terrain slope, and it is easily computed from the DEM and the known antenna position. The knowledge of the imaged target may be either deterministic in the case of man-made reflectors (Nasr & Vidal-Madjar, 1991) or statistical in the case of extended natural areas (Armand & Vidal-Madjar, 1992). In a rigorous SAR scene simulation, the raw signal is simulated pulse by pulse, conside-

Figure 2.a.

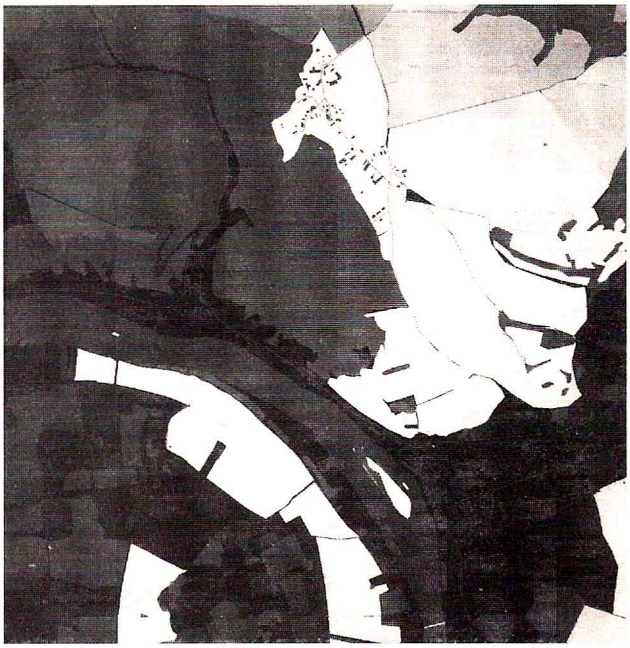

Figure 2.b.

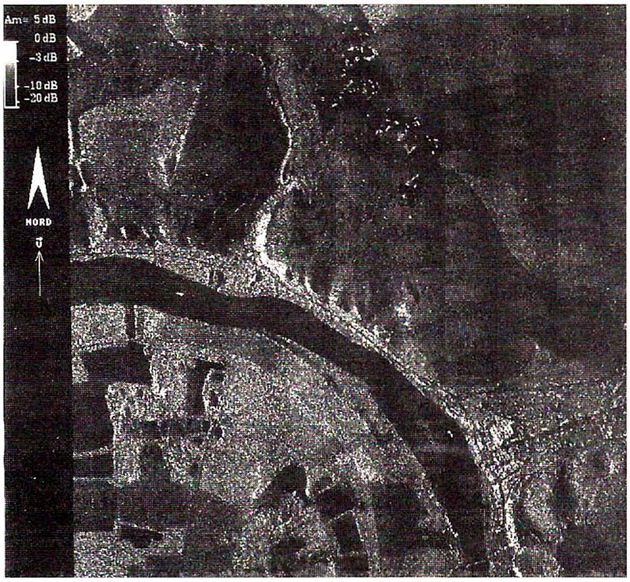

Figure 2.c.

Figure 2.d.

Figure 2 - Example of SAR image simulator output:
2.a: Input digital elevation model (© ISTAR).
2.b: Input land use map.
2.c: Simulated image (illumination West to East).
2.d: Simulated image (illumination East to West).

ring all relevant sensor parameters (PRF, chirp bandwidth, pulse length, transmitted power...) and the SAR image is obtained by SAR processing.

Speckle noise is produced by the reflexion of the coherent radar wave on a rough surface. Two main approaches can be mentioned for speckle modelling. Indeed, the simulator can either compute the coherent sum of a number of complex echoes, or multiply a non coherent simulation by a pure speckle noise drawn at random. We show below that the first method is preferable for SAR mapping validation.

As an illustration, synthetic airborne SAR images, simulated with the SAMOTHRACE raw signal simulator (Armand 1993) are shown in figure 2.

Satellite image simulators are useful during the design of space systems, for the adjustment of sensor specification, the validation of ground-segment facilities or the training of future users. The following section shows that simulated images can also be used to test 3D mapping algorithms, provided that some specifications are satisfied.

3.2 Specifications of a SAR image simulator for DEM validation

In the context of DEM validation, we have established specifications for SAR image simulation, based on the parametric modelling of both the SAR system and the imaged landscape.

SAR sensor and orbit

The SAR sensor is modelled through a set of parameters, in particular:
- carrier frequency;
- pulse length;
- band width;
- PRF;
- antenna pattern and gain;
- noise equivalent $\sigma°$;
- range sampling rate;
- near and far range.

The SAR processor has an influence on both amplitude and phase in the SAR image. This effect can be rigorously taken into account by simulating each radar pulse and running a standard SAR processor. However, since this method is very time consuming in the case of complex landscapes, it is possible to directly compute the single-look complex data, provided that the behaviour of the SAR processor is modelled in terms of amplitude and phase.

The position and speed of the platform are modelled through a time polynomial in a cartesian system. This polynomial can be derived from keplerian parameters or ephemeris data, but this is not part of the simulator.

Landscape geometric properties

The landscape geometry is modelled at two different scales, namely, at a pixel scale and at a wavelength scale.

On the one hand, the pixel scale geometry is modelled by an input DEM expressed in the same cartesian system as the platform position polynomial as illustrated in figure 1. Basically, this DEM is used for the computation of slant range and incidence angle. We will show in the next section that DEM resampling is recommended before the simulation.

On the other hand, the wavelength scale geometry refers to the spatial distribution of the scatterers within the resolution cell. It is drawn at random, with a uniform distribution for the horizontal position within the ground element and a Gaussian distribution for the height over the DEM surface (see figure 3). The number of scatterers can take any value, typically between 10 and 100 (higher concentrations lead to very time consuming simulations). The number of scatterers and the statistical parameters of their spatial distributions are specified for each land use class. It is important to note that one must be able to reproduce this distribution exactly for a rigorous modelling of speckle noise and baseline decorrelation as analysed by Zebker & Villasenor (1992).

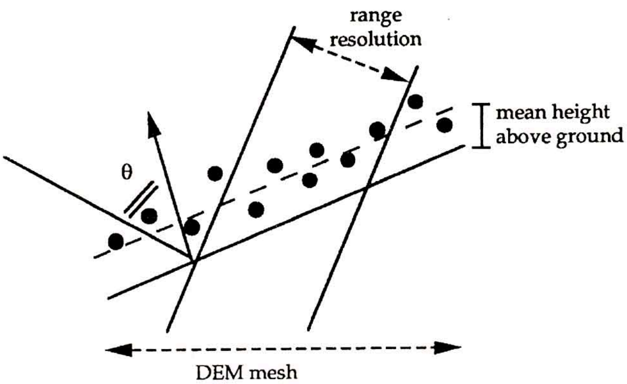

Figure 3 - Simulated SAR image (above) and interferogram (below) showing the effects of vegetation growth (A) and snow melt (B).

So far, volumetric scattering has not been considered (this is a limitation in the case of interferometric processing over forested area).

Concerning the dielectric modelling of the imaged landscape, each scatterer is associated with two magnitudes: the amplitude of the echo and the reflexion-induced phase shift. They are modelled with normal distributions, the parameters of which are specified for each land use class. These parameters depend on the land cover but also on temporary characteristics like moisture, frost or wind (Lefort *et al.* 1993).

The atmospheric effect on the radar phase is not modelled yet.

Temporal changes

Time is another important parameter in landscape modelling. Indeed, radargrammetry and interferometry use image pairs which may be taken at different dates, so that surface changes may have occurred. Therefore, the geometric and dielectric landscape characteristics must be modelled as functions of time, so that an image can be simulated at any date over a changing landscape. These changes can concern either surface displacements, changes in the amplitude, in the reflexion-induced phase shift or in the scatterers distribution. They are applied to each scatterer independently. Figure 4 illustrates the effect of surface changes, namely, snow melt (A) and vegetation growth (B). Both of them concern a height variation as well as a very slight change in the dielectric properties. Provided that the coherence is not too low, these changes result in local height errors which are proportional to the altitude of ambiguity (about 400 m in this example). It can be observed that these errors amount to 100 m (A) and 300 m (B).

Although we have not implemented this yet, we could also consider temporal changes in the sensor (e.g. clock drift).

3.3 Principle of simulation-based DEM validation

A SAR image simulator can provide a variety of realistic images in order to test a mapping technique. The idea of simulation-based DEM validation is to derive a DEM from a set of simulated images (for instance a radargrammetric or interferometric stereopair) and to compare this output with the input DEM. Indeed, even if the input DEM is not accurate with regards to a real surface, it can be considered as an exact ground truth for the simulated data. Figure 5 represents the architecture of a validation environment. It is important to note that simulation and mapping should be clearly independent tasks. In particular, the data used as simulation inputs (such as DEM or orbit) are not supposed to be known during the mapping process.

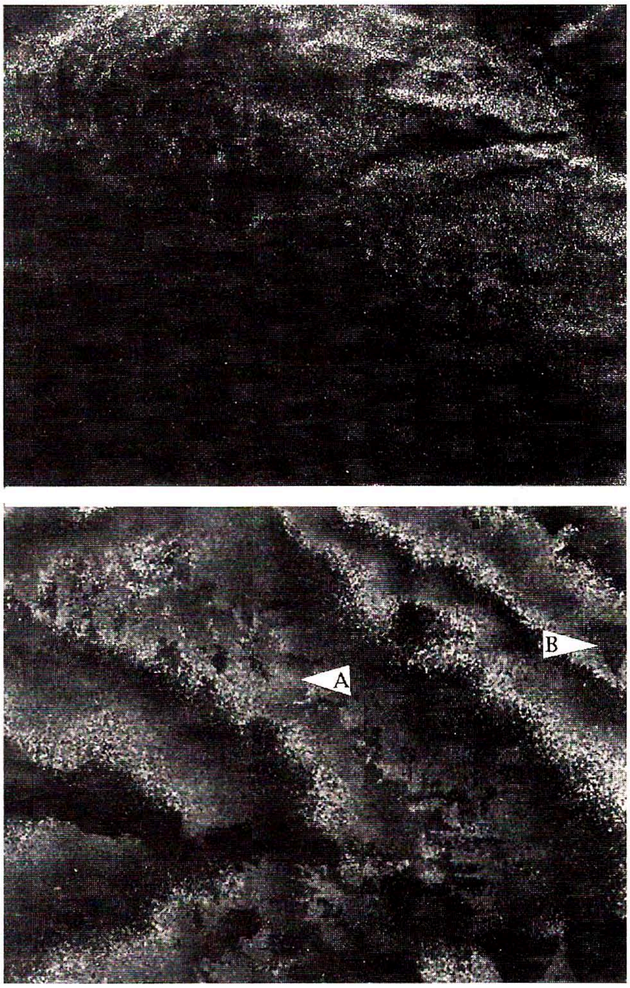

Figure 4 - Random spatial distribution of scatterers within resolution cell.

Apart from the simulator which has to comply with the above specifications, the simulation-based validation environment includes the following tools.

Landscape model preprocessing

In order to evaluate the sensitivity of an algorithm to high spatial frequencies or to particular shapes, it is necessary to synthesize them in the input landscape model. A landscape synthesis toolkit should include DEM resampling, target incrustation, microrelief synthesis and surface change modelling. Indeed, most digital elevation models

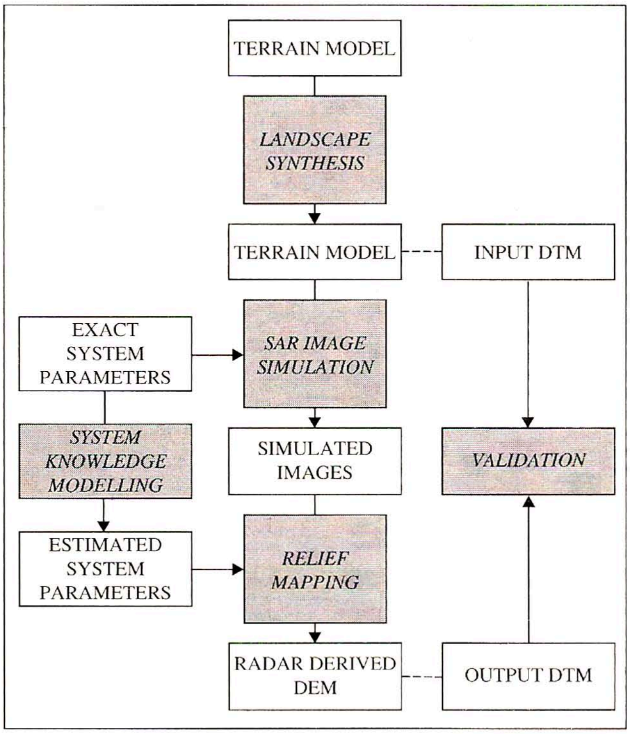

Figure 5 - Architecture of simulation-based validation environment.

are obtained by interpolating elevation values between digitized contour-lines or coarse altimetric grids, and the most common interpolation methods use smooth functions such as splines, so that the high frequencies of relief, which are already missing in the input map, are not even suggested in the resampled DEM. Therefore, microrelief synthesis is recommended. Since the two simulated images of a stereo pair have to be influenced by the same terrain shapes, the high frequencies of relief have to be simulated in the object space, i.e. on the DEM itself. Microrelief synthesis can use a stochastic surface model such as 2D fractional Brownian motion (Polidori & Chorowicz 1993). It is also important to note that the landscape resampling has to be performed off-line, i.e. before the simulation, so that the resampled DEM can be physically stored and used for the validation of the output DEM (Polidori 1994).

System knowledge modelling

The system parameters (sensor, platform, SAR processor) are perfectly controlled in the simulation. However, the parameters used in operational mapping correspond to measurements or estimates which differ from the real values. Therefore, realistic errors have to be introduced between real and estimated parameters in order to ensure that they are not better known than they would be in operational circumstances. These errors have an impact on the accuracy of the output DEM, and this impact can be studied from a parametric viewpoint. Such a system error management tool can be associated with an image quality budget software.

DEM evaluation

The radar derived DEM is compared with the input reference DEM using a DEM-to-DEM comparison toolkit, designed to evaluate height accuracy, slope accuracy and the rendering of specific terrain features (texture, hydrographic network...). Internal validation should be avoided, unless it has been carried out previously for the input DEM. Indeed, internal errors, such as striping or other unrealistic textures, may be contained in the input DEM.

4. ADVANTAGES AND LIMITATIONS OF THE SIMULATION APPROACH

4.1 Advantages

The simulation-based approach has several basic advantages:

First, a wide variety of image data over different landscapes and with different viewing configurations can be generated and analysed, so that wider conclusions may be drawn.

Second, the variety just mentioned can be handled with relevant parameters, namely:
- system parameters (platform, instrument, processor) but also the error on these parameters;
- topographic parameters (height, slope, orientation, roughness);
- environment parameters (atmosphere, surface change between two data takes).

The control of each of these parameters allows to evaluate its impact on the performances of a mapping technique. Consequently, not only the limitations can be evaluated, but they can also be understood, so that the algorithms can be improved more easily. For instance, the impact of surface changes on a radar interferogram can be characterized as illustrated in figure 3.

Finally, the simulation approach enables the comparison with a reference datum. Indeed, even if the input DEM differs from the real surface, it is supposed to represent a reference landscape with an infinite accuracy. The DEM derived from the simulated images is required to be as similar as possible to the reference DEM. This allows an objective and quantitative comparison. The comparison with the input DEM is more efficient than the mere comparison with a set of GCPs for several reasons already listed. In particular, the reference data set is dense enough to allow the evaluation of height derivatives.

4.2 Limitations

Testing a relief mapping technique on simulated image data has some limitations.

The landscape over which images are simulated must be as realistic as possible, but the approximations made in the geometric and radiometric models also limit the representativity of the simulated images. The behaviour of a radar wave in the atmosphere or in the vegetation cover cannot be modelled easily, and an oversimplification of these complex phenomena has obvious consequences on the realism of the simulated images.

In the case of interferometric applications, the phase errors produced by the SAR processor must be introduced in the complex images.

The land cover variations between two data takes should also be as realistic as possible, and modelled with time as a model parameter. To do so, an important task of landscape synthesis has to be carried out with care.

4.3 Applications of the simulation approach

Validation of mapping techniques

It has been shown in the previous sections that SAR image simulation can be used to test radar mapping techniques in a specific validation environment. In particular, the radargrammetric or interferometric processing of SAR stereo images can be tested, validated and improved using the input DEM as a perfectly accurate reference.

However, the simulation approach can be applied to any other technique, provided that it uses images which can be simulated in a realistic way, for instance:
- optical stereomapping;
- radar altimetry;
- optical / radar data fusion;
- dynamic mapping (differential interferometry, radargrammetric ice tracking).

This method may be useful at different levels. On the one hand, mapping facilities which are already operational can be controlled so that their quality can be quantified. On the other, new methods which are still investigated (SAR interferometry, automated urban mapping) can be tested at different stages of their development, so that the algorithms can be optimized.

Specification of future systems

Finally, it is important to note that image simulation can be used to question the aptitude of existing satellite observation systems for a given mapping technique. For instance, the aptitude of ERS-1 for interferometric applications has been evaluated for an orbit viewpoint (through baseline statistics) but with no regards to the surface coherence between the data takes (Solaas 1994). Simulating interferometric SAR images over changing landscapes could help to quantify the impact of these changes on the aptitude of ERS-1 for DEM generation, provided that these changes are modelled in a parametric way. Some improvements could then be suggested concerning the orbital maintenance strategy or the sensor parameters.

More generally, analysing the impact of the main system parameters on the accuracy of the output maps could justify some recommendations for the specification of future systems. In particular, new concepts which are being proposed (Moccia and Vetrella 1992, Gatelli *et al.* 1993) could be tested in a variety of cases before an operational design.

CONCLUSION

A relief mapping technique can be tested using simulated images. In the case of SAR mapping techniques (radargrammetry, interferometry, shape-from-shading), this approach is particularly useful. Indeed, radar mapping has not reached a fully operational level, and the limitations of SAR for mapping are not well understood. A simulation-based validation environment has been described, and its potential applications have been listed, namely, improvement of standard or new algorithms and contribution to the specifications of future radar systems.

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