IONOSPHERIC PERTURBATIONS ON GPS OBSERVATIONS

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ABSTRACT — The new satellite positioning system, the Global Positioning System (GPS), is having a great impact in solving all problems involving threedimensional position determination, on earth or space, with applications that go beyond Geodesy.

At the present state-of-art of receiver technology, the measuring precision is no longer a limiting factor in the final accuracy of the results. The utmost accuracy attainable with this system depends upon our capability to model the errors that may affect the observations, such as orbit and atmospheric propagation errors.

In this article we shall be concerned with ionospheric disturbance of radio signals transmited from the Navstar/GPS satellites. A summary of the different proposed ionospheric time delay models is presented and some comments concerning its application to the analysis of real data are made.

1 – INTRODUCTION

The principle of operation of GPS is based on the measurement of station-satellite distances using the radio signals that are continuously transmitted by the NAVSTAR / GPS satellites and subsequent computation of the observer's coordinates.

Instrumental errors have already been reduced to a few centimeters in the measured phase (Evans [1]); therefore orbital and propagation errors play a decisive role in the final accuracy of the results.

Here we shall discuss only problems related to the propagation of the signals in the ionosphere.

Ionospheric effects are extremely hard to model due to the high degree of variability of the neutral atmosphere. The result is mainly a delay of the propagation time. Because this delay is frequency dependent, a first order correction may be obtained observing in two frequencies properly chosen. However, for the purpose of very precise geodetic positioning, the accuracy with which that correction is determined still needs to be improved.

The availability of better prediction models of ionospheric propagation delay along specific paths, all over the world, is of great interest for GPS users operating with single frequency receivers. These will perhaps be the most popular in the future, not only because they are less expensive but also because, for security reasons, the Departement of Defense of the United States may restrict the use of the second frequency.

The ionospheric delay at the primary GPS frequency (1575.42 MHz) can reach 50 nanoseconds in worst conditions. This will result in an error of about 15 m in the measured station-satellite range. Single frequency users are able to correct only 60 % of this error and the ionosphere will be a major limiting factor in the final accuracy. Due to the variability of the ionosphere in space, time and geophysical conditions, it is impossible to extrapolate ionospheric parameters for different locations. Users who require the highest accuracy must use the dual frequency capability of GPS.

In what follows we shall start with a short description of the GPS system and a brief review of some aspects concerning ionospheric behaviour at L-band frequencies. How specific characteristics of the GPS signals may be explored, in the different models, to analyse ionospheric effects, will then be our main concern.

2 — SYSTEM DESCRIPTION AND USE

GPS is a satellite based system, that when in full operation by the end of this decade, will be supported by a constellation of 18 satellites (actually 9 are already in orbit), at an altitude of about 20000 Km, equally spaced in 6 planes (3 by plane) with an inclination of 55° over the equator. The period of the near circular orbits is about 12 hours.

The satellites transmit continuously in two L-band frequencies, L_1 at 1575.42 MHz and L_2 at 1227.60 MHz, multiples of the basic frequency of the on-board oscillator, of 10.23 MHz, and a navigation message containing the satellite ephemeris is encoded on those carriers.

An observer, equipped with a GPS receiver, will be able to receive the signals, simultaneously, from at least four satellites, at any place on earth, 24 hours a day, under all atmospheric conditions. The corresponding station-satellite distances may be computed, using the known satellite position, and the observer can have, in a few minutes, his coordinates in the same threedimensional geocentric system to which the orbits are referred.

The most accurate method to obtain the station-satellite range is to measure the phase of the incoming signals. The range error may be of a few decimeters, depending on the degree of accuracy with which instrumental, orbital, clock, multipath and atmospheric propagation errors are modelled. The system reaches its maximum accuracy in relative positioning determination, i. e., baseline measurements.

With a GPS receiver we can measure the carrier phase difference between the signal transmitted by the satellite and the one generated in the receiver's oscillator. This difference may be expressed as (Goad [2]):

$$\Phi^i_j\,(t_r) = \Phi^i\,(t_t) - \Phi_j\,(t_r)\ , \tag{2.1}$$

where t_t refers to transmit time from satellite i, and t_r to receipt time at receiver j. Assuming we have highly stable oscillators we can express the transmit time as:

$$t_t = t_r - (f/c)\ \rho^i_j\ ,$$

with f being the frequency, c the speed of light in vacuum and ρ^i_j the station-satellite range.

Ignoring for the time being all sources of error (resulting from time, orbit and propagation errors), we can rewrite equation (2.1) as

$$\Phi^i_j\,(t_r) = \Phi^i\,(t_r) - (f/c)\,\rho^i_j - \Phi_j\,(t_r) + N^i_j \tag{2.2}$$

where N^i_j is an integer that has been introduced to account for the uncertainty in the number of cycles of the first measurement. In the reduction procedure it will be considered as an additional unknown.

In equation (2.2) the station coordinates are implicit in the term $(f/c)\ \rho^i_j$, and can be derived once the positions of the satellites are known.

In the present stage of development of GPS, allowing observations not in the most favourable conditions, the results already reach an accuracy of 1 to 5 p.p.m. in the determination of baselines with some tens of kilometers.

Precise modelling of ionospheric perturbations on GPS observations is essential for achieving a 0.1 p.p.m. accuracy in longer baselines; this is expected for the near future.

3 – IONOSPHERIC PERTURBATIONS AT L-BAND FREQUENCIES

The ionospheric effect on radio wave propagation is mainly a delay in the propagation time, although a bending of the trajectory is also observed. As is well known, the ionospheric behaviour is highly correlated with the columnar electronic density along the path ray. This quantity is greatly influenced by earth rotation, geomagnetic latitude and solar activity and therefore it is difficult to predict.

At frequencies above 400 MHz the ionospheric phase refraction index can be given by the approximate formula (Davidson et al. [3]:

$$n_{ph} \simeq 1 - (40.3/f^2)\ N_e\ , \qquad (3.1)$$

where f is the carrier frequency and N_e the columnar electronic density. The total phase delay experienced by a wave propagating through the ionosphere will then be given by:

$$\delta\Phi = (f/c) \int (n_{ph} - 1)\ ds$$

or, using (3.1),

$$\delta\Phi = - [40.3/(fc)] \cdot \int N_e\ ds \qquad (3.2)$$

As the ionosphere is a dispersive medium, the group refraction index does not equal the phase refraction index; it is given by:

$$n_g = n_{ph} + f \ dn_{ph} / df \ .$$

Substituting n_{ph} given by (3.1) we get for n_g :

$$n_g = 1 + (40.3/f^2) \ N_e$$

and for the group delay

$$\delta t = [40.3/(f^2 c)] \ . \ N_t \tag{3.3}$$

N_t is the integral of the columnar electronic density along the line of sight, usually referred to as Total Electron Content (TEC).

Comparing equations (3.2) and (3.3) we conclude that the phase velocity is advanced while a correspondent retardation is observed for the group velocity. These effects depend mostly on the value of TEC.

For observations near the zenith δt can grow up to 30 nanoseconds. As N_t is quickly changing with the propagation direction, the ionospheric error in the measured range can reach tens of meters for directions far from the zenith. Since we know that TEC is very much influenced by solar activity (Clynch [4]), we can expect very severe perturbations in periods of maximum solar activity in the eleven year solar cycle, such as in the early nineties. The need for worldwide TEC models based on direct measurements can be easily understood from what has been said.

4 – ANALYSIS OF IONOSPHERIC PERTURBATIONS ON GPS SIGNALS

There is no doubt that the improvement of GPS results depends on the precise determination of ionospheric effects upon the observed signals. The tests undertaken so far (Lachapelle [5], Kleusberg [6]) show that the importance of this correction grows with baseline length and that the error is of the order of 1 p.p.m. over the measured distance. A rotation of the baseline has also been detected as a result of atmospheric effects.

The methods commonly used to compute ionospheric parameters are based on Faraday rotation measurements of the signals transmitted by geostationary satellites and Doppler or range measurements using satellite observations in two frequencies. The disadvantage of these methods is that the spatial coverage of the observations is limited and we are not able to correct the total ionospheric error.

Let us see how ionospheric perturbations can be handled in GPS observations.

The GPS satellites transmit in two L-band frequencies as mentioned before. The carrier frequencies, L_1 and L_2 are biphase modulated with a pseudo random noise (PRN) binary code at a rate of 10.23 MHz (Spilker [7]).

If we have a dual frequency receiver, the specific characteristics of those signals can be explored in different ways to get further knowledge about the ionosphere, as we shall see next.

4.1 — We have seen in paragraph 3, that the ionosphere is responsible for a phase advance, which is inversely proportional to the frequency. Neglecting other sources of error, we can rewrite equation (2.2) to account for this effect [2]:

$$\Phi^i_j\ (t_k) = \Phi^i\ (t_k) - (f/c)\ \rho^i_j - \Phi_j\ (t_k) + N^i_j + (A/f)\ ,$$

where t_k is the receipt time at epoch k.

Since L_1 and L_2 are multiples of the same basic frequency, the respective phases differ by the ratio f_1/f_2.

Observing in both frequencies we may write:

$$\Phi^i_j\ (t_k)_{L1} = \Phi^i\ (t_k) - \Phi_j\ (t_k) - (f_1/c)\,\rho^i_j + N^i_j\ (L_1) + A/f_1 \tag{4.1.2}$$

and

$$\Phi^i_j\ (t_k)_{L2} = f_2/f_1\ [\,\Phi^i\ (t_k) - \Phi_j\ (t_k) - (f_1/c)\ \rho^i_j\,] + N^i_j\ (L_2) + A/f_2 \tag{4.1.3}$$

Now these two equations can be combined in the form:

$$\delta I = \Phi^i_j\ (t_k)_{L1} - f_1/f_2\ \Phi^i_j\ (t_k)_{L2}$$

The resulting quantity is independent of time errors:

$$\delta I = N_j^i \, (L_1) - f_1/f_2 \; N_j^i \, (L_2) + (1 - f_1^2/f_2^2) \; (A/f_1) \; . \qquad (4.1.4)$$

If phase lock is maintained the integers N will remain constant during the observation session, and epoch to epoch changes in δI will be only due to the ionosphere.

In figure 1 we have plotted epoch changes of this L_1/L_2 phase combined quantity relative to the initial epoch, for satellite 9.

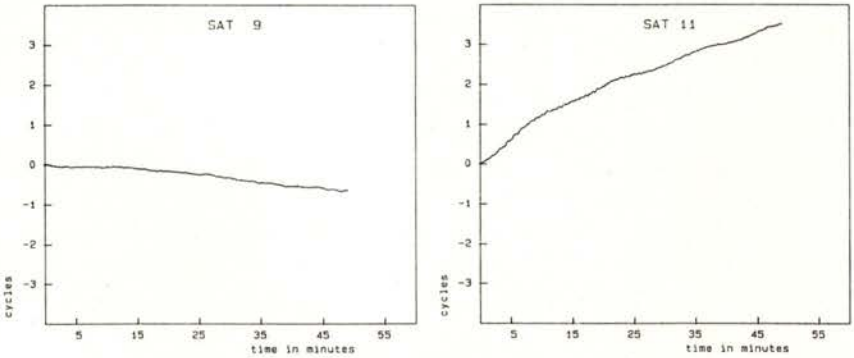

Fig. 1 — L_1/L_2 phase combination for satellites 9 and 11

The observations were made during the early hours of one morning in September 1986. Data were collected, with dual frequency Tl 4100 receivers, every 3 seconds. The station was located south of Munich at about 47° north latitude and 11° east longitude. Near sunrise, the ionosphere is still relatively quiet. The satellite elevation angle, above 60°, was slowly changing during this 45 minutes observation span, giving the smooth trend observed.

Figure 1 shows also similar data for satellite 11. Taking into account that the elevation angle of this satellite was below 30° and increasing, we can see δI monitoring the ionospheric behaviour.

In figure 2, δI was plotted for satellite 6 observed from two close stations (Bastos and Landau [8]). It shows a high degree of correlation what was expected since ionospheric disturbance is highly correlated with earth location and line of sight.

One way to avoid ionospheric effects on GPS observations, without having to compute any ionospheric parameters is suggested by Goad [2]. It consists in using a linear combination of the type

$$\Phi^i_j\,(t_k) = \alpha_1\,\Phi^i_j\,(t_k)_{L1} + \alpha_2\,\Phi^i_j\,(t_k)_{L2}\;;$$

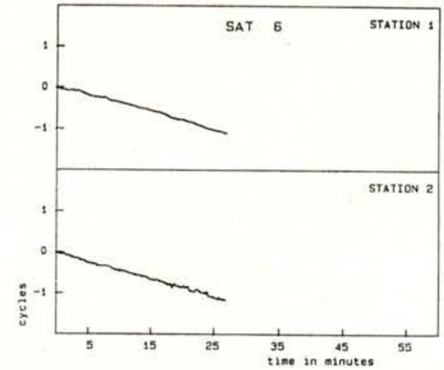

Fig. 2 — L_1/L_2 phase combination for satellite 6 and two stations

where α_1 and α_2 are appropriate functions of the two frequencies f_1 and f_2. However this ionospheric corrected phase has the disadvantage of increasing, by a factor of 2 or 3, instrumental and multipath errors (Evans [1]); therefore one should avoid this phase combination and use the raw phases, computing accurately the correspondent ionospheric correction.

4.2 – One of the most common techniques to compute the group delay is based on dual frequency observations making use of the dispersive nature of the ionosphere. We have seen in paragraph 3 that the group delay is inversely proportional to the square of the frequency. Following Jorgensen, we can write:

$$D_{L1} = K/f_1^2 \qquad \text{and} \qquad D_{L2} = K/f_2^2\;,$$

where K is the constant of proportionality, and D_{L1} and D_{L2} the delays, in meters, respectively at the L_1 and L_2 frequencies.

With a dual frequency receiver we are able to measure the difference in the delays at each carrier frequency:

$$D = D_{L1} - D_{L2}$$

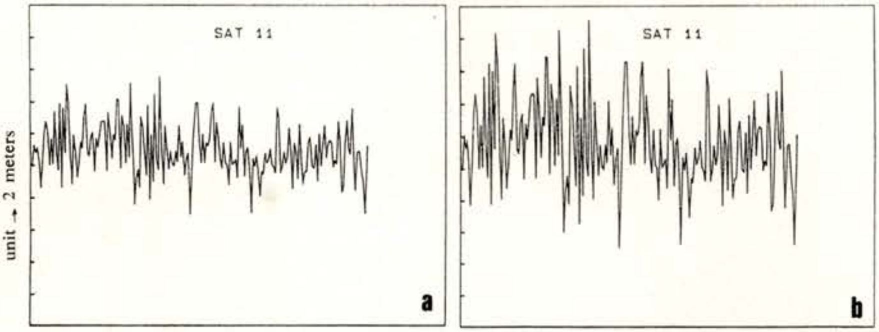

Fig. 3 — Absolute ionospheric delays for frequencies L_1 (3a) and L_2 (3b)

After simple calculations and substituting f_1 and f_2 for its values we get:

$$D_{L1} = 1.54573 \ D \tag{4.2.1}$$

and

$$D_{L2} = 2.54573 \ D \tag{4.2.2}$$

Neglecting higher order terms these equations give us the absolute value of the first order correction for the ionospheric delay.

In figures 3 and 4 we have plotted this ionospheric delay for satellite 11, for the L_1 and L_2 frequencies respectively.

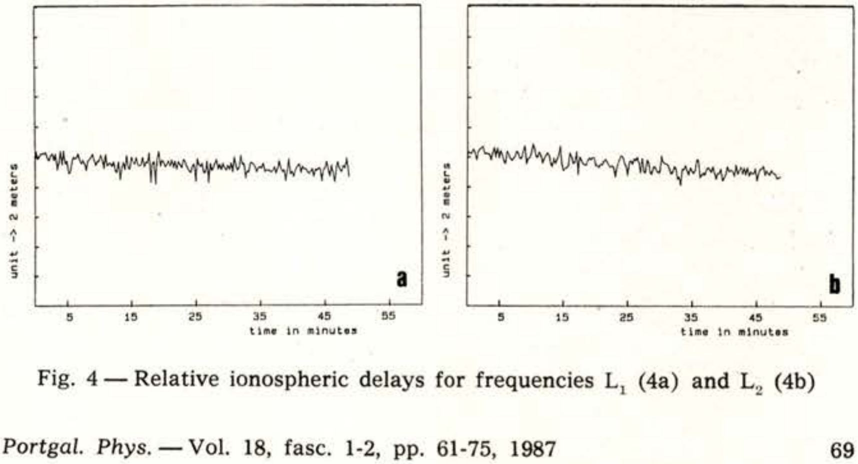

Fig. 4 — Relative ionospheric delays for frequencies L_1 (4a) and L_2 (4b)

We can see that this is a very 'noisy' quantity, with an r.m.s. reaching several meters, and that the delay is of course bigger in the L_2 frequency. Due to problems with the reception of the signals, we have used only a part of the data, where no interruptions occur, covering a small time interval. Neverthless,

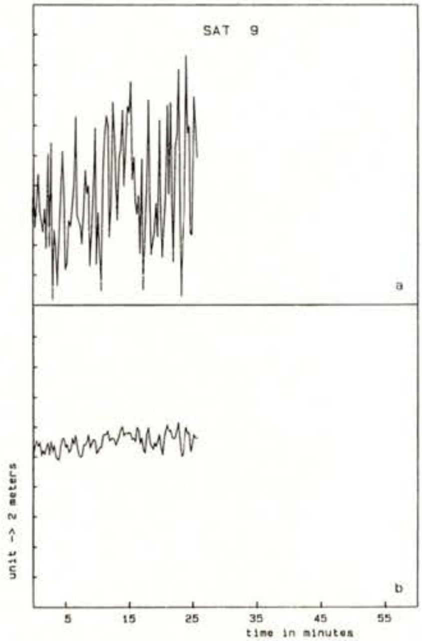

Fig. 5 — Absolute (5a) and relative (5b) ionospheric delay

analysing the global trend we recognize a decrease of the time delay, expressed in meters, which is in agreement with the increase of the satellite elevation angle during that observational period. In figure 5a we have plotted the ionospheric delay for satellite 9, observed from another station, at a slightly later time. The increase of the observed values again agrees with the decrease of the satellite elevation angle.

The short period variations shown in the figures are due to multipath effects (Klobuchar [10]), another problem to be solved but that is outside the scope of this article.

Taking into account the time of the year (Klobuchar [11]) and the hour of the day when the observations took place we recognize the importance this effect may have in the final accuracy of the measured station-satellite range.

Accordingly to Klobuchar [12] the residual error after this first order correction, computed as above, is around 2 meters, still too big for the purpose of very precise positioning.

4.3 – Profiting from the fact that with code frequency receivers we can have measurements on the carrier and on the modulation of that same carrier, the structure of the GPS signals can be used to compute epoch to epoch changes in the ionospheric delay [9].

The ionosphere is responsible for a phase advance on the carrier and a group delay, of the same amount, on the modulation.

Using the code modulation we can compute the station-satellite range at two epochs and measuring the carrier phase at the same epochs we can have the correspondent change in range. As the ionospheric effect is the same, with the opposite sign, for both code and carrier, we can write:

$$D = 1/2\ [\rho_j^i\ (t_k) - \rho_j^i\ (t_{k-1})\ ] - \int_{t_{k-1}}^{t_k} \rho\ dt$$

Although this expression gives only relative values of the ionospheric time delay, it has the advantage of requiring only one frequency. In order to compare this method with the previous one we have plotted D, for the same satellites, in figures 3b, 4b and 5b. We can see that the noise level is much smaller. As this technique, based on the group delay/phase advance, is more accurate to compute the epoch to epoch changes of the ionospheric delay, we may combine it with the dual frequency technique, referred in 4.2, to improve the final accuracy of the determination of the effect of the ionosphere.

4.4 – Another way of analysing the ionospheric behaviour and determining its effect on GPS observations is suggested by MacDoran [13]. The method is referred to as SLIC (Satellite L-band Ionospheric Calibration) and is based on the measurement of the time interval between code transitions in two frequencies.

It can be used by dual frequency code or codeless receivers users, to compute the Total Electron Content in the line of sight dirction.

The observable group delay between L_1 and L_2, as we have seen, is given in nanoseconds by:

$$\Delta T = \delta t_2 - \delta t_1 = (40.3/c)\ N_t\ [1/f_2^2 - 1/f_1^2]$$

For the GPS frequencies this expression may be rewritten as:

$$\Delta T = 3.5\ N_t\ , \qquad (4.4.1)$$

where N_t is TEC in units of 10^{17} el/m^2:

This method allows TEC measurements with an accuracy of a few times 10^{15} el/m^2 and according to Royden [15], the results are in good agreement with Faraday rotation measurements.

Although this method has disadvantages concerning equipment and reduction procedures, it offers some advantages over Faraday rotation: better distribution of the measurements in time and space, better accuracy and no phase ambiguity. Adittional advantage for the GPS user results from the fact that no knowledge of the P-code is necessary and he still can take advantage of the dual frequency emission. As we have noticed before, the P-code may not be accessible to civilian users in the near future.

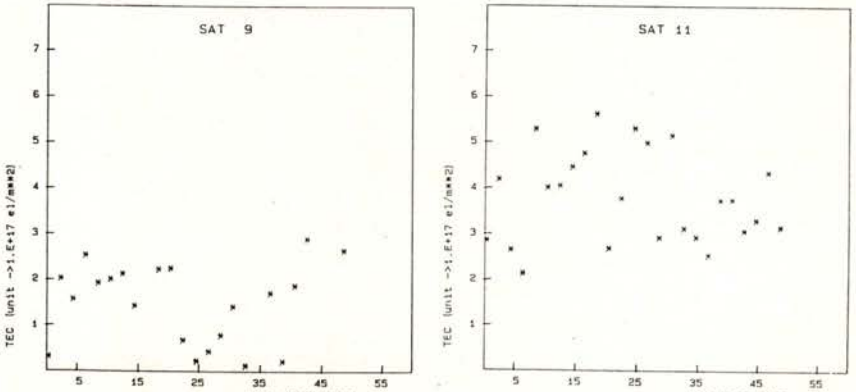

Fig. 6 — TEC (total electron content) in the lign of sight direction for satellites 9 and 11

Since the observations we have were taken with a code receiver we have used (4.2.1) and (4.2.2) to compute the delay in L_1 and L_2 and (4.4.1) to calculate TEC, for satellites 11 and 9 observed from the same station. Figure 6 show the values of TEC computed with a two minute interval. We can see the high rate of change of TEC whose values are almost double for satellite 11, which has a lower elevation angle. This is in agreement with what we have said in paragraph 3. Note that a value of 5.10^{17} el/m^2 induces an error of about 10 m in distance measurements with the L_1 frequency.

5 – CONCLUSIONS

A deeper analysis is needed of the effects of the ionosphere on GPS observaitons. For that more data, taken at different times and under different conditions, are needed. Nevertheless, from what has been said some conclusions can be drawn about the role of the ionosphere on GPS baseline measurements and about the role of GPS data for the development of ionospheric models.

Ionospheric effects on GPS observations can be dealt with in different ways. Besides the direct computation of ionospheric parameters, as we have described, some attempts have been made to remove this effect from GPS observations using different combinations of the observed phase, such as suggested in paragraph 4.1. For baseline determination between close stations, the ionospheric effects cancel out when differencing the observations, due to the correlation of the ionospheric behaviour with earth location. This correlation can also de used in dynamic applications where one of the stations is fixed, and may have difficulties in computing ionospheric parameters relatively to the other, more affected by other kinds of perturbations due to its motion.

Much work is still needed to improve accuracy in the determination of ionospheric effects on GPS observations. According to Lachapelle [6], the ionosphere is responsible for errors of the order of 1 p.p.m. (or greater) in baseline measurements. Using GPS to measure long baselines (some hundreds of kilometers), with an accuracy of 0.1 p.p.m. will still be a challenge, even for the dual frequency user, demanding an improvement of the existing ionospheric models.

On the other hand it must be emphasized that GPS data can play a decisive role on the improvement of those models because it is well distributed all over the world and will be available at different epochs and under a variety of geophysical conditions. TEC measurements can be better carried out using GPS data, and considering that the number of satellites still available for Faraday rotation measurements is decreasing, GPS can be seen as an alternative solution.

Prilepin [16], also pointed out the superiority of GPS information for the determination of the two major terms of the integral ionosphere refraction index and the correction for the bending of the trajectory.

In view of the results obtained so far with GPS, and keeping in mind that a lot of work is still being done concerning precise orbit determination and modelling of propagation effects, a significant improvement is to be expected when the system is in full operation in the early nineties.

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