A velocity field estimation of the Brazilian portion of the SOAM plate

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Abstract With the proposition for the adoption of Geocentric Reference System for the Americas (SIRGAS) as a terrestrial reference frame for South America, the need for temporal monitoring of station coordinates used in its materialization has become apparent. This would provide a dynamic characterization of the frame. The Brazilian Network for Continuous Monitoring of GPS (RBMC) has collected high accuracy GPS measurements since 1996. The Brazilian Institute of Geography and Statistics (IBGE) maintains this network in collaboration with several universities and organizations. Most of the stations are also part of the SIRGAS network. The RBMC also contributes data to the International Terrestrial Reference System (ITRS) to densify the global frame. Two of the RBMC stations are also part of the International GPS Service (IGS). This paper reports initial results from these stations. To estimate the velocity field defined by these stations, ten IGS stations located on the border of the South American plate and in adjacent plates, along with nine RBMC stations, were used. Observations covering five groups of 15 days each were used. These groups of observations were at epochs 1997.3, 1997.9, 1998.3, 1998.9 and 1999.2. Seven IGS stations were chosen to have their coordinates constrained to those epochs. IGS products (precise ephemeris and clocks) were used to process the daily solutions, which were carried out with Bernese software. Carrier phase double differences were formed using the ionospheric-delay free observable. The troposphere was modeled using a combination of the Saastamoinen model and the Niell mapping function. A tropospheric parameter was estimated every two hours. The results of the daily baseline solutions were combined using the summation of normal equations technique, in which the final coordinates and velocities were estimated. The results were compared with various models, such as the NNR-NUVEL1 and the APKIM8.80. Velocity vectors estimated for the RBMC stations show good agreement with those two models, with rates approximately equal to 2 cm/year.

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Introduction

Monitoring of the motion of the lithospheric plates has grown in importance in the last decade or so in dealing with the realization and maintenance of coordinate reference systems. The plates move continuously with different direction and magnitude depending on location. Because of this motion, the coordinate of a point on the Earth's surface varies with time. If those elements (direction and magnitude) are known, the variation of the coordinates of points on the plates can be established.

Several plate models have been derived based solely on geophysical evidence (DeMets et al. 1990; Argus and Gordon 1991; DeMets et al. 1994). Later on, geodetic space techniques (e.g., VLBI, SLR, GPS), whose resolution allows detection of those motions on short time scales, were used to define a kinematic model (Drewes 1993). The development and enhancement of geodetic space techniques has made them the systems of choice for the realization of the ITRS (McCarthy 1996). The realization and use of coordinate systems requires knowledge of the motion of the frame in time (Vaníček et al. 1988).

With the establishment of the IGS in 1994 the GPS technology became a systematic contribution towards

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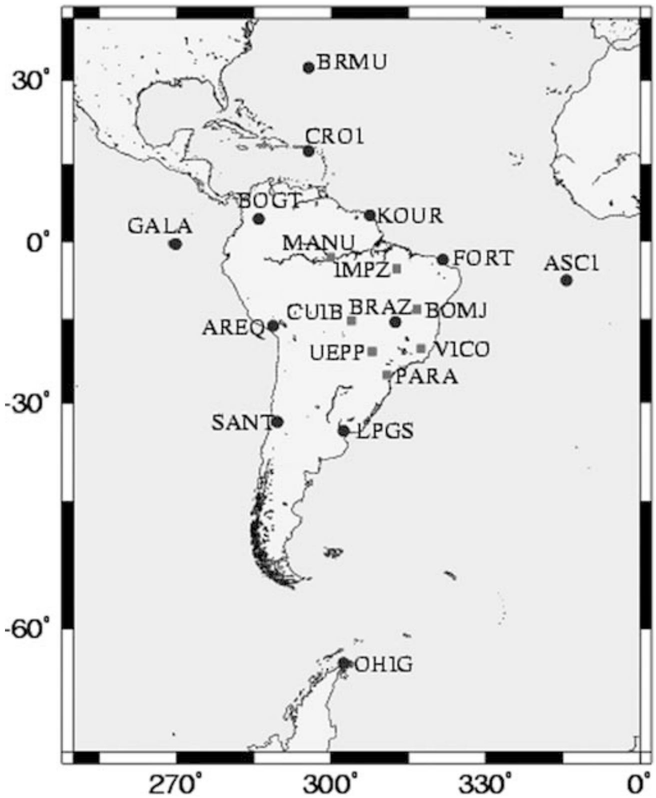

Fig. 1
Distribution of RBMC and IGS stations

global geodynamics with the IGS (Larson et al. 1997). Currently, the IGS network is composed of over 300 stations around the world. The data collected daily by these stations allows for the estimation of several products such as orbits, ionospheric and tropospheric parameters. The GPS technology has also contributed to regional geodynamics (e.g., Xu et al. 2000; Caporali et al. 2000; Dietrich et al. 2000).

Few studies about geodynamics have been made in South America (e.g., Drewes 1998), especially in Brazil, because it is located on a stable part of the South American Plate (SOAM). The proposition to adopt SIRGAS (the Geocentric Reference System for the Americas) as a reference frame for South America (IBGE 1997; United Nations 2001) created the need for temporal monitoring of the set of station coordinates that realize the frame. This eventually will result in better knowledge of the velocity field, which in turn will provide a better understanding of the kinematic characteristic of the frame. In Brazil, SIRGAS is realized by the RBMC network. The RBMC network has been operational since 1996. Currently, it is composed of 13 GPS stations. New stations will become part of the RBMC before the end of 2003. Measurements collected by the RBMC will improve the description of the velocity field for the Brazilian portion of the SOAM plate. Figure 1 shows the distribution of the RBMC stations as well as the IGS stations used in the computations described in this paper.

Geodetic modeling of plate motions

Until recently, geodesy used networks with geodetic coordinates that were invariant in time. With the advent of higher-accuracy space geodetic techniques, time variation of coordinates became measurable. These variations are the result of plate motion and deformations at the Earth's surface. Global deformation models have been derived from geophysical studies since the 1970s. The models yield surface velocities from the geometry of a set of rigid plates, and estimate their parameters of motion as the rotation of a non-deformable spherical cap. The geophysical model currently adopted by the International Earth Rotation Service (IERS) is the NNR NUVEL-1. This model was recently updated to the NNR NUVEL-1A (DeMets et al. 1994; McCarthy 1996). Some authors (Drewes 1993; Larson et al. 1997) indicate some characteristics of geophysical models, such as:

- Part of the information they are based upon comes from the borders of the plates, where the largest deformations take place (in this case not representing the behavior of the central regions of the plate);
- The velocities are extrapolated from geological eras;
- The instabilities, such as earthquakes, are represented as a continuous function.

An alternative is to use geodetic plates models. A description of plate motion that has taken place in the last decades can be devised by monitoring small displacements on the Earth's crust as detected by repeated space geodetic measurements. One such model is the APKIM8.8, developed by the Deutsches Geodätisches Forschungsinstitut (DGFI; Drewes 1982). Its most recent version is APKIM2000 (Drewes and Angermann 2001). Other models are found in the literature such as the ones by Larson et al. (1997) and Sella et al. (2002). To compute these models, several considerations are made. First, the Earth is regarded as a rigid body spinning around its axis. The surface of this body is covered by a set of lithospheric plates with only relative, non-intraplate motion. The relative motion of a plate (a rigid spherical cap) in a determined coordinate system (active transformation) is described by Euler's geocentric rotation vector. The modulus of Euler's vector is proportional to the angular velocity at one end of the vector located on the Earth's surface. This place is known as Euler's pole (or rotation pole). This vector (Ω) can be represented, in a Cartesian coordinate system by its three components Ω_X, Ω_Y, and Ω_Z, or in a spherical coordinate system by the geodetic coordinates of the rotation pole (Φ, Λ) and rotation velocity of the plate (ω). Therefore, the geometrical problem of plate motion consists in establishing the rotation pole for each plate and its angular velocity. The rotation vectors can be estimated from the observations by means of simple spherical computations. Since the motion of the lithospheric plates (Δx) is very small with respect to the Earth's radius (r), the Earth can be considered as a sphere. The geocentric angle

($\Delta\psi$), corresponding to the surface motion of the point, is constant for points located on the same latitude ($\Delta x = r\Delta\psi$). The motion ($\Delta\mathbf{x}$) of a point $P_i(\mathbf{x}_i)$ on the plate k in a time interval (Δt), is given by:

$$\Delta x_i = (\Omega_k \times x_i)\Delta t, \quad (1)$$

where $\Delta\mathbf{x}$, Ω_k and $\mathbf{x}_i$ can be defined in a arbitrary reference system. If a spherical coordinate system is adopted, then the rotation vector Ω_k is represented by Φ_k, Λ_k and ω_k. The vector $\mathbf{x}_i$ is now represented by the geodetic latitude and longitude (ϕ_i ,λ_i) and the displacements of point P_i by $\Delta\phi_i$ and $\Delta\lambda_i$. Developing Eq. (1) with respect to a time interval, Δt yields the relationship between the small displacements $\Delta\phi$and $\Delta\lambda$ and the parameters of the plate (Φ, Λ and ω; Drewes 1982):

$$\Delta\phi_i = d\phi/dt = \omega_k \cos\Phi_k \sin(\lambda_i - \Lambda_k), \quad (2)$$

$$\Delta\lambda_i = d\lambda/dt = \omega_k(\sin\Phi_k - \cos(\lambda_i - \Lambda_k)\tan\phi_i \cos\Phi_k). \quad (3)$$

The displacement can be represented in a Cartesian system as (McCarthy 1996):

$$\Delta x = dx/dt = \Omega_Y Z - \Omega_Z Y, \quad (4)$$

$$\Delta y = dy/dt = \Omega_Z X - \Omega_X Z, \quad (5)$$

$$\Delta z = dz/dt = \Omega_X Y - \Omega_Y X. \quad (6)$$

Any variation in distance between stations located on different plates reflects the relative rotations of the lithospheric plates. With that in mind, a relative rotation vector between two plates is considered, $\Omega = \Omega_k - \Omega_j$, and one plate is maintained as fixed with respect to the other. The observation equation that expresses the variation in distance Δs in a certain time interval Δt between a point P_0 (λ_0, ϕ_0) located on a fixed plate and P_1 (λ_1, ϕ_1) located on a plate in motion, whose parameters are Ω (ϕ, λ and ω), is given by:

$$\begin{aligned}\Delta s = ds/dt = [\omega r)/(\sin s)][&\sin\Phi\cos\phi_0\cos\phi_1\sin(\lambda_1 - \lambda_0)\\ &+\cos\Phi\cos\phi_0\sin\phi_1\sin(\lambda_0 - \Lambda)\\ &+\cos\Phi\sin\phi_0\cos\phi_1\sin(\lambda_1 - \Lambda)]. \quad (7)\end{aligned}$$

The estimation of the three rotation parameters (Φ, Λ and ω) in each plate requires observations $\Delta\phi$, $\Delta\lambda$ or Δs from at least two stations per plate. With redundant observations, least-squares adjustment is used. The kinematic reference is realized by fixing the rotation parameters of one plate (Ω=constant) or introducing at least three coordinate displacements ($\Delta\phi$ and/or $\Delta\lambda$). In this case, the reference is the same as that of the station coordinates used in the adjustment.

Data collection and processing

The network used in this experiment was comprised of ten IGS stations (located at the border of South American and adjacent plates), plus nine RBMC stations. The stations are listed in Table 1. The observations covered five periods of 15 days each: 1997.3, 1997.9, 1998.3, 1998.9 and 1999.2. Data files covered 24-h periods, at a sampling interval of 30 s (IGS) and 15 s (RBMC). There were different combinations of receiver and choke-ring antennas.

The GPS data processing was carried out using Bernese software (Hugentobler et al. 2001). This is a suite of programs with each one performing a distinct task. The daily processing of the data from the 19 stations was carried out using IGS orbits combined with earth orientation parameters. Since the program is based on relative positioning, the daily set of baselines (daily sessions) were formed in a network adjustment involving all stations for each particular day. During the parameter

Table 1
Stations from which GPS data was used

Station (four-digit code)	Station name	Latitude	Longitude	Network	Operational since
AREQ	Arequipa	−16°27′	−71°29′	IGS	1994
ASC1	Ascension Is.	−7°57′	−14°24′	IGS	1996
BRMU	Bermuda	32°22′	−64°41′	IGS	1993
BOGT	Bogota	4°38′	−74°04′	IGS	1994
BOMJ	Bom Jesus da Lapa	−13°15′	−43°25′	RBMC	1997
BRAZ	Brasília	−15°56′	−47°52′	RBMC	1995
CRO1	St. Croix	17°45′	−64°35′	IGS	1994
CUIB	Cuiabá	−15°33′	−56°04′	RBMC	1997
FORT	Fortaleza	−3°52′	−38°25′	IGS/RBMC	1993
GALA	Galapagos	−0°44′	−90°18′	IGS	1996–2002
IMPZ	Imperatriz	−5°29′	−47°29′	RBMC	1997
KOUR	Kourou	5°15′	−52°48′	IGS	1992
LPGS	La Plata	−34°54′	−57°55′	ÌGS	1995
MANU	Manaus	−3°06′	−60°03′	IGS	1997
OHIG	O'Higgins	−63°19′	−57°54′	IGS	1995–2002
PARA	Curitiba	−25°26′	−49°13′	RBMC	1996
SANT	Santiago	−33°09′	−70°40″	IGS	1992
UEPP	Presidente Prudente	−22°07′	−51°24′	RBMC	1997
VICO	Viçosa	−20°45′	−42°52′	RBMC	1997

estimation process, carrier-phase double-difference data were used in an ionospheric-delay-free mode. The elevation cut-off angle used was 10°. Tropospheric errors were dealt with through a combination of the Saastamoinen a priori model and the Neill mapping function, with tropospheric parameters estimated every 2 h. During the data processing, the observations were referred to the antenna phase center. Ambiguities were dealt with independently in each baseline, using the quasi-ionosphere-free (QIF) observable.

Daily network solutions were processed constrained to seven IGS stations, using their nominal precisions as given by the ITRF96 (1997.0) realization. Coordinates of each one of those stations were reduced to the mean day of each period. Each daily solution consisted of a set of station coordinates and normal equations. The solutions were combined by a least-squares adjustment, in which station coordinates and velocities were estimated.

The combination of solutions can be configured in two ways: either as a constrained or as a free network.

A constrained network solution consists of applying weights to a set of a priori (constrained reference) stations. A free network adjustment consists of applying loose constraints, allowing the estimation of transformation parameters (besides the estimation of coordinates and velocities) to an external reference frame such as the ITRF96. The constrained network solution has two inconveniences. First, the fixing of at least three stations coordinates results in a small displacement of the solution's origin, the geocenter, which is the most adequate origin for any Earth reference system. Second, errors in any of the constrained stations would propagate to the solution as a whole.

The combination of the daily systems of normal equations consists of having, for every daily solution s at every station i, coordinates represented by vector X^{i}_{s} at epoch t_s and velocity X^{i}_{s} expressed in a certain frame. The combination of normal equations consists in the estimation of (Boucher at al. 1998):

1. Coordinates X^{i}_{ITRF} in a determined epoch t_s and velocity $\dot{X}^{i}_{ITRF}$ in ITRS
2. Transformation parameters T_k at epoch t_k and its temporal variations $\dot{T}_k$ from the ITRF of each individual system k, which occurs only in the case of free network

The model used in this transformation is given by:

$$X^i_s = X^i_{ITRF} + (t^i_s - t_0)\dot{X}^i_{ITRF} + T_k + s_k X^i_{ITRF} + R_k X^i_{ITRF} + \left(\dot{T}_k + \dot{s}_k X^i_{ITRF} + \dot{R}_k X^i_{ITRF}\right)\left(t^i_s - t_0\right), \quad (8)$$

$$\dot{X}^i_s = \dot{X}^i_{ITRF} + \dot{T}_k + \dot{s}_k X^i_{ITRF} + \dot{R}_k X^i_{ITRF}. \quad (9)$$

For every individual solution k, s_k is the scale factor, T_k is the translation vector, and R_k is the rotation matrix. The normal equations given in a system of observation equations s, assume the following matrix form:

$$\left(A^T_s P_s A_s\right)X = \left(A^T_s P_s L_s\right), \quad (10)$$

$$\left(\sum_{i=1}^{s} A^T_i P_i A_i\right)X = \sum_{i=1}^{s} A^T_i P_i L_i, \quad (11)$$

where X is a vector of either 7 (translations, rotations and a scale factor) or 14 (translations, rotations, a scale factor, and their time derivatives) transformation parameters, plus the coordinates and velocities of the stations involved in the computation. The weight matrix P is given by the inverse of the covariance matrix ($C^{-1}{}_{x}$) of each daily solution. For free network solutions, the covariance matrix undergoes a change, in a process known as orthogonal projection, to allow a similarity transformation. An orthogonal projection consists of modifying the original covariance matrix in such a way that the covariances are related to an internally defined system, i.e., attributing small values so that the solution is weakly constrained. Therefore, for every individual solution s, the projected covariance matrix $\bar{C}_s$ is given by:

$$\bar{C}_s = \left(C_x^{-1} + B^T C_0^{-1} B\right)^{-1}, \quad (12)$$

where:

$$B = \left(A^T C_x^{-1} A\right)^{-1} A^T C_x^{-1}, \quad (13)$$

and C_0 is the covariance matrix of the transformation parameters. Matrix A is composed of the coordinates from each solution s. It is a block diagonal matrix. Each one of its blocks takes the form:

$$A = \begin{vmatrix} 1 & 0 & 0 & x & 0 & z & -y \\ 0 & 1 & 0 & y & -z & 0 & x \\ 0 & 0 & 1 & z & y & -x & 0 \end{vmatrix}. \quad (14)$$

The dimension of matrix A is a function of the number of (either 7 or 14) daily solutions and the number of transformation parameters. In the final solution, all daily solutions were combined and constrained to the seven IGS stations. The constraints used were scaled by a factor of 10 to compensate for the fact that GPS solutions tend to have optimistic standard deviations. In doing so, we have the final coordinates in the ITRF96 frame at epoch 1998.2. The velocities are a product of an extrapolation of the

Table 2
Standard deviation of unit weight

Station	Number of solutions	*N* (mm)	*E* (mm)	*h*(mm)
BOMJ	61	10.9	10.3	12.8
BRMU	64	16.4	28.0	28.6
FORT	74	11.6	11.9	20.0
KOUR	73	11.5	11.2	20.1
MANU	70	11.4	10.3	25.7
PARA	74	11.7	10.1	12.9
UEPP	70	10.5	9.3	11.2
BRAZ	72	10.3	9.3	15.3
AREQ	47	9.3	8.9	7.6
ASC1	67	8.3	9.8	9.8
BOGT	56	10.7	11.4	20.0
CRO1	72	10.7	13.0	10.8
GALA	57	11.1	31.3	43.2

Table 3
Velocities and standard deviations

Station	V_X (mm/year)	σ(mm/year)	V_Y (mm/year)	σ (mm/year)	V_Z (mm/year)	σ (mm/year)
AREQ	4.4	0.25	−6.1	0.11	24.3	0.21
ASC1	−0.6	0.07	−10.5	0.26	14.3	0.22
BOGT	0.2	0.26	1.7	0.08	19.2	0.20
BOMJ	−1.9	0.18	9.2	0.19	20.8	0.20
BRAZ	−0.5	0.20	−8.9	0.18	19.6	0.20
BRMU	−13.1	0.48	4.3	0.26	15.0	0.21
CRO1	−1.6	0.26	5.8	0.13	18.6	0.17
CUIB	−2.2	0.23	−8.1	0.16	19.9	0.20
FORT	−3.9	0.16	−7.2	0.21	21.1	0.20
GALA	16.8	0.34	−0.3	0.01	16.9	0.22
IMPZ	−4.2	0.22	−6.7	0.20	21.9	0.22
MANU	−4.3	0.23	−4.0	0.13	23.4	0.20
KOUR	−7.1	0.23	−2.8	0.17	2.2.3	0.20
LPGS	−0.2	0.23	−12.1	0.18	14.5	0.17
OHIG	8.0	0.25	−5.1	0.22	4.3	0.09
PARA	−0.4	0.21	−11.9	0.19	18.4	0.19
SANT	2.0	0.24	−13.9	0.15	21.0	0.17
UEPP	−1.4	0.21	−10.3	0.18	17.6	0.19
VICO	−2.2	0.20	−12.6	0.21	18.3	0.20

Table 4
Velocity components according to models NNR-NUVEL-1A and APKIM 8.8, and as provided by the RNAAC SIR

Station	NNR-NUVEL-1A			APIM 8.8			RNAAC SIR		
	V_X (mm/year)	V_Y (mm/year)	V_Z (mm/year)	V_X (mm/year)	V_Y (mm/year)	V_Z (mm/year)	V_X (mm/year)	V_Y (mm/year)	V_Z (mm/year)
AREQ	−2.3	−3.6	9.0	−2.4	−5.0	13.6	6.7	3.5	16.1
ASC1	8.9	24.8	17.6	8.8	24.0	18.3			
BOGT	−6.1	−1.0	9.0	−4.8	−0.2	14.0	−13.1	27.1	12.4
BOMJ	−1.5	−5.4	11.3	−1.6	−6.1	12.9	−2.5	−19.4	14.7
BRAZ	−1.3	−5.4	11.0	−1.6	−6.4	13.1	−3.2	−9.3	12.4
BRMU	−13.0	−1.2	7.0	−11.7	−0.9	6.7			
CRO1	2.1	4.5	9.8	6.9	8.6	15.0	−5.6	26.3	9.5
CUIB	−1.9	−4.7	10.5	−2.0	−5.8	13.5	−2.4	−11.2	15.5
FORT	−2.8	−4.8	11.7	−2.4	−4.4	12.7	−5.4	−10.2	14.3
GALA	71.4	−1.2	65.8	37.7	−0.4	17.9	45.7	−1.5	16.6
IMPZ	−3.2	−4.4	11.4	−2.7	−4.2	13.5	7.5	−22.9	10.3
MANU	−4.3	−3.1	10.5	−3.5	−2.9	14.2	−3.2	−16.0	20.7
KOUR	−5.3	−2.7	11.1	−4.1	−1.5	13.8	−2.0	−8.4	16.5
LPGS	1.6	−6.2	8.8	0.3	9.3	11.6	−4.8	−6.0	12.1
OHIG	18.7	1.0	4.6	18.9	7.0	8.1	20.6	−4.3	−6.8
PARA	0.3	−6.1	10.2	−0.5	−8.2	12.4	−4.1	−15.9	11.9
SANT	0.9	−5.1	7.9	−0.3	−8.3	11.9	18.6	−10.7	11.4
UEPP	−0.4	−5.7	10.4	−1.0	−7.4	12.8	−6.3	−14.0	11.9
VICO	−0.1	−6.1	10.8	−0.7	−7.6	12.3	−9.0	−14.0	17.4

coordinate results obtained at distinct epochs. Therefore, there are no epochs associated with them. They are also in the ITRF96 frame.

Analysis of results

A reference system is specified through a priori information of station coordinates and velocities. Since all crustal plates are in motion, a kinematic reference should be used (Larson et al. 1997), i.e., the transformation parameters must be referred to a determined epoch. Its realization is made by the station coordinates and respective covariance matrix. Transformation parameters can be estimated to transform a free network into a specific frame (e.g., one of the ITRFs). The quality of this transformation will depend on the precision of the coordinates and velocities of the reference frame used for the derivation of the transformation (a priori values) and in the geographical distribution of its stations.

GPS solutions can also be integrated to an ITRFyy by using combined IGS orbits. Particularly in this case, they are given in two distinct materializations of the ITRS (for 1997 the frame is ITRF94; for 1998 and 1999 the frame is ITRF96). According to Boucher et al. (1998) the definition of a reference frame (origin, scale, orientation and time evolution) for a combination of solutions is obtained in such a way that both ITRFs are compatible. Therefore, it was decided to adopt a priori ITRF96

Table 5
Velocity components according to models ITRF96 and ITRF97 and our solution (referred to as RBMC)

Station	ITRF96			ITRF97			RBMC		
	V_X (mm/year)	V_Y (mm/year)	V_Z (mm/year)	V_X (mm/year)	V_Y (mm/year)	V_Z (mm/year)	V_X (mm/year)	V_Y (mm/year)	V_Z (mm/year)
AREQ	11.4	1.3	12.3	12.2	2.0	10.0	4.4	−6.1	24.3
ASC1	3.2	−0.2	7.2	−8.0	−2.1	6.6	−0.6	−10.5	14.3
BOGT	7.6	3.4	16.1	6.7	0.9	13.0	0.2	1.7	19.2
BOMJ							−1.9	9.2	20.8
BRAZ	−8.9	1.7	11.5	−8.5	1.0	9.8	−0.5	−8.9	19.6
BRMU	−11.3	−3.0	7.9	−11.4	−2.5	5.6	−13.1	4.3	15.0
CRO1	7.9	8.5	14.5	9.3	4.5	10.6	−1.6	5.8	18.6
CUIB							−2.2	−8.1	19.9
FORT	1.0	−3.6	11.4	−0.6	−4.7	9.8	−3.9	−7.2	21.1
GALA	77.2	−24.0	19.1	53.2	−16.6	14.7	16.8	−0.3	16.9
IMPZ							−4.2	−6.7	21.9
MANU							−4.3	−4.0	23.4
KOUR	−1.0	0.1	11.4	−2.2	−2.5	10.3	−7.1	−2.8	2.2.3
LPGS	3.5	−6.1	8.0	−2.0	−3.7	8.4	−0.2	−12.1	14.5
OHIG	17.9	0.6	2.5	20.4	−3.9	−7.8	8.0	−5.1	4.3
PARA							−0.4	−11.9	18.4
SANT	21.9	−7.4	7.0	21.6	−7.2	6.9	2.0	−13.9	21.0
UEPP							−1.4	−10.3	17.6
VICO							−2.2	−12.6	18.3

coordinates and velocities, since it is of better accuracy and has coordinates and velocities for all reference stations. An assessment of the accuracy of the combined solution of each one of the five epochs with respect to the ITRF96 was possible by applying similarity transformations. The RMS of the residuals of these transformations are 6 mm for the north component, 7.6 mm for the east component and 14.3 mm for the vertical component. The highest residual equals 2.9 cm in the vertical component.

Table 2 presents the unweighted standard deviations of the coordinates derived from a comparison of the daily station solution with those coming from the combined solution. These numbers represent the daily accuracy of the coordinates. The RMS is equal to 1.9 and 7.7 mm for the north and east components and 12.3 mm for the height. Table 3 shows the final station and velocities, as well as their respective standard deviations.

The velocity field estimated in this solution is compared with velocity obtained from other models. This comparison is only qualitative. Tables 4 and 5 show velocity components according to models NNR-NUVEL-1A, APKIM8.8. The results originated from the RNNA SIR (SIRGAS regional analysis center, provided by the GFI) and the ITRF96 and ITRF97. These comparisons are diagrammatically shown in Figs. 2 and 3. Figure 2 shows the final RBMC derived velocity vectors compared with the ones derived from NNR-NUVEL-1A and APKIM8.8, and Fig. 3 shows the estimated velocity vector compared with the ones derived from IGS RNAAC SIR and ITRF96. There is a very reasonable agreement between the Brazilian stations located in the stable part of the plate and the established velocity field and the other sources used in this comparison, and major disagreements with those said factors and stations located at the periphery. The velocities of

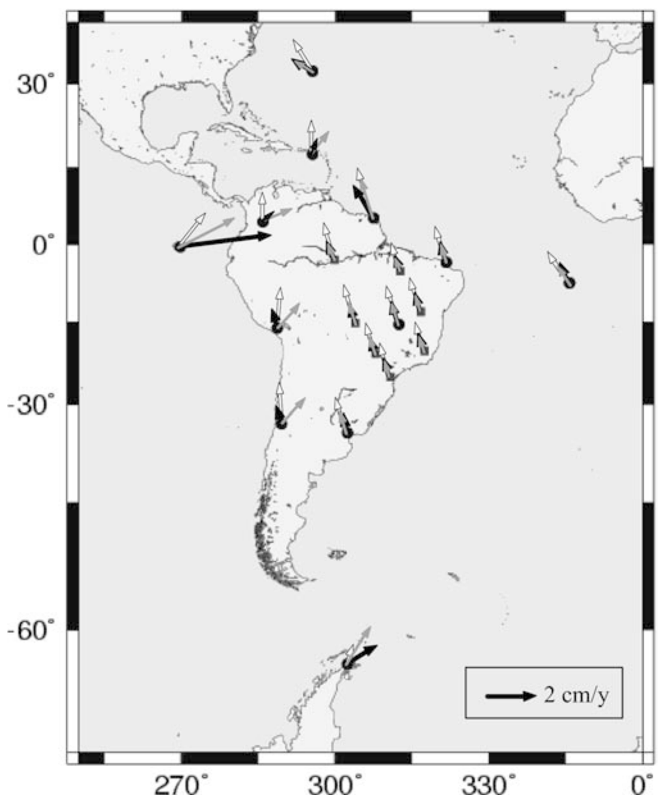

Fig. 2
Representation of the final velocity vectors (indicated by *open arrows*) compared with the ones derived from NNR-NUVEL-1A (indicated by *gray arrows*) and APKIM8.8 (indicated by*black arrows*) models

the Brazilian stations, obtained by different models or geodetic solutions, follow a similar direction and magnitude. On the other hand, for those stations that occupy

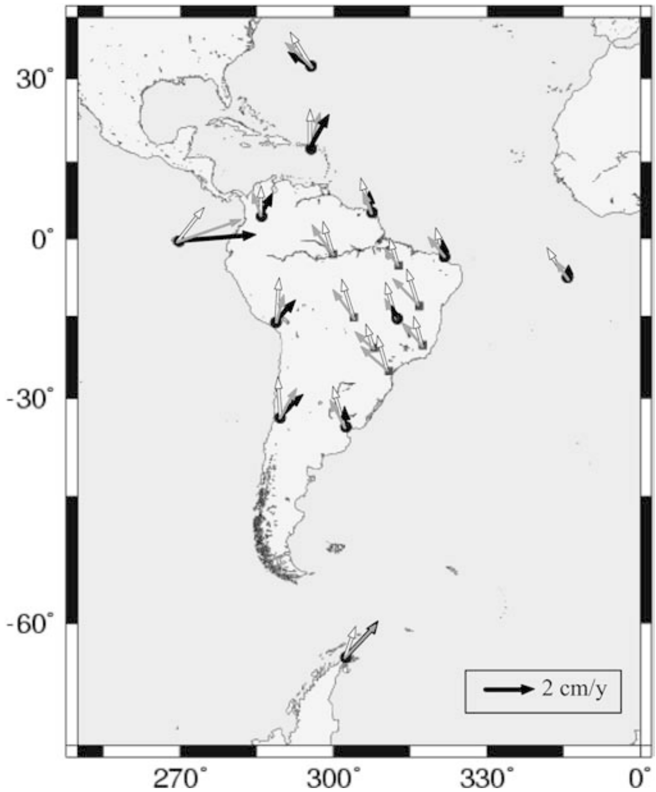

Fig. 3
Representation of the final velocity vectors (indicated by *open arrows*) compared with the ones derived from IGS RNAAC SIR (indicated by *gray arrows*) and ITRF96 (indicated by *black arrows*) models

Table 6
Baseline variation and respective standard deviation

Baseline	Length variation (mm/year)	Standard deviation (mm)
UEPP-BRAZ	1.8	0.04
BOMJ-IMPZ	0.5	0.04
FORT-BOMJ	0.0	0.04
FORT-IMPZ	0.3	0.09
MANA-CIUB	2.5	0.05
MANA-IMPZ	−1.3	0.10
BRAZ-BOMJ	0.2	0.04
BRAZ-VICO	−1.7	0.08
PARA-UEPP	−1.4	0.03
CUIB-UEPP	0.9	0.04

deformation regions on the South American plate, the estimated solution differs from the other sources. Another interesting analysis is the indication of the variation in baseline length according to the velocities of the stations forming the baseline within the portion of the South American plate that covers the Brazilian territory. This variation represents the relative velocity between two RBMC stations and can be a consequence of intraplate motions or an artifact in the computations. These values are shown in Table 6.
A final analysis is possible by means of the computation of Euler's vector (according to the X, Y and Z-axes) for

Table 7
Comparison between SOAM plate rotation vectors according to models NNR-NUVEL-1A, APKIM8.8 and derived from the RBMC

Model	Ω_X(sec/My)	Ω_Y (sec/My)	Ω_Z(sec/My)
NNR-NUVEL-1A	−0.0595	−0.0868	−0.0498
APKIM8.8	−0.1161	−0.0536	−0.0401
RBMC	−0.1607	−0.0957	−0.0621

Table 8
Comparison between SOAM plate rotation vectors (in spherical coordinates) according to models NNR-NUVEL-1A, APKIM8.8 and derived from the RBMC

Model	Φ (degree)	Λ (degree)	ω (degree/My)
NNR-NUVEL-1A	−25.35	−235.58	0.1164
APKIM8.8	−19.39	−210.06	0.1268
RBMC	−18.38	−210.78	0.1971

the SOAM plate, derived from the velocities of the Brazilian stations. These results would represent a more realistic representation of the motion of the stations in Brazil, i.e., in the representation of the velocity field. Table 7 presents our results (computed using the RBMC stations and represented in Cartesian coordinates) as compared with models NNR-NUVEL-1A and APKIM8.8. Table 8 presents the same comparison in spherical coordinates.

Concluding remarks

This paper has presented results for the velocity field of the South American plate using GPS data collected by the RBMC network and some IGS stations in South America. The results showed that the velocity vectors estimated for the RBMC stations had an average magnitude of 2 cm/year. A comparison of the results with other models indicated a better agreement with the GPS derived results. An assessment of the precision of our results suggested that they agree with the ITRF96 frame within 2 cm, which was the highest value for the height component. Also, the standard deviation of unit weight of the coordinates, representing the daily precision of the coordinates, was better than 2 cm. It is interesting to mention that these results have been obtained with a relatively small temporal distribution of the data. We believe that improved RBMC derived velocities will be obtained using data covering longer periods of time. These are initial results and a first estimation based on the RBMC data set. An improvement in the RBMC derived velocities may come about from using other type of solutions.

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