Atmospheric Models applied to DGPS and RTK Network in Brazil: Preliminary Results

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ABSTRACT

Several positioning techniques have been developed to explore the GPS capability to provide precise coordinates in real time. However, a significant problem to all techniques is the ionosphere effect and the troposphere refraction. Recent researches in Brazil, at Sao Paulo State University (UNESP), have been trying to tackle these problems. In relation to the ionosphere effects it has been developed a model named Mod_Ion. Concerning tropospheric refraction, a model of Numerical Weather Prediction (NWP) has been used to compute the zenithal tropospheric delay (ZTD). These two models have been integrated with two positioning methods: DGPS (Differential GPS) and network RTK (Real Time Kinematic). These two positioning techniques are being developed at São Paulo State University (UNESP), Brazil. The in-house DGPS software was already finalized and has provided very good results. The network RTK software is still under development. Therefore, only preliminary results from this method using the VRS (Virtual Reference Station) concept are presented.

INTRODUCTION

The Global Navigation Satellite System (GNSS) has been widely used in several applications. Supporting these applications several positioning techniques have been developed, mainly to explore the GPS capability to provide precise coordinates in real time. But a great limitation to the positioning techniques accuracy is the atmospheric refraction.

Trying to solve this problem, some researches are being accomplished in Brazil at São Paulo State University. Related to the ionosphere effect the Mod_Ion model has been developed (CAMARGO, 1999; CAMARGO et al., 2000, AGUIAR, 2005). This model uses GPS double frequency data from a network of reference stations to compute the ionospheric parameters using a Fourier series. Mod_Ion was extensively tested in point positioning and provided promising results for real time applications. Concerning tropospheric refraction, a model of Numerical Weather Prediction (NWP) has been used to compute the zenithal tropospheric delay (ZTD) and the Niell mapping function to project it in the receiver-satellite direction. The procedure used to compute ZTD from NWP was jointly developed by UNESP and CPTEC (Center for Weather Forecasting and Climate Studies) from INPE (National Institute for Space Research) (SAPUCCI et al., 2006).

These two models have been used together with two positioning methods: DGPS (Differential GPS) and network RTK (Real Time Kinematic). Two in-house softwares have been developed at Sao Paulo State University for such aim.

The DGPS software was already finalized and the results obtained so far are very promising. They improved up to 66% when the Mod_Ion and NWP models were used together. In relation to the network RTK, the software is still under development. In this software, multiple reference stations data, Mod_Ion and ZTD from NWP were used to generate the VRS (Virtual Reference Station) data. So far, no attempt was made to solve the ambiguities and compute the residual errors from the network. This will be tackled in a next step, in which the cited models will also be used to try to improve the ambiguity solution.

In this paper, the theoretical revision of atmospheric models, DGPS and network RTK, preliminary results and analyses are presented.

IONOSPHERE MODEL

In the absence of the limitation imposed to the civil users by the Selective Availability (SA), the ionosphere is the largest error source in the positioning for single frequency GPS users. It affects directly the point positioning technique, while in the relative positioning of short baselines, this degradation is practically reduced. The errors due to the temporary behavior of the ionosphere, which depends on several variables, such as: time of day, season, solar cycle, geographical location of the observer and geomagnetic field of the Earth, are difficult of being corrected.

A general description of ionosphere models for correcting data collected from single frequency GPS receiver, of global, regional or local scale, can be found in Camargo (1999). Most of these models have as input the pseudoranges or the carrier phase measurements collected by dual frequency receivers.

In the derivation of a model, errors due to the non-synchronism between the satellite and receiver clocks, ephemerides and tropospheric refraction won't be considered. These errors contaminate the measurements of both frequencies in same way and do not affect the development of the model. It is based on the difference between the two original pseudoranges ($P^s_{1_r}, P^s_{2_r}$) or pseudoranges filtered by the carrier phase. It is expressed by (CAMARGO, 1999; CAMARGO et al., 2000):

$$F(P^s_{2r} - P^s_{1r}) = I^s_{1r} + F[(S^s_{p2} - S^s_{p1}) + (R_{p2} - R_{p1})_r] + F\varepsilon_{P_{21}}, \qquad (1)$$

with $F = f_2^2 / (f_1^2 - f_2^2)$, s representing the satellites and r the receivers.

Equation (1) is used to estimate the ionospheric slant delay (I^s_{1r}) in the L_1 carrier. The differences ($S^s_{p2} - S^s_{p1}$) and $(R_{p2} - R_{p1})_r$ represent, respectively, the L_1-L_2 satellites and receivers interfrequency biases and the $\varepsilon_{P_{21}}$ represents differential unmodeled errors. The ionospheric delay along the path linking the satellite and receptor can be obtained as function of the vertical ionospheric delay (I_1^v), using an geometric mapping function, thus:

$$F(P^s_{2r} - P^s_{1r}) = \frac{I_1^v}{\cos(z'^s)_r} + F[(S^s_{p2} - S^s_{p1}) + (R_{p2} - R_{p1})_r] + F\varepsilon_{P21}, \qquad (2)$$

where z'^s is the zenital angle of the satellite signal path, in relation to a simple ionospheric layer.

Mod_Ion was implemented in FORTRAN Lahey 95, with the objective of estimating the unknown parameters of the model and provide corrections to L_1 carrier observables. These parameters consist of the coefficients of the series and the L_1-L_2 interfrequencies of the L_1 carrier, of the satellites and the receivers. They are estimated through the batch least squares adjustment using the observation equations method with constraints. Quality control based on the Chi-square statistical test (χ^2) was implemented for the analysis of the adjustment (TEUNISSEN, 1985), as well as the test of significance of the parameters, with the objective of validating the estimated parameters of the used series (ZHONG, 1997). The observation files used as input to calculate the coefficients, as well as the corrected ones, must be in the RINEX format. This makes possible to process GPS data with all GPS softwares, once they should accept the RINEX format.

Mod_Ion_FK, an extension of Mod_Ion, was also implemented in FORTRAN Lahey 95, with the objective of estimating the unknown parameters of the model and provides corrections to the L_1 carrier observables in real time. These parameters consist of the coefficients of the series and the L_1-L_2 interfrequencies of the L_1 carrier from the satellites and receivers. They are estimated through the Kalman Filter (KALMAN, 1960) and the Gauss-Markov process (GELB et al., 1974) for prediction. As a modeling function, a 19 coefficient Fourier series is used (AGUIAR, 2005). This model presented good results for a simulated real time Precise Point Positioning (PPP) test. So, its efficiency will be tested in RTK Network positioning.

TROPOSPHERE MODEL

Nowadays, the use of Zenithal Tropospheric Delay (Z_{TD}) prediction from models of Numeric Weather Prediction (NWP) (KINTER et al., 1997) is a good alternative to minimize the effects of the troposphere in the radio frequency signs for real time applications. This process is denominated Z_{TD} Dynamic Modeling (SAPUCCI et al., 2006). Center for Weather Forecasting and Climate Studies of the National Institute for Space Research (CPTEC/INPE) has made available operationally Z_{TD} prediction for South American region (available in: http://satelite.cptec.inpe.br/htmldocs/ztd/zenital.htm). This modeling technique has already been explored by others researcher and good results were found (JENSEN et al., 2003; JUPP et al., 2003; SCHULER et al., 2000).

The ZTD is divided in two components: wet (Z_{WD} - Zenithal Wet Delay) generated by influence of water vapor, and hydrostatic (Z_{HD} - Zenithal Hydrostatic Delay), generated by influence of the other atmospheric gases. The Z_{HD} values depend of atmospheric air density and can be given by the equation (SPILKER, 1994):

$$Z_{HD} = 10^{-6} \int_{h_0}^{\infty} k_1 \, R_h \rho \, dh \qquad (3)$$

in which R_h = 287,0538 J kg-1 K -1 is specific constant of hydrostatic air and ρ is air density varying in function of altitude (h). The Z_{WD} values can be obtained using the following expression (SPILKER, 1994):

$$ZWD = 10^{-6} \int_{h_0}^{\infty} (k_2' \, \frac{e}{T} \, Z_w^{-1} + k_3 \frac{e}{T^2} \, Z_w^{-1}) dh \, , \qquad (4)$$

where e is partial pressure of water vapor and T is temperature values, both varying in function of altitude (h), Z_w^{-1} is inverse compressibility factor of the water vapor, k_1 = 77,60 $K \ hPa^{-1}$, k_2' = 22,10 $K \ hPa^{-1}$ and k_3 =373900 $K^2 \ hPa^{-1}$ are atmospheric refractive constants.

The Z_{HD} prediction are obtained applying the atmospheric temperature and pressure profile predict by NWP model (for some "A" point from model grid) in a numeric integration in the equation (3). In a similar form, the Z_{WD} values can be obtained applying temperature and humidity profiles generated by NWP model for the same point in the equation (4). The Z_{TD} predicted for this “A” point is obtained adding the values of both components and applying the same process to all points of the grid is obtained a surface with information about the space distribution of that variable. Using interpolation process is possible to obtain Z_{TD} predict values to any other internal point of the grid.

DGPS

In DGPS, the rover receiver coordinates may be improved when using corrections generated by a base station. These corrections, which may be sent via a communication link to the rover station, are either in relation to the position or pseudoranges. DGPS provides a reasonable accuracy for short baselines, which is degraded with distance growth due to spatial decorrelation of the errors (ionosphere effect, troposphere refraction and satellites orbit errors), reducing the method efficiency (SEEBER, 2003). Therefore, to obtain a better positioning quality is indispensable to model such errors.

In order to solve this problem and consequently improve the conventional DGPS performance, an expansion of DGPS concept has been tested, which is quite close to the WADGPS (Wide Area DGPS) concept. Mod_Ion, ZTD from NWP and precise ephemeredes provided by IGS (International GNSS Service) were applied for DGPS in the base and rover stations. Using such concept, tests were carried out.

NETWORK RTK

Using the network RTK concept it is possible to obtain more availability, accuracy and reliability in the positioning if compared with conventional RTK method (ALVES et al., 2003, FOTOPOULOS, 2000). Besides, using network RTK positioning, it is possible to model the distance dependent errors, such as ionosphere effect (WANNINGER, 1999; COLOMBO et al., 2002; ODIJK, 2000b) and troposphere refraction (SEEBER, 2003). The errors derived from satellite orbits can be minimized using precise orbit provided by IGS.

Several methods have been developed to formulate corrections from network stations data: Partial Derivative Algorithms (WÜBBENA, 1996; FOTOPOULOS, 2000; VARNER, 2000), Interpolation Algorithms (GAO and LI, 1998; ODIJK, 2000a), Condition Adjustment Algorithm (RAQUET, 1998; FORTES, 2002; FOTOPOULOS and CANNON, 2000) and VRS (ZHANG and ROBERTS, 2003; van der MAREL, 1998; HU et al., 2003; RETSCHER, 2002). The first three methods concentrate in correction generation, which require changes of rover (user) receiver software, while the last one generates a virtual station near the user, which is compatible with the rover existing software. Therefore, in this research, it was decided to use the VRS concept, which may be quite useful in Brazil. Several organization and users in Brazil have recently purchased several receivers together with the resident software, and they need to recover investments and expand applications.

The VRS data are not provided by a real receiver, but its data are generated from real GPS observations collected by an active multiple reference station network. The idea is that the VRS data resemble as much as possible a real receiver data at the same location. Therefore, the user has the possibility of using the VRS as if it were a real reference station in your proximities, and to accomplish the relative positioning even with a single frequency receiver (ALVES, 2006).

BRIEF DESCRIPTION OF THE SOFTWARES

Both, DGPS and Network RTK software’s are being developed at São Paulo State University. They have been developed in C++ Builder.

The DGPS software accomplishes the DGPS positioning and the expansion of DGPS concept using precise ephemerides and Mod_Ion and the CPTEC NWP models (DALBELO et. al, 2005).

The network RTK software uses multiple reference stations data, Mod_Ion_FK and ZTD from NWP for generating the VRS data (ALVES, 2006). Until this stage, no attempt was made to solve the ambiguities and to compute the residual errors from the network. This will be tackled in a next step, in which the cited models will also be used to try to improve the ambiguity solution.

DGPS: EXPERIMENTS AND ANALYSES

In order to verify the performance of the proposed DGPS method, some experiments were accomplished. Tests were carried out using data collected from RBMC (Brazilian Continuous Network of Monitoring GPS Satellites) (FORTES, 1997). UEPP station was considered the base station. The stations PARA, VICO and SALV, with baselines lengths ranging of 430, 897 and 1693 km were considered the rover stations. It was processed 22 hours of data on April 04, 2005. Concerning the Mod_Ion, data from PARA, CUIB and RIOD (red lines) were used to correct UEPP; data from BRAZ, BOMJ and RIOD stations (green line) were used to correct VICO; data from UEPP, RIOD and POAL stations (blue line) WERE USED TO CORRECT PARA and to correct SALV it was used BOMJ, RECF and VICO stations (pink line) (Figure 1).

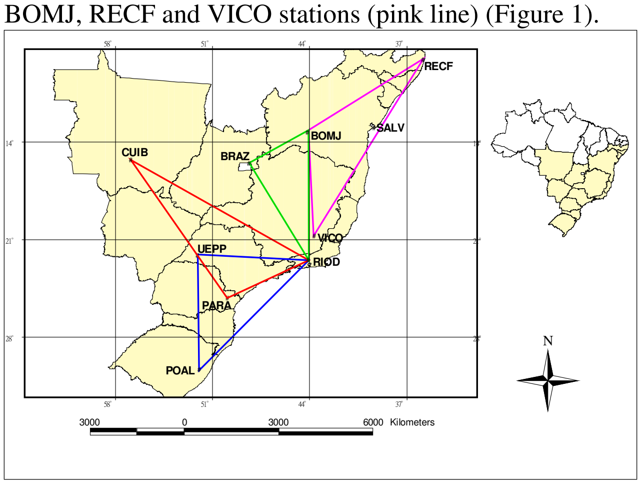

Figure 1 – RBMC stations used in the experiments

The results obtained by DGPS and from the proposed DGPS approach were compared with the "ground truth" coordinates. Figure 1 shows the results obtained at UEPP-PARA baseline with DGPS, DGPS using the ionosphere model Mod_Ion (DGPS+I), DGPS using the troposphere model NWP (DGPS+T) and DGPS using both ionosphere and troposphere models (DGPS+I+T).

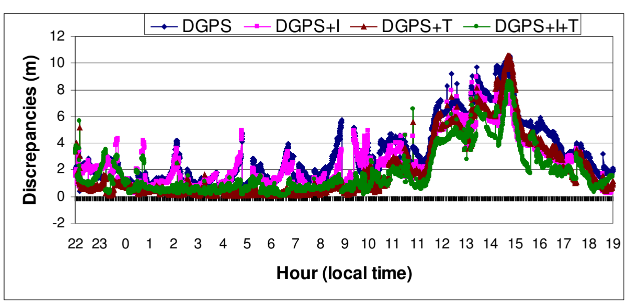

Figure 2 – Resulting discrepancies for UEPP-PARA baseline

Figures 3 and 4 present the results for UEPP-VICO and UEPP-SALV baselines respectively.

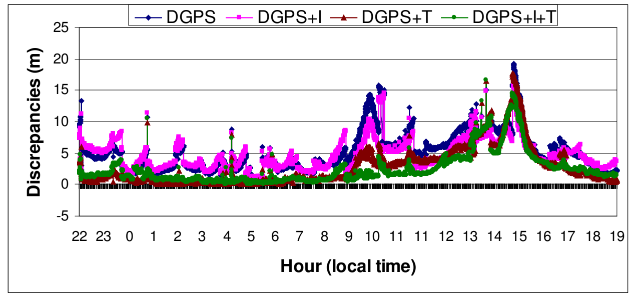

Figure 3 – Resulting discrepancies for UEPP-VICO baseline

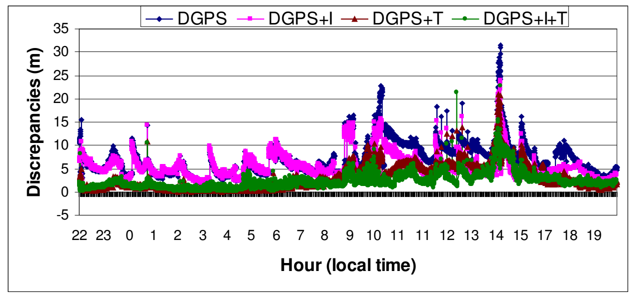

Figure 4 – Resulting discrepancies for UEPP-SALV baseline

In Figures 2, 3 and 4 one can observe that the best results were obtained by DGPS+I and DGPS+I+T methods. The worst results are presented by pure DGPS. Besides, it is possible to verify that during the day, for the four methods, the worst results are around 14 h (local time). This was expected, because in this time the ionosphere effects are more relevant.

Table 1 summarizes the average (AV) and standard deviation (SD) values for this experiment.

Table 1 – Average discrepancies and standard deviations for UEPP-PARA, UEPP-VICO and UEPP-SALV baselines

	UEPP-PARA (430 km)			
	DGPS	**DGPS+I**	**DGPS+T**	**DGPS+I+T**
AV	3.136	2.496	2.019	1.787
SD	2.288	1.843	2.341	1.741
	UEPP-VICO (897 km)			
	DGPS	**DGPS+I**	**DGPS+T**	**DGPS+I+T**
AV	5.072	4.641	2.771	2.406
SD	3.046	2.331	3.102	2.548
	UEPP-SALV (1693 km)			
	DGPS	**DGPS+I**	**DGPS+T**	**DGPS+I+T**
AV	6.902	5.402	3.032	2.342
SD	3.479	2.582	2.669	1.820

In Table 1 one can observe that for UEPP-PARA baseline the average resulting discrepancy in relation to the "ground truth" coordinates improved from 3.13 m using DGPS to 1.78 m for DGPS+I+T (about 43%). For UEPP-VICO baseline, it improved from 5.07 m to 2.40 m (about 52%). And the best results were obtained with the longest baseline, UEPP-SALV. With DGPS the resulting discrepancy was of 6.90 m reducing to 2.34 m (about 66%) using DGPS+I+T.

In these experiments it was used the Mod_Ion, post processed mode. In the future, new experiments must be carried out to test the Mod_Ion_FK in DGPS positioning.

PRELIMINARY EXPERIMENTS AND ANALYSES CONCERNING THE RTK NETWORK METHOD

In order to test the performance of the method, it is necessary to use the data from a network of reference stations. In Brazil, there is the RBMC. However, the distances among the reference stations are very long. So, it was also used extra-stations as it is shown in Figure 5. CUIB, NEIA, PARA and UEPP are stations from RBMC. PIRA, QUAT and MARI are the extra-stations. The data were collected from 16 to 25 May 2005 around the period between 11 h and 15h local times. The VRS was generated on QUAT position, and the data of this station were used just for comparison.

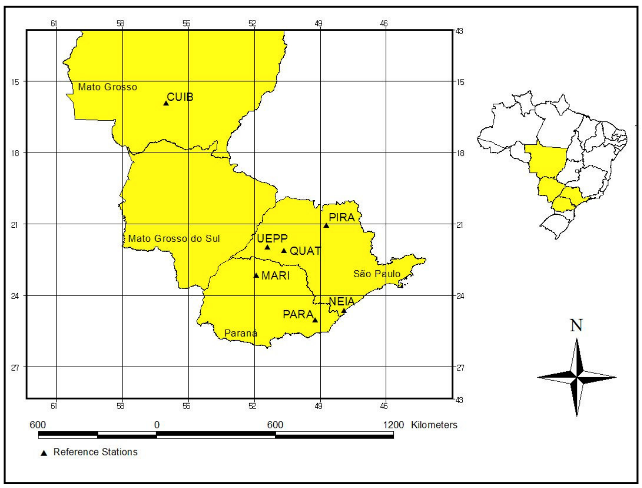

Figure 5 – Reference stations used in the experiments

To analyze the quality of the generated VRS data it was accomplished the relative positioning between the real data (QUAT station) and the VRS. As stated before, no attempt for solving the ambiguities was tried. Therefore, it was performed the relative positioning just with the C/A and P2 codes derived observations. It was used the software GPSeq (MACHADO and MONICO, 2002) to accomplish the epoch by epoch relative positioning.

The results from the generated VRS with different methods are considered. They are: just geometric corrections (Hu el. al, 2003) (GC); geometric corrections plus NWP (GC+T); geometric corrections plus Mod_Ion_FK (GC+I); and geometric corrections plus NWP plus Mod_Ion_FK (GC+I+T).

Table 2 and 3 presents the obtained accuracy.

Table 2 – *E* component accuracy from 10 days of data

Day		***E* Component (m)**			
		GC	**GC+I**	**GC+T**	**GC+I+T**
16/05	Bias	0.490	0.256	0.285	0.051
	SD	0.293	0.300	0.283	0.293
17/05	Bias	0.258	0.156	0.111	0.009
	SD	0.292	0.305	0.275	0.288
18/05	Bias	0.325	0.215	0.159	0.049
	SD	0.313	0.316	0.295	0.299
19/05	Bias	0.360	0.269	0.175	0.084
	SD	0.293	0.303	0.289	0.301
20/05	Bias	0.493	0.287	0.286	0.080
	SD	0.304	0.312	0.298	0.301
21/05	Bias	0.332	0.204	0.120	-0.008
	SD	0.306	0.327	0.299	0.325
22/05	Bias	0.325	0.236	0.119	0.029
	SD	0.277	0.296	0.269	0.291
23/05	Bias	0.277	0.310	0.065	0.098
	SD	0.262	0.261	0.249	0.254
24/05	Bias	0.254	0.272	0.039	0.057
	SD	0.263	0.257	0.254	0.252
25/05	Bias	0.288	0.167	0.085	-0.036
	SD	0.265	0.303	0.258	0.293
Mean	Bias	0.340	0.237	0.144	0.041
	SD	0.287	0.298	0.277	0.290

Table 3 – *N* component accuracy from 10 days of data

Day		***N* Component (m)**			
		GC	**GC+I**	**GC+T**	**GC+I+T**
16/05	Bias	-0.364	-0.280	-0.313	-0.229
	SD	0.436	0.414	0.428	0.410
17/05	Bias	-0.021	0.064	0.033	0.118
	SD	0.468	0.480	0.445	0.457
18/05	Bias	-0.016	0.017	0.024	0.056
	SD	0.444	0.449	0.428	0.437
19/05	Bias	-0.138	-0.102	-0.102	-0.066
	SD	0.349	0.351	0.337	0.344
20/05	Bias	-0.295	-0.246	-0.258	-0.209
	SD	0.460	0.455	0.436	0.432
21/05	Bias	-0.016	0.055	0.019	0.091
	SD	0.392	0.379	0.368	0.357
22/05	Bias	-0.077	-0.039	-0.039	-0.001
	SD	0.345	0.342	0.332	0.333
23/05	Bias	-0.141	-0.128	-0.104	-0.091
	SD	0.333	0.336	0.317	0.319
24/05	Bias	-0.177	-0.137	-0.139	-0.098
	SD	0.395	0.389	0.372	0.364
25/05	Bias	-0.178	-0.165	-0.137	-0.124
	SD	0.370	0.392	0.351	0.375
Mean	Bias	-0.142	-0.096	-0.102	-0.055
	SD	0.399	0.399	0.381	0.383

In Table 2 one can observe that, as expected, the worst results are related to the GC (mean of 0.34 ± 0.28 cm), because the errors due to the atmosphere are not corrected. The best results are related, in almost all cases, by the GC+I+T (mean of 0.04 ± 0.29 m). Just in two days (23 and 24) GC+T presented the best results. This may happen mainly because of the inadequacy of the reference network configuration. Concerning the SD, one can notice that the results are always very similar.

In Table 3 it is possible to verify that the worst results are also presented by GC (mean of -0.14 ± 0.39 m). Besides, the best results are presented by GC+I+T (mean of -0.05 ± 0.38 m). Just in 3 days (17, 18 and 21) the biases were larger for GC+I+T solution; but this does not happen with the SD. Again, in relation to SD, the results also are very similar.

Comparing the results presented in Tables 2 and 3 one can observe that with the best method (GC+I+T) the mean bias presented by *E* and *N* components are quite similar, but the SD is larger for the *N* component.

Table 4 shows the obtained accuracy of the *h* component.

Table 4 – *h* component accuracy from 10 days of data

Day		***h* Component (m)**			
		GC	**GC+I**	**GC+T**	**GC+I+T**
16/05	Bias	-0.110	-0.111	0.024	0.024
	SD	0.848	0.843	0.828	0.828
17/05	Bias	-0.156	-0.138	0.120	0.138
	SD	1.255	1.222	1.087	1.061
18/05	Bias	0.113	0.199	0.320	0.407
	SD	1.087	1.047	0.968	0.953
19/05	Bias	0.239	0.251	0.433	0.445
	SD	0.932	0.925	0.865	0.865
20/05	Bias	-0.143	0.027	0.001	0.170
	SD	0.856	0.825	0.828	0.835
21/05	Bias	-0.029	-0.040	0.147	0.135
	SD	0.940	0.931	0.846	0.830
22/05	Bias	0.272	0.303	0.388	0.418
	SD	0.806	0.803	0.702	0.703
23/05	Bias	0.074	0.091	0.232	0.249
	SD	0.806	0.820	0.707	0.709
24/05	Bias	0.148	0.171	0.325	0.348
	SD	0.867	0.897	0.771	0.785
25/05	Bias	0.366	0.535	0.466	0.635
	SD	0.797	0.785	0.719	0.738
Mean	Bias	0.077	0.129	0.246	0.297
	SD	0.919	0.910	0.832	0.831

Analysing the results presented in Table 4 it is possible to notice that the best values for the bias are obtained by the CG method, but the best values concerning the SD are provided by GC+I+T one.

Table 5 presents the mean values obtained from the 10 days of data. It is taken into account the planimetric (PR) and altimetric (AR) components.

Table 5 – Mean values for the planimetric and altimetric components for the 10 days of data

Day		**(m)**			
		GC	**GC+I**	**GC+T**	**GC+I+T**
PR	mean	0.548	0.492	0.441	0.421
	SD	0.295	0.292	0.269	0.268
AR	mean	0.721	0.728	0.687	0.707
	SD	0.598	0.594	0.556	0.562

In Table 5 it is possible to verify again that the best results are presented by the GC+I+T method for both components.

Comparing the planimetric and altimetric components showed in Table 5 one can see that the accuracy of the altimetric component is worse than that presented by the planimetric components, an expected result. On average, the discrepancies obtained by CG+I+T are of about 0.42m and 0.70 m for planimetry and altimetry respectively. Besides this, the standard deviations are also larger for altimetry. The mean values for the CG+I+T method are 0.26 m and 0.56 m for planimetric and altimetric components respectively.

A comment that should be stated out is related to the reference stations used in these experiments, which has an inadequate configuration. But at this moment it was the only reference station network available to test the proposed method. By the end of 2006 a GPS network at São Paulo State, Brazil, will be available which will provide a better geometry. Data of this network will be used to accomplish new tests.

CONCLUSIONS

In this paper was presented the results obtained with the DGPS and RTK network software's that are being developed at UNESP.

Using the DGPS software it is possible to generate the corrections using the different atmosphere models that are being developed at UNESP. Using the atmospheric models the results obtained by DGPS presented improvements of 43% (430 km) for the shortest baseline and 66% for the longest one (1693 km).

Concerning the Network RTK software, just preliminary results were presented. Using it is possible to generate a VRS station to a specific position with different atmosphere models, among them those developed at UNESP. So far, no attempt was directed to solve the ambiguities. This will be tackled in a next step, in which the cited models will also be used.

So far, just code derived observables were processed. It was accomplished the relative positioning between the generated VRS and the actual data. It was obtained a reasonable accuracy, about 0.42 m and 0.70 m for planimetric and altimetric component respectively.

A problem that should be tackled in the future is related to the ionosphere model used so far. The results obtained with Mod_Ion_FK were not very good, probably due to the reference stations configuration. More experiments will be accomplished in the future with another reference station network in order to investigate the Mod_Ion_FK performance in the proposed method.

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