SAR INTERFEROMETRY DEM QUALITY CONTROL METHOD: ASSESSMENT AND APPLICATION

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Abstract

Studies performed on DEM, realized by means of photogrammetry, SPOT satellite images or others methods show that the precision in the *z* coordinate is different than the horizontal precision. In the case of the Interferometry SAR (IFSAR), the precision in the azimuth axis may be different then the precision in the range-axis. More over, the error in elevation is correlated with the error in the range axis. A method proposed recently allows the evaluation of the DEM accuracy –vertical and horizontal- under some conditions of topographic unevenness. A reference DEM is required. In these recent works it has been shown, by simulation, that in some cases the evaluation is reasonably good. In this paper we develop an IFSAR DEM quality control method based in these works but taking into account the mentioned correlation.

We reformulate the method for the evaluation of IFSAR DEM accuracy. We obtain the precision in the azimuth-axis, range-axis and in elevation. These last two values may depend on the value of the range coordinate and the H parameter (overage antenna height). The method is viable depending on the surface feature conditions.

We develop an application to use the method with real or simulated DEM's. Finally, we propose a way to determine the evaluation of the results precision, so that, applying the method to a particular IFSAR DEM, a user knows the precision of the obtained results.

1. Introduction

A typical way to build surface numerical models or Digital Elevation Models (DEM) for Geographical Information Systems (GIS) is by processing the stereo images obtained from, for example, aerial photography or SPOT satellite data. These GIS can perform many computations involving their geographic databases. The quality control of a geographic database and in particular the topological and geometric integrity are, therefore, important topics [5,7,14,20,21,25]. The geometric quality control of the stored DEM is what we are concerned with here. « Quality » means the geometric precision measured in terms of the difference between a DEM and a reference DEM (R-DEM). We assume the R-DEM is a faithful model of the actual surface. Its point density may be greater than the DEM point density.

In the literature, several unsatisfactory solutions were proposed for the DEM control with respect to a reference. A critical problem in the error estimation (evaluated using the difference referred to in the previous paragraph) is to establish for each selected point of the DEM the corresponding homologous point in the R-DEM. Other kinds of problems and errors are related to the existence of aberrant points, systematization, etc. These problems were studied for horizontal errors in maps in [1,4,9]. These authors found that the dissymmetry model-reference was the most important factor to determine homologous pairs.

Several solutions have been proposed for the 'punctual control method' (recognition algorithms, filtering methods, adjustment of histograms to theoretical laws) without obtaining completely satisfactory results [2, 13]. Later, Abbas, Grussenmeyer and Hottier [1,4, 9,10] present an alternative to the punctual control method: the 'linear control method' based on the dissymmetry of the Hausdorff distance.

Habib [6] analyzes precision and accuracy in altimetry and mentions some of the proposals of the last decade for the elevation control of quality.

In the case of the DEM's, to asses the difference that gives rise to the error we wish to compute, we need to identify without ambiguity each point M in the DEM with its homologous point P in the R-DEM.

Two reasons make this task difficult:

1) many points M are not identifiable, those situated on regular sides, which are indistinguishable from their neighbors. Potentially identifiable points are those located on sharp slope variations, and possibly those with zero slope (tops, bottoms and passes),

2) a point identifiable on the DEM is not necessarily identifiable in the R-DEM, because of a difference in scale ("generalization") or aberrant errors.

To find identifiable homologous pairs of points is difficult for an operator. Automating this is a very delicate process.

In the case of the precision assessment of a DEM from an ASTER (Advanced Spaceborned Thermal Emission and Reflection Radiometer) [8] profiles or benchmarks (particular points) are used for the elevation accuracy assessment. This elevation accuracy assessment refers to the vertical error of the DEM. However, using profiles the horizontal error is not taken into account and also there is a model-reference discrepancy. Moreover, the choice and number of the benchmarks might not be a good stochastic sample of points.

In light of the above difficulties, in [22] an estimator for the variances of the vertical and horizontal errors was proposed. The values obtained for the estimator according to the type of terrain, its unevenness, and the number of sample points in the DEM were studied using simulations in [23,24]. Throughout these studies, it is assumed that the errors in elevation and in the horizontal plane are independent Normal random variables - in agreement with Liapounov's theorem [11]. This proposed method is called the Perpendicular Distance Estimation Method (PDEM).

Let $e(M_k) = M_k - P_k$ where M_k, P_k are the k selected homologous pairs of points in the DEM and R-DEM respectively. Estimating $\sigma^2(e)$ (variance of the error as distance between M and P) without measuring each vector $e(M_k)$ completely, is the key advantage of the proposed PDEM. Only the projection of each $e(M_k)$ in particular directions maters. Given an M_k it becomes unnecessary to find the homologous P_k in the R-DEM. How this is done is the subject of the following section.

For three-dimensional DEM's built with the usual techniques, such as photogrammetry or remote sensing, there are expected normal deviations in altimetry (σ_z) and in the horizontal plane (σ_x, σ_y)which are 'a priori' known. They are generally different from each other due to the manner in which the values of the *z* coordinate (altimetry) and the *x* and *y* coordinates (the horizontal plane) are evaluated. The goal of this PDEM is to evaluate the actual errors ('a posteriori') of a given DEM.

2. – Description of the PDEM

The gap between the DEM and the R-DEM is represented by a function that links each point of the DEM to the vector e(M)=M-P in $\mathbf{R}^3$ where P is the homologous point to M in the R-DEM. M and P represent the same relief element, however P is not vertically aligned with M.

The DEM precision is a function of the vectors $e(M_k)$ of a sample of $\{M_k\}$ points. This function is used in the construction of the covariance matrix $\sigma^2(e)$.

If the errors in the three directions are different (as in interferometry radar) the rank of $\sigma^2(e)$ is three. Its eigenvalues are the variances in the three main coordinates.

When the errors in the orthogonal directions in the plane are equal (stereo images techniques), we can consider that the rank of the covariance matrix $\sigma^2(e)$ is two. The eigenvalues are the variances σ_z^2, and $\sigma_x^2 = \sigma_y^2 = \sigma_{x,y}^2$.

In a rotated frame of reference, the new covariance matrix will no longer be diagonal. The new components are expressed in terms of the eigenvalues of $\boldsymbol{\sigma}^2$. The following expression corresponds to the first component $\sigma_{x'}^2$ of the new covariance matrix:

$$\sigma_{x'}^2 = a_{11}^2\sigma_x^2 + a_{12}^2\sigma_y^2 + a_{13}^2\,\sigma_z^2 \qquad [1]$$

where a_{1j} are the managing cosines of the unit vector in the x' coordinate of the rotated reference frame.

The value of the variance in the x′ direction is equal to the square of the distance between the two planes normal to the x′ direction: one tangent to the "distribution indicative ellipsoid" (whose parameters are $a = \sigma_x$; $b = \sigma_y$; $c = \sigma_z$) and the other passing through its center.

In figure 1, the plane normal to the x' direction and tangent to the 'distribution indicative ellipsoid' is drawn in the general case.

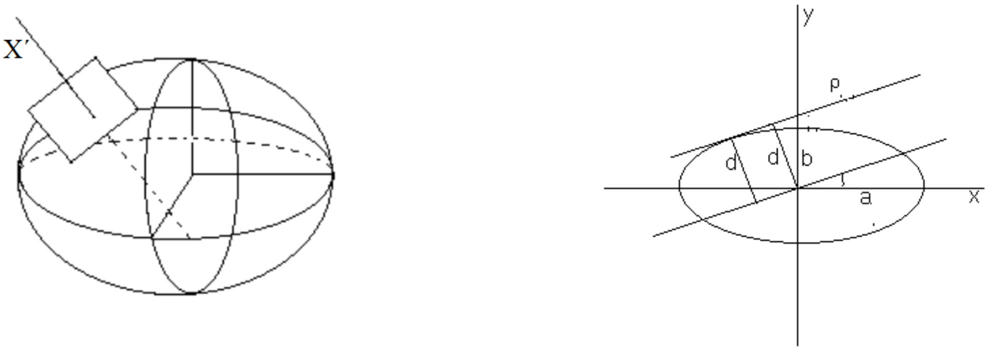

Figure 1: distribution indicative ellipsoid and tangent plane Π , and, distribution indicative ellipse and tangent straight line ρ.

The algebraic form of equation [1] is used to obtain the variance in any direction ***d***, replacing the coefficients a_{ij} with the managing cosines *(cos α, cos β, cos γ)* corresponding to this direction ***d***:

$$\sigma_d{}^2 = \sigma_x{}^2 \cos^2 \alpha + \sigma_y{}^2 \cos^2 \beta + \sigma_z{}^2 \cos^2 \gamma \qquad [2]$$

$\sigma_d{}^2$ can be estimated with $\Sigma e_i^2/n \quad 0<i<I$ where the e_i are the error components in the ***d*** direction.
We construct a mesh of triangles from the points of the R-DEM. We call this a model of the surface. Given a point M in the DEM, its projection onto the *x,y* plane is inside the projection of a unique triangle *T* from this model. We call this the corresponding triangle *T* to M. The e_i component in the direction $\boldsymbol{d_i}$ is the distance d_i, from each point to the plane of the corresponding triangle. The squares of the distances d_i, between each point of the model and the plane of the corresponding triangle, allow us to establish a least squares estimator for the assessment of ($\sigma_x{}^2$, $\sigma_y{}^2$, $\sigma_z{}^2$).

3. Ifsar correlation problem: method reformulation

Now we outline the way in which the general estimator for variances in the three-dimensional case is applied for the IFSAR-derived DEM.

The figures 2 shows the geometrical problem and the correlation between the range-axis y and the z-axis. The covariance matrix is diagonal (no correlation) when a rotation around the azimuth-axis x is done. The rotation make the z'-axis in the direction of the beam. This hypothesis is justified by the formulas presented in [3,12,15,16,17,18,19] where the coordinates in the range-axis and the elevation value are function of the distance radar-target and the radar-target direction.

The x-axis (the azimuth-axis) is parallel to the antenna trajectory A1. The y'-axis is normal to the z'-axis and belongs to the plane defined by the z'-axis and the vertical direction. With this rotation the three directions will not have correlated random variables. In the case of an IFSAR-derived DEM, the measured errors in the z'-axis and in the y'-axis (after the rotation) are the ones caused by the measurement error of the antenna-target distance and the antenna-target direction. The rotation angle θ is the angle between the vertical direction and the beam direction.

H is the antenna A1 height and R is the distance from the antenna to the target C. The z value is given by:

$z = H - R \cos \theta$: H and R are known but $\cos \theta$ is unknown.

But:
$\cos \theta = \cos \varepsilon \text{ cosinus } (\theta - \varepsilon) - \sin \varepsilon \text{ sinus } (\theta - \varepsilon)$
And,
$\cos (\theta - \varepsilon) = (1 - \sin^2(\theta - \varepsilon))^{1/2}$

In the A1 A2 C made by the two antennas A1et A2 and the target C; R + r is the distance between A2 and C, and ε the angle in A1.
Then:

$(R+r)^2 = B^2 + R^2 + 2BR \cos \varepsilon$

Where R, B, r (r is function of the difference of phase and the wave length) are known and

$\varepsilon = 90 + \theta - \varepsilon$

With:

$\cos \varepsilon = \sin (\theta - \varepsilon)$,

The height z of the target is equal to:

$z = H - R \cos \theta$
and,
$y = R \sin \theta$

That is y and z are correlated

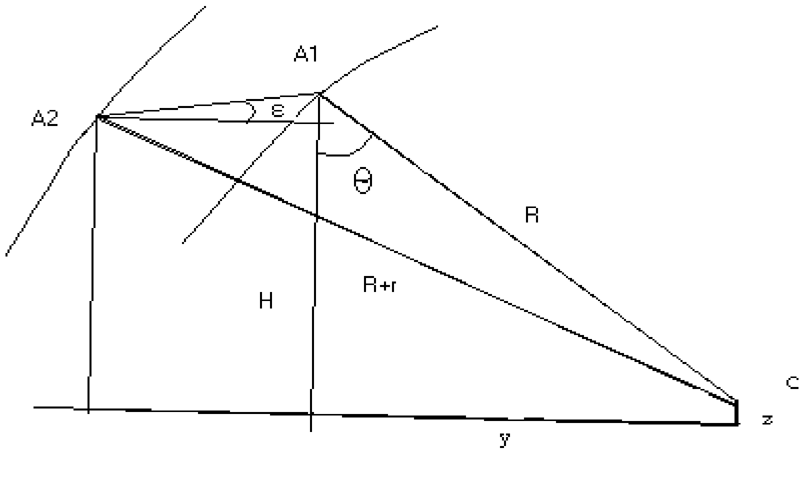

Figure 2: IFSAR geometry

Different hypothesis may consider in relation with the distance and direction errors. The distance error (in the z' direction) and the direction error (y' normal to z' direction and in the yz plane) may be functions of the measured distance. For the simulations we will consider arbitrary values, but these errors may be linear functions of the distance. Other functions of the distance can be assumed to model these errors. We may guess independence of the distance for one or for both errors as we assume. The error evaluation in each particular real case will give the elements to fix these functions. Indeed, a way to establish these functions could be to evaluate these errors for far and for near range points. With this information functions may be derived.

3. - Method description

Recall [24,26,27] that a R-DEM will be used as the control for a DEM, real or simulated. Also recall that a R-DEM, being a discrete set, allows constructing a mesh of K triangles defined by the points on the reference surface. Each triangle T_k, $(k=1,\ldots,K)$, belongs to a plane which has a normal unitary vector n_k, $(k=1,\ldots,K)$.

The mesh of K triangles of the R-DEM is constructed using, for instance, the Delaunay method in two dimensions.

In the case of a simulation we have to:

- determine the mass center of each triangle, and express their coordinates it in the rotated system. The rotation angle will be a function of the coordinate value in the range-axis of the triangle mass center,
- Adopt a standard deviation for each coordinate σ_x, $\sigma_{y'}$ and $\sigma_{z'}$ and add three random normal variables to the center mass coordinates that are expressed in the new coordinate system. These points simulate the DEM to be evaluated. Note that $\sigma_{y'}$ and $\sigma_{z'}$ eventually have to take into account the distance between this simulated point and the antenna. This distance is easy to determine knowing the height of the antenna trajectory.

In the case of a real DEM we have to:

- Determine the triangle of the R-DEM containing the homologous point of each point of the DEM. The procedure is as follows [Zelasco 2001]: given a DEM point M_s , its homologous point P in the R-DEM will be in a plane define by the triangle T_s, if the projection of the point M_s on the *(x,y)* plane is inside the projection of the triangle T_s on the same plane. We establish a practical limit to avoid border problems given by the 'a priori' standard deviation $\sigma_{p'}$ (horizontal error in the x or the y' new coordinates direction) which allows us to select the points of the DEM in the sample. If the horizontal distance between the projection of M_s and the limits of the projected triangle is, v.g., at least three times greater than $\sigma_{p'}$, the point is accepted. Otherwise, it is rejected. This is because $\sigma_{p'}$ is the standard deviation of a normal random variable.
- Express the coordinates of the selected point in the rotated frame. The rotation angle will be a function of the range-axis DEM point value.

In both cases we have to:

- Express the normal unitary vector n_k the new coordinate system,
- Calculate the distance from each point (point of the simulated or of the real DEM) to the plane of the corresponding triangle,
- Evaluate, using the PDEM, the standard deviation of the DEM points: σ_z, $\sigma_{y'}$ and $\sigma_{z'}$. In the case of the simulation their values should be similar to the ones already used.

Note 1: Knowledge of the γ angle makes it possible to select a R-DEM with more or less unevenness.

Note 2: For each one of the planes having the direction d given by the normal unitary vector n_k in question, the distance from the point M_j , *(j=1..J<=I)* to the corresponding plane is a measure (in the direction d) of the error $e_{d,}$.

4.- Result assessment

We have a DEM of 100,000 points obtained by stereo correlation. The bi-dimensional Delaunay algorithm allows us to triangulate, in the plane *(x,y)*, any subset of this DEM. This subset of triangles will be our R-DEM. In figure 3 we can see the histograms of the selected R-DEM of 1500 triangles, before and after the rotation.

The goodness of the evaluation of the errors in the z'-axis direction and in the y'-axis direction depends on the interval of the φ angles selected.
but also on the relation values of the three coordinates errors (σ_x, $\sigma_{y'}$, $\sigma_{z'}$) (respectively in the x-axis, y'-axis and z'-axis) [Zelasco, 2002].

The α angle is the one between the normal unitary vector n_k to the triangle, and the x-axis. The precision on the evaluation of the error in the x-axis direction can be improved selecting triangles with an α angle as small as possible.
The big advantage in the evaluation of a DEM derived from IFSAR is the angle of the beam.
In Zelasco,02 it is shown that the results in altimetry are always very good. This is because many triangles may have a small value in φ angle (φ is in this case the angle between the normal unitary vector n_k and the z-axis. But in SAR Interferometry the result in the evaluation of the error in the direction of the beam (y'-axis) is good enough, because the rotation stretches the histogram. (see the histograms in figure 3).

The conditions for the terrain's unevenness were given in terms of angle φ. After the rotation of the θ angle, around the x-axis, the condition is given in terms of the φ'.
Several test were done with different values of the errors in the three axes. In all the cases 23 simulations were performed (n =23). We obtain mean values of the error estimations and the standard deviation of these estimations.

The standard deviation of σ is defined as $\{[\Sigma_n(\sigma_n - \sigma_{(n)})^2]/N\}^{1/2}$ where $\sigma_{(n)}$ is the true value of the sample.

First test: ($\sigma_x = 10;\ \sigma_{y'} = 15;\ \sigma_z{}' = 20$)
$(\Sigma_n\sigma_{Xn})/N$; mean of the assessed σ_X = ----
$(\Sigma_n\sigma_{Y'n})/N$; mean of the assessed $\sigma_{Y'}$ = 15.302
$(\Sigma_n\sigma_{Z'n})/N$; mean of the assessed $\sigma_{Z'}$ = 19.943
Standard deviation of σ_X = -----
Standard deviation of $\sigma_{Y'}$ = 1.353
Standard deviation of $\sigma_{Z'}$ = 0.568

Second test: ($\sigma_x = 10;\ \sigma_{y'} = 20;\ \sigma_z{}' = 15$)
$(\Sigma_n\sigma_{Xn})/N$; mean of the assessed σ_X = 13.401
$(\Sigma_n\sigma_{Y'n})/N$; mean of the assessed $\sigma_{Y'}$ = 20.172
$(\Sigma_n\sigma_{Z'n})/N$; mean of the assessed $\sigma_{Z'}$ = 14.975
Assessed standard deviation of σ_X = 4.121
Assessed standard deviation of $\sigma_{Y'}$ = 0.920
Assessed standard deviation of $\sigma_{Z'}$ = 0.544

Third test: ($\sigma_x = 15;\ \sigma_{y'} = 20;\ \sigma_z{}' = 10$)
$(\Sigma_n\sigma_{Xn})/N$; mean of the assessed σ_X = 18.302
$(\Sigma_n\sigma_{Y'n})/N$; mean of the assessed $\sigma_{Y'}$ = 20.069
$(\Sigma_n\sigma_{Z'n})/N$; mean of the assessed $\sigma_{Z'}$ = 9.889
Assessed standard deviation of σ_X = 1.751
Assessed standard deviation of $\sigma_{Y'}$ = 0.731
Assessed standard deviation of $\sigma_{Z'}$ = 0.564

Fourth test: ($\sigma_x = 15;\ \sigma_{y'} = 10;\ \sigma_z{}' = 20$)
$(\Sigma_n\sigma_{Xn})/N$; mean of the assessed σ_X = 18.168
$(\Sigma_n\sigma_{Y'n})/N$; mean of the assessed $\sigma_{Y'}$ = 10.298
$(\Sigma_n\sigma_{Z'n})/N$; mean of the assessed $\sigma_{Z'}$ = 19.951
Assessed standard deviation of σ_X = 3.285
Assessed standard deviation of $\sigma_{Y'}$ = 1.660
Assessed standard deviation of $\sigma_{Z'}$ = 0.564

Fifth test: ($\sigma_x = 20;\ \sigma_{y'} = 10;\ \sigma_z{}' = 15$)
$(\Sigma_n\sigma_{Xn})/N$; mean of the assessed σ_X = 22.764
$(\Sigma_n\sigma_{Y'n})/N$; mean of the assessed $\sigma_{Y'}$ = 10.137
$(\Sigma_n\sigma_{Z'n})/N$; mean of the assessed $\sigma_{Z'}$ = 14.947
Assessed standard deviation of σ_X = 1.817
Assessed standard deviation of $\sigma_{Y'}$ = 1.031
Assessed standard deviation of $\sigma_{Z'}$ = 0.483

Sixth test: ($\sigma_x = 20;\ \sigma_{y'} = 15;\ \sigma_z{}' = 10$)
$(\Sigma_n\sigma_{Xn})/N$; mean of the assessed σ_X = 22.664
$(\Sigma_n\sigma_{Y'n})/N$; mean of the assessed $\sigma_{Y'}$ = 15.036
$(\Sigma_n\sigma_{Z'n})/N$; mean of the assessed $\sigma_{Z'}$ = 9.923
Assessed standard deviation of σ_X = 1.444
Assessed standard deviation of $\sigma_{Y'}$ = 0.650
Assessed standard deviation of $\sigma_{Z'}$ = 0.474

Seventh test: ($\sigma_x = 15;\ \sigma_{y'} = 15;\ \sigma_z{}' = 15$)
$(\Sigma_n\sigma_{Xn})/N$; mean of the assessed σ_X = 18.160
$(\Sigma_n\sigma_{Y'n})/N$; mean of the assessed $\sigma_{Y'}$ = 15.161
$(\Sigma_n\sigma_{Z'n})/N$; mean of the assessed $\sigma_{Z'}$ = 14.937
Assessed standard deviation of σ_X = 2.238
Assessed standard deviation of $\sigma_{Y'}$ = 0.910
Assessed standard deviation of $\sigma_{Z'}$ = 0.481

5. Results discussion

The error evaluation in the x-axis is not very good. Only in same cases depending on the distribution ellipsoid shape reasonable results are obtained. In the worst case we could not get any result. This was foreseen in Zelasco, 2002.
In the y'- axis the results are reasonable good. This is because de rotation around the x-axis; rotation we could do because the SAR look angles.
The error evaluation in the z'-axis is excellent.
Nevertheless is important to consider the fact that [Dupont, 1997] over a value of the land slope the IFSAR not allow to know the elevation because the surface cannot be seen from the radar. The corresponding triangles have to be excluded from the R-DEM and the points on the DEM corresponding that area have to be considering as aberrant points.

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