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Proposed Methods to obtain Satellite and Receiver Instrumental Delays

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Abstract

The GPS system main purpose is to determine the position and velocity of a fixed or mobile object, placed over or near the earth surface, using the signals of 24 satellites on earth's orbit. Due to the effect of the ionosphere on the propagation of the electromagnetic waves transmitted by the GPS satellites, in 1575.42 and 1227.60 MHz, it is possible to obtain the total ionospheric electron content (TEC), using the standard data for navigation purpose. The TEC is the amount of free electrons along the path of the electromagnetic wave between each satellite and the receiver.

Absolute determination of TEC is difficult mainly because satellite and receiver instrumental delays require very complicated methods to calculate them. This work proposes some simple methods for this purpose.

INTRODUCTION

The Total Electron Content (TEC) is the amount of free electrons along the path of the electromagnetic wave between each satellite and the receiver, given by

$$TEC = \int_{receiver}^{satellite} N \cdot ds$$

where N is the electron density.

It is an important geophysical parameter, which has also applications for correcting navigation measurements for single frequency receivers.

The TEC has been measured for decades using the Faraday Rotation effect on a linear polarized propagating plane wave (Klobuchar, 1985 and 1996). Special transmitters in geostationary and non-geostationary satellites were used for this purpose. But today there is a complex and expensive constellations of 24 satellites distributed in 6 orbital planes, 4 satellites per plane, at 20,200 km altitude, with an orbit inclination of 55 degrees and an approximately 12 hour period available, which can provide at least 4 and up to maybe 9 TEC values within 1000 km from the receiving station simultaneously every 30 seconds (usual period).

This satellite constellation called Global Positioning System (GPS) was developed for other than geophysical motives, but can and should be used by the geophysics community.

The main purpose of the GPS is to determine the position and velocity of a fixed or mobile object, placed over or near the earth surface, using the signals of the 24 satellites on earth orbit.

There are today a great number of GPS receiving stations able to provide TEC measurements. The International GPS Service has 196 stations (26 October 1998), being 2 in Brazil and 15 in South and Central America. Besides those, there are local GPS stations networks.

GLOBAL POSITIONING SYSTEM (GPS)

Each satellite transmits two carrier electromagnetic waves with frequencies, L1, and L2, both in the L-band

L1 = 1575.42 MHz (154 × 10.23 MHz) λ = 19 cm
L2 = 1227.60 MHz (120 × 10.23 MHz) λ = 24 cm

with codes modulations, so that by comparing with a reference code, it is possible to measure the travelling time of the code and the carrier between the satellite and the receiver, providing the following 4 observables:

1) pseudoranges from the code travelling time

$$P_i = \rho + c \cdot (dT - dt) + \Delta i_i^{iono} + \Delta^{trop} + b_i^{P,r} + b_i^{P,s} + m_i^P + \varepsilon_i^P$$

2) and the carrier phases

$$\Phi_i = \lambda_i \cdot \phi_i \;= \rho + c \cdot (dT - dt) + \lambda_i \; N_i - \Delta_i^{iono} + \Delta^{trop} + b_i^{\phi,r} + b_i^{\phi,s} + m_i^{\phi} + \varepsilon_i^{\phi}$$

where

i = 1,2 corresponding to carrier frequencies L1 and L2
P is the code pseudorange measurement (in distance units)
ρ is the geometrical range between satellite and receiver
c is the vacuum light speed
dT, dt are the receiver and satellites clock offsets from GPS time

$\Delta_i^{iono} = 40.3\ TEC/f_i^2$ is the ionospheric delay
TEC is the Total Electron Content
f_i is the carrier frequency Li
Δ^{trop} is the tropospheric delay
b_i are the receiver and satellite instrumental delays on P and Φ
m_i are the multipath on P and Φ measurements
ε_i are the receiver noise on P and Φ
Φ_i are the carrier phase observation (in distance units)
ϕ_i are the carrier phase observation (in cycles)
$\lambda = c/f$ is the wavelength
N_i are the unknown Li integer carrier phase ambiguities

More details can be found in Hoffmann-Wellenhof et al.(1994), Seeber(1993), Leick(1995) and Komjathy(1997).

TEC CALCULATION

Combining the pseudoranges observations P_i , a TEC value is obtained

$$TEC_P = 9.52 \cdot (P_2 - P_1) + instrumental\ delays + multipath + noise$$

which is very noisy.
And after combination of carrier phase observations Φ_i we get:

$$TEC_\phi = 9.52 \cdot [(\Phi_1 - \Phi_2) - (N_1\lambda_1 - N_2\lambda_2)] + instrumental\ delays + multipath + noise$$

which is less noisy than TEC_P , but ambiguous.
The ambiguity is removed by averaging (TEC_P - TEC_ϕ) over a satellite pass (phase connecting arc)

$$TEC_L = TEC_\phi - \langle TEC_\phi - TEC_P \rangle$$

This "levels" the TEC to the unambiguous TEC_P, has the TEC information of the less noisy TEC_ϕ , but includes the instrumental delays, multipath and noise. The carrier phase observations have sometimes a sudden jump, that is removed ("cycle slip correction") by adjusting the continuity of (Φ_1 - Φ_2) .
It is of geophysical and applications interest a "local" TEC, the vertical TEC (TEC_V), that depends only on geographical location and time, and not on a slant TEC function of the satellite and receiver locations. To relate these TEC's, it is used a mapping function M(E), where E is the satellite elevation angle at the receiver. The simplest function used is M(E) = 1/cosχ, where χ is the zenith angle at the subionospheric point, a point between the satellite and the receiver at a height given by the center of mass of the ionospheric profile, usually between 350 and 450 km (thin shell model).

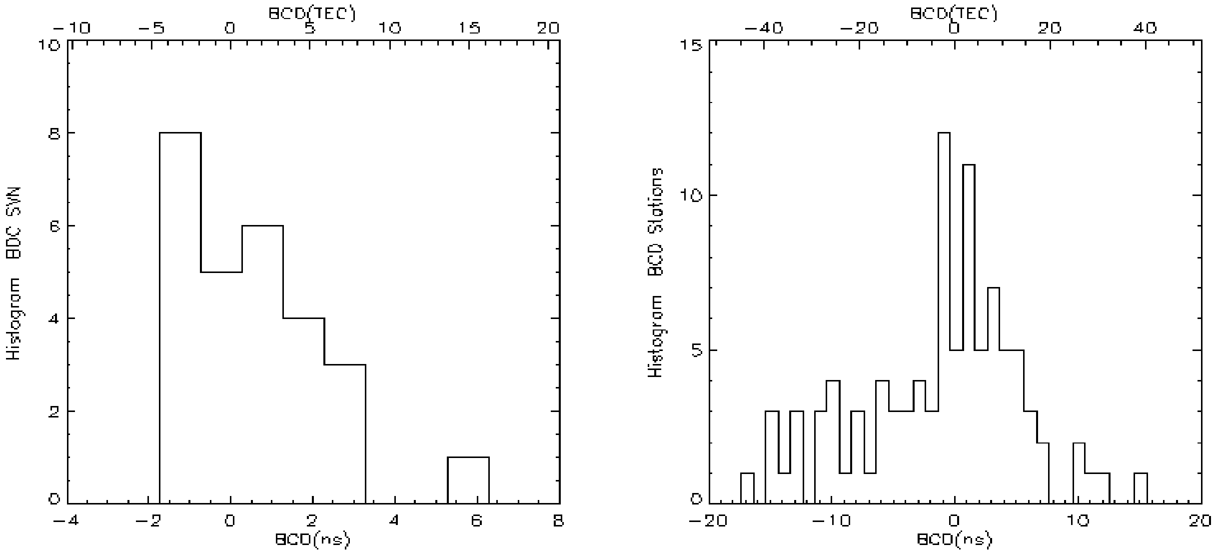

Figure 1 - Histogram of satellite and receiver instrumental delays in nanoseconds and in UTEC.

ABSOLUTE TEC AND TEC MAPPING

To study perturbations in the ionosphere, the $TEC_V = TEC_L \cdot \cos\chi$ is sufficient, but when the absolute value of the TEC is needed the satellite and receiver instrumental delays must be known, because they can be significant.
To obtain the instrumental delays and also make regional or global mapping of the ionospheric TEC an estimation strategy is applied. The TEC_L measurement $T^{rs}(t)$ between receiver *r* and satellite *s* at epoch *t* can be modeled by

$$T^{rs}(t) = M(E)\cdot I(\theta,\varphi,t) + b^r + b^s$$

where

M(E) is the mapping function for the elevation *E*
I(θ,φ,t) is an ionospheric TEC model
θ,φ are latitude and longitude
t is the measurement epoch
b^r, b^s are the differential instrumental delays of the receiver *r* and satellite *s*

Given the satellite orbits, *θ, φ* and *E* are determined, and with the TEC_L measurements, the b's and the parameters of the ionosphere TEC model *I(θ,φ,t)* can be determined by least square fit or Kalman Filter (Lanyi and Roth, 1988; Coco et al., 1991; Gail et al.,1993; Mannucci et al., 1993; Wilson and Mannucci, 1993; Sardón et al., 1994; Komjathy and Langley, 1997). These methods can be quite complicated to apply. Figure 1 shows a histogram of satellite and receiver delays. Figure 2 shows the trajectories of the subionospheric point for all satellites.

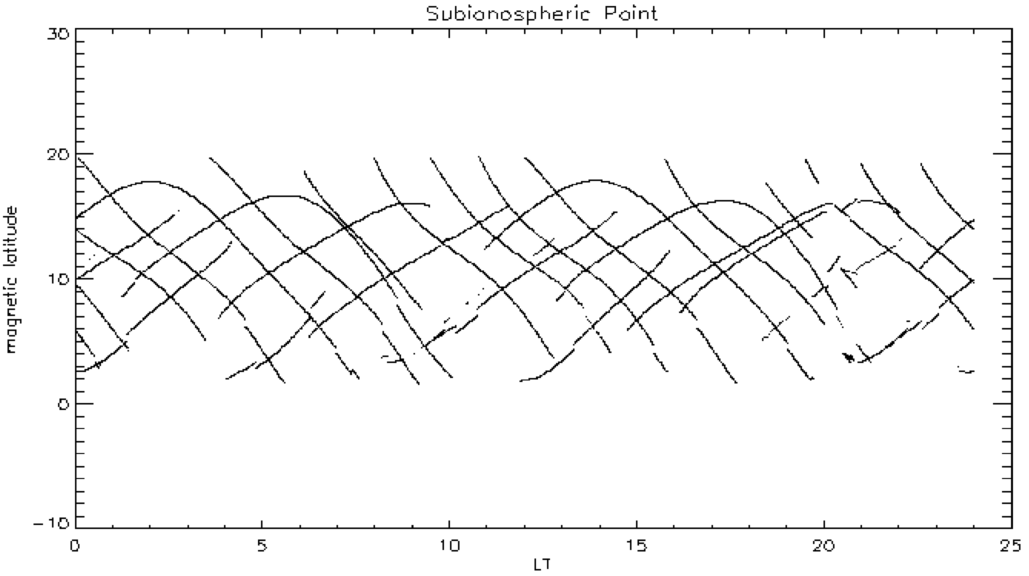

Figure 2 - Trajectory of the subionospheric point with magnetic latitude and local time for Kouru station.

Precalculated biases b's are available in CDDIS (Crustal Dynamics Data Information System) at the Internet. Simpler methods to obtain the biases are to assume TEC of about 3-5 TECU at vertical nighttime data (about 4 AM local time), or, to assume no TEC gradients (fixed zenith TEC value) over an arc of GPS data (Mannucci, 1998).

PROPOSED METHODS FOR OBTAINING SATELLITE INSTRUMENTAL DELAYS

Three methods are proposed:

1) Minimization of the difference between all satellite data and the average value in latitude and time interval cells.
2) Minimization of the difference of data between points of same latitude and time. In Figure 3 it is represented by crossing trajectories ("basket knitting")
3) ("Similitude")

For a receiving station and for each satellite, over an arc of data the measured vertical TEC is

$$I^{r,s}(LT) = [T^{r,s}(LT) - (b^r + b^s)]\cdot\cos\chi^{r,s}(LT)$$

where *LT* is the subionospheric local time. Varying the delays *b*'s in the above expression, *I(LT)* curve will vary its shape from ∩ to ∪ (U-shape). See Figure 3. This gives a range of possible values for (b^r + b^s). Two data arcs for different satellites at similar local times should have similar shapes, but not a pronounced U-shape, otherwise they would cross each other. The similarity is imposed by adding a "floating constant" , α_S, to *I(LT)* , so that

$$\sum_{s,LT}[I^{r,s}(LT) - \alpha_S - \langle I^{r,s}(LT)\rangle_S]^2$$

is minimum. $\langle\,\rangle_S$ denotes average over all satellites. Satellite and receiver delays cannot be separated, and can be determined for each satellite, but if one assumes that the receiver delay is more significant than the satellite delays, the solution is much simpler.

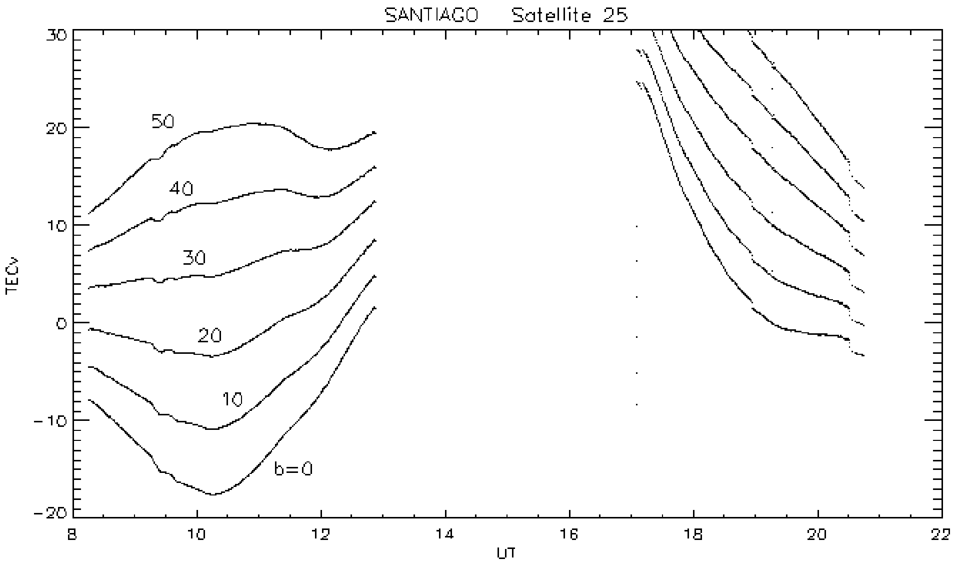

Figure 3 - Variation of TEC if *b* would change, presenting U shape variation.

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