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Results of the SIRGAS Campaign 2000 and Coordinates Variations with Respect to the 1995 South American Geocentric Reference Frame

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Abstract. The geocentric reference system for the Americas (SIRGAS) was initially realised for South America only. A GPS campaign in 1995 covered 58 sites. In 2000 these stations were re-observed and the network was extended to North and Central America as well as the Caribbean. The objectives of the project were completed by the establishment of a unified vertical reference system connecting the classical national height systems. The processing of the 2000 observation data was performed by three analysis centres at DGFI and BEK in Munich as well as IBGE in Rio de Janeiro. The Bernese and GIPSY/OASIS software packages were used. The processing and the comparisons with the 1995 coordinates are described.

Keywords: Terrestrial reference frame, GPS, South America, unified height system

1 Introduction

The South American geocentric reference frame (Sistema de Referencia Geocéntrico para América del Sur, SIRGAS) was installed by a ten-day GPS campaign in May 1995 (SIRGAS 1997). A total of 58 stations were observed. The coordinates were obtained in the ITRF94 at epoch 1995.4 with a precision of ±3 ... ±6 mm. In May 2000 the first repetition campaign was performed extending the project to North and Central America as well as to the Caribbean (Sistema de Referencia Geocéntrico para las Americas, Luz et al. 2002). The geodetic objectives were extended to the establishment of a unified vertical reference frame connecting all the national height systems (Drewes et al. 2002). A total of 184 stations were observed during ten days including all the tide gauges defining a national height system and some levelling points at the borders between neighbouring countries (figure 1).

2 Data Processing and Performance

The data processing of the entire SIRGAS 2000 network was done by three analysis centres: DGFI, BEK and IBGE. As a large variety of receiver and antenna models were involved, considerable efforts were necessary to identify the correct receivers and antenna types in order to make the RINEX data files compatible with the IGS naming conventions. The same holds for the antenna heights where the type of measurement (slant or vertical) and the reference points were not as well documented as in the permanent GPS networks. Both tasks were done in collaboration between DGFI and IBGE. First results of the data processing were reported during an International Symposium (IAG) in Cartagena, Colombia (Costa et al. 2002, Kaniuth et al. 2002).

For the final solution DGFI and IBGE used the latest version of the Bernese software. The principal characteristic of this system is the processing of phase differences between stations and satellites, i.e., the double difference approach (Hugentobler et al. 2001). The third analysis centre, BEK, used the GIPSY/OASIS II software developed at Jet Propulsion Laboratory (JPL) which processes undifferenced code and phase observations (Webb and Zumberge 1997). The precise point positioning strategy (Zumberge et al. 1997) was applied. Some processing features were aligned to each other, but in general each analysis centre was free to select certain options and settings according to its experience. The common features include:

- Application of a 10° elevation angle cut-off in all network adjustments and the tropospheric mapping function of Niell (1996).

- Application of the relative antenna phase centre offset and phase centre variation models proposed by IGS, if necessary supplemented by calibrations performed at the National Geodetic Survey (NGS), USA (http://www.igscb.jpl.nasa.gov/igscb/station/general/igs_01.pcv).

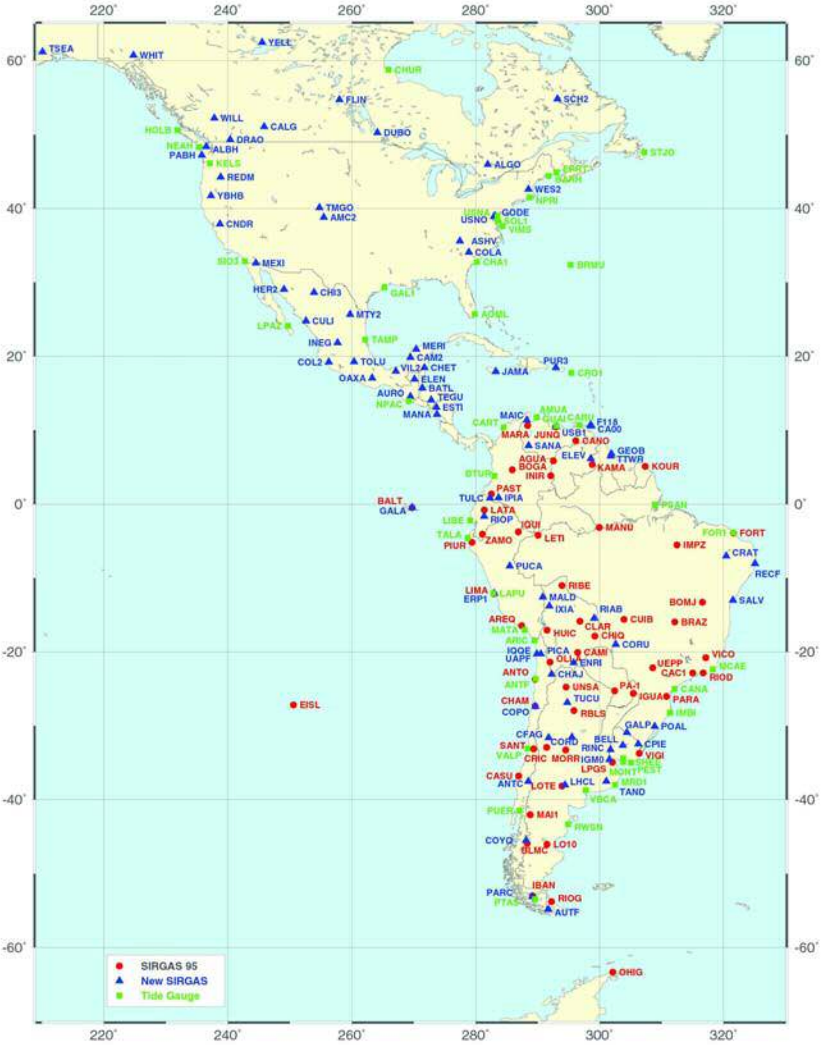

Fig. 1: SIRGAS stations 1995 and 2000

Regarding satellite orbits, satellite clock offsets with respect to GPS time and Earth orientation parameters, both DGFI and IBGE referred the network adjustments to the combined IGS solutions. BEK used the corresponding JPL products including a subsequent empirical transformation to the International Terrestrial Reference Frame 2000 (ITRF2000) also provided by JPL. In case of the Bernese software the receiver clock errors are estimated with sufficient accuracy in a code single point positioning adjustment, whereas in GIPSY/OASIS II they are estimated together with all the other parameters in the precise point positioning solutions.

The different algorithms used in the two software packages, least squares adjustment and square root information filter, respectively, lead to different approaches for modelling the tropospheric zenith delay. In the GIPSY/OASIS II solution the variation is modelled as a random walk process constrained to 10 mm/√ hour. The Bernese software models the zenith delay as a step function allowing a smoothing of the variation with time by setting certain parameters appropriately. Both DGFI and IBGE set the time windows to two hours and left the variation practically totally free because the available satellite constellation allows an unconstrained estimation. Major processing differences between the two Bernese solutions relate to the observation weighting and the outlier handling:

- According to previous experience (Kaniuth et al. 2002), DGFI did not down-weight the observations with decreasing elevation angle and rejected data only after editing the baseline adjustment residuals;
- IBGE weighted the data according to cosine zenith distance and applied the outlier rejection strategy available in the Bernese software.

GIPSY/OASIS II also does not apply elevation dependent weighting but all phase observations with residuals exceeding 2.5 cm are rejected.

The daily network adjustments using the double differencing technique could not be performed in one step. Both analysis centres had to partition the network, IBGE did it in nine and DGFI in three blocks, which were then combined on the normal equation level. The only small deficiencies of this strategy are:

- Tropospheric zenith delays at the sub-network junction points are set up twice and independently.
- The correlation due to including observations of junction points into two baselines is neglected.

As examples, table 1 and figure 2 display the point positioning performance achieved in terms of daily repeatability with respect to the individual ten-day solution for four South American stations which were already included in the SIRGAS 1995 campaign. The sites Bogotá (BOGA) and Latacunga (LATA) are situated in the equatorial region where the ionospheric disturbances were rather high during the 2000 observation epoch. The other two (HUIC and MAI1) are in southern latitudes.

In the horizontal components there are hardly any differences between the two Bernese solutions with an average daily repeatability slightly better than ±3 mm. In the height component the differences are also small. GIPSY/OASIS II shows the best repeatability of all three solutions in the north component where the network extends to more than 13.000 km. The inferior performance in the east component is easily explained by the fact that in the precise point positioning mode no phase ambiguities can be resolved.

3 Datum Realisation and Combination of the Solutions

The solutions of the three analysis centres have to be referred to a unique datum. Therefore it was necessary to select an adequate set of stations to be used for the reference frame realisation. The criteria for selecting these fiducial sites were:

- Good tracking performance during the entire campaign in order to propagate the fiducial position accuracy fully into the SIRGAS network.
- Co-location sites with VLBI and/or SLR are preferred, assuming that different space techniques contribute in particular to accuracy and reliability of the vertical position and velocity components.
- The position and velocity estimates of the ITRF2000 at co-location sites should rely on accurate local ties between the GPS, SLR and VLBI reference points.
- Highest accuracy level in ITRF2000, based on sufficiently long time series of the observations and redundant solutions, e.g. vertical velocity standard deviation ≤ 1 mm/a.
- The distribution of the fiducials should be homogeneous over the entire network area.

These criteria lead to the selection of 14 fiducial sites. They are displayed in figure 3. Each analysis centre realised the reference frame individually. The Bernese type analysis centres extended their normal equation system by seven Helmert transformation parameters. The estimation of these parameters is based on the 14 fiducial sites which realise the datum of the Bernese solutions in the ITRF2000 at the observation epoch.

Table 1: R.M.S. repeatability in North (N), East (E), and Height (H) of daily solutions with respect to the entire ten-day adjustment [mm]

Station ID	Location		BEK			DGFI			IBGE		
	φ [°]	λ [°]	N	E	H	N	E	H	N	E	H
BOGA	4.64	74.08	1.4	5.0	6.6	2.5	3.0	4.6	3.2	2.8	5.7
LATA	-0.82	78.62	1.9	5.0	4.0	2.9	2.5	4.9	2.9	2.0	7.2
HUIC	-17.03	68.45	3.8	6.8	3.9	2.3	2.5	4.7	2.5	2.7	4.9
MAI1	-42.02	71.20	2.5	5.5	6.7	3.9	2.3	5.0	4.1	2.9	5.4

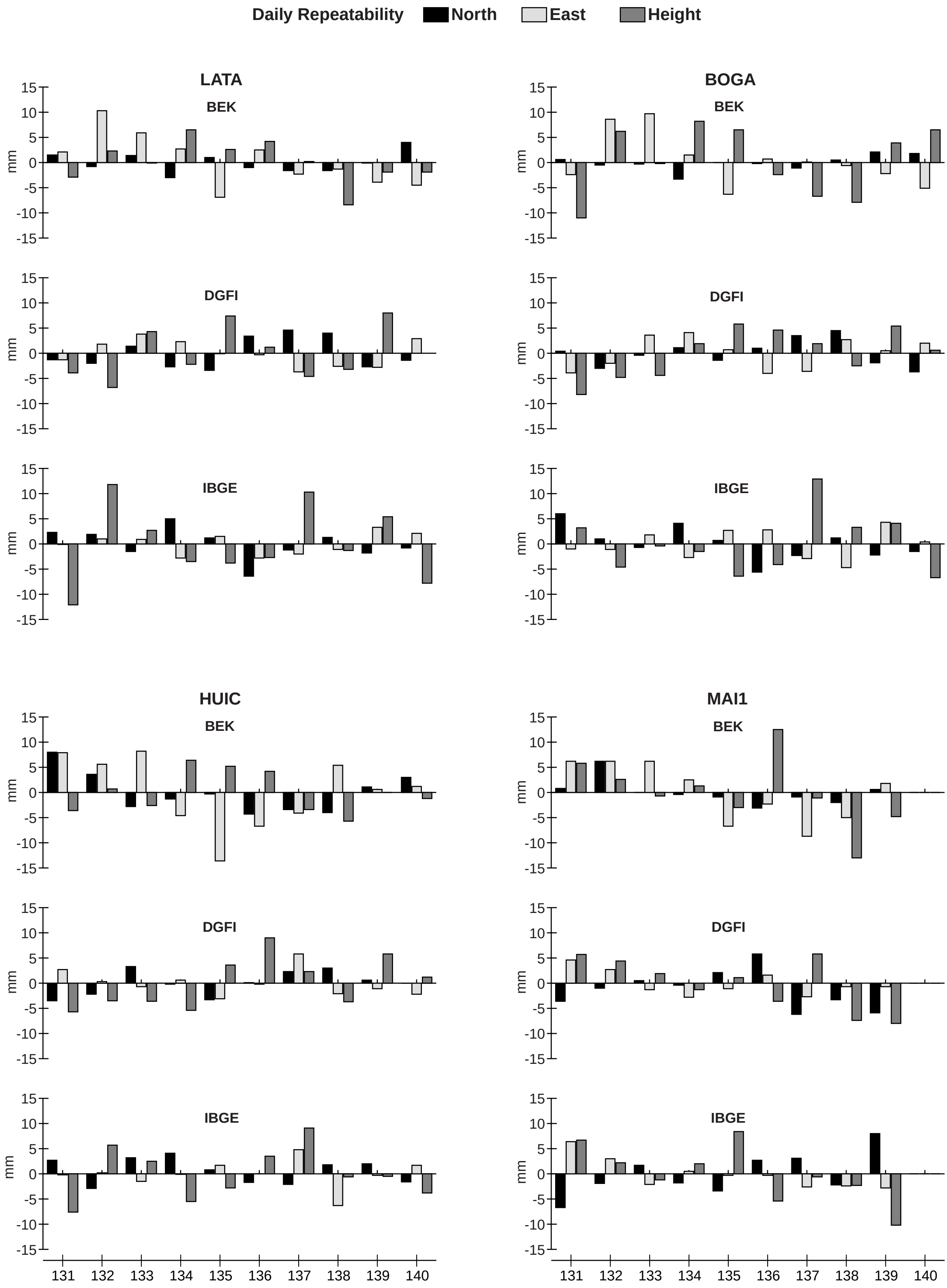

Fig. 2: Daily repeatability in four selected SIRGAS 2000 stations

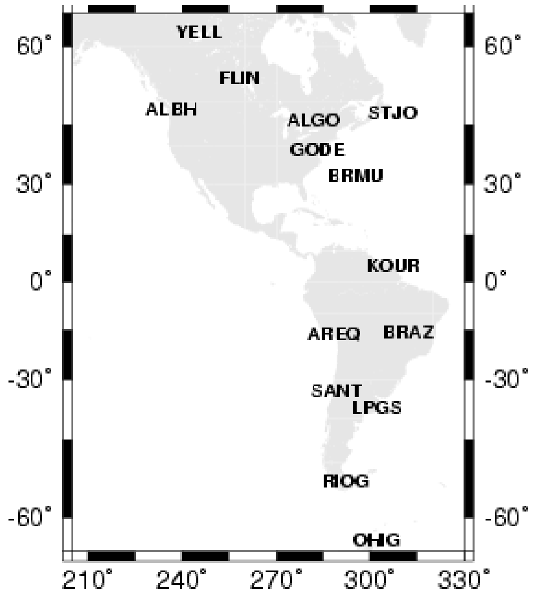

Fig. 3: Sites selected for the reference frame realisation. The 4-character IDs are those used by the IGS.

As mentioned earlier, the GIPSY/OASIS II solution was processed in a non-fiducial system realised by the JPL orbits and satellite clocks. Usually a transformation into a fiducial frame is carried out using parameters supplied by JPL. In our case the non-fiducial solution of each individual day has been transformed to the 14 fiducial sites to realise the ITRF2000 at the observation epoch. Following this procedure any possible distortion of the network is minimised.

The next step is the combined adjustment of the solutions of the three SIRGAS analysis centres. Usually Bernese type solutions are realised by stacking the normal equations of the individual sessions and then solving for the parameters. This very flexible approach could not be used because GIPSY/OASIS II does not deliver normal equations since it is based on a filter.

As a consequence the combination was done on the basis of coordinates and their covariance matrices. This is not a disadvantage because the adjustment on the level of normal equations containing only coordinates and the adjustment based on coordinates and their covariances should yield identical results. Therefore the individual analysis centres generated coordinates and covariance information in SINEX format. The weighting of the individual solutions prior to the combination remains as the major problem.

GIPSY/OASIS II estimates its statistics on the level of coordinates misclosures from the individual session solutions and from some predefined settings (e.g. phase and code noise). The observation interval was set to 300 seconds only while the Bernese type analyse centres used a much higher rate of 30 seconds, which also has an impact on the error estimates of the coordinates. The Bernese statistics strongly depend on the degree of freedom stemming from the large amount of phase observation and the stochastic model assuming uncorrelated observations. Therefore they are usually by far too optimistic; this also holds for the GIPSY/OASIS II coordinates estimates.

Therefore a re-scaling of the individual variance/covariance matrices was applied. The scale factor is derived from the mean point errors of the individual solutions. This is based on the assumption that the adjusted "absolute" coordinates should have the same level of accuracy in all the individual solutions. It seems to be the most reasonable approach which treats the contribution of each analysis centre evenly. As a result the solutions of the Bernese type were scaled down by factors of 5.20 (IBGE) and 5.65 (DGFI) with respect to the GIPSY/OASIS II solution. The combined adjustment of these sets provides the final set of coordinates.

In order to evaluate the combined solution a comparison with the individual solutions is done by performing 7-parameter Helmert transformations. Table 2 gives the r.m.s. deviation of the north, east and height components with respect to the combined solution. All three individual solutions appear to be represented well in the combination.

Table 2: R.M.S. agreement in north, east and height components between the individual solutions and the combined solution after applying a 7-parameter Helmert transformation [mm].

	North	*East*	*Height*
BEK	± 2.2	± 4.0	± 6.8
DGFI	± 2.6	± 3.7	± 7.0
IBGE	± 2.6	± 3.6	± 7.8

We also looked at the formal errors of the baselines. For this evaluation the re-scaled solutions were used. Figure 4 shows the mean baseline error relative to the baseline length. The dotted line shows the baseline errors of the GIPSY/OASIS II solution while the dashed line shows the errors for the Bernese type solutions. It should be mentioned that the DGFI and IBGE solutions show the same behaviour and are therefore summarised as the Bernese type solution.

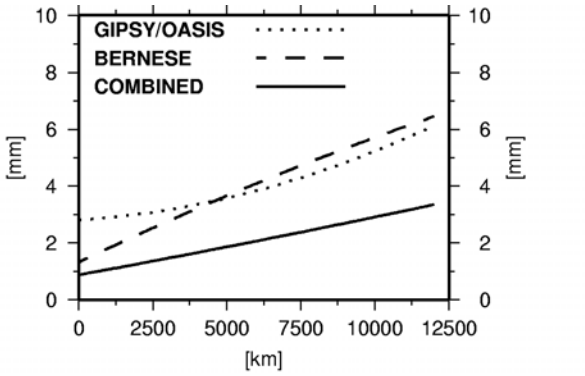

Fig. 4: Baseline length standard deviations relative to the baseline length.

Figure 4 shows quite clearly the difference between the precise point positioning approach and the relative positioning strategy of the Bernese software. Common errors in the data of neighbouring stations cancel out when applying relative positioning. The correlation of the data leads to higher precision between neighbouring stations. This is not the case for precise point positioning. Here the formal error of the baseline components increases with $\sqrt{2}$ of the coordinates components. Nevertheless, with increasing length (approx. 5000 km) the formal error of the baseline length approaches the formal error of the relative positioning. One should keep in mind that figure 4 is based on the re-scaled solutions.

4 Comparing 1995 and 2000 Results

To compare the results for the coordinates determination with those of 1995, the 2000 coordinates were transformed from ITRF2000 to ITRF94 where the 1995 results are referred to. The official ITRF transformation parameters were applied. The coordinates differences were divided by 5 years in order to get linear velocities and to make them comparable with the velocities derived from the IGS Regional Network Associate Analysis Centre for SIRGAS (DGFI02P01). The comparison is graphically illustrated by figure 5.

We see the quite homogeneous velocity field of the stable part of the South American plate which coincides well with the NNR NUVEL-1A model and the different behaviour of velocities in the Andean deformation zone. The average difference in 20 comparable stations included in both SIRGAS campaigns and the DGFI02P01 solution is +2 mm/a in latitude, −1 mm/a in longitude and 2 mm/a in height. After removing the systematic difference we get a deviation of ±1.2 mm/a in latitude, ±2.3 mm/a in longitude and ±4.3 mm/a in height. There are some stations with obviously large discrepancies in height (Bogotá, Maracaibo, Easter Island) where the 1995 and 2000 estimates differ by up to 5 cm.

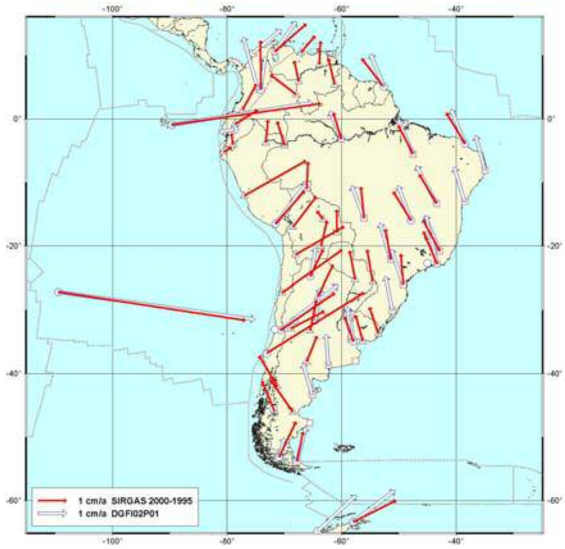

Fig. 5: Comparison of horizontal velocities from SIRGAS 1995 to 2000 and IGS RNAAC-SIR

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