Distortion Modeling between Geodetics Network in Brazil: A Grid-Based Approach

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Key words: distortion modeling, geodetic network, distortion grids, Shepard's interpolator.

SUMMARY

A national geodetic network is the fundamental structure for geodetic positioning and spatial data base in a country. In the search for the better accuracy, several countries have updated their geodetic network by adopting a geocentric reference system. As a consequence, solutions have to be available to provide to the users tools (software and library of functions) for conversion among the different networks. Brazil follows this global tendency and since February 2005 the users can adopt the new frame, so called SIRGAS2000 (Geocentric Reference System for the Americas) as a new official referential. During the transition time, which will extend until 2014, a huge data set in different frames has to be converted to the new frame. In order to collaborate with this demand, six Work Groups were created to study and propose conversion approaches, giving emphasis on the distortion modeling. The distortion in the network does not allow the optimal relationship between the frames. With a set of stations in both old and new frames, it is possible to compute the residual distortion in each point of the network. Search and interpolation procedures are applied in this sparse data set producing a regular structure (grid) that has distortion values for each node. In this context, this paper presents one of the approaches proposed by the work groups, using Shepard interpolator to compute the distortion for all the points in the regular grid. Among the characteristics of the approach are the interpolation weighting by the relative station position used in the Shepard method and the use of isometric coordinates in the grid generation. The results obtained were very promising, reducing the RMS error to up to 50% and improving the agreement of the station coordinates between the old and the new frame in more than 90% of the tested stations.

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1 INTRODUCTION

In geodetic surveys or other applications that involves georeferencing data, it is necessary a reference system associated to its coordinates. A reference system or geodetic referential is materialized by a set of terrestrial stations that form a geodetic network that represents the fundamental structure for the mapping and positioning activities in a country.

The importance of the geodetic networks implies that it should be consistent, precise and should be able to accomplish the tendencies and technological evolution. In Brazil, the geodetic network is one part of the Geodetic Brazilian System (SGB – Sistema Geodésico Brasileiro) that is of responsibility of the Brazilian Institute of Geographic and Statistic (IBGE – Instituto Brasileiro de Geografia e Estatística).

Following the world tendencies and the technological evolutions, the SGB has been updated along the years. The main and more recent change occurred in February 2005 with the adoption of the Geocentric Reference System for the Americas (SIRGAS – Sistema de Referência Geocêntrico para as Américas) as a new official referential.

The modernization process of the geodetic network, using both different data survey equipments and adjustment methods, sometimes technologically and computationally limited, implies in distortion accumulation in the Brazilian geodetic network. The distortions, when not appropriately modeled, make the conversion process not so reliable. In Brazil, the problem becomes more complex due to non homogeneous distortions behavior in some regions and to the variation in the amplitude of the distortions values. Besides, there are products to be converted in at least 3 different referential systems with at least 7 different frames.

Aiming to provide support to the users in terms of computational applications and procedures for the coordinate conversion, there were developed the Geodetic Referential Change Project (PMRG – Projeto Mudança de Referencial Geocêntrico) and the National Geospatial Framework Project (PIGN – Projeto da Infraestrutura Geoespacial Nacional), both coordinated by the IBGE with support of others organizations. The PMRG was structured in 6 working groups (GT – Grupo de Trabalho), and GT3 is the group responsible to study, analyse and suggest the most appropriate referential conversion approaches, focusing on distortion modeling.

Approaches have been proposed by some education and research institutes to support the development of computational application programs that make possible to the users the realization of coordinates conversion and also the distortions modeling. One of these approaches is presented in this paper, and it is based on the coordinate transformation through the official parameters and on the subsequent application of the distortion grids generated using the Shepard's interpolation method. The results and analyses here presented are related to the coordinate conversion and distortion modeling between the SAD69 (realization of 1996) and SIRGAS (realization of 2000) frames.

2 THE GEODETIC BRAZILIAN SYSTEM AND THE REFERENCE SYSTEM ADOPTED

The Geodetic Brazilian System (SGB) is defined from the set of geodetic points materialized in the land surface portion delimited by the country frontiers. These points are determined by operational proceedings and computed coordinates, according to geodetic models with precision compatible to the finalities that they are destined to (IBGE, 1983).

The SGB establishment has been developed in a systematized form since May 1944. The development of SGB activities can be classified in two different phases: previous and subsequent to the advent of the satellites positioning systems.

Since its establishment, the SGB has been changing, mainly in its planimetric component aiming to follow the state of the art in terms of the geodetic sciences. Different approaches were employed in his establishment, as well as different reference systems. Among the main reference systems associated to the SGB there are: the Córrego Alegre System (CA); the South American Datum of 1969 (SAD69); and the SIRGAS2000 actually.

2.1 Adopted Referential

In the sequence, it will be presented some of the principal reference systems adopted by the Geodetic Brazilian System.

2.1.1 Córrego Alegre (CA)

The Geodetic System of Córrego Alegre was adopted in the first planimetric network adjustment of the SGB in the 40’s. It is characterized as a topocentric orientation system, where the origin is the triangulation station Córrego Alegre located in the Minas Gerais State.

The reference surface is the Hayford International Ellipsoid of 1924 and the positioning and orientation of the point was carried out from astronomical observations.

The Córrego Alegre System was widely used and it resulted in 3 frames, in the years of 1961, 1970 and 1972.

2.1.2 South American Datum of 1969 (SAD69)

SAD69 was adopted officially in 1977 as a reference system for geodetic and cartographical works in national territory in substitution to the CA.

The Earth's geometrical surface adopted for SAD69 was the International Reference Ellipsoid of 1967 (f = 1/298.25) that has topocentric orientation established through geodetic coordinates of the station CHUÁ.

The SAD69 planimetric network was adjusted by the first time in the 60's. Due to the long triangulation, trilateration and poligonation networks along the South American continent and to the computational limitations of that time, the adjustment was performed in blocks or areas as a piece-meal method (COSTA, 1999). This procedure was one of the main factors to distortions accumulation in the geodetic network.

The availability of new data sets incorporated to the network, like that ones provided by satellite positioning, culminated in a new adjustment that derivate the SAD69 realization of 1996. A requisite established in this new adjustment was the use of all the available observations simultaneously in the GHOST (Geodetic adjustment using Helmert blocking Of Spacing and Terrestrial dates) software, which carries out the adjustment for the decomposition of the network in Helmert's blocks.

2.1.3 Geocentric Reference System for the Americas (SIRGAS)

The SIRGAS project was developed in 1993 with the motivation of adopting in the South American continent a network with precision compatible to the current survey techniques, especially which those associated to the GPS.

In the first frame, so called SIRGAS1995, only stations located in South America was considered. In the second realization (SIRGAS2000) others stations had been incorporated, as those from Caribbean, Central and North America region.

SIRGAS2000 is a densification of the International Terrestrial Reference Frame 2000 (ITRF2000) in South America through GPS stations. The coordinate precision based on the repeatability of the results, is on the order of 4 to 6 mm (MONICO, 2005).

The adopted reference ellipsoid is the Geodetic Reference System of 1980 (GRS80) and the final coordinates are linked to the ITRF 2000 at epoch 2000.4.

3 THE COORDINATE TRANSFORMATION PROCESS AND THE DISTORTION PROBLEM

In the conversion of reference frames the problem consists in finding the position of know stations in another frame of interest.

If the problem is analysed in an abstract space, a mathematical function would be enough for this transformation. But, the problem becomes more complex due to the distortions and other influences in the realization, caused mainly due to equipments and/or data integration of different survey techniques.

There are in the bibliography several models used in the transformation of geodetic coordinates. Oliveira (1998) classifies such models in five categories: 1) cartesians equations; 2) differential equations; 3) regressions; 4) analytical modeling; and 5) interpolation maps.

In the SGB case, the developed models are based on its majority on the cartesians and differential equations (categories 1 and 2).

3.1 Distortion and Transformation Grids

The regular grids are widely used in the conversion between reference frames. It is a standardized way to perform the transformation without requiring direct complex models application by the users.

It is important to mention the difficulty to find an adequate mathematical function to model the network distortions, considering the non homogeneous behavior of the distortions.

There are two alternatives to use the regular grids. The first one is to model only the distortions between frames with the creation of Distortion Grids (DG), whose components are computed separately for both coordinates ($\delta\varphi$, $\delta\lambda$). The coordinate conversion is performed by the application of the transformation parameters (f') and subsequent interpolation of the corrections in the DG. The second alternative is to perform a complete transformation of the differences (shifts) between the realizations. In this case, the grid is called Transformation Grid (TG) and the values interpolated in each point of the grid provide the direct transformation (f) between the realizations, including the distortions modeling. These alternatives are illustrated in the Figure 3-1.

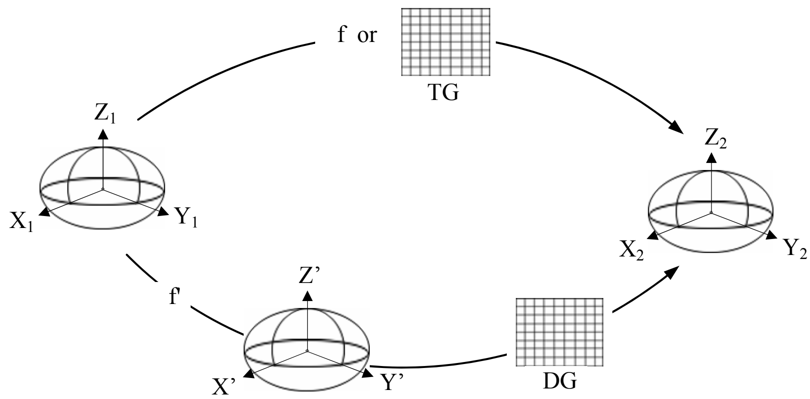

Figure 3-1: Grid-based transformation.

The informations in the grid's nodes (DG and TG) are produced from a set of stations in both frames involved. With the grid, interpolations like the bilinear can be performed in order to obtain the distortions or coordinate differences in the points of interest.

4 COORDINATE TRANSFORMATION AND THE DISTORTION PROBLEM

In many activities, spatial points are associated with measured attributes producing an irregularly spaced structure of points. These points can be interpolated in regular structures like a regular grid. There are several interpolation techniques presented in the literature, such as: linear interpolation; bilinear; quintic; multiquadratic; inverse-distance weighting; Kriging, and others.

For the generation of distortion grids between SAD69 and SIRGAS2000 was used the interpolation method proposed by Shepard (1968).

4.1 Selection of the Interpolation Points

An interpolation function must consider as more significant only the influence of the closest points to each interpolation point. Then, points more distant can be excluded of the interpolation process saving unnecessary computational efforts. To select the n nearest points of the interpolation point (P), two criterions can be employed:

1. an arbitrary distance criterion, for example, all n points contained in a radius r from the point P; and

2. a numerical arbitrary criterion, for example, the n nearest points of P.

A combination of the two criterions should join the advantages of both in a complementary way. The criterion adopted by Shepard's method uses this strategy. So, the selection of the nearest points works in the follow way (SHEPARD, 1968):

- a minimal (n_{min}) and a maximum (n_{max}) number of points that will be used in the interpolation is defined;

- an initial search radius (r) is selected based on the available points density.

- a set C' of the nearest points of P and a final search radius (r') should be set. First, an initial set of points C contained in the initial search radius r is selected: $C_P = \{D_i \,/\, d_i \leq r\}$. The number of elements in C_P is $n(C_P)$. Next, it is performed an ordering in the set C in a crescent order of the distances to P.

A new search radius (r') is calculated by the distance of the neighbor point nearest to P and not contained in the C_P^n set. Finally, there is a set of P neighbor and the finals search radius:

$$C_P^{'} = \begin{bmatrix} C_P^{n\max} & if \;\; n_{\min} \le n(C_P) \le n_{\max} \\ C_P & if \;\; n_{\min} < n(C_P) \le n_{\max} \\ C_P^{n\max} & if \;\; n_{\max} < n(C_P) \end{bmatrix}, \quad \text{and} \quad r_P^{'} = \begin{bmatrix} r'(C_P^{n\min}) & if \;\; n(C) \le n_{\min} \\ r & if \;\; n_{\min} < n(C) \le n_{\max} \\ r'(C_P^{n\max}) & if \;\; n_{\max} < n(C_P) \end{bmatrix}. \quad (4.1)$$

4.2 Set of the Weighting Factors and Interpolation Function

The Shepard's method uses two weighting criteria for the interpolation: distance and direction. The distance weighting takes into account the correlation between points nearest to the interpolation point. The direction weighting has the intension of representing the "shadowing" of the influence of a data point *P* by the nearest one in the same direction.

Tha distance and directional factors are defined as (SHEPARD, 1968):

$$s_i = s(d) = \begin{bmatrix} \frac{1}{d} & if \;\; 0 < d \le \frac{r'}{3} \\ \frac{27}{4r'}\left(\frac{d}{r'} - 1\right)^2 & if \;\; \frac{r'}{3} < d \le r' \\ 0 & if \;\; r' < d \end{bmatrix} \quad \text{and} \quad t_i = \frac{\sum_{D_j \in C'} s_j [1 - \cos(D_i P D_j)]}{\sum_{D_j \in C'} s_j}. \qquad (4.2)$$

The weighting function including the distance (s_i) and directional (t_i) factor can be defined as:

$$w_i = (s_i)^2 .(1 + t_i). \qquad (4.3)$$

The interpolation function *f(P)* in the case that $d_i=0$ to all D_i is $f(P)=z_i$. Otherwise, when $d_i \neq 0$ to all D_i the directional and distance weight is included and the function becomes:

$$f(P) = \sum_{D_i \in C'} w_i z_i \Big/ \sum_{D_i \in C'} w_i . \qquad (4.4)$$

where z_i is the value to be interpolated and in this research assumed the values of the distortions in latitude and longitude (δφ, δλ).

5 DISTORTIONS MODELING APPROACH

The distortion modeling approach proposed in this paper is based on three phases:

1. to compute de distortions between the frames based on the know coordinates in both frames;

2. to generate the regular grid with a pre-defined spacing and covering the country territory;

3. to interpolate the distortions of the interested points from a regular grid, through the known coordinates in the origin system.

5.1 The Distortions Computation

The distortions can be defined by the differences between the known coordinates (determined in the network adjustment process) and the calculated coordinates (through the official transformation parameters) for a set of stations. Then, the distortions for each coordinate component (latitude - φ and longitude - λ) are given as follows:

$$\delta\varphi = \varphi_2 - \varphi_2' \qquad (5.1)$$
$$\delta\lambda = \lambda_2 - \lambda_2'$$

where:

φ_2, λ_2 - latitude and longitude geodetic coordinates known in the destination frame;
φ_2', λ_2' - latitude and longitude transformed to the destination frame; and
$\delta\varphi, \delta\lambda$ - latitude and longitude distortions.

5.2 Distortion Grid Generation

The distortion grid generation process consists in finding the distortion values of the grid nodes, through the known distortions in the control stations. First, a base grid is generated containing only coordinate of the nodes. Aiming to supply the effects of the terrestrial curvature and to have a grid with a really regular spacement the isometric coordinates was used to generate the base grid. Then, the Shepard's interpolation method was used to find the distortion values in the grid nodes.

It is also important to know how reliable is this interpolation or, in other words, to know the precision of the interpolated points. The computation of the precision indicator is presented by Junkins and Erickson (1996):

$$P = \sqrt{\frac{\sum w_i^{\,2}}{\left(\sum w_i\right)^2} \cdot \frac{\sum\left(\delta_i - \bar{\delta}\right)^2}{n-1}}\ . \qquad (5.2)$$

where:

P - the precision indicator associated to each grid node;
$\bar{\delta}$ - the distortion computed to each grid node in latitude and longitude;
δ_i - the distortion of a nearby point i to the latitude and longitude;
w_i - the weight in the point i; and
n - the number of points used in the interpolation.

5.3 Distortion Interpolation of the Interest Points by using the Distortion Grid

In this phase, the station coordinates in the origin frame are converted to the destination frame by the application of the transformation parameters and incorporation of the distortion modeling through the distortion grid. For each given point, it is identified in the grid the corresponding cell formed by the four nodes in which this point is contained. With these four points is performed the bilinear interpolation to compute the distortion and the precision indicator.

6 EXPERIMENTS AND RESULTS

6.1 Considerations and Preliminary Analyses

The data set used in this experiment was made available by IBGE via Working Group 3 – GT3. These files contain coordinates of 7297 homologous stations in SAD69 (realization of 1996) and SIRGAS2000. To perform the experiments, 6634 stations were used in the distortions computation and 663 stations (approximately 10%) were used to perform the quality control.

By using this set of 6634 homologous stations it was possible to compute the distortions between the frames and to check its behavior in the whole territory. The resultant distortions are represented in form of vector in Figure 6-1.

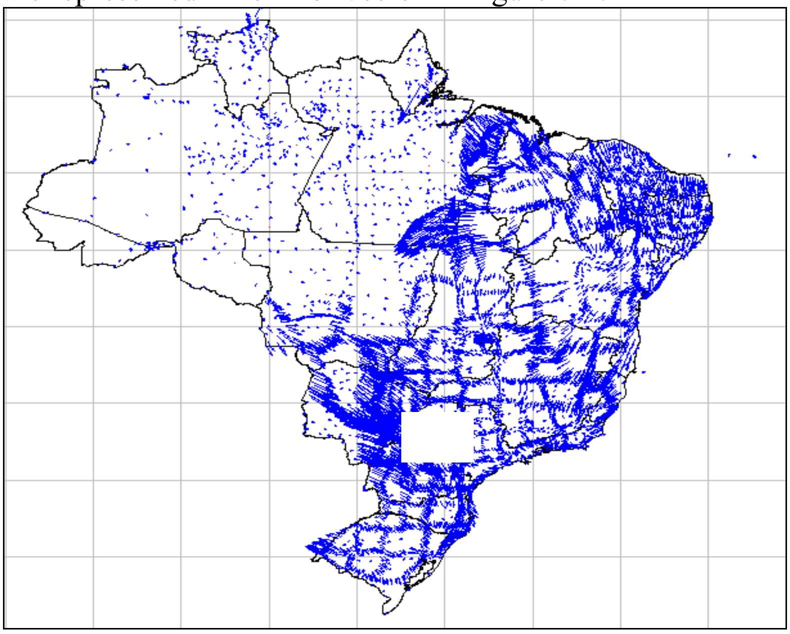

Figure 6-1: Resultant distortions of each control station in Brazil.

It can be observed in the Figure 6-1 that there is a great variability in the distortion behavior along the Brazilian territory. There are regions where the distortion vectors follow a systematic tendency, like in the South and Southeast and, on the other hand, there are regions with not systematic behavior as in part of Middle West region.

The modeling distortions quality is related to the behavior of the distortion. The well-behaved regions have a tendency to provide better results after the modeling. Then, it is important to identify the regions that suffered the effects due to this factor.

Some statistics related to the computed distortions between SAD69 (realization of 1996) and SIRGAS2000 are presented in the Table 6-1.

Table 6-1: Distortions statistics

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Distortion	Latitude (m)	Longitude (m)
Minimum	-5.661	-3.676
Maximum	5.338	3.696
Average	-0.437	0.011
Standard deviation	0.627	0.532
RMS (*)	0.764	0.032

(*) Root Mean Square

It can be noted by the values that there is more variation in latitude than in longitude.

6.2 Generation and Analyses of the Distortion Grid

The distortion modeling was carried out by a distortion grid with a spacing of 1º x 1º, covering the Brazilian territorial limits. The spacement, as well as the initial parameters of Shepard's interpolator was analysed based on experiments performed and described in Magna Junior (2007).

Concerning the initial Shepard's parameters values, it was stipulated a minimum of 4 and a maximum of 10 stations for the interpolation in the grid nodes. Besides these values, it was determined an initial search radius of the order of 60 km, which was chosen based on the Brazilian territorial extension (8,514,876.599 km^2) and the number of used stations (6634). The Table 6-2 presents some statistics related to generated distortion grid.

Table 6-2: Distortion grid statistics

		Latitude	**Longitude**
Distortion (m)	Minimum	-3.053	-1.943
	Maximum	1.479	1.885
	Average	0.254	0.080
Precision Indicator (m)	Average	0.152	0.092
	Nodes number	2024	

Figure 6-2 shows the distortion quality in the grid for each component.

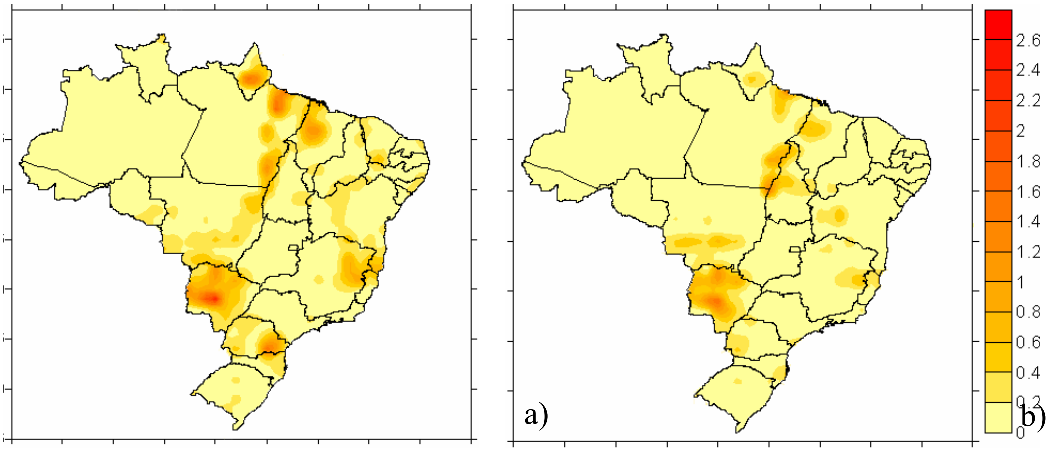

Figure 6-2: Distortion precision indicator to a) latitude and b) longitude

It can be observed from Figure 6-2 that the modeling quality is directly associated to the distortion behavior in the control stations. So, in the regions where the behavior of the distortions is not homogeneous, there is an inferior precision indicator associated. It was evident, for example, in the Middle West region.

6.3 Modeling Analyses in the Stations Test

To check the modeling results it was computed the distortions in the remaining stations and performed the comparison of the computed coordinates and the known ones. The graphics in the Figure 6-3 show the distortions in latitude, longitude and in the resultant after and before the distortion modeling.

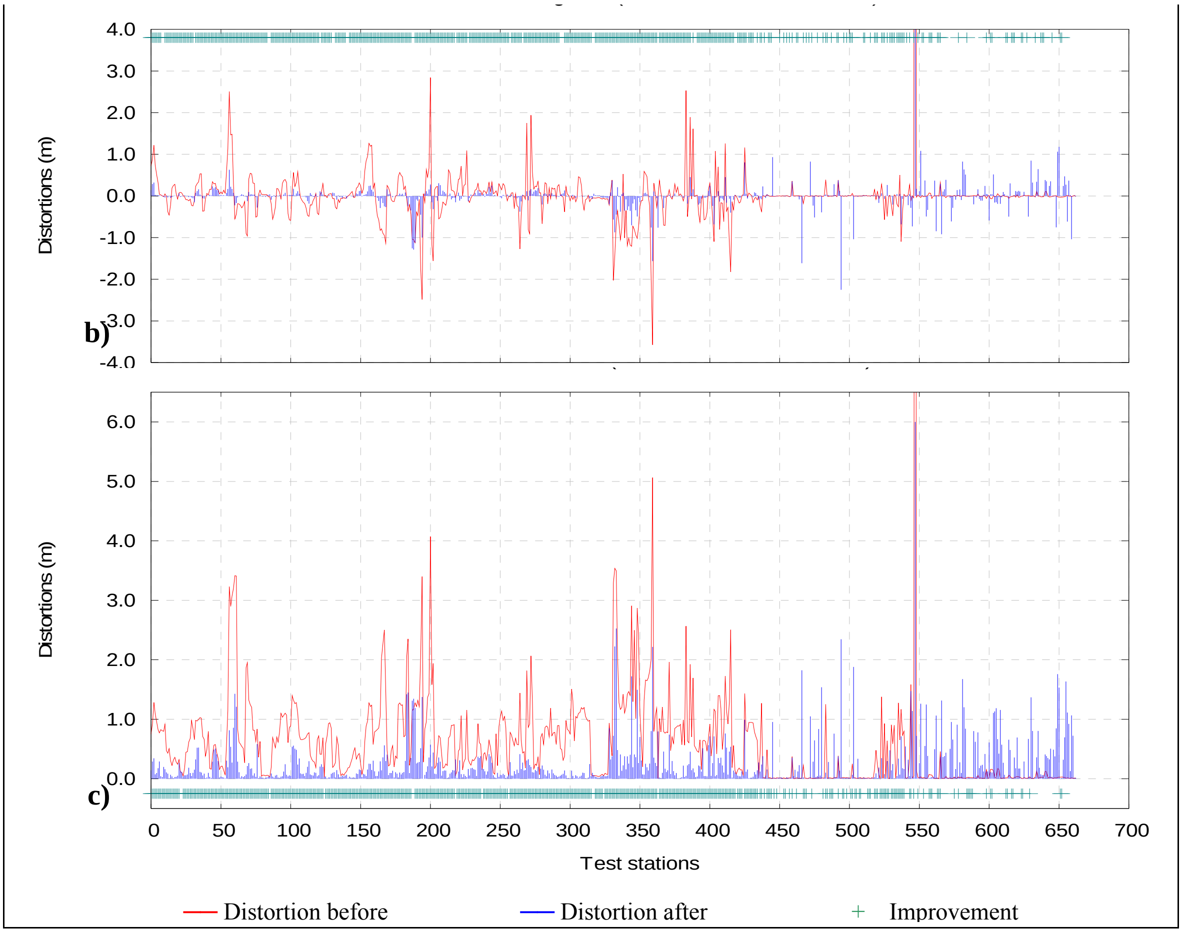

Figure 6-3: Distortion in the test stations in a) latitude, b) longitude and c) in the resultant, before (red) and after (blue) the distortion modeling.

By observing Figure 6-3, it can be verified the improvements after the distortion modeling. It is also observed a possible outlier near the station 550. Besides, it can be verified that in the three cases, the final stations in the graphics have not improved their values and, in many cases the results were worst. These stations with worse results are in the great majority derivate from satellite positioning techniques, so, these are stations with a better precision that the other ones from classic techniques. So, the modeling does not provide improvement in this case and, instead of this, it introduces distortions.

Table 6-3 shows some modeling statistics in the test stations

Table 6-3: Modeling statistics in the test stations

		Distortions		
		Latitude	**Longitude**	**Resultant**
Before	**Average (m)**	-0.4401	0.0230	0.6112
	Standard (m)	0.6284	1.1169	1.2159
	RMS (m)	0.7668	1.1163	1.3601
After	**Average (m)**	-0.0054	0.0253	0.2827
	Standard (m)	0.4034	1.0429	1.0888
	RMS/Improvement	0.4031 (-47%)	1.0425 (-7%)	1.1241 (-17%)
	Number of improved stations	478→72.09%	484→73.00%	505→76.17%
	Test stations	663		

It can be verified that on average 74% of the test stations have reduction in the distortion after the modeling. It is also possible to see the RMS reduction.

There was performed another test, but now without stations from satellite techniques. The results are presented in Table 6-4.

Table 6-4: Statistics for the test of stations without satellite techniques

		Distortions		
		Latitude	**Longitude**	**Resultant**
Before	**Average (m)**	-0.6221	-0.0199	0.8187
	Standard (m)	0.6488	0.5848	0.6947
	RMS (m)	0.8983	0.5845	1.0732
After	**Average (m)**	-0.1155	-0.0336	0.2179
	Standard (m)	0.2847	0.2564	0.3382
	RMS/Improvement	0.3069 (-66%)	0.2583 (-56%)	0.4020 (-63%)
	Number of improved stations	398→91.49%	401→92.18%	418→96.09%
	Test stations	435		

In this last test it is possible to verify that the modeling results are better in the classic stations. In these cases more than 90% of the test station improved the results after applying modeling. The RMS also improved in more of 50% of the tested stations.

7 Final Considerations and Conclusions

The question involving the conversion between reference frames is complex, current and requires research, mainly related to distortion modeling process, in order to provide better coordinate agreement between the involved reference frames.

In this paper, a contribution related to the modeling distortion process was realized, considering SAD69 (realization of 1996) and SIRGAS2000 reference frames. The aim was to propose an approach of easy application, efficient in computational time burn and that could offer a unique solution.

The average distortion computed for the distortion grid for these specified frames was of about 0.254m with a precision indicator of 0.152m. The experiments using the test stations showed that the stations originated from satellites techniques do not require corrections. For other stations, an improvement occurred in about 90% of the tested stations.
In general, the experiments provided good results, evidencing that the Shepard's method applied to distortion models based on grids appears to be very promising and may be an alternative for being used in the SGB for coordinates conversion and distortion modeling between frames.

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