Assessment of GPS data for meteorological applications over Africa: Study of error sources and analysis of positioning accuracy

A. Walpersdorfa,⁎, M.-N. Bouinb, O. Bocc, E. Doerflingerd

aLGIT, Maison des Géosciences, BP 53, 38400 Grenoble Cedex 9, France
bIGN/LAREG, 6 et 8, Av. Blaise Pascal, 77455 Marne-la-Vallée, France
cService d'Aéronomie du CNRS, Université Pierre et Marie Curie, 4, place Jussieu, 75252 Paris Cedex 5, France
dLDL, Université Montpellier II, Place E. Bataillon, 34095 Montpellier Cedex 5, France

Received 9 June 2006; received in revised form 28 March 2007; accepted 19 April 2007
Available online 6 May 2007

Abstract

The aim of this study is to assess the availability and quality of data from the International GNSS Service (IGS) Global Positioning System (GPS) network in Africa, especially for retrieving zenith tropospheric delay (ZTD), from which precipitable water vapour (PWV) can be derived, in view of application to the African Monsoon Multidisciplinary Analysis (AMMA) project. Three major error sources for the GPS data analysis evaluating PWV in Africa are the accuracy of the satellite orbits, the correction for the radio delay induced by the ionosphere and the vertical site displacements due to ocean loading. The first part of this study examines these error sources and the validity of GPS data for meteorological applications in Africa in dedicated analyses spanning the year 2001. These analyses were performed using the IGS precise orbits. Weak degradation of baseline precision with increasing baseline lengths suggests that the average orbital error is not limiting the GPS analysis in Africa. The impact of the ionosphere has been evaluated during a maximum of solar activity in 2001. The loss of L2 data has actually been observed. It amounts to 2% on average for 2001, with maxima of 8% during magnetic storm events. A slight decrease in formal accuracy of ZTD seems to be related to the loss of L2 data at the end of the day. This indicates that scintillation effects are present in the GPS observations but however are not a major limitation. The impact of ocean loading is found to be significant on ZTD estimates (up to ±2 mm in equivalent PWV). The use of a proper ocean loading model eliminates this effect.

The second aspect of this study concerns the IGS analysis quality for the African stations. The accuracy has been assessed through position dispersion between individual solutions and the most recent version of the IGS combined solution IGb00, and residuals from the transformation of the IGS combined solution into the International Terrestrial Reference Frame 2005. The positioning performance of the IGS analysis is consistent with an accuracy in ZTD of ±6 mm (±1 mm in PWV), as requested for meteorological applications such as planned in AMMA.

Keywords: GPS meteorology; Zenith total delay; Precipitable water vapour; African Monsoon Multidisciplinary Analysis (AMMA); International GNSS Service for Geodynamics (IGS)

⁎Corresponding author. Tel.: +33 4 76828104; fax: +33 4 76828101.
E-mail address: andrea.walpersdorf@obs.ujf-grenoble.fr (A. Walpersdorf).
1. Introduction

The Global Positioning System (GPS) is used for a wide variety of scientific applications. In geodesy, data from permanent GPS stations are contributing together with very long baseline interferometry (VLBI), satellite laser ranging (SLR), lunar laser ranging (LLR) and Doppler orbitography and radiopositioning integrated by satellite (DORIS) data to establish the International Terrestrial Reference Frame (ITRF, Altamimi et al., 2002), with the latest version ITRF2005 recently published (http://itrf.ensg.ign.fr/ITRF_solutions/2005/ITRF2005.php, Altamimi et al., 2007). Permanent and temporary GPS measurements are used to precisely describe active tectonics, by constraining deformation rates between several cm/yr to fractions of mm/yr over distances of tens to thousands of km (California, e.g. Murray and Segall, 2001, Japan, e.g. Sagiya et al., 2000, Mediterranean Area, e.g. McClusky et al., 2000, Alps, e.g. Vigny et al., 2002; Calais et al., 2002). Large-scale hydrologic phenomena have been observed by combining vertical motions of the global permanent GPS network with high-resolution space gravity data (Kusche and Schrama, 2005).

GPS data, from stations with well-known coordinates, can be used to estimate tropospheric delays which can be transformed into precipitable water vapour (PWV). Methodological studies of meteorological GPS applications have been carried out since more than 10 years (e.g. Bevis et al., 1992; Businger et al., 1996; Tregoning et al., 1998; Bock and Doerflinger, 2001) and enable us now to infer PWV from GPS observations with the same precision as conventional meteorological measurements, such as radiosondes and microwave radiometers (WVR), to about 1–2 mm PWV.

GPS tropospheric delay or PWV estimation has several advantages over traditional meteorological measurements of water vapour: It can be done at low cost (either by using already existing GPS stations or by installing new GPS stations which are less expensive than other instruments), it is performing under all weather conditions and the method is intrinsically stable. Effectively, GPS PWV measurements are based on the exploitation of propagation delays excluding any instrumental drifts. Nevertheless, modifications of the analysis strategy or the change of instruments (receiver and/or antenna) can induce instantaneous offsets in the coordinate time series. However, the effect is reduced on the
tropospheric parameter estimates (see Section 2). The GPS performances have been tested mainly for mid-latitude networks where they have shown high efficiency. Presently, applications in meteorological analysis and weather forecast are widely spread in e.g. European, US and Japanese weather services (Gendt et al., 2004; Guerova et al., 2006; Gutman et al., 2004; Nakamura et al., 2004).

Examining the tropospheric water cycle is one major goal of the African Monsoon Multidisciplinary Analysis (AMMA) project (http://www.amma-international.org/). Water vapour observations are lacking in Africa and a significant increase of their amount could be obtained by the exploitation of existing permanent GPS stations and the installation of a dedicated GPS network in the AMMA study area (15°W–15°E by 0°N–25°N). The continuous GPS measurements provide PWV observations with a complete coverage of the time scales from diurnal cycle to multi-annual variations.

On the African continent, a total of 14 IGS stations are presently available, among which only two are located in the AMMA zone strictly spoken, and five in the slightly larger study area selected for our work (Fig. 1). This is to be compared to 84 in Europe, more than 100 in North America, and about 25 in South America, 50 in Asia and 20 in Australia. The IGS includes only a subset of all existing permanent stations, for example it does not include the 1000 site network in Japan and the hundreds of additional stations in California or in Europe.

The African GPS network has three particularities with respect to most mid-latitude networks: The network is sparse, the ionosphere is very active (see Fig. 3 and Section 3.3), and most stations are situated close to the ocean. The sparseness of the African network implies long inter-station distances. In the present study area, only the NKL-GMSKU and TGCV-DAKA baselines are shorter than 1000 km. This sparseness of IGS stations in Africa could also lead to a lack of constraints on the orbit solution established by IGS. Hence, the orbit errors could be more important over Africa than in places with a denser IGS network. These orbit errors would then limit baseline precisions on the long baselines typically found in the African GPS network. Therefore, three error sources will be specifically addressed in the present paper: (1) Orbit errors could induce relative positioning errors which are increasing with baseline length; (2) high ionospheric activity could result in data losses and
un-modelled signal delays; (3) vertical motions due to ocean loading could be mixed up with tropospheric variability if ocean loading is improperly modelled.

The organisation of the paper is the following. In Section 2, we describe the principle of GPS data processing and emphasise the error sources specific to the study area. In Section 3, we quantify these error sources and assess their impact on raw data and estimated parameters (station coordinates and tropospheric delay). Therefore, we analysed GPS data over a 1-year period, using various analysis procedures. In Section 4, we analyse the long-term quality of the GPS data of the African IGS network and the stability of the IGS solutions.

2. GPS error sources

The precise determination of GPS station parameters (coordinates and tropospheric delays) is achieved from the processing of dual-frequency signals (at wavelengths $L_1 = 19\,\text{cm}$ and $L_2 = 24\,\text{cm}$) transmitted by satellites at 20\,200\,km height and received by ground-based receivers. The observables actually processed for precise determinations (of geodetic quality) are carrier phase differences between a satellite and a receiver. This observable is subject to a number of effects of different nature, some of which can be modelled explicitly, the others being considered as error sources. Eq. (1) gives some insight into most effects acting on the phase difference $\Delta \phi_j^i$ (measured in units of cycles) between receiver $i$ and satellite $j$ at wavelength $\lambda$.

$$
\lambda \Delta \phi_j^i = c(t_R - t_E) + c(\delta t_i - \delta t_j) - \lambda N_i^j = L_j^i + \Delta L_{\text{ino}} + \Delta L_{\text{tropo}} + c(\delta t_i - \delta t_j) - \lambda N_i^j.
$$

(1)

The phase signal is ambiguous: The phase delay measurement cannot distinguish the number of entire wavelengths (ambiguity) between the transmitter and the receiver ($N_j^i$), but takes into account only the instantaneous fractional part of the phase delay. The ambiguity $N_j^i$ of a phase measurement is an integer number and remains constant as long as the phase measurement is not interrupted. Its value is estimated as one of the parameters of the GPS
data analysis. The complete phase delay $\Delta \phi_i$ is due to the differences of the time of reception and the time of emission of the signal ($t_R$ and $t_E$), the signal travel time. However, clock errors on both the receiver and the transmitter sides are also included in the complete phase delay ($\delta t_R$ and $\delta t_E$, respectively). The signal travel time is due to the geometrical distance $L_i = |X_i - X'|$, between the receiver (of coordinates $X_i$) and the satellite (of coordinates $X'$), with additional delays created by the refraction of the electromagnetic signal in the Earth’s ionosphere and troposphere ($\Delta l_{\text{iono}}$ and $\Delta l_{\text{tropo}}$).

Eq. (1) represents a model for the observations which contains explicitly a number of effects that are either corrected a priori or adjusted during the data analysis with the help of specific models. There are other effects, not explicit in this equation, which act mainly as error sources, such as multi-path near the GPS receiver antenna which will not be considered in the following. Among the modelled effects are antenna phase centre variations, variations in station height due to geophysical phenomena (Earth tides, ocean loading, atmospheric loading, varying hydrological conditions) and variations in tropospheric delay with satellite-viewing angle. The ionospheric delay is dispersive and can be eliminated to a first order using the two GPS frequencies (see below). Clock errors can be reduced significantly using double-differenced phase observations (differences between two receivers and two satellites). The analysis of GPS data requires also the knowledge of precise satellite orbits (term $X'$ in the geometrical distance).

Precise satellite orbits are obtained from IGS; they are calculated in a precise post processing based on observations from the permanent IGS network. The IGS final orbit solution reaches now average precisions of less than 5 cm. This means that in general the orbit errors no longer represent a major error source for post processing. However, the IGS network is sparse in Africa, which may have two impacts: the orbits could be less well constraint over Africa, and the baselines are long and therefore more affected by potential orbit errors than short baselines. Orbit errors affect baseline precisions in the following way:

$$\frac{dr}{r} = \frac{db}{b} \quad (2)$$

(the relative orbit error equals the relative baseline error). This effect is quantified in Section 3.2.

Several geophysical phenomena create sub-diurnal periodical vertical motions, for example Earth tides with amplitudes which can reach more than 40 cm and ocean loading (up to 6 cm) (Scherneck, 1991; Vey et al., 2002). Atmospheric loading causes vertical motions of up to 2 cm over several days to weeks (van Dam and Wahr, 1987). If these phenomena are not modelled correctly, they represent a strong error source for the estimated parameters (in particular vertical positioning and zenith tropospheric delay, see below). Earth tides can be modelled precisely, as the Earth deforms like a homogeneous body due to the action of the tidal forces. Although known for decades, ocean loading (the flexure of continental crust due to the weight of the ocean water pushing down the shallow sea bottom close to the coastline during the tides, e.g. Francis and Mazzega, 1990; Scherneck, 1991) and atmospheric loading (the flexure of continental crust under the weight of air masses due to stationary high-pressure systems, e.g. van Dam and Wahr, 1987) are still gaining increasing attention in space geodesy. While the loading effect on station positions is averaging out on the long-term, sub-diurnal parameter evaluation like hourly tropospheric delays is sensitive to any unmodelled vertical motion. Tests of the impact of ocean loading modelling on tropospheric parameter evaluation are part of our methodological study and will be shown in the following Section 3.4.

The troposphere creates a variable and non-dispersive delay of the GPS signals, which cannot be corrected a priori with sufficient precision. Therefore, the estimation of additional parameters has been included in the GPS data analysis, representing a variable tropospheric delay. A first parameter quantifies the tropospheric delay with respect to zenith (ZTD). It is evaluated several times per day during an analysis estimating coordinates over 24 h. ZTD can be divided into two parts, a hydrostatic delay (ZHD) with typical values of 2.30 m at sea level, and a wet delay (ZWD) with variable values between 0 and 0.4 m, ZTD = ZHD + ZWD (Davis et al., 1985). Mapping functions are used to relate the ZTD to the tropospheric delay at any elevation angle ($\Delta l_{\text{tropo}}$ in Eq. (1)). A tropospheric delay is minimal at zenith, and increases with $1/\sin$(elevation) towards lower elevation angles whereas the delay due to variations of the vertical position is maximal for a satellite at zenith and decreases with $\sin$(elevation) towards low elevation angles. To de-correlate the two quantities (zenith delay and
vertical position) successfully, satellite observations are required at varying (and in particular at low) elevation angles. The simultaneous estimation of vertical position and ZTD is characterized by the following relation between GPS positioning error and errors on the tropospheric observables: A 20 mm error on vertical position corresponds to 6.5 mm of error on ZTD, which in turn corresponds to a 1 mm error on PWV (e.g. Santerre, 1991; Niell, 1996). 1 mm being the precision of classical meteorological PWV measurements, we will use this error limit as objective in the GPS data analysis and the subsequent PWV extraction. A comparison of GPS inferred PWV with independent data over Africa is presented in Bock et al. (2007).

While the neutral atmosphere creates a non-dispersive delay on GPS radio signals, the ionosphere is dispersive, with an index of refraction that can be expressed as (Seeber, 1993; Hofmann-Wellenhof et al., 1998).

\[
n_{\text{iono}} = 1 + \frac{c_2}{f^2} + \frac{c_3}{f^3} + \frac{c_4}{f^4} + \ldots ,
\]

where \(c_i\) are constants and \(f\) the signal frequency, with \(c_2 = -40.3\) Ne and \(Ne\) the electron density along the travel path. The ionospheric delay can thus be approximated to the first order as

\[
\Delta l_{\text{iono}} = \int n_{\text{iono}} \, ds - \int ds_0 = \int \left(1 + \frac{c_2}{f^2}\right) \, ds - \int ds_0,
\]

\[
\Delta l_{\text{iono}} = -\frac{40.3}{f^2} \int Ne \, ds_0,'
\]

where \(ds_0\) is an increment of distance in a vacuum and \(ds\) along the radio path (we assume the geometrical lengths of these paths are identical in the second equality). The total electron content \(TEC\) is defined as

\[
TEC = \int Ne \, ds_0.
\]

It is easily shown that the following linear combination of \(L_1\) and \(L_2\) phase observations (Eq. (1)), named LC, eliminates the ionospheric delay as modelled in the preceding:

\[
\Delta \phi_C = -\frac{f_1^2}{f_1 - f_2^2} \phi_1 - \frac{f_2 f_1}{f_1^2 - f_2^2} \phi_2
\]

\[
= \frac{f_1}{c} L + f_1 \Delta t + \frac{f_1}{c} \Delta l_{\text{tropo}}
\]

where subscript 1 refers to \(L_1\) and subscript 2 refers to \(L_2\). This linear combination is used as observable in the GPS analysis.

Similarly, TEC can be estimated from dual-frequency GPS measurements using another combination of \(L_1\) and \(L_2\) (Rius et al., 1997; Calais et al., 1998). TEC estimates produced at CODE http://www.ex.unibe.ch/aiub/ionosphere.html are used in the following (Section 3.3) to characterize the ionospheric activity above the present study area. CODE’s ionospheric maps are representing the vertical total electron content (VTEC) and are produced on a daily basis using data from about 200 GPS/GLONASS sites of the IGS and other institutions. The time resolution is 2 h and the spatial resolution \(5^\circ \times 5^\circ\). The maps are available in IONEX format at http://igs.iub.code/ionex/.

3. Evaluation of error sources and validity of GPS data for meteorological applications in Africa

3.1. GPS data analysis

A GPS data analysis has been carried out to evaluate the impact of the most important error sources on the quality of the analysis products (station positions and tropospheric parameters). The year 2001 has been chosen to test the GPS measurement performances during high solar activity (see Fig. 3). The software used is GAMIT/GLOBK 10.10 (King and Bock, 2002). Eleven African and 10 surrounding stations have been included in the analysis. IGS final orbits have been held fixed and corresponding Earth orientation parameters have been used. The Niell tropospheric mapping function has been used (Niell, 1996). In a first analysis step, precise positions have been evaluated. In a second step, 7 IGS stations outside Africa have been constrained to their ITRF2000 position (Altamimi et al., 2002), while for all other stations the position constraints were held loose and hourly ZTD and horizontal tropospheric gradients have been evaluated. These analyses were performed with ocean loading corrections (tide model CSR4.0, Eanes, 1994, and Gutenberg–Bullen Green’s function from Bos and Scherneck’s web page http://www.oso.chalmers.se/~loading/, Scherneck and Bos, 2002). The impact of using no
3.2. Accuracy of position estimates

A classical indicator of the GPS positioning precision is the short-term scattering between several independent baseline solutions (repeatability), evaluated over a few days. It helps quantifying the quality of GPS data and the analysis procedure. This measure can also be interpreted in terms of ZTD precision, using the relationship mentioned in Section 2. Using a limited time interval (here 10 days) implies that the station position does not change due to seasonal signals or long term tectonic deformation, so that the short term scattering presents only the instantaneous measurement precision. Ten successive daily GAMIT solutions in 2001 have been compared and the repeatability has been displayed in Fig. 2 for each baseline with respect to its length. This measurement repeatability has been established without any adjustment between individual daily solutions and is therefore a conservative value for the measurement precision. The comparison of the individual GAMIT solutions yields mean scatters of 2.9, 4.0 and 6.0 mm on the North, East and vertical baseline components, respectively. The site SEY1 has been excluded from

![Fig. 2. Short-term baseline repeatability over 10 days in 2001. Each dot represents the dispersion on a particular baseline, indicated with respect to the baseline length (up to 10,000 km). The North, East and vertical baseline components are shown in the upper, middle and lower box, respectively. Average values are displayed in the upper right corner of each box.](image-url)
this evaluation because the old GPS receiver is highly affected by data losses due to ionospheric activity and degrades the average precision significantly. This phenomenon is discussed in Section 3.3 for the RABT site which is concerned to a lower extent. As for the IGS solutions (presented below), in our own analysis the vertical component is determined to better than 10 mm, providing sufficient precision for significant tropospheric parameter evaluation.

The position error of our analysis can be evaluated from the global positioning solution established in the ITRF2000 reference frame. The solutions for IGS sites are compared with their a priori values in ITRF2000. Two classes of stations are considered: (1) stations with precise coordinates in the ITRF2000 reference frame being used to establish this reference (which means that their coordinates are tightly constrained to their ITRF2000 values); (2) stations with precise ITRF2000 coordinates but unconstrained in our analysis. The freely adjusted coordinates of 11 unconstrained stations can be used to evaluate the coherence of our solutions with respect to ITRF2000: The mean bias between the adjusted coordinates and ITRF2000 over 1 year yields −1.9, −0.7 and −3.1 mm on the North, East and up coordinates, with standard deviations of 5.3, 14.7, and 19.3 mm. These biases and standard deviations can be compared to the differences between the IGS combined solution and ITRF2005 as shown in Section 4, Table 1 (average biases between 0.1 and 1.1 mm and standard deviations of 1.5–10.7 mm). Keeping in mind that the IGS combined solution is more precise than individual analysis centre solutions (see comparison in Fig. 9), that the interval of comparison is longer (station-dependent between 1.5 and 8 years), and that ITRF2005 is an improved reference frame with respect to ITRF2000 (Altamimi et al., 2007), this comparison shows that the present analysis centred on the African GPS network reaches precisions comparable to other, denser networks analysed by the IGS analysis centres.

In relative positioning, orbit errors are propagated into baseline errors as a function of the baseline length (see Eq. (2)). In our analysis, the orbits used are IGS final solutions. An increase of dispersion with increasing baseline length related to orbit errors can not be noted (Fig. 2), showing that orbit precision is not limiting the positioning quality, and as a consequence it should also not limit the quality of ZTD estimates.

### 3.3. Ionospheric refractivity

At the global scale, ionospheric activity is particularly high in the region of the equatorial anomaly (±17° to both sides of the magnetic equator) and creates large gradients of TEC which can give place to high variations of GPS signal propagation delays (Skone et al., 2004). Few studies have considered the effect of this phenomenon for high-precision GPS positioning and tropospheric parameter estimation, however, its impact could be significant. The temporal variability in TEC shows a number of periodicities, from the 11-year sun spot cycle to a diurnal cycle. High TEC contents can also be observed during intermittent periods of magnetic storms. In addition to the diurnal cycle of TEC, ionospheric inhomogeneities appear during nighttime and produce scintillation effects in the GPS signals observed from ground-based receivers (Kintner et al., 2004).

Fig. 3 displays the time series of daily mean TEC in the present study area (larger box 2 in Fig. 1) covering 8 years, deduced from CODE’s global ionosphere maps. The diurnal variability of the TEC values is indicated by two additional curves indicating the daily maximum and minimum value. The daily mean values reached in the study area (15–80 TEC units during a 8 years time span) can be considered as high compared to global mean TEC evaluated at CODE (5–60 TEC units during a 10 years time span). The decrease of TEC and its variability from 2000 to 2005 is evident. In the years 2005–2007, during the AMMA enhanced observing period (EOP), we can expect that the majority of TEC values in the AMMA zone remain below 50 TEC units.

<table>
<thead>
<tr>
<th>Station</th>
<th>$E$</th>
<th>$N$</th>
<th>$U$</th>
<th>No. of weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>DAKA</td>
<td>−0.3</td>
<td>1.6</td>
<td>−0.1</td>
<td>2.2</td>
</tr>
<tr>
<td>HRAO</td>
<td>−0.5</td>
<td>3.2</td>
<td>−0.2</td>
<td>2.0</td>
</tr>
<tr>
<td>MSKU</td>
<td>0.8</td>
<td>4.6</td>
<td>0.1</td>
<td>2.2</td>
</tr>
<tr>
<td>NKLG</td>
<td>0.1</td>
<td>2.2</td>
<td>0.0</td>
<td>1.5</td>
</tr>
<tr>
<td>YKRO</td>
<td>−0.7</td>
<td>4.7</td>
<td>−0.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>
The most important consequence of high ionospheric activity (scintillation) is the loss of the $L_2$ frequency. This phenomenon happens at some receivers with respect to individual satellites at some epochs. Only the $L_1$ observations of the concerned satellite are then available. In the dual-frequency analysis, these single frequency data would be rejected, since $L_2$ is needed to establish the LC signal from which the ionospheric delay is removed. The number of simultaneous observations at one site would then be decreased, reducing thus the accuracy or even leaving gaps in the estimated parameters (e.g. coordinates and ZTD). Usually, the number of simultaneously observed satellites is 6–10, so that the $L_2$ loss reduces the total number of observations by some percent.

Fig. 4 illustrates the loss of $L_2$ data during year 2001, at the four African stations that were operating at the time and SFER (in the south of Spain), as a reference. The percentage of loss is calculated with respect to the total number of observations. The daily mean TEC is also presented for each site by a grey line (Fig. 4). A correlation between $L_2$ loss increase and higher TEC (mainly in spring and autumn) can be observed. For example, for station NKLG, the amount of $L_2$ loss varies between 2% and 7% of the total number of observations in low and high TEC periods. At the RABT station, $L_2$ loss is high, varying between 15% and 35% and is correlated with TEC. This is due to the use of old GPS receivers (here ROGUE SNR-8000), which are more sensitive to ionospheric variability than the more recent receivers operated at the other African sites.

Fig. 5 illustrates $L_2$ data loss in a different manner. The number of satellites for which the $L_2$-signal is lost at each epoch of measurement (30-s) is plotted as a function of time. TEC is also plotted for each station. Two short periods (highlighted as vertical bars in Fig. 3) are presented: one with relatively low (days 202–207) and one with relatively high (days 300–305) ionospheric activity. Both TEC and satellite-loss exhibit a diurnal cycle. However, during the quiet period, the number of satellites lost remains below 4 and its diurnal cycle has small amplitude. During the active period, a large diurnal cycle is observed at RABT, with up to 8 satellites lost. A smaller one can be distinguished at MAS1 and NKLG, where the number of satellites lost peaks in the evening, with peak values between 4 and 8 (but over much shorter periods than at RABT). Overall, the spikes in satellite-loss are correlated with peaks in TEC. Note that even in the high activity interval with up to 8 satellites lost in individual epochs the average loss per day does not exceed the 8%, except for the old GPS receiver at RABT (Fig. 4).

The impact of $L_2$-signal loss has been investigated from ZTD formal accuracy through the (a posteriori) standard deviation (std) in ZTD, a parameter that is available in the analysis report generated by
the GPS data analysis software. Fig. 5 shows this parameter, superimposed to the satellite-loss and TEC. It can be seen that ZTD std is strongly correlated with $L_2$-signal loss. The magnitude of ZTD std is typically between 5 and 10 mm (excepting RABT), with occasional peaks above 10 mm (at MAS1 and NKLG). The tendency for ZTD std to peak at midnight might also be due to the processing strategy which uses 24 h windows (from 00 to 00 UTC); it is common to observe an std
increase at the start and end of the windows due to the weaker observational constraints.

This study shows that data loss due to ionospheric activity and related degradation of tropospheric parameter precision in Africa is generally low and comparable to sites situated outside the equatorial region (SFER in our tests). The results obtained for the accuracy of position estimates (Fig. 2) are therefore confirmed. The only exceptions are the RABT and SEY1 sites with old equipment which must be avoided to be operated in regions with high ionospheric activity.

3.4. Ocean loading

The impact of ocean loading correction on ZTD estimates has been assessed in the second analysis step. An hourly ZTD has been evaluated with and without ocean loading modelling. The ocean tide model used is CSR4.0 (Eanes, 1994) and the loading is modelled by Gutenberg–Bullen Green’s Functions (Scherneck and Bos, 2002). The differences between the two evaluations are displayed in Fig. 6 for 4 GPS stations, 3 are close to the ocean (less than 500 km) and one (MBAR) is situated about 1000 km inland. The time series of ZTD differences are shown for a 1 month time span. Significant values of 10 mm ZTD (equivalent to 1.5 mm PWV) are reached at NKLG and TGCV, indicating that sub-diurnal height variations due to ocean loading are absorbed in ZTD evaluations when not corrected a priori. Even for the GPS station 1000 km inland (MBAR), 4–6 mm ZTD differences are observed.

Fig. 5. These graphs represent the number of satellites presenting $L_2$ losses at the same epoch (one epoch = 30 s) for 5 African stations plus SFER in the south of Spain as reference. For each epoch, every 30 s, a dot is indicated if 1 or more satellites are lost. The left graphs show satellites with $L_2$ losses during a relative minimum of ionospheric activity (days 202–207 in 2001), the right graphs during a relative maximum (days 300–305 in 2001, according to Fig. 3). For each site, the time evolution of ZTD sigmas is indicated by the black line. The grey line indicates the 2-hourly TEC evolution at each station. The full vertical axis corresponds to 140 TEC units.
Comparing vertical position error (here represented to a first order by the amplitude of the major ocean loading component M2 which is related to the semi-diurnal lunar tides) and ZTD error, we find a scaling factor between ZTD error and station height variations of a little more than 3 (e.g. M2 amplitudes of 19, 17 and 10 mm at NKLG, TGCV and MBAR, with ZTD errors of 6, 5 and 3 mm, respectively). This is consistent with Santerre’s error analysis (1991). A scaling factor of 4.4 has been evaluated by Vey et al. (2002) in a study of ocean loading impact in Brittany, where extreme tidal amplitudes are observed. Our and Santerre’s estimation of the impact of vertical position error on ZTD evaluation is more conservative than the result of Vey’s study, however, the common conclusion is that ocean loading has to be modelled carefully to keep the uncertainty of ZTD (and thus PWV) evaluation at an acceptable level.

The amplitude differences between the tide model used in our study (CSR4.00, Eanes, 1994) and other common tide models (GOT00.2, Ray, 1999, TPX0.7.0, Egbert et al., 1994) is for NKLG, TGCV, HRAO, MKSU and MBAR 0.4–2% of the amplitude. We can therefore evaluate that the influence of the choice of the tide model is negligible.

Francis and Mazzega (1990) and Scherneck and Bos (2002) evaluated also the influence of using different loading models that convert the ocean tides to crustal deformation related to the varying water masses. The difference in loading using Green’s functions of the Gutenberg–Bullen (Farrell, 1972) or the PREM (Anderson and Dziewonski, 1981) Earth model is evaluated to 1% in amplitude and 0.6° in phase. Moreover, Francis and Mazzega (1990) show that using Green’s Functions taking into account the viscoelastic behaviour of the Earth, differences of at maximum 1.5% in amplitude and 0.3° in phase were observed with respect to a purely elastic Earth. This means that also the choice of the loading model is not critical for the evaluation of ZTD.
4. IGS data availability and analysis quality

4.1. Data availability and data quality

In this section, data availability and positioning solutions for African IGS stations will be presented over a time span of 5 years. The objective is to evaluate the long-term impact of the low network density and the high ionospheric activity in Africa.

The GPS permanent stations have varying performances of data acquisition. Fig. 7 displays the time series of data availability for the 5 permanent stations in the AMMA region, from 2001 to the end of 2005. The oldest station NKLG is recording almost continuously. MSKU and TGCV have been installed during 2001 and have large data gaps. DAKA has been operating more or less regularly since the end of 2003. YKRO has provided only a few months of data in 2004. The station performances depend strongly on the motivation of the host organisation, on the availability of local collaborators and on the data transfer facilities.

Fig. 6. Differences in ZTD evaluated with and without ocean loading modelling (CSR4.0, Eanes, 1994). In the bottom of each box, the most important tidal component (M2) of the ocean loading model is displayed for each station location.
We have checked the raw data quality of the African stations. Fig. 7 shows the number of data acquired per day. The South African station HRAO has been added to the comparison as a very reliable reference site (IGb00 site since 2003). The African sites show a very good performance whenever they record data.

These results show that, in principle, running GPS stations in the AMMA zone is possible and yields satisfactory raw GPS data. The main problem is the delay in restarting the recording after a serious failure of a site.

4.2. Quality of IGS data analysis

How do the African stations behave in the global IGS analyses? Positioning results of global networks are established on a day-by-day basis in several analysis centres. We use the centres CODE, EMR, ESA, GFZ, JPL, MIT, NGS and SIO to compile our statistics (Kouba et al., 1998). Weekly solutions of individual analysis centres are combined at IGS and constrain the global IGb00 solution (Ferland, 2003) of station coordinates and velocities. We compare individual weekly solutions with the IGS combined solution aligned to IGb00 over a time span from beginning of 2004 until autumn 2005 (Fig. 8). While the solutions of individual analysis centres show highly variable differences with respect to IGb00 from one week to another (reaching average biases of 3 mm and rms of 5 mm on the horizontal components), the weighted mean difference is very low (less than 1 mm with a standard deviation of less than 1.5 mm). The values are comparable between the AMMA zone stations and the HRAO reference site. We conclude that the GPS positioning of stations in the AMMA zone is of a comparable quality as the
positioning of the best African GPS stations in the IGS network.

Finally, we have tested how the IGb00 solution (based uniquely on GPS data) compares to the International Terrestrial Reference Frame ITRF2005 (Altamimi et al., 2007), which is a combination of several space geodetic observation techniques (VLBI, SLR, LLR, DORIS, GPS,
Fig. 9. Differences between weekly IGS combined solutions aligned to IGB00 and ITRF2005 (Altamimi et al., 2007) for HRAO, NKLG and DAKA. The three upper lines present the differences on the North, East and up components. The forth line shows daily mean TEC at each of the three stations for the same time interval as above.
Altamimi et al., 2002). Time series of the differences between ITRF2005 and IGS weekly combined solutions aligned to IGb00 are shown on Fig. 9. An average value has been calculated over the available data for each station and displayed in Table 1. Here again, the AMMA zone stations show the same residuals with respect to ITRF2005 as the station (HRAO) with mean differences on the vertical component reaching 1 mm and standard deviations of 5–10 mm. The higher standard deviations as in the GPS internal evaluation are due to correlated noise, like for example seasonal signals present in the GPS analysis but not in the other techniques. These signals could be related to atmospheric or groundwater loading not accounted for in the models as well as seasonal biases due to mismodelling (Earth tide corrections, mapping functions systematic errors, second order of ionospheric delay...). To test the hypothesis that the residuals are related to unmodelled ionospheric residuals, station TEC has been compared to the residuals in the last line of Fig. 9. No clear correlation can be seen, except of some hints on the vertical component. However, the positioning residuals show a lower (about annual) frequency than the time evolution of station TEC.

5. Conclusions and perspectives

A special analysis of IGS data in the AMMA zone has been performed covering the year 2001 of high ionospheric activity. The loss of \( L_2 \) data has been evaluated to 2–7% between relatively quiet and active ionospheric situations in 2001. A diurnal cycle can be recognised, particularly during high ionospheric activity. To investigate sub-daily disturbances in the GPS analysis due to the ionospheric activity, we compared the diurnal cycle of \( L_2 \) data losses with the time evolution of the standard deviation of zenith delay estimates. Some correlation is found. ZTD std of more than 10 mm (corresponding to 1.5 mm PWV) are reached in some limited cases: during high ionospheric activity, for the last hours of the 24 h analysis session, when \( L_2 \) losses related to scintillations at night fall and the data discontinuity at the end of the session both decrease the constraints on ZTD evaluation.

Highly active ionosphere could eventually lead to higher-order ionospheric delays not eliminated by the linear combination of \( L_1 \) and \( L_2 \) (Eq. (3)) (Kedar et al., 2003; Fritsche et al., 2005). Taking into account a second-order ionospheric model, Hawarey et al. (2005) show that these additional delays induce differences in VLBI vertical positions of less than 0.5 mm, even for sites close to the equator and during high ionospheric activity, and therefore negligible for ZTD estimations. Generally, we can confirm the capacity of GPS to estimate significant tropospheric parameters even during high solar activity. Moreover, the AMMA EOP and SOP in 2005–2007 will take place during a minimum of solar activity. Absolute values for TEC and its variability will be relatively low (TEC mostly below 50 TEC units). This means that the GPS capacities will be even less degraded than during our study interval in 2001.

The low coverage of the African continent by IGS stations could possibly lead to poorly constrained orbit estimates above Africa. However, no decrease of precision with increasing baseline length is observed, which is the typical signature of limited orbit precision.

The modelling of ocean loading is necessary to obtain significant zenith delay estimates along the African coast and even far inside the continent. Omitting ocean loading leads to errors equivalent to up to 1.5 mm PWV for the stations tested. The differences between various ocean tide models do not exceed 2% of the amplitude of the main tidal component M2. The ocean loading models are implemented by different Earth models, leading to less than 2.5% of variations of the amplitude. The choice of a particular ocean loading model or tide model is therefore not critical.

The study of 5 years of IGS data shows that the reference network in Africa is not only very sparse, the data of existing stations also have important gaps. However, when data are available, they are generally of good quality, comparable to mid-latitude stations. The positioning quality of African stations has been evaluated by comparing solutions from different IGS analysis centres to the IGb00 combined solution. While individual solutions can show punctually differences of up to 30 mm, the average difference over all analysis centres is less than 1 mm. These results for stations in the AMMA zone are comparable to mid-latitude stations. The position residuals of the IGb00 solution with respect to ITRF2005 are \( \pm 1 \) mm on the vertical component with standard deviations of up to 10 mm. The higher std than for GPS internal comparisons seems to be due to seasonal signals present in the GPS data but not in the ITRF solution. However, the std of 10 mm for the vertical component corresponds to...
0.5 mm PWV (Santerre, 1991; Bevis et al., 1992). This means that the IGS positioning precision is largely sufficient to evaluate significant IWV variations. Six years of IGS tropospheric solutions are available in SINEX format, and usable for tropospheric studies. These data have been exploited in Bock et al. (2007).

Apart from qualifying the IGS solutions as significant source of tropospheric data in West and Central Africa, our study also shows the interest of producing independent, more detailed data analyses with respect to the IGS solutions. Methodological tests on different analysis parameters could improve the precision of tropospheric parameters, especially on sub-diurnal time scales. This has been shown for ocean loading in this study, but many other parameters could be examined: higher temporal resolution for ZTDs than 2 hourly like in the classical IGS analysis (interesting for the study of the diurnal water vapour cycle), which is provided also by a new tropospheric IGS product calculated by a single analysis centre (JPL) with a resolution of 5 min ftp://cddis.gsfc.nasa.gov/gps/products/trop_new>, multi-path filtering, constraints on the tropospheric parameter adjustment and variability, reference frame realisation, mapping functions (e.g. comparing the here used Niell’s mapping function (Niell, 1996) to global atmospheric model based mapping functions like VMF (Boehm et al., 2006a) and GMF (Boehm et al., 2006b)), the use of a sliding-window strategy for the tropospheric parameter evaluation, the use of ground pressure measurements for the evaluation of a priori values for the ZTD estimation, antenna phase centre variation models, etc. To illustrate this latter point, the influence of the modelling of antenna phase centre variations (PCV) on the evaluation of ZTDs has been tested in this study, motivated by the upcoming absolute PCV models which also include the satellite antennae. These models are not yet used in the IGS analysis, because the switch from the presently used relative PCV models limited to the receiver antennae to absolute antenna models including the satellites would create offsets in the station coordinate time series. Recalculating ZTD over a period of 60 days in 2001, we state an average bias of 7 mm over 10 African stations (ZTDs with absolute antenna calibrations being lower than using relative calibrations). This is consistent with the values published by Schmid et al. (2005) and Steigenberger et al. (2007). Schmid et al. (2005) show in particular that the use of absolute antenna calibrations decreases drastically the bias between GPS and VLBI ZTD estimates, which is an important step toward more consistency between the techniques, essential for any application of space geodetic techniques monitoring the global change. For future applications of GPS to meteorological and climatological studies, the use of absolute antenna phase centre calibrations is therefore recommended.

Moreover, processing data is the only way to get access to the full information on the processing parameters which can be evaluated in the analysis. Only the station coordinates and ZTDs have been analysed in the present study, but others are available, in particular to complete the tropospheric information contained in the GPS measurements:

- Tropospheric gradients could be evaluated, to improve the spatial resolution of tropospheric information in the sparse African network, by adding a horizontal tendency to ZTD or PWV values related to zenith (Champollion et al., 2004).
- Postfit phase residuals could be evaluated: These high-resolution parameters (one value every 30 s in all visible satellites’ directions) could include tropospheric activity related information, as shown for example by Pany et al. (2001). Moreover, residuals give access to antenna phase centre variations and the multi-path environment of the sites (Wuebbena et al., 1997; Champollion et al., 2005), both constituting important error sources for tropospheric parameter evaluation.

It is thus expected that a network of special GPS stations deployed within the framework of the AMMA project can be used to retrieve significant PWV observations (see Bock et al., 2007). The tropospheric solutions based on this dedicated network are expected to be improved with respect to the presently available tropospheric solutions provided by IGS, due to the densification of the sparse African network, an increased frequency of tropospheric parameter estimation and the exploitation of the horizontal gradients.

Acknowledgements

We are grateful to Zuheir Altamimi for making the new ITRF2005 available to us. M.S. Bos’ and H.-G. Scherneck’s ocean loading tools http://www.oso.chalmers.se/~loading> have been
particularly helpful for our study. The constructive reviews provided by H. Schuh and an anonymous reviewer were a valuable help for improving the manuscript.

References


Ferland, R., 2003. IGS Mail 4642: IGS00 (v2).


