

Measurements for GPS meteorological applications

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(reçu le 30 Mai 2007 – accepté le 25 Juin 2007)

Abstract - *The Global Positioning System (GPS) is at present used for the location and the synchronization of the ground, marine and air meteorological measurements as well as for wind measurements. In the first part of the paper, are presented results of measurements of the positioning of a point known with the Algerian National Center of Space Techniques, CNTS [1] of Arzew and it is included of the national geodesic network and the world network Tyrgeonet : 305 site. The purpose is the study of the total electron content (TEC) using measurements of GPS signal code. For that, two methods are used: Dual-frequency and Klobuchar model method. To eliminate possible skews from the satellite and the receiver. For a GPS receiver alone, one can use the model of Klobuchar to determine the vertical time on the code transmitted by the signal L1. A comparison between the two models will be made to choose that which characterizes best the ionospheric effect. In the second part of this article, we describe the principle of a new technique which is the radio occultation allowing to sound the troposphere by using the GPS signal. Finally, the study of the ionosphere has for application the spatial telecommunications, whereas the study of the troposphere has for application the meteorological phenomena.*

Résumé - *Le système de positionnement global (GPS) est actuellement utilisé pour le positionnement et la synchronisation des mesures météorologiques terrestres, marines et aériennes ainsi que pour des mesures radiométriques de la vitesse du vent. Dans la première partie de cet article, sont présentés les résultats de mesures de position d'un point connu au Centre National des Techniques Spatiales CNTS [1] d'Arzew. Le but est l'étude du contenu électronique total (TEC) par la mesure du code du signal GPS. Pour cela, deux méthodes sont employées : la méthode de la double fréquence et celle de Klobuchar. Pour éliminer les biais possibles du satellite et du récepteur, on emploie la méthode à double fréquence. On a donc utilisé un seul récepteur GPS bi-fréquence pour effectuer des mesures en absolu. On peut employer le modèle de Klobuchar pour déterminer le temps vertical sur le code transmis par le signal L1. Une comparaison entre les deux modèles sera effectuée. Dans la seconde partie de cet article, on décrit le principe d'une nouvelle technique qui est la radio occultation permettant de sonder la troposphère en utilisant le signal GPS. Enfin l'étude de l'ionosphère a pour application les télécommunications spatiales, tandis que l'étude de la troposphère a pour application les phénomènes météorologiques.*

Key words: GPS – Ionosphere – Troposphere – TEC – Modelling - Klobuchar model - Dual-frequency model – Meteorology - Water vapour.

1. INTRODUCTION

In the first part of this paper, are presented the results of the processing data GPS as well as calculation of the ionospheric effect. We use the model of the dual-frequency and that of Klobuchar to the measure of the distance between a satellite and a receiver. An analysis of the results obtained by each model as well as the comparison and the choice of the most representative model is presented. With an aim of starting an approach of ionospheric modelling, measurements in absolute were carried out with the CNTS of Arzew, Algeria. In the second part of this paper are presented procedures of tropospheric modelling of signal GPS.

Water vapour is a highly variable atmospheric constituent and one of the most poorly characterized meteorological parameters.

Improved knowledge of water vapour is needed for a variety of atmospheric research applications and for weather forecasting. Ground-based GPS receivers can provide continuous information on water vapour at a site being water vapor closely related to the wet component of the tropospheric zenith path delay.

The objective of these measurements is the determination of the vertical TEC starting from GPS data. This paper presents measurements of GPS signals made at the CNTS, as well as the processing GPS data with analysis of the results.

2. ACQUISITION OF GPS DATA

Their transformation, data-gathering GPS into RINEX format (Receiver INdependent EXchange), as well as obtaining the files of navigation and observation is presented by the flow chart shown in Figure 1. GPS receiver Ashtech-Z12 was used to record with a 15 seconds rate during approximately 1 hour. These data were exploited to estimate the value of the TEC above 305 site.

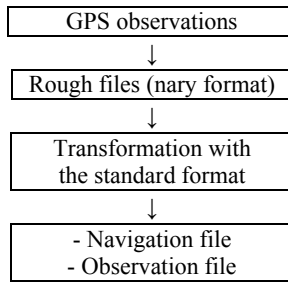


Fig. 1: Transformation Ashteh-Rinex

3. IONOSPHERIC EFFECT ON GPS SIGNAL

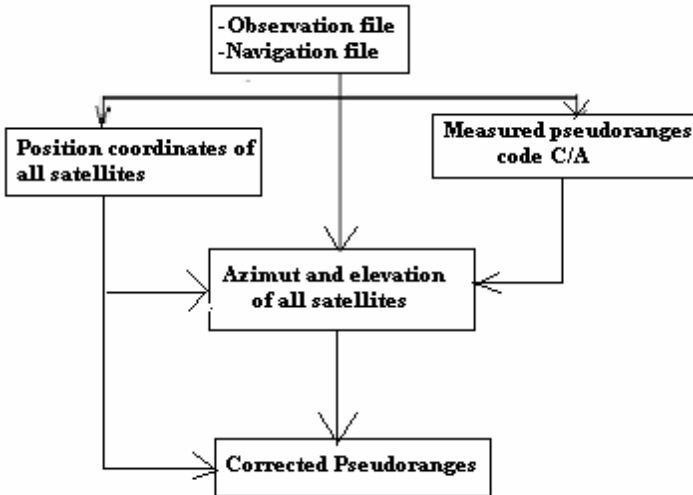


Fig. 2: Flow chart of determination of the position of an item [2]

3.1 Calculation of the position of GPS antenna

The following flow chart illustrates the great stages in general to be followed for the determination of the GPS position shown on figure 2.

3.2 Model of measurement [3]

Let us suppose that one has N satellite, placed at known positions, $X_i = (x_i, y_i, z_i)^T$ $i=1, K, n$, visible by a receiver whose true position is: $X_r = (x_r, y_r, z_r)^T$

$$r_i = d_i + c t_r + \xi_i, \quad i = 1, \dots, n, \quad (1)$$

where:

$$d_i = \|X_i - X_r\| = \sqrt{(x_i - x_r)^2 + (y_i - y_r)^2 + (z_i - z_r)^2} \quad (2)$$

is the true distance between satellite i and the receiver, t_r is the skew of clock of the receiver, c is the speed of the light and ξ_i is a noise of measurement, presumably Gaussian of null average and variance σ^2 .

Let us define the pseudo distance as function of X_r and t_r :

$$(X_r, t_r) \rightarrow r_i = \|X_i - X_r\| + c t_r + \xi_i$$

Let us consider the vector of measurements.

$$R = (r_1, \dots, r_n)^T$$

By linearizing the function compared to the vector around the estimated point, one obtains

$$Y = R - R_0 \approx H_0 (X_e - X_{e0}) + \xi$$

where

$$X_e = \begin{pmatrix} X_r \\ t_r \end{pmatrix}, \quad R_0 = (r_{10}, \dots, r_{n0})^T, \quad r_{i0} = \|X_i - X_{r0}\| + c t_{r0}, \quad \xi = (\xi_1, \dots, \xi_n)^T$$

$$H_0 = \frac{\partial R}{\partial X_e |_{X_e = X_{e0}}} \text{ is the Jacobean matrix of dimension } n \times 4.$$

One obtains the solution repeatedly by applying the algorithm of least squares :

$$\hat{X}_e = X_{e0} + A_0 (R - R_0),$$

where: $A_0 = (H_0^T \cdot H_0)^{-1} H_0^T$.

With the following condition:

$$\|\hat{X}_e - X_{e0}\| = \|A_0 (R - R_0)\| \leq \delta \quad (= \text{small constant}).$$

3.3 Ionospheric effect by the dual-frequency method

For the needs to our study, one highlighted the ionospheric effect on GPS signals by the use of the observations collected by Ashtec-Z12 receiver located on 305 site. The receiver being fixed. Measurements consisted of the recording of a one hour session approximately, lasted largely sufficient for the mode in absolute. The rate of record is 15 seconds. The ionospheric effect is generally proportional to the distances higher than 100 km between the mobile receiver and that of reference of several authors [4]. For the base lines lower than 10 km, its effect is generally lower than 10 % wavelength (lower than 1.9 cm for L1) and can be neglected [5].

The combination of two measurements of the code P, modulated on the two frequencies L1 and L2, makes it possible to quantify the delay of with the ionosphere to measure GPS. This is possible by carrying out the differentiation between these two measurements.

The equation of observation of the measurement of the code (pseudo-distance) is :

$$\begin{aligned} P_2 &= d + \varepsilon d + c(\varepsilon t - \varepsilon T) + t_{\text{ion},2} + t_{\text{trop}} + \varepsilon_{\text{mp}} + \varepsilon_p \\ P_1 &= d + d\rho + c(d t - d T) + d_{\text{ion},1} + d_{\text{trop}} + \varepsilon_{\text{mp}} + \varepsilon_p \end{aligned} \quad (3)$$

where

d is the distance between the satellite and the receiver (m); εd is the error of orbit (m);

c is the speed of the light (m/s); εt is the error of clock of the satellite (s);

εT is the error of clock of the receiver (s); t_{ion} is the Ionospheric delay (m);

t_{trop} is the Tropospheric delay (m); ε is the error of multi-way on the code (m);

ε_p is the Noise of the receiver for the measurement of the code (m).

According to the preceding formula one can write for each carrier :

$$P_1 = d + \varepsilon d + c(\varepsilon t - \varepsilon T) + t_{\text{ion},1} + t_{\text{trop}} + \varepsilon_{\text{mp}} + \varepsilon_p \quad (4)$$

$$P_2 = d + \varepsilon d + c(\varepsilon t - \varepsilon T) + t_{\text{ion},2} + t_{\text{trop}} + \varepsilon_{\text{mp}} + \varepsilon_p \quad (5)$$

where P_1 and P_2 are the pseudo-distances provided by the code P modulated on the two frequencies L1 and L2 respectively. The errors affecting two measurements of the code (P_1 and P_2) are all identical, with share the ionospheric effect which depends on the frequency of the carrier wave.

The errors due to the multi-way and the noise of the receiver cannot be eliminated by differentiation because of their decreed nature. Here, their effect can be neglected because the ionospheric error is dominating. The difference between (4) and (5) will give :

$$P_1 - P_2 = t_{\text{ion},1} - t_{\text{ion},2} \quad (6)$$

with:

$$t_{\text{ion},2} = t_{\text{ion},1} \left(1 - \frac{f_1^2}{f_2^2} \right) \quad (7)$$

By substitution of (7) in (6), one obtain :

$$P_1 - P_2 = t_{\text{ion},1} \left(1 - \frac{f_1^2}{f_2^2} \right) \quad (8)$$

$$t_{\text{ion},1} = \left(\frac{f_2^2}{f_2^2 - f_1^2} \right) (P_1 - P_2) \quad (9)$$

In the same way, the ionospheric delay for L2 can be expressed by:

$$t_{\text{ion},2} = \left(\frac{f_1^2}{f_2^2 - f_1^2} \right) (P_1 - P_2) \quad (10)$$

3.4 Modelling of the ionospheric effect by Klobuchar model

For a GPS receiver [7] alone, one can use the model of Klobuchar to determine the vertical time on the code transmitted by the signal L1.

$$t_{\text{zion}} = dc + A \cdot \cos \left[\frac{2\pi \cdot (t - t_0)}{P} \right] \quad (11)$$

t is the local time with the receiver (sec),

t_0 is the local time of the maximum ionospheric correction (14:00 hrs),

t_{zion} is the time of with the ionosphere in the zenith direction (sec),

dc is the basic ionospheric time (taken equal to 5×10^{-9} sec),

A is the amplitude of function of ionospheric time (sec), and

P is the period of the function of ionospheric time (sec).

The quantities A and P are calculated starting from the coefficients alpha and beta of the message of navigation:

$$A = \sum_{i=0}^3 \text{alpha}_{i-1} \cdot \phi_{om}^{i-1} \tag{12}$$

$$P = \sum_{i=0}^3 \text{beta}_{i-1} \cdot \phi_{om}^{i-1} \tag{13}$$

where ϕ_{om} is the geomagnetic latitude of the ionospheric point :

$$\phi_{om} = \phi_i + 0.064 \cdot \cos(\lambda_i - 1.617) \tag{14}$$

and represent latitudes and longitudes expressed in half-circles. The terms ‘alpha’ are the coefficients of the cubic equation representing the magnitude of the time vertical, and the terms ‘beta’ are the coefficients of the cubic equation representing the period of the model.

The quantity must put on the scale by the graphic function to determine the time along the direction of the satellite.

$$t_{ion} = t_{zion} \cdot SF \tag{15}$$

and

$$SF = \sec \left[\sin^{-1} \left[\frac{r \cdot \cos(\text{elev})}{(r + h)} \right] \right] \tag{16}$$

where:

- elev is the elevation angle of the satellite (rad),
- R is the average radius of the Earth, and
- H is the average ionospheric height (either 350 km).

A simple approximation is always used with GPS receivers:

$$t_{ion} = \left[1 + 16 \cdot (0.53 - EL)^3 \cdot 5 \times 10^{-9} \right] \tag{17}$$

3.5 Analyze of results

3.5.1 Dual-frequency method

Figures 3 and 4 describe the evolution of the ionospheric effect to the measure of the distance antenna-satellite. This error varies between 9 and 13.5 meters.

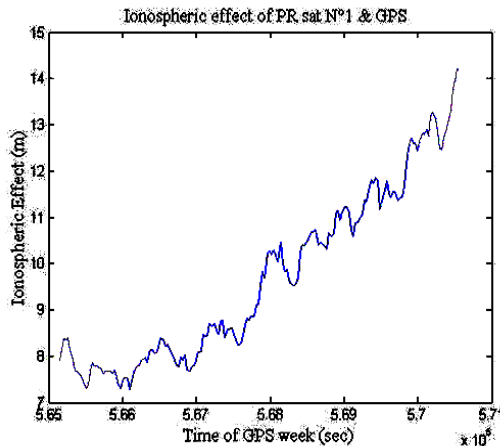


Fig 3: Ionospheric effect of dual frequency of measure of the distance satellite n° 1 and GPS

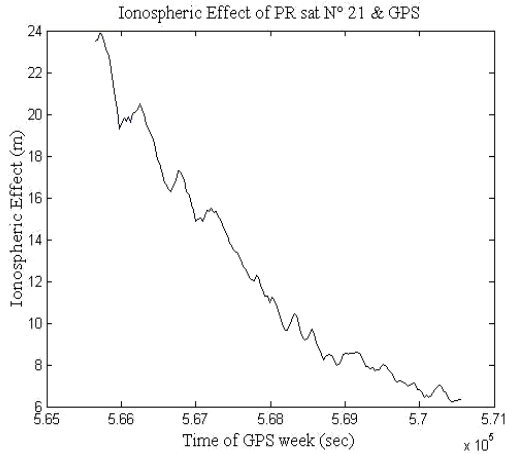


Fig 4: Ionospheric effect of dual frequency of measure of the distance satellite n° 21 and GPS

Its effect on satellite 01 shows a continuous increase in time, contrary to the satellite 21 which presents a waning.

This is with the fact that the rise in satellite 21 increases whereas that of satellite 01 decreases, which explains very well that the ionospheric effect is considerable when satellites of low rise are observed because GPS signal must It should be noted that this error also depends on the solar activity. During the night, the ionospheric delay is much less significant than during the day.

3.5.2 Results of Klobuchar Method

Table 1: Coordinates of the satellites

N° sat	Xs	Ys	Zs	Pr
1	7.32239991660750 e+006	-1.76100622260348 e+007	1.86590815054840 e+007	2.322003 e+007
5	1.35550094513372 e+007	1.45931145742657 e+007	1.74971389624345 e+007	2.206074 e+007
17	1.40527118416459 e+007	2.05098735627832 e+007	1.05851042386309 e+007	2.361361 e+007
24	4.32314075667853 e+006	1.86328255269814 e+007	1.86869430406402 e+007	2.418458 e+007
25	3.96540683344284 e+006	-1.54275214344112 e+007	2.16293893064749 e+007	2.372071 e+007
14	2.04986521357902 e+007	-1.57640673191932 e+007	6.06437889327783 e+006	2.237195 e+007

Table 2: Pseudo-distances

N°sat	Xs	Ys	Zs	Pr
1	7.32239991660750 e+006	-1.76100622260348 e+007	1.86590815054840 e+007	2.322003 e+007
5	1.35550094513372 e+007	1.45931145742657 e+007	1.74971389624345 e+007	2.206074 e+007
17	1.40527118416459 e+007	2.05098735627832 e+007	1.05851042386309 e+007	2.361361 e+007
24	4.32314075667853 e+006	1.86328255269814 e+007	1.86869430406402 e+007	2.418458 e+007

25	3.96540683344284 e+006	-1.54275214344112 e+007	2.16293893064749 e+007	2.372071 e+007
14	2.04986521357902 e+007	-1.57640673191932 e+007	6.06437889327783 e+006	2.237195 e+007
30	1.53644946836477 e+007	3.86092963508057 e+006	2.10776266308760 e+007	2.057296 e+007

Table 3: Azimut ; elevation

7.95274771799326e-001	2.64300390922223e+000
1.31735171712241e-001	8.29562482435563e-001
2.46856094363736e-001	6.92821587741461e-001
2.72384197850516e-001	2.48688643963012e-001
8.60675188078895e-001	2.79350892120330e+000
5.73581133788841e-001	2.12483687687192e+000
2.51584049356156e-001	1.35392434289145e+000

Ionospheric time: 8.200135040000000e-009 seconds

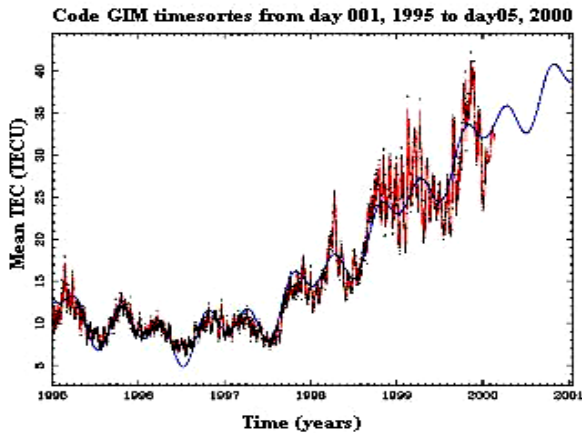


Fig. 5: Average electronic density of the ionosphere determined as from five years of continuous measurements GPS [8]

In fact dual-frequency makes it possible to reduce the ionospheric effect. While the method of Klobuchar, being based on several corrections related to the satellites, the rotation of the Earth as to the noises of measurements makes it possible to reduce the ionospheric effect.

4. TROPOSPHERIC EFFECT ON GPS SIGNAL

4.1 Modelling of troposphere

The lower part of the atmosphere, called the troposphere, is electrically neutral and non dispersive for frequencies as high as about 15 GHz. Within this medium, group and phase velocities of the GPS signal on both L1 and L2 frequencies are equal. The resulting delay is a function of atmospheric temperature, pressure, and moisture. Without appropriate compensation, tropospheric delay will induce pseudorange and carrier-phase errors from about 2 metres for a satellite at zenith to more than 20 metres for a low elevation satellite.

Many geophysicists have developed a number of algorithms for the prediction of the tropospheric delay. For most of the models, the atmosphere is assumed both horizontally stratified and azimuthally symmetric. The tropospheric delay is modelled as the sum of two components: a

hydrostatic component associated with primarily the dry molecular constituents of the atmosphere, and a non-hydrostatic (primarily wet component) associated with the water vapor in the atmosphere. Mathematically, it can be expressed by:

$$d_{\text{trop}} = d_{\text{hyd}}^z \cdot m_{\text{hyd}} + d_{\text{wet}}^z \cdot m_{\text{wet}} \quad (18)$$

where d_{trop} is the total troposphere delay, d_{hyd}^z and d_{wet}^z are the hydrostatic and wet zenith delays, m_{hyd} and m_{wet} are the corresponding mapping functions which are used to map the zenith delay to the slant signal direction (Fig. 6).

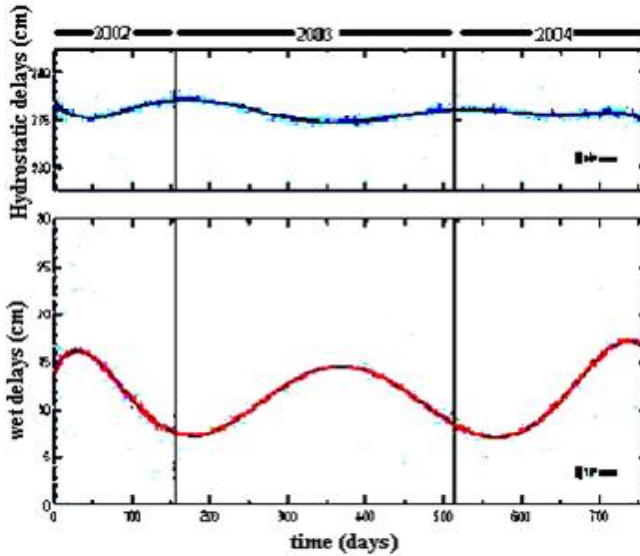


Fig. 6: Hydrostatic delays and zenith wet delays calculated during two years

The disturbance most with difficulty quantifiable is the tropospheric delay. Indeed, this delay is not generally identical in each of the sites of measure and cannot be thus eliminated by single difference.

The disturbance is all the more important as the part of the troposphere crossed by the signal of the same satellite towards each of the sites of reception is different (big made uneven and big difference of weather conditions). It affects mainly the height GPS because of the geometry of the system. But this quantity, which is source of error for the location GPS, is a datum rich in information for the meteorologists. To reach millimetre length precision GPS, we can use orbits predicted (for which case the measure can be real time made) or orbits more precise but worked out again in posteriori (in which case the measure will be obtained in batch mode).

4.2 Principle of the wind measurements by GPS

For reasons of weight and cost, the receiver GPS associated with the radiometer does not give directly access to the position of the vehicle. The measure of the speed and the direction is not thus made from the successive positions of the radiometer.

The method bases on the measure of the Doppler effect affecting the signal emitted by the GPS satellite, the effect which is directly proportional in the relative speed between the transmitter and the receiver. With the information Doppler of at least four satellites, we can so determine the relative speed between the satellite and the radiometer. This information is passed on by radio since the radiometer, twice per second, towards a ground station.

By using the receiving second GPS on the ground, we measure the Doppler Effect between this reference station and the satellite. The information Doppler radiometer satellite and receiving grounds-satellites are handled in differential mode by the reference station.

The result is the vector speed of the radiometer with regard to the ground station. This speed is real time calculated twice per second. These data are then filtered to eliminate the pendular effect of the radiometer with regard to the ball. Certain released radiometers also use the GPS technology for the measure of the wind; the principle is identical, but the reference station can be aboard the plane.

IV.3 Water vapour measurements by GPS (Fig. 7)

Ground-based GPS receivers can provide continuous information on water vapour at a site being water vapour closely related to the wet component of the tropospheric zenith path delay.

Two strategies can be followed to determine the tropo delay:

Use 'standard' atmosphere parameters:

ambient air temperature $T_{amb} = 15 \text{ }^\circ\text{C}$

ambient air pressure $P_{amb} = 101.325 \text{ kPa}$

ambient vapour pressure $P_{vap} = 0.85 \text{ kPa}$ (corresponding with a relative humidity of 50 % at the ambient temperature)

Use actual measurements at the receiver antenna location of T_{amb} , P_{amb} and P_{vap} .

There are numerous tropo models available, we picked Hopfield's model which splits the tropo delay into two parts: a contribution of the 'dry' atmosphere and a contribution of the 'wet' atmosphere. For a detailed explanation, see any textbook on GPS.

The zenith delay of the dry component is given by :

$$Kd = 1.55208E-4 * P_{amb} * (40136.0 + 148.72 * T_{amb}) / (T_{amb} + 273.16) \text{ [m]}$$

The zenith delay of the wet component is given by :

$$Kw = -0.282 * P_{vap} / (T_{amb} + 273.16) + 8307.2 * P_{vap} / (T_{amb} + 273.16)^2 \text{ [m]}$$

Multiply the zenith delay's with their 'mapping functions' to correct for elevations lower than 90 deg and add the components to obtain the SV's tropospheric delay correction:

$$dR_{trop} = Kd / \sin(\sqrt{El * El + 1.904E-3}) + Kw / \sin(\sqrt{El * El + 0.6854E-3}) \text{ [m]}$$

with El the SV's elevation in [rad].

When we use the standard atmosphere values, the expression reduces to

$$dR_{trop} = 2.312 / \sin(\sqrt{El * El + 1.904E-3}) + 0.084 / \sin(\sqrt{El * El + 0.6854E-3}) \text{ [m]}$$

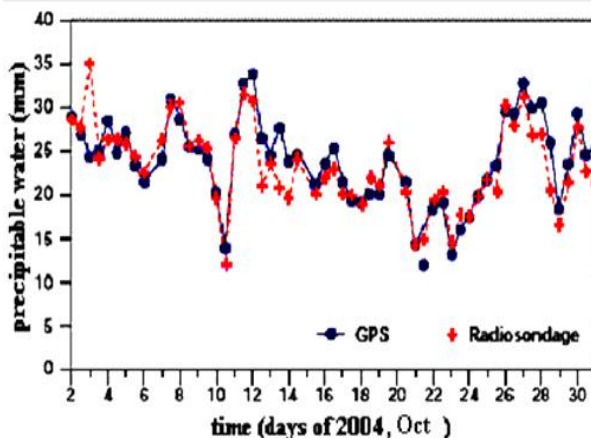


Fig. 7: Measure of the precipitable water by radiosonde GPS

5. DISCUSSION

For ionosphere, the result obtained by the Klobuchar model shows well that there is a time on the course of signal GPS.

This time is related to the corrections carried out on the various stages of calculation of the position of the point.

The various methods of calculation are directed all towards a minimization of this time.

The result obtained by the model of dual-frequency and shown on figure 3 reflects well the pace of the results obtained by Schaer, 1999 and shown on figure 5, except that for our case of study, it is about a two hours observation, whereas figure 5 shows six years a permanent observation.

From where the idea that these results can be a base with any study possible of the vertical TEC on a large scale.

For troposphere, the results obtained shows the capacities of the GPS to characterize the atmosphere (ionosphere and troposphere). On the other hand, there is an analogy between the study of the TEC and that of the contents of the steam in the atmosphere.

6. CONCLUSIONS

The signal emitted by satellites GPS on the frequencies L1 and L2 is slowed down, during its propagation in the atmosphere, by interactions with the components of the crossed mediums.

This deceleration, which is one of the principal sources of error in positioning, thus contains information on the contents of the atmosphere: the GPS is in fact an atmospheric tool of survey.

In this paper, one studied the ionospheric effect by two simple models: the model dual-frequency and that of Klobuchar.

There exists however of other models like the model of grid which allows a study on a large scale, and which one was satisfied to give the theoretical bases and of application in this memory.

A priori the bi-frequency is the most dominating model to eliminate the ionospheric effect. While the model of Klobuchar only makes it possible to reduce this effect.

In space telecommunications, the calculation of the minimal frequency usable rests on two criteria different according to choice's from the user.

In the first case, it is fixed by a given maximum attenuation; in the second case, by a required minimum signal-to-noise report/ratio (by taking of account antennas E/R). The LUF is smallest of the lower limits of the frequencies reflected by the various modes selected.

The reliability of reception is the probability, for a connection given, that a specified quality of operation is reached, by taking account of all the emitted frequencies.

Currently, the quality standard retained is given by the signal-to-noise report/ratio required for the mode of propagation dominating.

The present one, based on data GPS real obtained starting from observations of signal GPS with the CNTS of Arzew, represents a base with any future development of a model of grid for a atmosphere study on a regional network.

7. RECOMMENDATIONS

A particular strategy of use of the GPS is the permanent observation. It makes it possible to reduce part of the errors of measurement by antennas assembled in a permanent way on a stable and durable geodetic monument, lowering in fact the threshold of detection of a tectonic signal.

Moreover, it provides continuous time series which make it possible to analyze in detail the processes which affect the determination of the position of the stations in the course of time (tectonic deformations, tropospheric variability related on the weather conditions and the seasons,

stability of the geodetic monument, forecasts ionospheric) and to determine the statistical models as well as possible describing the results and their uncertainties.

We recommend so that there is in the future very near to stations GPS or similar for the follow-up permanently of the atmospheric evolution, and this for the various applications quoted in this paper.

In particular applications of telecommunications like the transfer of the various data of a site to another rather remote at the end of the world; terrestrial deformations, and why not the forecast seismic, because the geophysicists currently use the GPS like working tool.

Acknowledgments - We are very grateful to the team of the laboratory of geodesy of the CNTS, for the assistance and the setting at our disposal of the material necessary to the development of the measurements presented in this paper.

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