COMPARISON BETWEEN TEC VALUES DERIVED FROM ANTARCTIC GPS MEASUREMENTS AND ATMOSPHERIC SOUNDINGS

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Abstract

Ionospheric refraction introduces a delaying effect on GPS observables (code and carrier phase measurements) and therefore on the precise relative position derived. This cannot be completely solved by GPS dual frequency techniques that only take into account the geometric effect of the ionosphere (first order approximation; Ciraolo, 1994) considered as an undisturbed region associated with a constant vertical gradient of Total Electron Content TEC (Menge, 1996). Non-geometric effects also play a fundamental role in signal-ionosphere interactions mainly in equatorial and auroral regions (such as Antarctica) where the severe ionospheric conditions influence the GPS signals (scintillation phenomena).
In an attempt to understand and model this effect, we computed the TEC values from selected 1993 GPS Antarctic data-set, using different GPS-based methods (Georgiadou et al., 1988; Beutler et al., 1996). Finally we compared the GPS-derived TEC values with those computed with the ionospheric model based on atmospheric soundings, performed simultaneously to the GPS measurements and in the same region (Terra Nova Bay, Antarctica) by a researcher from the Istituto Nazionale di Geofisica (Rome).
The TEC values from GPS observables and atmospheric soundings showed good agreement, taking into account the extreme variability of the phenomenon investigated and the strong dependence on satellite orbital parameters (elevation and azimuth).

1. Objectives

The aim of the research was to obtain TEC values from GPS measurements on both observables, code and carrier phase, using different computational strategies. Then to compare the values obtained with those given by the models based on the atmospheric soundings.
Once correct TEC values are available it will be possible to attempt to quantify the influences of the Antarctic ionospheric delay on GPS-derived relative positioning. This can help us to better understand the data acquired and therefore the post-processing strategies required.
Using the TEC variations as an index of ionospheric activity over a short time scale, depending on the rapid change of the electron distribution, we can also take into account phenomena like scintillation that give us an anomalous behaviour on the different time and space scaled solutions. This phenomenon is generally present when high ionospheric activity occurs and extremely accurate determination of precise relative positioning is critical, because the solutions can depend on the GPS post-processing software chosen. This is probably due to the increased difficulties in finding solutions for a correct ambiguity set.
There is a main effect on GPS acquisition due to ionospheric scintillation: the short-term variation in GPS signal amplitude and phase. The variation in amplitude consists of a continuous fading and enhancement of the signal strength towards the antenna phase centre. This increases the probability of the signal level dropping below the threshold of the receiver, and thus loss of satellite tracking. Then there is an increased number of cycle slips.
The phase scintillation induces rapid variations in the signal phase, due to the variations in ionospheric refraction conditions. During these conditions the phase fluctuations complicate the correct increment or decrement of the number of integer cycles inside the receiver and the detection and the repairing of cycle slips becomes critical.

2. Ionospheric activity over Antarctica

Ionospheric activity is particularly significant over the Antarctic region, as compared with the middle latitudes, because of the vicinity to the geomagnetic pole. This can be demonstrated by computing the TEC values epoch by epoch, i.e. from GPS code measurements, in Antarctica and in a middle latitude area. Figure 1 shows the TEC variations for both situations (difference between contiguous epochs values).

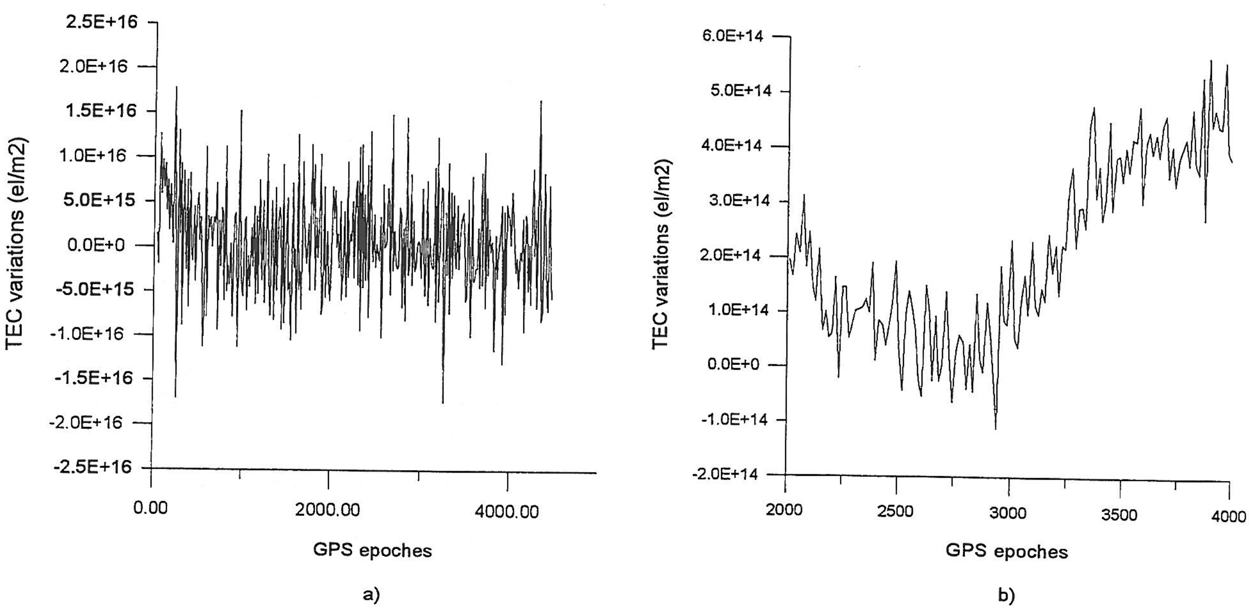

Fig. 1 –TEC variations in Antarctica (a) and in middle latitudes area (b)

As can be observed at the middle latitudes there is a TEC variation (index of the ionospheric activity) which is one tenth less than in Antarctica. Under such conditions it is very important, for high accuracy networks, to study the scintillation effects on GPS measurements.

3. Different ways of computing the TEC

GPS data were acquired at the same time and from the same area (Terra Nova Bay, Antarctica) on the atmospheric soundings in November and December 1993, and the TEC values were obtained using different GPS-based models. The atmospheric sounding-based values were taken as a reference due to the international standardisation of the sounding procedure and associated algorithm.

To do this we used GPS code observables, P1(C/A) and P2(Y1-Y2), the local ionospheric model computed by the Bernese software, and the so called, baseline estimation method.

TEC values always refer to the TEC Units (where 1 TEC Unit is equal to 10^{16} electrons per square meter) and represent the total number of electrons included in an imaginary cylinder which has a section centred along the satellite-to-receiver signal path. Then also the higher regions of the ionosphere with a low electron density contribute to the ionospheric formation process delay.

3.1 TEC values from vertical sounding measurements

During a vertical sounding the radio-waves emitted by an ionosonde are reflected back by the different ionospheric layers and captured by a receiver antenna. All the reflected frequencies and the associated travel time are plotted as ionograms.

The ionogram gives all the input parameters needed from the ionospheric model to compute the electron density profile, generally close to a height of 400-500 km. The output profile from the ionospheric models is very similar, in shape, to the Chapman curve (fig. 2), approximation of the typical ionisation rate.

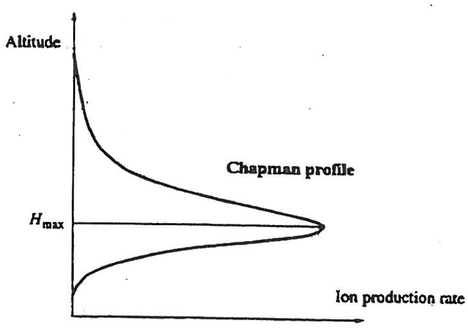

Fig. 2 – Chapman curve of the electron density profile (from Beutler et al 1996)

3.2 TEC values from GPS measurements: code observables

TEC values can be obtained directly, without having to resolve the ambiguity problems, from the pseudo-range measurements on dual frequencies related to a single satellite. P1(C/A) and P2(Y1-Y2) codes can be easily extracted from the RINEX format files.

We used the equations (1) that relate code-pseudoranges to the other variables on L1 and L2 frequencies:

$$\begin{aligned} P_{1k}^{i} &= \sigma_k^i + I_k^i + \Delta\sigma_k^i + c\delta_k - c\delta_i \\ P_{2k}^{i} &= \sigma_k^i + \frac{f_1^2}{f_2^2} I_k^i + \Delta\sigma_k^i + c\delta_k - c\delta_i \end{aligned} \quad (1)$$

where

i = satellite index,

k = receiver index,

P_1, P_2 = cross-correlated P-code on dual frequencies (meters),

σ_k^i = geometric distance between satellite and receiver,

I_k^i = ionospheric refraction index,

$\Delta\rho_k^i$ = tropospheric refraction effect,

δ_i, δ_k = satellite and receiver clock error,

f_1, f_2 = carrier frequencies (Hertz).

Subtracting the equations above, and introducing the relations between the Total Electron Content and ionospheric refraction index we have:

$$P_{1k}^i - P_{2k}^i = I_k^i\left(1-\frac{f_1^2}{f_2^2}\right) = TEC\left(\frac{40.3}{f_1^2}-\frac{40.3}{f_2^2}\right) \qquad (2)$$

The equation (2) can be used to evaluate the TEC value from GPS code measurements. To have correct and continuous (from an epoch point of view) TEC determinations it is necessary to have a sufficient signal level, in terms of signal to noise ratio, as well as an uninterrupted signal, without loss of lock and then cycle slip.
Signal reliability can be checked continuously by monitoring the ambiguity terms on the dual frequencies or by controlling the signal to noise ratio, which could be very useful to monitor the amplitude scintillation.
It is also possible to obtain a more correct TEC value by differentiating dual frequency measurements before solving the ambiguity terms. After some calculations we have:

$$TEC = S\cdot(\phi_1 - \phi_2 + d^i + d_k) \qquad (3)$$

where

ϕ_1, ϕ_2 = unambiguous phase measurements (units of length),

d^i, d_k = satellite and receiver equipment delay,

S = scaling factor (TEC units/m).

with

$$S = \frac{1}{40.3}\cdot\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\cdot 10^{-16} \qquad (4)$$

3.3 TEC values using the ionospheric model of the Bernese software

The local ionospheric model, included in the code program of the Bernese post-processing software, provides the parameters needed for the TEC computation under the single layer hypothesis. The local ionospheric model uses a two dimensional Taylor series expansion:

$$E(\beta, s) = \sum_{n=0}^{n_{max}}\sum_{m=0}^{m_{max}} E_{nm}(\beta-\beta_0)^n (s-s_0)^m \qquad (5)$$

where

n_{max}, m_{max} = degree of the series,

E_{nm} = TEC coefficient,

β_0, s_o = latitude and longitude of the origin of the development,

β, s = geocentric latitude and sun-fixed longitude of the ionospheric pierce point.

Therefore the series expansion used requires knowledge of the origin of the development, the geocentric latitude of the ionospheric pierce point and the sun-fixed longitude of the same point, that is the intersection of the ionospheric layer, with an associated infinitesimal thickness due to the single layer hypothesis, and the line representing the satellite to receiver signal path, as shown in figure 3.

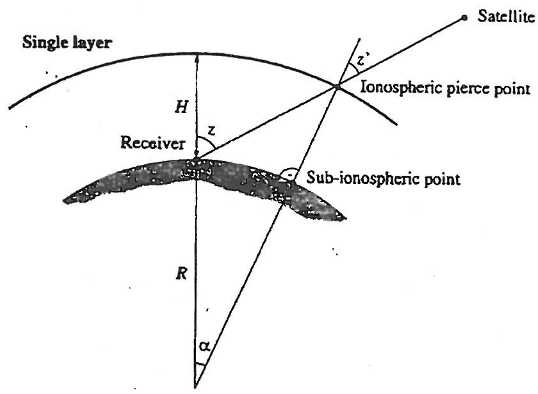

Fig. 3 – Geometric scheme (from Beutler et al 1996)

3.4 TEC values using the baseline estimation method

The third way to obtain TEC values begins with the relations between differential ionospheric delay and its effect on the baseline length value considering the ionospheric layer as homogeneous (fig. 4) and using single frequency GPS measurements.

$$dL_{ik} = dI_{ik}^j \cos\alpha^j \qquad (6)$$

where

i, k = stations at ends of baseline,

α^j = = satellite j elevation angle (mean value at stations i and k),

dL_{ik} = baseline length ionospheric delay effect,

dI_{ik}^j = differential ionospheric delay.

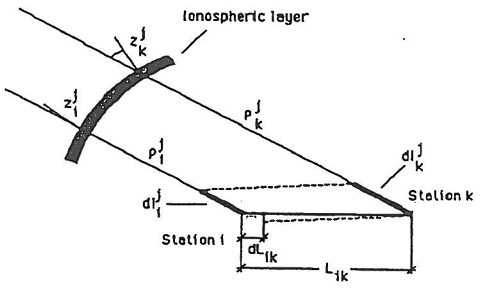

Fig. 4 – Delay effect on baseline length (form Georgiadou et al 1988)

First the effect on the baseline length was computed by subtracting the ion-free (L3) from the single frequency (L1) solutions. From the equation (6) it is possible to obtain the differential ionospheric delay to substitute in the following,

$$dI^i_{jk} = dI^i_k - dI^i_j = dV\left(\frac{1}{\cos z^i_k} - \frac{1}{\cos z^i_j}\right) \qquad (7)$$

where

z^i_j, z^i_k = zenith angles,
dV = vertical component of ionospheric delay.

makes it possible to determine dV and, using the equation (8), the VEC (Vertical Electron Content), in fact:

$$dV = 40.3\frac{VEC}{f_1^2} \qquad (8)$$

Ideally all the values of electron content should be expressed as vertical content, this means using the satellite as a reference in the zenith position, otherwise it is necessary to correct the TEC values (referred to slant situations) to VEC (referred to a vertical situation). It must be remembered that at Terra Nova Bay the satellite elevations reach maximum values of between 55 and 60 degrees above the horizon and never reach the zenith. So it is necessary to correct the computed TEC from the slant to the vertical situation. This can be done by using the so-called 'mapping function' which relates the Total and Vertical Electron Content through the satellite zenith distance z'. Referring to the figure 3 we have:

$$VEC = TEC \cos z' \qquad (9)$$

with the z' obtained from:

$$\sin z' = \frac{R}{R+H} \sin z \qquad (10)$$

where

R = mean radius of the earth,
H = height of the ionospheric layer under the earth surface.

4. Comparison between the TEC values obtained from the different models

Table 1 shows the values, always referred to the vertical situation, obtained with two different acquisition days. The data are expressed in TEC units with one TEC unit equal to 10^{16} *electrons* $/ m^2$

Tab. 1 – Some of the TEC values obtained

Model	TEC Units Nov -21- 1993 PRN 24	TEC Units Dec –10 - 1993 PRN 17
Ionospheric sounding	16.0	6.1
Code measurements	12.0	11.9
Bernese software	13.8	13.6
Baseline estimation	-	25.0

First it can be observed that values obtained from GPS measurements and atmospheric soundings are of the same order of magnitude. This is really true for the first column values. In spite of the apparently large difference between the second column values it must be pointed out that the TEC values derived from the atmospheric soundings have large fluctuations, with the same variability observed between the different methods.

Figure 5 shows the variation, due to the change in satellite elevation, in the TEC values derived from the pseudo-range measurements not corrected for the error due to the satellite elevation angle.

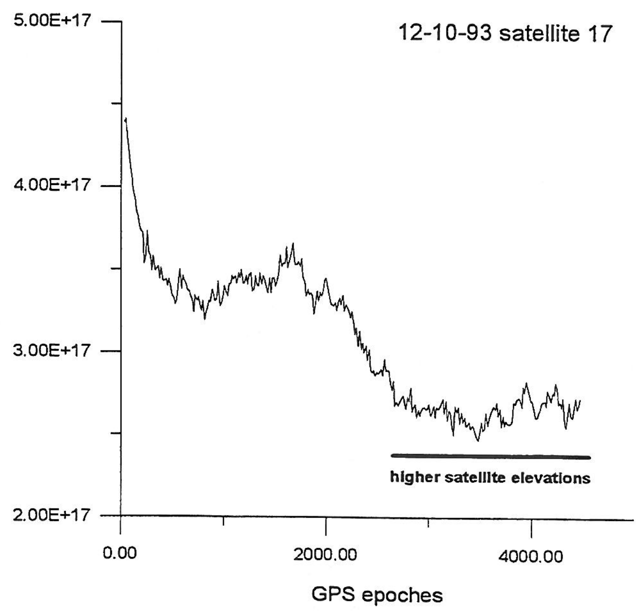

Fig. 5 – TEC values from pseudo-range measurements (not corrected for verticality)

Here the relations between the absolute numeric values and the satellite elevation are clear. With high elevations, right side of the plot, the TEC value is reduced due to the decreasing width of the ionospheric layer crossed by the GPS signal.
The most reliable TEC values were obtained when the satellite elevations were high (underlined data in figure 5).

5. Conclusion

We can conclude that TEC values obtained from GPS observables are in good agreement with those derived from atmospheric soundings.
The tracking of the TEC value and its variation between epochs can therefore be derived directly from the GPS data and can be helpful during the data processing, particularly in auroral zones where the high ionospheric activity increases the probability that scintillation phenomena occur with the increased difficulties for solving and recovering cycle slip. In fact considering the continuous TEC as an index of ionospheric activity we have information about the signal reliability during the session. These periods of the session can be better analysed and eventually eliminated during the post-processing operations.

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