Searching for the Optimal Relationships Between SIRGAS2000, South American Datum of 1969 and Córrego Alegre in Brazil

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Abstract Brazil has moved towards the adoption of a geocentric system, SIRGAS2000. With the adoption of this system, starting in 2005, a great demand has been created towards transforming the current data sets from the South American Datum of 1969 (SAD-69), in its two distinct realizations, and the Córrego Alegre frames into SIRGAS2000. The fact that these four frames will co-exist until 2014 creates positive and negative situations. Due to the distortion between those frames, the relationships among them cannot be well established with Helmert transformation parameters alone.

To solve this problem, five Study Groups were created to look for the optimal relationships for coordinate transformation between those frames. The approaches being investigated to augment the parameter transformation are based on: Collocation, Delaunay, Regular grids (NTv2 and Sheppard method) and Neural Networks. The research is currently going on.

This paper describes the current efforts towards defining the optimal relationships among these four frames, from the mathematical point-of-view.

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Keywords Reference frames · Coordinate transformations · Distortion modelling

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1 Introduction

Brazil is already user of a geodetic geocentric system since February 2005, due to the publication of a Resolution from the President of *Fundação Instituto Brasileiro de Geografia e Estatística* – IBGE, the institution responsible for the establishment and maintenance of the Brazilian Geodetic System – SGB. In reality, until 2014 the SIRGAS System, realization 2000, will be used simultaneously with the South American Datum of 1969 (SAD 69) – for geodetic reasons – and also with the Córrego Alegre (CA) system – this only for cartographic reasons. This 10 years time interval is called the "transition period".

IBGE and a group of institutions, among them universities and public and private companies, developed the Geodetic Reference Change Project (PMRG) and the National Geospatial Framework Project (PIGN), this one in partnership with Canadian institutions The PIGN is dedicated to study the impacts, solutions and tools used in the process of migrating from the current classical systems to the geocentric SIRGAS. Amongst these activities, there is one inherent to coordinates transformation modelling, tasks under the responsibility of Working Group 3 (WG 3) on reference conversion.

Amongst the actions linked to WG 3 stands out the choice of the methodology that allows the conversion of coordinates to the new system, minimizing impacts and maximizing quality. In a way to develop a better solution for this challenge, five approaches were proposed, currently being developed through Study Groups (SG). This paper presents theoretical aspects from on-going research, as well as the complementary aspects to the conversion process.

2 Dimension of the Transformation

One of the most important issues debated within WG3 deals with the dimension of the coordinate transformation, i.e., identify if the conversion of the coordinates should only involve geodetic latitude (φ) and geodetic longitude (λ) components or all geodetic coordinates (including geodetic height (h)). WG 3 and the SG opted for a horizontal conversion affecting only latitude and longitude coordinates. This choice is based on:

(a) The adjustment process of the RGB (Brazilian Geodetic System) into either SAD69 or SIRGAS2000 were carried out on the ellipsoid (φ, λ), although using a 3D geodetic modeling, control and observations from GPS and besides the fact that SIRGAS2000 is a 3D system. So, there is no advantage in operating the full components coordinates transformation (φ, λ, h);
(b) Conceptually the orthometric height is independent from the ellipsoid used in the geodetic system, being interesting and recommended that the orthometric height (H) values be kept on the stations where these values are known, not generating differences to users;
(c) The planimetric network adjustment is independent from the vertical network adjustment (orthometric height). In this way, it is probable that the distortion modeling using only the components φ and λ minimize the eventual inconsistencies between the networks, avoiding the effect of possible problems existing on the H coordinate to affect the components φ and λ;
(d) There is no geoidal map for Córrego Alegre (CA). In terms of the existing geodetic and cartographic documents, there should be no risk of having different methodologies for the distortions modeling from SAD69 and CA to SIRGAS, since there are contiguous areas of mapping;
(e) There are at least 3 geoidal maps already available – two to be used with SAD69 and other to be used with SIRGAS. A distortion modelling where there is the necessity of using geoidal maps could lead less experienced users to error, fact that should be avoided;
(f) At the level of the SIRGAS project, the definition of the vertical system has not been reached. That being so, the production of SIRGAS heights should be avoided because this value may be altered in the near future;
(g) It is necessary to design a solution that merges quality, credibility and easiness of use, since they are essential to society, as gauged by an opinion poll carried out by WG 3 on the user community independent of their familiarity with aspects related to Geodesy or applications in Cartography.

Therefore, for the stations that already have coordinates in the Córrego Alegre or SAD 69 frames, the transformation of planimetric coordinates (φ and λ)

will be done according to the methodology to be defined by WG 3. Concerning the vertical component, in the existence of:

✠ Orthometric heights (H): they will continue with the same value on the SIRGAS2000 frame. In this way, the quality of H is kept and there is no need to calculate the orthometric height of the stations in the new system;

✠ Geometric heights (h): this is a specific case for the SAD 69 system or alternatively for the user that has "WGS 84 coordinates." The component h should be converted to orthometric height and after that be subject to the same treatment as outlined for orthometric heights. It is suggested that the conversion from h to H should be done using the Geoidal Map *MAPGE2004*, already available on http://www.ibge.gov.br/home/geociencias/geodesy/modelo_geoidal.shtm?c=15.

3 Analysis of Distortions in Horizontal Networks

The present section overviews the proposal that the IBGE Study Group will submit to WG 3, along with some preliminary results, dealing with the modelling of distortions that exist among the different realizations of the Planimetric Network of the Brazilian Geodetic System. This proposal contemplates the distortions network modelling through NTv2 software – National Transformation, version 2, developed by the Geodetic Survey Division (GSD) of Natural Resource Canada.

NTv2 is a set of programs that has among its functions the following tasks: evaluation of inconsistencies found between two frames, coordinate transformation between systems applying only the Helmert transformation and "grid" calculation, the latter used to represent the model of distortions derived from the materializations of the reference systems.

In a first stage the file containing all planimetric stations belonging to the SGB underwent a filtering where all stations at the Northern hemisphere were removed. This procedure was necessary, as the NTv2 software do not work with the hemisphere change, or rather, during its processing it considers the latitudes absolute value, what makes impossible the network processing as a whole. Other stations also were removed from the original file, as they did not take part on the adjustments, either in SAD69 – realization 1996, either in SIRGAS2000. The GPS stations that were removed from the file were not adjusted due to the non-availability of the primary data for the processing and adjustement. This was a procedure defined by all GEs.

The following stage consisted on the coordinate transformation between the two realizations (SAD69-1996 and SIRGAS2000) applying to the coordinates a conformal transformation (Helmert). The objective of this transformation is to keep the geometry of the geodetic structure, or rather, keep the relationship between the coordinates to be transformed.

Therefore, given two sets of coordinates belonging to all common stations in both materializations, deriving from the SAD69-1996 and SIRGAS2000 ($SAD69_{AJD}$ and $SIRGAS_{ADJ}$) adjustments, the transformation parameters that consist of the RPR 01/2005 from the Presidency of IBGE are applied to the set of $SAD69_{AJD}$ coordinates, resulting in SIRGAS2000 transformed coordinates ($SIRGAS_{TRANS}$).

The following stage will consist of the selection of the stations that will be used to assess the performance of distortions modeling between the two sets of coordinates. For that it will be used the difference remaining (residuals) after the model application and their respective values adjusted. It is important to notice that both the magnitudes as well as the spatial distribution of the residuals are important. Generally a good model leads to small residuals.

The resulting differences between $SAD69_{TRANS}$ and $SIRGAS_{AJD}$ coordinates will be treated by a polynomial modeling that will represent the regional tendencies given by the correction vectors on the control stations. In this case, from the sets of $SIRGAS_{TRANS} = (X_i^1, Y_i^1)$ and $SIRGAS_{AJD} = (X_i^2, Y_i^2)$ coordinates, corrections are calculated. They will be used on the interpolation of any point that does not belong to the $SIRGAS_{TRANS}$ and $SIRGAS_{AJD}$ set as the formulation below. Consider:

$$X_0 = \Sigma X_i{}^1/np; \qquad Y_0 = \Sigma Y_i{}^1/np;$$
$$U_i = X_i{}^2 - X_i{}^1; \qquad V_i = Y_i{}^2 - Y_i{}^1;$$
$$U_0 = \Sigma U_i/np; \qquad V_0 = \Sigma V_i/np;$$
$$S_x = 1/X^1_{max}; \qquad S_Y = 1/Y^1_{max};$$
$$S_u = 1/(U_{max}{}^2 - U_0{}^2)^{1/2}; \qquad S_v = 1/(V_{max}{}^2 - V_0{}^2)^{1/2};$$
$$S_{U0} = \max(X_i{}^2 - X_i{}^1); \qquad S_{V0} = \max(Y_i^2 - Y_i^1);$$
$$Z_{xi} = S_x(X_i^1 - X_0); \qquad Z_{yi} = S_y(Y_i^1 - Y_0);$$
$$E_{xi} = S_u(U_i - U_0); \qquad E_{yi} = S_v(V_i - V_0);$$

where:

X_0 = average latitude of the control stations;
Y_0 = average longitude of the control stations;
U_i = differences in latitude between $SIRGAS_{TRANS}$ and $SIRGAS_{AJD}$ control stations;
V_i = differences in longitude between $SIRGAS_{TRANS}$ and $SIRGAS_{AJD}$ control stations;
U_0 = average in latitude differences;
V_0 = average in longitude differences;
S_x = latitude scale factor;
S_y = longitude scale factor;
S_u = latitude differences scale factor;
S_v = longitude differences scale factor;
X^1_{max} = control stations maximum latitude;
Y^1_{max} = control stations maximum longitude;
U_{max} = maximum value of control stations latitude differences;
V_{max} = maximum value of control stations longitude differences;
np = quantity of control stations (i).

The estimated corrections in any station P are based on a weighted average of the estimated coordinate corrections for all the control points around it. The correction in any latitude Cx and longitude Cy is given by:

$$Cx_i = \Sigma w_i Ex_i / \Sigma w_i, \quad Cy_i = \Sigma w_i Ey_i / \Sigma w_i,$$

where Ex_i and Ey_i are corrections on the control points i, according to latitude and longitude, respectively. The weight (w_i) assigned to each control point i is a function of the distance (d_i) between the control point and the points where both the corrections and the distance (k) will be estimated for the selection of the control points for interpolation (Fig. 1). The weight is calculated according to the following formula:

$$w_i = e^{-(di/k2)};$$
$$d_i = Zx_i\,Zy_i$$

The residuals in latitude and longitude (Rx_i and Ry_i) are estimated for each control station by:

$$Rx_i = Fu_i + Cx_i - U_i,$$
$$Ry_i = Fv_i + Cy_i - V_i,$$

where:

$$Fu_i = U_i - Ex_i/S_u, \qquad Fv_i = V_i - Ey_i/S_v.$$

Prelimimary solutions have been generated and two types of cartograms generated. The first, shown in Fig. 2, contains a thematic map with the distortions values forming a grid of 10′ by 10′, using the whole network (classical network + GPS network) and a number of 25 neighbouring stations. A second cartogram, similar to the one presented in Fig. 4, contains the displacement vectors and their direction throughout the country.

The next stage consists of the evaluation of the networks separately, i.e., Classical Network and GPS Network, so the distortion grids with magnitudes and residual spatial distribution inherent to each

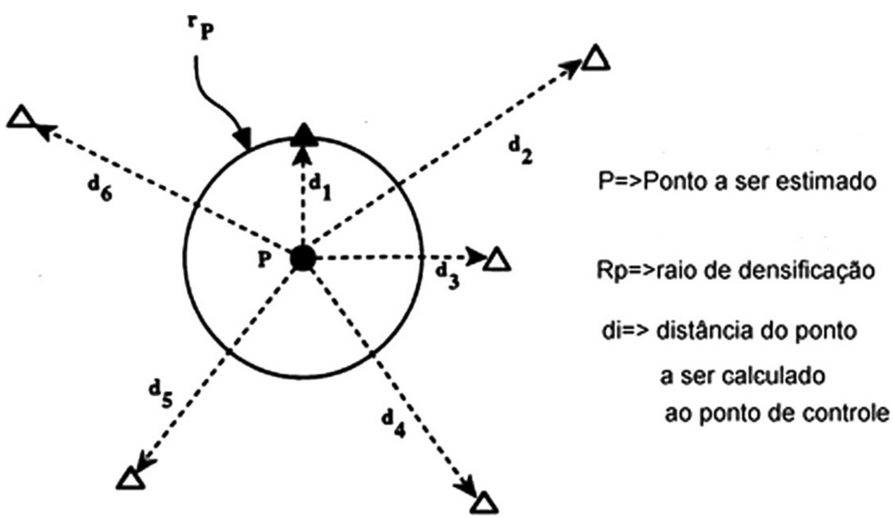

Fig. 1 Estimated weighted average parameters of any point–ESTPM Program. [Source Junkins & Erickson, 1996]

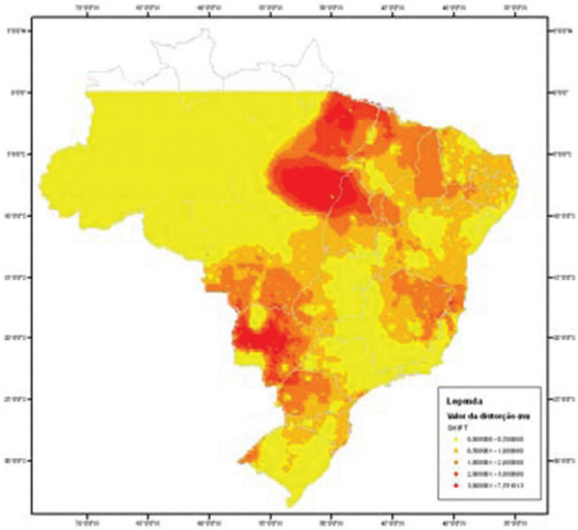

Fig. 2 Thematic map with distortions values em spacing de $10'$ by $10'$

technology can be determined. Another point that needs to be better studied is the distortion modeling on the region between the Northern and the Southern hemispheres.

4 Distortion Modelling Based on Collocation

Collocation is based on a simultaneous adjustment and regression model carried out in two steps, where the covariance function is formed based on the residuals of the first step. The basic model reads:

$$\underline{A}\underline{\hat{\delta}} + \underline{B}\underline{\hat{r}} + \underline{\Phi^T}\,\underline{\hat{\lambda}} + \underline{w} = \underline{0},$$

where $\underline{\hat{\delta}}$, $\underline{\hat{r}}$ and $\underline{\hat{\lambda}}$ represent, respectively the estimated solution, residual and coefficient vectors, $\underline{A}$, $\underline{B}$ the first and second design matrices, $\underline{\Phi^T}$ the Vandermonde's matrix and $\underline{w}$ the misclosure vector.

In the solution, we formulate the observation equations in terms of local Cartesian coordinates (Northing, N; Easting, E; Up, U). We believe they form the best coordinate basis for distortion modeling (i.e., the most natural directions and units), as compared to global Cartesian coordinates (X, Y, Z), geodetic coordinates (latitude, longitude, height), and arc-length coordinates (meridian arc-length, parallel arc-length, height).

We provide both functional and stochastic models for distortion. The functional model is made of a low order polynomial: one polynomial (function of latitude and longitude) for each of the three types of coordinates (N, E, U). This trend modeling is a requirement for the stochastic modeling to follow. The random yet correlated portion of the discrepancies, called "signal" in the collocation literature, is modeled populating the observations prior covariance matrix employing an empirical covariance function.

The estimation process yields values and associated standard deviations for the functional parameters (similarity transformation and polynomial), as well as for the signal at observation points. Those estimates are then employed subsequently to predict distortion at any other point, e.g., on a regular grid for distribution to end users.

5 Coordinates Conservation Method

The Coordinates Conservation Method (MC2) is based on Oliveira (1998). The MC2 philosophy is to try to maximize the numerical integrity of coordinates referring to the coordinate networks associated to the geodetic systems involved in the transformation process. The way found for this purpose was to associate computational geometry concepts in a single methodology, geometric transformation and numeric interpolation, using solutions by least squares as well as deterministic solutions.

The methodology can be summarized as being composed of the addition of two terms, one referring to the change of system and the other related to the distortion modeling, or rather:

$$\text{Trf\_Crd.} = \text{Mud\_Sis} + \text{Mod\_Dist.}$$

The change of system (Mud_Sis) is carried out by the application of the 3-parameter model, or simply through the translations between the coordinates (X, Y and Z) of the involved systems, whose mathematical model is expressed by:

$$[X, Y, Z]^T{}_D = [\Delta X, \Delta Y, \Delta Z]^T + [X, Y, Z]^T{}_O.$$

The superscript T indicates a transposed array. The subscripts D and O represent, respectively, the final system and system of origin. This solution was chosen due to the fact that the systems involved are, by definition, parallel. The translation values will involved only the coordinates of *Chuá* datum marker, for the SAD 69 system, and Córrego Alegre datum marker, for the CA system, obeying the definition of the systems. The differences between the transformed coordinates and the original coordinates correspond to the distortions to be modeled.

The distortion modeling (Mod_Dis.) is the result of the term referring to the local distortion (Dis_Loc) and the term relative to the residual distortion (Dis_Res), or rather:

$$\text{Mod\_Dis} = \text{Dis\_Loc} + \text{Dis\_Res}$$

The term Dis_Loc will be obtained through a set of selected stations and the application of an affine geometric transformation (AGT), quantified through its linear model and the least squares method. The set of stations will be defined with the support given by the Delaunay Triangulation (DT), or rather, the station network nearest to the station of interest and its neighbours – the stations that compose the triangulation. It must be said that to avoid inconsistencies between the inverse and direct mapping between the coordinates, the triangulation will be constructed using the coordinate averages for either the CA and SIRGAS2000, and SAD69 and SIRGAS2000 geodetic networks, guaranteeing a unique triangulation for each set. The computational system to be used to the DT is the QHULL.

The linear mathematical model for the AGT is given by:

$$x_D = ax_D + by_D + \Delta x,$$
$$y_D = cx_D + dy_D + \Delta y,$$

where a, b, c and d are the parameters which implicitly model rotation, scale and lack of orthogonality. The residual generated by the AGT estimation will be taken as the residual distortions, last stage of the modeling process.

For the Dis_Res estimation two operations are fundamental: the first is with respect to the values to be used, while the second is related to the choice of the interpolator. The choice of the values occurs directly when it is identified in which triangle the point of interest is inserted. For such, it will be used the barycentric coordinates concept. As soon as the triangle is identified, i.e., the value to be used in the interpolation process, a Hermite interpolator operator is used. This interpolator has continuity as its main characteristic. It stands out that the solution used for the term Dis_Res is of deterministic nature, therefore, for the geodetic networks stations involved, it is guaranteed the maximization of the coordinate values integrity. The hypothesis is that the same integrity will also occur when modeling the distortion of stations which do not belong to the network.

Some practical aspects related to the implementation still should be observed, for example, the use of normalized coordinates, and the use of binary files.

6 NN-based Distortion Modelling

MODERNA is the acronym (in Portuguese) for Distortion modelling employing artifical neural networks. Artificial neural networks (NN) are an important field in Artificial Intelligence, which is an area from Computer Science. Sarle (1994) describes neural networks as being a wide class of discriminating models and non-flexible linear regression, models for data reduction and non-linear dynamic systems. Usually the NN's are composed by several artifical neurons (or simply neurons), i.e., elements of linear (or not) computation, and often organized in interconnected layers through links (synaptic links). Among the possible applications, the NN's can be used for data estimation and analysis.

Due to the mathematical complexity of a neural model with many neurons, the adaptation which is an adjustment of the synaptic weights (or parameters) of the network is done by means of learning algorithms, usually employing known patterns (or data) sets. The learning processes are sets of well defined procedures, capable of interactively adapting the parameters of a NN. There are several tools represented by several algorithms which differ from each other in the way the parameters adjustment happens, Braga et al. (2000).

The same characteristic which makes the treatment of the neural models complex, also make them extremely self-adaptable to different situations. NN's have been used in Geodesy in several applications, as described by Leandro et al. (2005). Besides the adaptation capability, neural models usually present a high generalization capability, which refers to their capability of producing outputs (or estimates) which are reasonable for the input (or observations) which have never been shown (during the learning process). This characteristic allows the solution of complex problems.

The objective of the MODERNA is to use an artificial neural network to model the distortion between the Brazilian frames SAD69 and SAD69/96, and the new South American frame SIRGAS2000. During the process of development of such model, the data available will be used to obtain the adequate configuration of the neural network for this particular application. This configuration includes the type of network, the adequate topology, the algorithm and the parameters of learning process. After defining all aspects concerning to the design of a neural model, it will be validated with the data of the aforementioned geodetic frames. The final goal is having a neural model capable of estimating the distortion between the different geodetic frames used in Brazil, for any location within the country, without the need of using any additional kind of information.

7 Distortion Modelling by Regular Grids

Initially, it is important to define the concept of distortions, in the context of this approach. Considering two frames (1 and 2) and a geometric transformation T that transforms from 1 to 2 (and its inverse T^{-1} for the inverse case), the difference between the coordinates on the frame 2 and the on frame 2′, obtained from the transformation T, is called distortion.

Although the distribution of points of the Brazilian geodetic network is not homogeneous in its extension, there are a great number of points, which permits to consider that a regular distortion grid can be generated from the distortions calculated on this irregular mesh. Once available, this regular mesh can be used for the interpolation of distortions at any point in the area covered by the mesh. This approach is based on the same principle used by NTv2. This methodology can be summarized on the following phases:

- Distortion calculation between the geodetic networks through stations with known coordinates in both realizations.
- Generation of a regular grid of defined spacing enclosing the whole national territory, containing in its nodes the distortion values between the different realizations.
- Distortion interpolation via a regular distortion grid regular for points of interest, through known coordinates on the system of origin, and conversion coordinates on the system of arrival.

The flowchart on Fig. 3 illustrates the principles of the method.

Some relevant aspects can be considered in this approach. The first is related to the spacing of the distortion regular grid, adjusted to be obtained the best results, when comparing the real distortions with the modeled distortion values. The second is referred to the interpolation method used on the generation of the regular grid. The third is connected with the optimum interpolation method (in phase 3), from the regular grid already available.

The third aspect, although important, is the least critical, depending on the adopted spacing of the regular grid. This way, it can be assumed that the spacing is such that a simple interpolation method could be used, as for example the bi-linear interpolation. It can

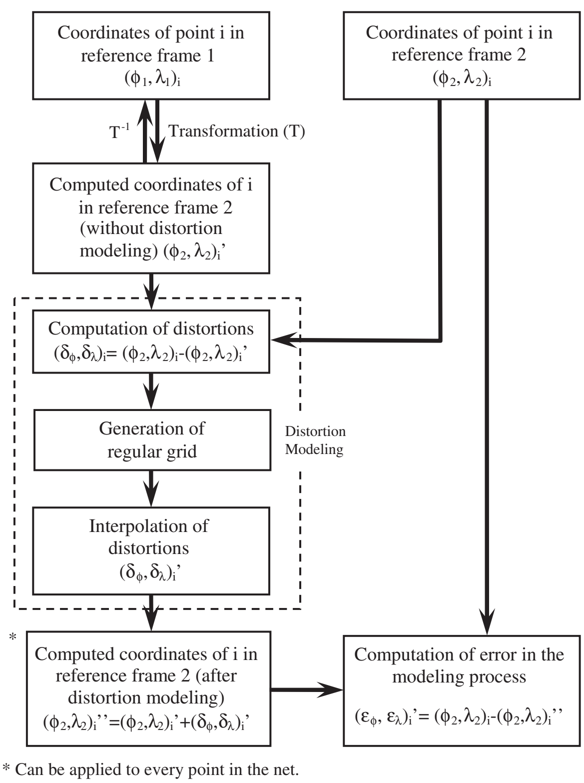

Fig. 3 Principle of distortions modeling from regular grids

be, therefore, considered that the quality of this interpolation will be strongly dependent from the first step (regular grid spacing).

The second aspect, referring to the distortions interpolation is critic, due to the irregular distribution of the sample points. For this reason, it was considered in this approach the interpolation principles used by Shepard (1968), which is based on the use of a weight function which considers both the distance as well as the direction.

Experiments with grids of several spacing are being done, with the objective to choose the dimension of the regular grid which permits the distortion modeling between the SIRGAS 2000 and SAD 69 reference, that allow to obtain results with EMQ smallest values for the distortions components φ and λ Fig. 4.

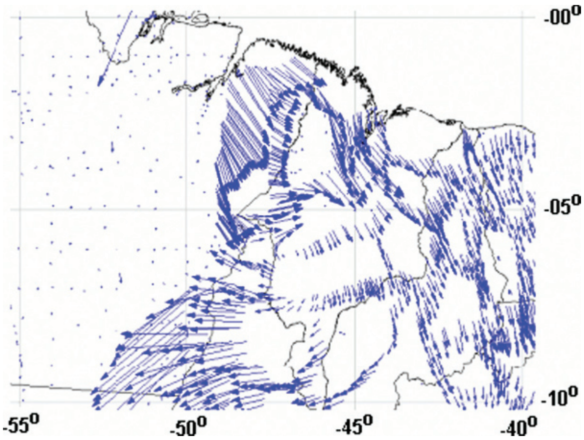

Fig. 4 Detailed North-Eastern view of map of distortions between SIRGAS2000 and SAD69

8 Choice of the Most Appropriate Methodology

The process of choosing a methodology among the proposed ones will happen in a particular event, programmed to occur in October 2007, in Rio de Janeiro. Some tests with the implemented methodologies will be carried out. Among them, it can be quoted:

(a) a test involving the geodetic stations not used in the modeling (playing the role of test points), with the objective of quantifying an indicator of external quality;
(b) testing the computational efficiency of the modeling technique;
(c) the assessment of the smoothness and continuity of the solution;
(d) testing the maintenance of the integrity of the coordinates integrity, i.e., to verify the quality of the transformation to and from two frames; and,
(e) other tests as necessary.

9 Conclusions

Brazil is going through a process which will culminate in the adoption of a new geocentric frame, SIRGAS2000. Several Study Groups have been formed, under the umbrella of the National Geospatial Framework Project, to investigate among several methodologies dealing with the modelling the distortions of geodetic networks, in order to come up with the optimum methodology (or combination of them). This paper presents a summary of each one of them. These methodologies are based in different methods. For example, one is based on Neural Networks, one on Least-Squares Collocation, a third one is based on Delaunay Triangulation and the last two make use of NTv2 program, with slight modifications. A Workshop will be held in Rio de Janeiro in October 2007 in order to discuss on the characteristics of each one of those methodologies, but also to choose the most efficient and accurate among them.

The inter-relation between the classical networks and SIRGAS2000 becomes even more important if we realize the size of the classical networks, composed of nearly 7,000 points (whereas reference GPS networks in Brazil amount to less than 100 points). Historically, all mapping, notably the ones in cadastral scale, have been done (even recently) attached to classical networks. For topographical scales, similarity transformation by itself would be sufficient. But, when one considers the cadastral applications, the distortions inherent to the classical networks must be taken into consideration.

Several institutions in Brazil have invested in the search of a solution to the coordinate's conversion and the products associated to them – such solution will allow minimizing the impacts cause by changing the geodetic framework. More than a consistent and necessary geodetic commitment, the project is based on a wider commitment for the country, playing the role of intermediaries to its social developement, without excluding the consequent technological and economic development.

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