Calibration of Interferometric Synthetic Aperture Radar Digital Elevation Models (DEM) Using Error Surface Interpolation Methods

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Digital elevation models (DEM) are numerical representation of terrain elevation data that has been used in a wide range of spatial analysis applications. The principles for acquisition, storage, management, update, spatial analysis, visualization as well as integration with other systems are reasonably well known. However, as DEM applications are becoming increasingly more widespread, so does concern about the quality of the available elevation data and the propagation of DEM errors through the analysis. Currently available DEMs frequently report only the average magnitude of errors as the root mean square error, which does not provide information on systematic bias nor on the spatial patterns of the DEM errors. The present work deals with DEM generated by synthetic aperture radar (SAR) interferometry (InSAR) and the main goal is developing a method for DEM correction that can be flexible and adaptive to local errors magnitude variations. The approach used in this work consists in SAR data acquisition, field topographic control structure determination, original DEM models geometric quality evaluation, development of strategies and algorithms for DEM error correction and calibration. Implementation of strategies and algorithms required to solve the problem was taken in IDL (Interactive Data Language) environment. The core of the methodology for DEM error correction and calibration intends to provide a DEM fitting to geographic space reality by calculating and incorporating error compensation surfaces generated by triangulation with linear interpolation and inverse squared distance interpolation methods. The DEM calibration methodology also includes determination of statistical spatial pattern accuracy parameters for processed DEM. The assessment of correction efficiency is done by analyzing statistical quality data extracted from fitted DEM that provided measures of DEM accuracy. Results revealed that DEM considered in analysis, like many other currently available, have local and global errors and needs to be corrected before their uses in posterior analyses applications. Final results also shown that application of proposed correction method, besides improving DEM geometric quality, also provided statistically confident numerical estimation of DEM global and local accuracy.

Keywords: error surface interpolation, DEM calibration, synthetic aperture radar interferometry.

1. INTRODUCTION

Digital elevation models (DEM) are extensively used in a wide range of earth science fields for different spatial analysis applications. Therefore, nowadays there is a great availability of DEM data representing earth surface altimetry, remarkably covering developed countries areas for applications such as orthophoto production, flood prevention planning, control of erosion, agriculture planning, visibility analysis, 3D visualization and so on. Such availability of DEM data, however, does not ever incorporate adequate form, resolution and geometric quality for all applications. Until recently it did not have many forms for acquisition of data and construction of DEM. However, during the last years some flexible ways had appeared to get them. So, currently there are many methods to reach that purpose, representing excellent perspectives to extend the capacities of DEM applications. The DEM basic principles for acquisition, storage, management, update, spatial analysis, visualization as well as integration with other systems are reasonably well known. But, while DEM applications are becoming more and more widespread also increases the concern about the quality of the available DEM elevation data and the propagation of DEM errors through the subsequent analyses. Presently, it is also well known by analysts and researchers that the results of many DEM-based quantitative operations are very influenced by the magnitude and by the spatial distribution of elevation errors in DEM. Currently available DEMs, however, frequently report only the average magnitude of errors as the root mean square error (RMSE), which does not provide information on systematic bias nor on the spatial patterns of the DEM errors (Heuvelink, 1998).

A very important critical point to be considered when remote sensing techniques are used for mapping earth resources is the geometric quality and error assessment of data and derived products involved in all processing steps. There is nowadays, among countries worldwide, a practice of adopting several cartographic standards, generally enforced by law, in order to guarantee geometric fidelity of survey data compatible to systematic mapping scales and its spatial resolution. In the case of 3D data for DEM applications the most suitable and general form to evaluate errors and provide adequate correction refinements is based in the establishment of a set of mapping functions to associate feature positions present in DEM to its corresponding in a cartographic reference frame. So far, many efforts have been made to solve registration and geometric correction problems based in that kind of approach (Audette et al, 2000; Gruen & Akca, 2005). However, relevant research contributions are still required in this field, mainly for development of non-rigid and some degree elastic correction and registration methods. It is also important to provide control and certify DEM internal quality (Pottmann et al, 2004). Such geometric guarantees considerations come to happen as an essential issue for terrain mapping applications.

The present work intends to develop a method for DEM altimetry calibration, using 3D data generated by synthetic aperture radar interferometry (InSAR) and a field control point structure determined by Global Positioning System (GPS) satellite tracking integrated to surveys made with electronic topographic stations. The approach used will provide statistical estimation of the calibration method's efficiency. The DEM presently analyzed were generated by SAR P band fully polarimetric system. Additionally a DEM was produced by X band in HH polarization. Data was collected in two-pass mode for P band interferometry and single-pass mode for X band interferometry. SAR radiation in X band do not penetrates into forest canopy so resulting DEM is related to top forest cover, while SAR radiation P band penetrates into forest volume returning after interaction with ground level, so producing a DEM related to forest ground (Hofmann et al, 1999). If both models from X and P band are submitted to adequate geometric correction and effectively calibrated the resulting difference between them will produce a forest digital height model (DHM). This product is considered an important request for many current natural resources applications. The methodology adopted in this work was limited to evaluate only P band data and mainly consists in the following topics: SAR data acquisition; field topographic control structure determination; geometric quality evaluation of original DEM models; development of strategies and algorithms for DEM error correction and calibration. All computational implementation of strategies and algorithms requested to solve the problem approach was taken in IDL (the *Interactive Data Language*), a complete computing environment for the interactive analysis and visualization of data that integrates a powerful, array-oriented language with several mathematical analysis and graphical display techniques. IDL environment is a time-saving alternative to programming in FORTRAN or C. It is possible to explore data interactively using IDL commands and then create complete applications by writing IDL programs.

The core of the methodology adopted here for DEM error correction and calibration is intended to provide a DEM fitting to geographic space reality by calculating and incorporating error compensation surfaces generated by triangulation with linear interpolation and inverse squared distance interpolation methods. The compensation surfaces for DEM calibration are calculated from comparison of original DEM data positions against corresponding known cartographic land marks. The correction surface is determined as regular grid with the same cell resolution as original DEM, then DEM-added in a pixel by pixel basis. The work also included efforts to determine global and local accuracy spatial patterns that help to characterize the geometric quality of resulting DEM. The assessment of correction efficiency is done by analyzing statistical quality data extracted from fitted DEM that provided measures of local and global DEM accuracy. The final results revealed that altimetry data considered in the present analysis, like many other currently available DEM, incorporate local and global error patterns and consequently need to be corrected prior to be used in other analyses applications. Final conclusions pointed out that application of proposed calibration method, besides improving DEM geometric quality, also provided statistically confident numerical estimation of DEM global and local accuracy parameters that can be used to evaluate error propagation in DEM derived products.

2. STUDY AREA AND DATA ACQUISITION

The study area that provided data to be used in this experiment is a parcel of Amazonian Tapajós National Forest, stated in southern region of Santarém County, inside Tapajós River basin, next to São Jorge village (Brazilian state of Pará). The region is covered by primary forest, various age re-growth vegetation, pastures and uncovered ground soil (Dutra et al, 2002). The data acquisition was conducted according to directions that follow. In September 2000, a X (HH polarization) and P band full polarimetric system, from *AeroSensing RadarSysteme GmbH*, was flown over sections of Brazilian Amazon in the framework of a cooperation between the Brazilian Army and the National Institute for Space Research (INPE). One-pass X band and two-pass P band InSAR data was acquired over the Tapajós National Forest and surroundings, Pará state. Digital Elevation Models for both frequencies were constructed by using the company proprietary software (Moreira, 1996). Because X band radiation does not penetrate the canopy, the DEM produced by X band data is related to the canopy top and is commonly called Digital Surface Model (DSM). The DSM-DEM difference is, so, related to the forest height and commonly known as Digital Height Model (DHM). During the mission flight corner reflectors were positioned on several points inside test area to ensure absolute altitude calibration. However, a problem with the airplane inertial system prevented the proper DEM calibration, so the method proposed in this paper intends to improve InSAR DEM calibration (Dutra et al, 2002). Some preliminary studies involving the study area can be found in Mura et al (2001) and Dutra et al, 2002. Figure 1 presents in the left side a tile of a RGB-543 TM LANDSAT/5 image with a rectangle in color red that delimits the DEM area which is represented in gray level at right side.

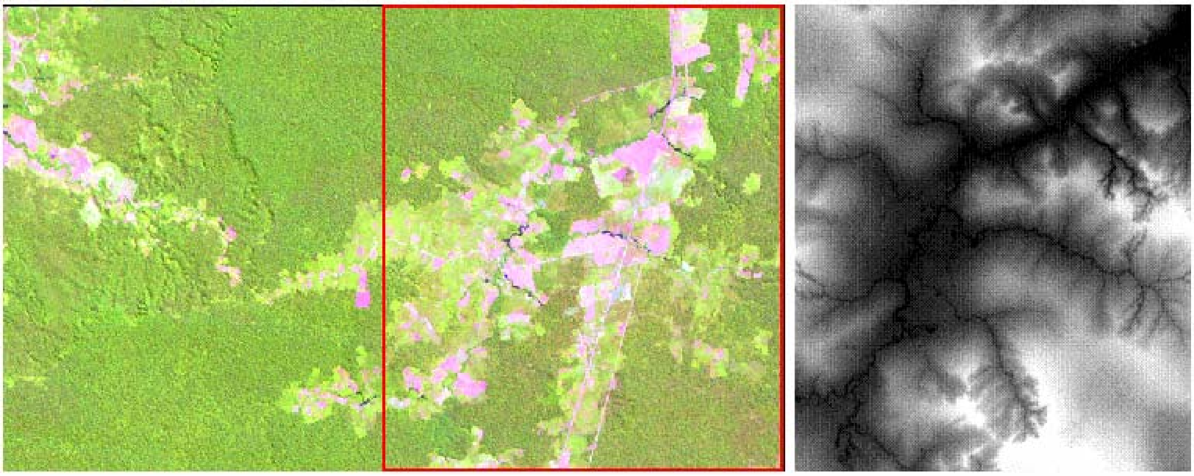

Figure 1 - TM LANDSAT/5 RGB-543 (left side). The red rectangle corresponds to P band InSAR DEM area (right side).

3. METHODOLOGY

The approach adopted to conduct the problem of DEM calibration encompasses several steps that can be summarized in the following general items: GPS satellite tracking and electronic topographic station field control structure survey; P band and X band InSAR data acquisition; preliminary assessment of original InSAR DEM geometric quality; cartographic conversion and registration of all data to unique terrestrial geodetic frame (WGS84); InSAR outliers detection and elimination; classification and selection of field control points; calibration of InSAR DEM from field control points using non rigid and elastic techniques; and information extraction from corrected DEM. The most important topics will briefly be described in the next sections.

3.1. Preliminary assessment of InSAR models

Remote sensing basic principles, SAR theoretical fundamentals and the measurement field instruments characteristics lead us to believe that P band DEM model should produce similar altimetry values to that obtained in field survey over uncovered areas such as roads, ploughed fields, pastures and naked ground (Hofmann et al, 1999; Baltzer, 2001). Another assumed hypothesis is that of all data in study are perfectly matched horizontally and errors to be corrected only occur in DEM altimetry component. These hypotheses had been strengthened by the existence of an excellent data set horizontal alignment confirmed through simplified numerical analyses integrated with comparisons over the study region made with available optical sensor images. Thus, the corrections, tests and evaluations had been carried out only on the DEM altimetry component. The preliminary evaluations done by simplified numerical and visual analyses did really confirm a good horizontal alignment but, at the same time, revealed the presence of outliers and a strong necessity of DEM altimetry calibration.

3.2. DEM models plane surface altimetry calibration

All DEM error calculations were done by direct comparison with the field topographic control structure data, considered true geographic positions due to its high precision. The selected control points were separated in two sets. One set to calculate the error surfaces and the other set to provide the evaluation tests and verifications. The first level of correction applied to DEM was conducted using the simplest possible way, that is, by determining an altimetry offset calculated by averaging differences between field control points and their corresponding in InSAR models. This procedure results in correction surface corresponding to a horizontal leveled plane (Dutra et al, 2002). Prior to offset calculation many interactive efforts was conducted to detect and eliminate outliers found in InSAR data. This step was done by using convolution filters based in local median developed in IDL environment. The simple mathematical formulation to determine plane correction surface is given in equation 1.

$$e_m = \frac{1}{N}\sum_{i=0}^{N}(h_T - h_S) \qquad (1)$$

where e_m is the offset corresponding to the plane surface correction, N is the total number of field control points used, h_T is the field control point altitude and h_S is the corresponding InSAR altitude. The offset precision (e_{RMS}) is given in equation 2.

$$e_{RMS} = \sqrt{\frac{1}{N}\sum_{i=0}^{N}(h_T - h_S)^2} \qquad (2)$$

Table 1 shows plane correction surface quality parameters for P band DEM that was analyzed in terms of minimum, maximum, mean, variance, absolute deviation and standard deviation. The *calculate* term refers to set points used to calculate the error surfaces and *test* refers to set points for evaluation and verifications. The *test* results were obtained comparing the independent set of control points for tests with corresponding points in corrected DEM.

Table 1 – Summary of global quality offset correction parameters for P band DEM.

	Minimum	Maximum	Mean	Variance	Abs deviation	Std deviation
Calculate	-11.240	6.760	-0.388	6.776	2.185	2.603
Test	-7.052	8.348	0.197	4.406	1.600	2.099

3.3. Triangulation with linear interpolation surface altimetry calibration

The offset correction discussed in the previous step applies a correction with the same value to all points over the entire DEM, so does not provide an efficient way to deal with local errors of different magnitudes that is very common in existing DEMs. A better alternative approach in those cases for DEM error calibration in order to provide adaptive fitting to geographic reality is the calculation and incorporation of error compensation surfaces generated by triangulation with linear interpolation methods. The triangulation with linear interpolation method adopted uses the optimal Delaunay triangulation. The implemented algorithm creates triangles by drawing lines between data points. The original points are connected in such a way that no triangle edges are intersected by other triangles. The result is a patchwork of triangular faces over the entire extent of the grid (Shewchuk, 1999). This method is considered an exact interpolator. Each triangle defines a plane over the grid nodes lying within the triangle, with the tilt and elevation of the triangle determined by the three original data points defining the triangle. All grid nodes within a given triangle are defined by the triangular surface (Burrough & McDonnell, 1998). Because the original data are used to define the triangles, the data are honored very closely. Triangulation with linear interpolation works best when vertices corresponds to significant data points on the area, that is, samples represents peaks and valleys in errors (Erxleben et al, 2002). Figure 2 shows at the left side a gray level representation of the correction surface for P band DEM generated by triangular with linear interpolation. Table 2 summarizes the global quality of correction parameters for P band DEM, the meaning of terms are the same as Table 1. Table 3 shows similar results for local DEM quality resulting from fifteen selected test areas distributed over DEM, these results were obtained comparing data of fifteen independent sets of control points for tests with corresponding points in corrected DEM.

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Table 2 – Summary of global quality triangulation correction parameters for P band DEM.

	Minimum	Maximum	Mean	Variance	Abs deviation	Std deviation
Calculate	-10.971	6.760	-0.741	4.436	1.690	2.106
Test	-5.608	8.391	0.253	4.592	1.675	2.143

Table 3 – Summary of local quality triangulation correction parameters for P band DEM.

Region	Minimum	Maximum	Mean	Variance	Abs deviation	Std deviation
1	-4.679	1.020	-1.345	1.723	1.044	1.313
2	-1.386	8.123	1.621	7.351	2.003	2.711
3	-0.302	3.270	1.858	0.941	0.770	0.970
4	-5.608	3.994	-1.182	4.858	1.768	2.204
5	2.845	4.933	3.595	0.302	0.433	0.550
6	-0.593	3.999	1.380	1.431	0.946	1.196
7	-1.691	2.893	-0.053	1.410	0.849	1.187
8	-3.119	1.264	-1.375	1.363	0.961	1.168
9	0.571	8.391	2.630	2.864	1.177	1.692
10	-5.103	6.350	-0.742	7.689	2.141	2.773
11	-2.907	1.033	-0.378	0.723	0.628	0.850
12	-3.394	1.433	-0.795	1.663	1.057	1.289
13	-0.963	1.289	0.362	0.363	0.459	0.603
14	-4.548	0.245	-1.682	1.613	0.995	1.270
15	-3.335	1.150	-1.093	2.932	1.496	1.712

3.4. Inverse squared distance interpolation surface altimetry calibration

Another DEM correction approach that can be applied to deal with local errors of different magnitudes is the inverse squared distance method that is a weighted average interpolator, which can be either exact or smoothing. With inverse squared distance data are weighted during interpolation, so that the influence of one point, relative to another, declines with distance from the grid node (Burrough & McDonnell, 1998). Normally, inverse squared distance behaves as an exact interpolator. When calculating a grid node, the weights assigned to the data points are fractions, the sum of all the weights being equal to 1. When a particular observation is coincident with a grid node, the distance between that observation and the grid node is 0 and that observation is given a weight of 1, all other observations are given weights of 0. Thus, the grid node is assigned the value of the coincident observation. One of the drawbacks of inverse distance is the generation of "bull's-eyes" surrounding the observation position within the grid area. A smoothing parameter can be assigned during inverse distance to reduce the "bull's-eyes" effect by smoothing the interpolated grid (Erxleben et al, 2002). The core of mathematical formulation to inverse distance interpolation surface is given in equation 3 where *j* refers to points to be interpolated, *i* refers to sample data points, *d* is the distance between both and *n* is the number of sample data points used to interpolate.

$$h_0 = \sum_{i=1}^{n} h_i \bullet d_{ij}^{-2} \Big/ \sum_{i=1}^{n} d_{ij}^{-2} \qquad (3)$$

Figure 2 shows at right side, in gray level representation, the correction surfaces for P band DEM generated by inverse squared distance interpolation. Table 4 summarizes the global quality parameters of correction for P band DEM generated by inverse squared distance interpolation. The meanings of general terms are the same as Table 1 and 2. Table 5, similarly to Table 3, shows results for local DEM quality resulting from fifteen selected test areas distributed over DEM, these results were obtained comparing data of fifteen independent set of control points for tests with corresponding points in inverse squared distance corrected DEM .

Table 4 – Summary of global quality inverse distance correction parameters for P band DEM.

	Minimum	Maximum	Mean	Variance	Abs deviation	Std deviation
Calculate	-11.203	6.759	-0.633	1.879	1.171	1.371
Test	-5.764	8.224	0.210	3.041	1.271	1.744

Table 5 – Summary of local quality inverse distance correction parameters for P band DEM.

Region	Minimum	Maximum	Mean	Variance	Abs deviation	Std deviation
1	-3.864	1.884	-0.427	1.722	1.028	1.312
2	-1.442	8.224	1.994	6.591	1.830	2.567
3	-1.574	2.057	0.920	0.793	0.738	0.891
4	-4.108	3.510	-0.473	3.065	1.334	1.751
5	-0.727	1.640	0.211	0.352	0.453	0.594
6	-3.244	3.651	0.593	2.736	1.296	1.654
7	-1.821	2.783	-0.096	1.411	0.870	1.188
8	-1.373	2.739	0.111	1.343	0.924	1.159
9	-0.225	7.584	1.811	2.845	1.135	1.687
10	-5.764	5.404	-1.627	7.448	2.094	2.729
11	-2.360	1.292	-0.039	0.582	0.551	0.763
12	-2.222	2.312	0.253	1.509	0.991	1.228
13	0.088	2.988	1.702	0.515	0.490	0.718
14	-4.055	1.211	-1.000	1.816	1.073	1.348
15	-3.550	1.006	-1.231	3.203	1.574	1.790

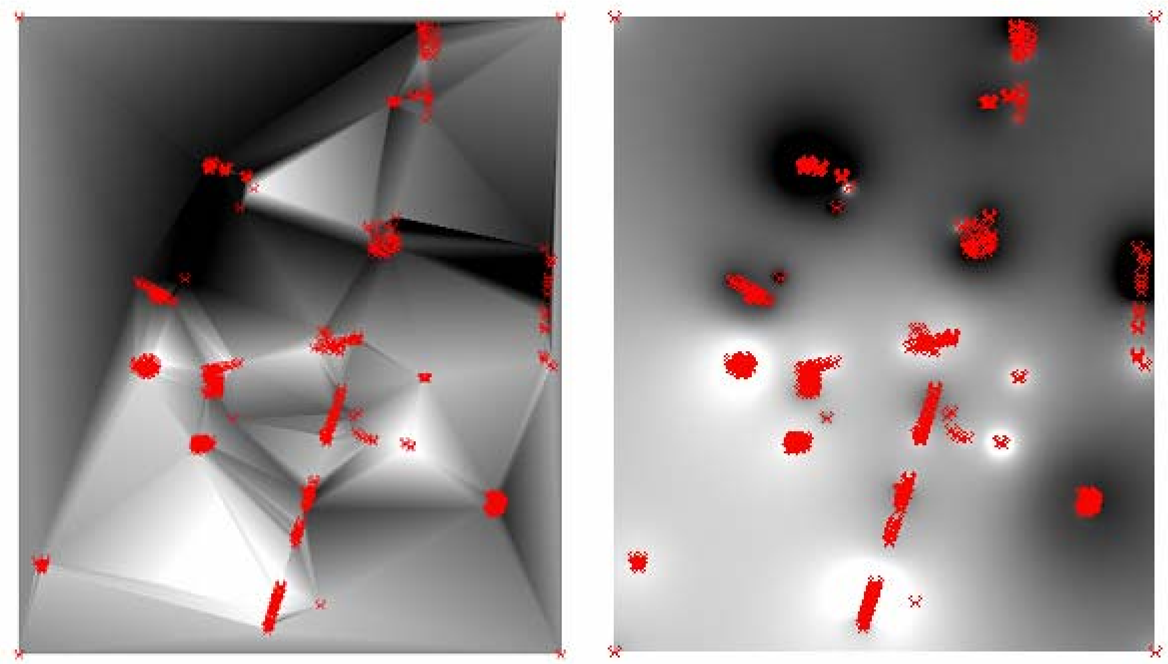

Figure 2 - Grey level representation of altimetry correction surfaces. Triangulation with linear interpolation (left) and inverse square distance interpolation (right).

4. RESULTS AND DICUSSIONS

The offset method is very simple and represents the least computational cost of all tested procedures, but it is inadequate to deal with errors spatially distributed because of its rigid way to compensate non-rigid errors. The other two methods are some degree elastic and consequently better to deal with local errors. Triangulation with linear interpolation, as can be observed in Figure 2, provides a patchwork of triangular faces over the entire extent of DEM. It is computationally more expensive than offset method but provides reasonably better results. As can be seen in Figure 2 the errors are corrected according to their extent and not in a fix manner. The comparison of parameters in Tables 1, 2 and 3 just strengthen this point where numeric values favored triangulation much more then offset method. Inverse squared distance provides a much more smooth variation appearance but presents the "bull's eyes" artifacts as can be seen in Figure 2. It is computationally more expensive than offset and triangulation. Like triangulation the errors in inverse distance are corrected according to their extent and not in a fix way as happen in the offset method. By comparing parameters in Tables 1, 2, 3, 4 and 5, it is possible to devise that inverse distance produces better results than offset method for DEM. Comparing it to triangulation we can observe that it is better than triangulation in some parameters but worse in others. Observing Tables 3 and 5 we can say that both methods confirmed that local errors exist in DEM. These errors are generally locally smaller than global errors. Measure of global errors alone, did not represent a good metric of DEM geometric quality.

5. CONCLUSIONS AND FINAL CONSIDERATIONS

For different DEM analyses applications the researchers can produce their own data and, of course, control de quality of the entire process of error propagation. However, production of DEM is not, in general, the major objective of scientific researchers and, so, they prefer to use available DEMs generated by other. The problem is that available DEMs do not report its own errors or report only the average magnitude of errors; therefore, hiding information on spatial patterns of the DEM errors. So, the method presented in this work will be very helpful for DEM evaluation and DEM correction using adaptive ways to deal with global and local errors. As discussed in previous sections our methodology for correction and calibration proved to make a good DEM fitting to geographic space reality and also provided the determination of statistical spatial pattern accuracy parameters for corrected DEM. So, it is possible to devise that main conclusions pointed out that proposed calibration method, besides improving DEM general geometric quality, also provided confident numerical estimation of DEM global and local accuracy parameters. This point is a very important issue involved in DEM analysis due to the possibility of error propagation assessments in DEM derived products. Future researches complementing this study are now being conducted using InSAR X band data and other advanced surface correction methods based in splines and kriging.

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