Atmosphere Sounding with SAC-C satellite and GPS network over Argentina

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Abstract

The development and/or improvement of largely already existing infrastructure (networks of GPS stations, orbiting GPS receivers, communication links, network and mission operation centers, data information and archival centers, analysis centers and related S/W systems, user interfaces) required for the use of ground- and space-borne GPS tracking data for atmospheric and ionospheric sciences and applications. This should be realized in such a short time and to such an extent, that already atmospheric/ionospheric data products from the forthcoming SAC-C satellite mission and from densified regional geodetic GPS networks in Argentina can be explored for their potential information content and operational availability in applications such as ionospheric physics and space weather monitoring.

Introduction

The weather in space has a huge impact on our telecommunications systems, electric power networks and spacecraft controls navigation systems. Space weather is driven by the activity of the sun, when massive explosions, known as coronal mass ejections send magnetic clouds containing billions of tons of materials hurtling into space. When the magnetic clouds reach the Earth they can cause geomagnetic storms which contribute to severe space weather conditions.
Stormy space weather can generate harmful electric surges in power grids, interrupt radio communications systems, damage Earth-orbiting satellites such as those carrying TV, mobile phone and pager signals.

Accurate information on TEC is essential for provides a valuable tool for investigating global and regional ionospheric structures. Important application for TEC data is in automatically controlling aircraft trajectories and learning how to predict TEC values in advance, researchers may also be able to set up early warning procedures that give us enough time to protect valuable communications satellites from the sun.

Data Derivable from GPS Signals

In the timing community, it has been said that GPS receivers are "good thermometers". What that really means is with various differencing techniques one can observe and estimate a variety of "environmental effects" on the system, including the effects of temperature on clock stability.

IGS Network

The U.S. Global Positioning System (GPS) constellation of satellites plays a major role in regional and global studies of Earth. In the face of continued growth and diversification of GPS applications, the worldwide scientific community has made an effort to promote international standards for GPS data acquisition and analysis, and to deploy and operate a common, comprehensive global tracking system.

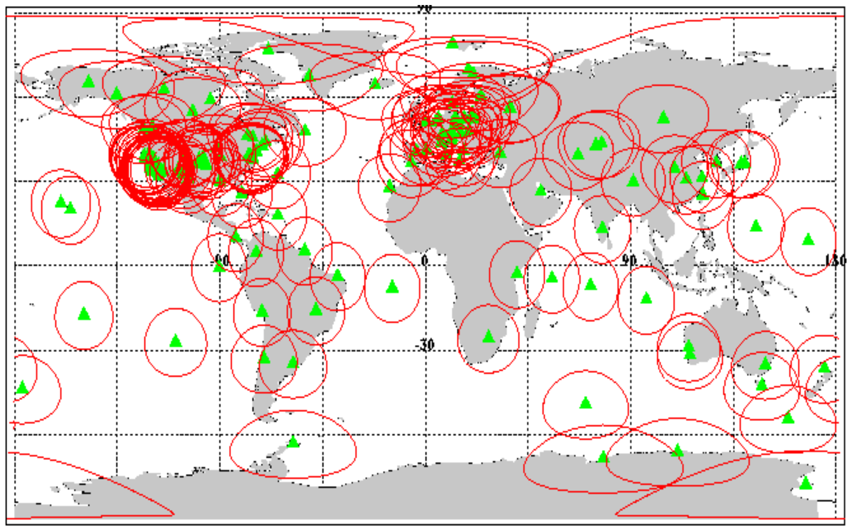
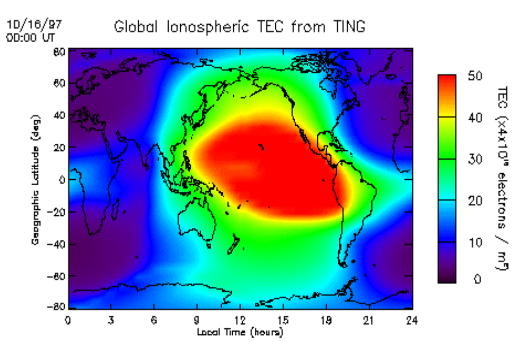
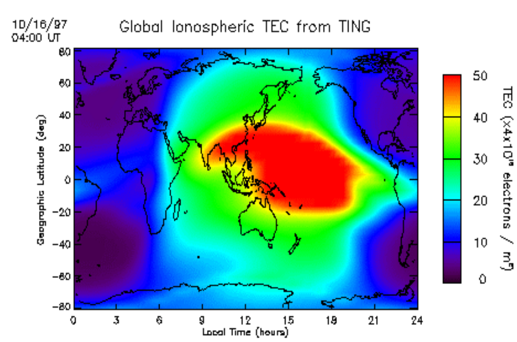


Fig. 1 It shows the stations of receiving permanent GPS in the world

The Global Ionospheric Monitoring and Forecasting System (GIMSYS) computer program generates global maps of the total electron content (TEC) (electron density integrated over all altitude) of the ionosphere, maps of ionospheric irregularities, and related data byproducts. The maps are generated primarily from signal-propagation measurements taken by more than 100 continuously operating two-frequency Global Positioning System (GPS) receivers in a world-wide network. GIMSYS interpolates the measurements temporally and spatially generating a global TEC map every 15 minutes. When updating the map with new measurements, GIMSYS uses a Kalman filter and stochastic estimation to obtain an optimal combination of the measurements with constraints derived from ionospheric physics and empirical ionospheric models. By applying time-series analysis to recent TEC maps, GIMSYS can also generate forecast TEC maps that are reasonably accurate for 2 to 4 hours.





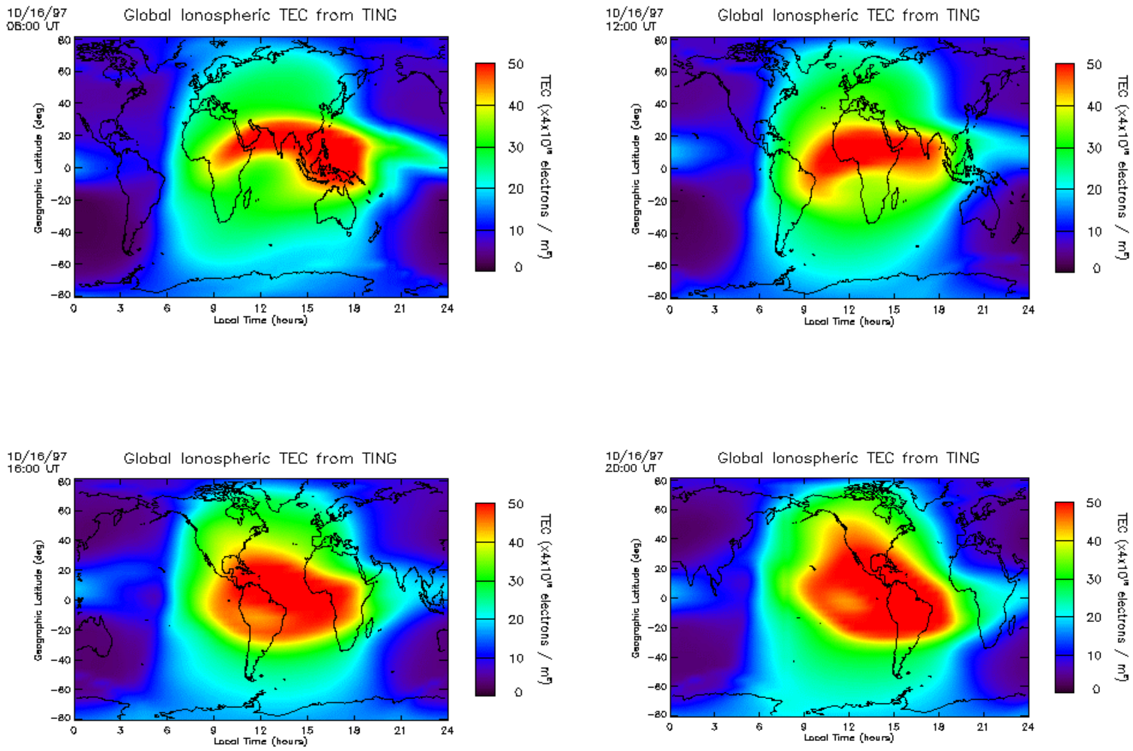
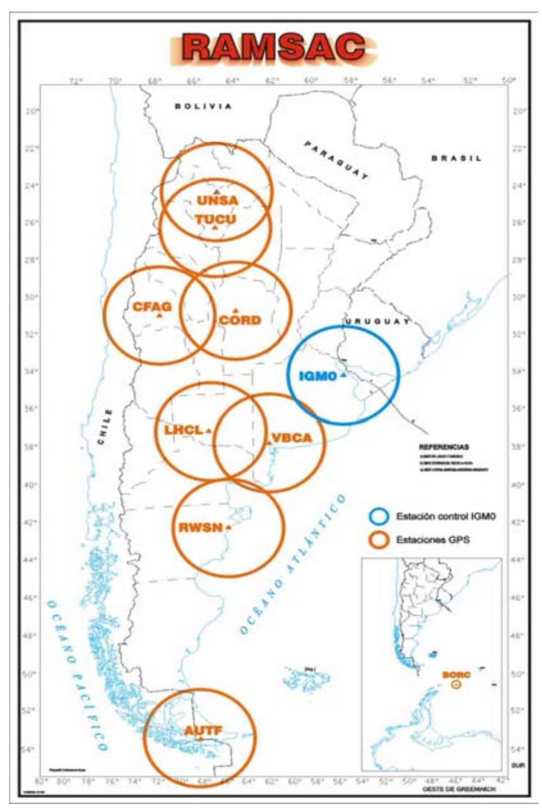


Fig.2 Global maps of TEC for different hours (UT)

For the study of regional models of TEC and of Ne we use the following configuration of receiving GPS in Argentina.

Fig.3 RAMSAC Network



What is GOLPE?

The GPS Occultation and Passive Reflection Experiment (GOLPE) is a proof-of-concept program, which is jointly sponsored by the Argentine Commission on Space Activities [(C O N A E)](), and the National Aeronautical and Space Administration [(N A S A)]() and the Jet Propulsion Laboratory [(JPL)](). The GOLPE receiver is one of two payloads that was carried into a Low Earth Orbit (LEO) on SAC-C satellite. SAC-C is one of a two satellite payload which was launched by a Delta 7320 rocket from Vandenberg Air Force Base on November 16 , 2000.

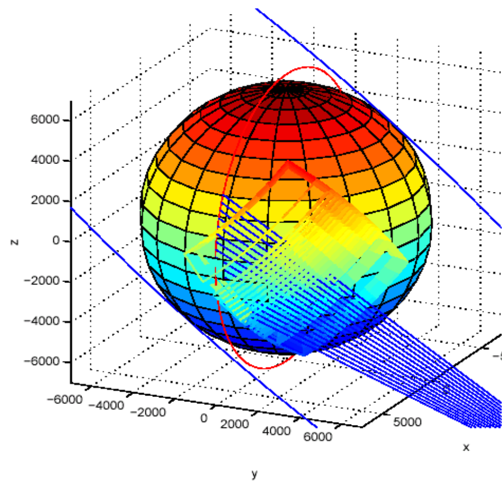


Fig.4 GPS occultation geometry

GOLPE will measure the refractivity or bending of GPS signals hidden by Earth's atmosphere and ionosphere and will demonstrate and utilize an innovative new GPS remote sensing to study weather and seasonal to long term climate change. At the heart of the GOLPE experiment is an advanced GPS receiver capable of automatically acquiring selected GPS transmissions that are refracted by the Earth's atmosphere and reflected from the Earth's surface.

Background on GPS radio occultations

When a signal transmitted by the GPS and received by a LEO passes through the Earth's atmosphere its

- Phase and amplitude are affected in ways that are characteristic of the index of refraction of the propagating medium.
- By applying certain assumptions on the phase change measurements yield refractivity profiles in the ionosphere and neutral atmosphere.

Occultations

- The GPS receiver is capable of tracking up to 8 GPS satellites simultaneously at both frequencies transmitted by GPS.
- Under an optimal mode of operation, provides 100-120 globally distributed setting occultations per day.

SAC-C positions corresponding to the observation epoch of January 17, 2001 tracing region. The Sun is at 12 hours of local time

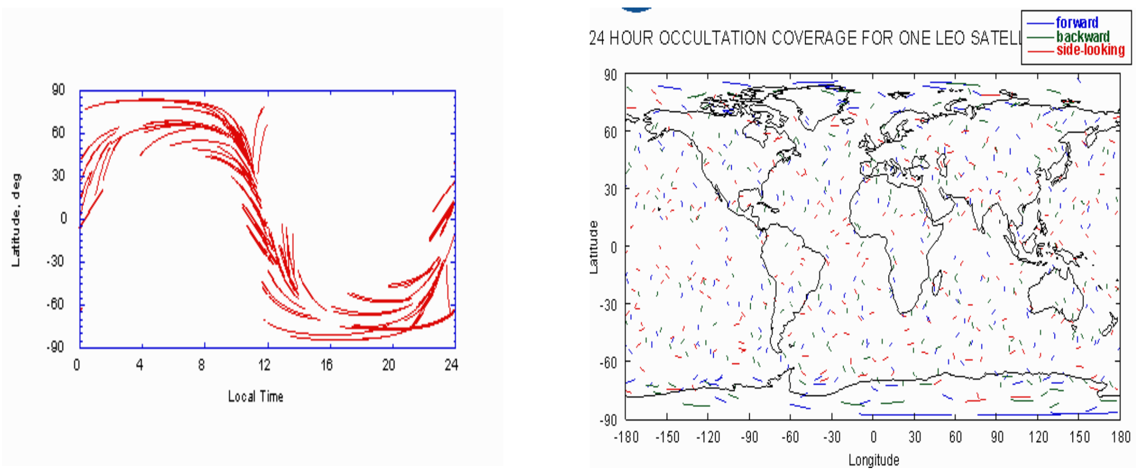


Fig. 5 SAC-C positions and 24 occultation for one LEO satellite

Bending angle

In the geometrical optics approximation, a ray passing through the atmosphere is refracted according to Snell's law （ Descartes'law ） due to the vertical gradient of refractive index. The overall effect of the atmosphere can be characterized by a total bending angle α , an impact parameter *a*, and a tangent radius *r* defined in fig. 5 depicting the instantaneous GPS-LEO occultation geometry.

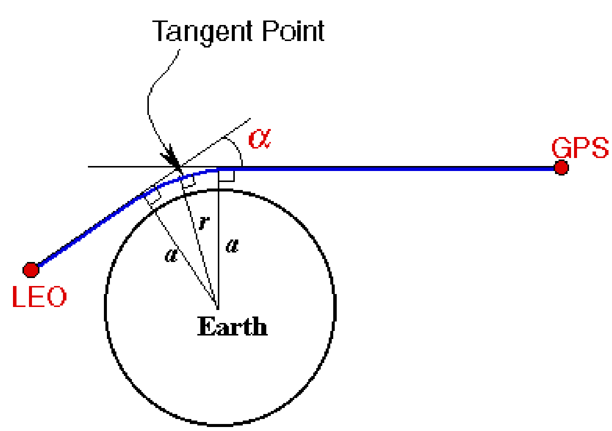


Fig. 6 Bending angle

During an occultation, the variation of a with *α* depends primarily on the vertical profile of atmospheric refractive index. This profile can be retrieved from measurements of α as a function of *a*. during the occultation, subject to the assumption of local spherical symmetry. The time dependence of both α and *a* during an occultation can be derived from accurate measurement of the Doppler-shifted frequency of the transmitter signal at the receiver. The Doppler-shift is determined by the projection of spacecraft velocities onto the ray paths at the transmitter and receiver, so that atmospheric bending contributes to the measured Doppler shift.

Inversion Technique

The basic observable for each occultation is the phase change between the transmitter and the receiver (Hajj et al. 1998, Hernandez-Pajares et al, 1999, Ware, et al., 1995). After removal of geometrical effects due to the motion of the satellites and proper calibration of the transmitter and receiver clocks, the extra phase change induced by the atmosphere can be isolated. Excess atmospheric Doppler shift can be used to derive the atmospheric induced bending as a function of the asymptote miss distance.

The relation between the bending and extra Doppler shift induced by the atmosphere is given by

$$\Delta f = \frac{f}{c}\left[\vec{v}_t \cdot \hat{k}_t - \vec{v}_r \cdot \hat{k}_r + \left(\vec{v}_t - \vec{v}_r\right) \cdot \hat{k}\right]$$

where

f : operating frequency ; c : speed of light

$\vec{v}_t$, $\vec{v}_r$: transmitter and receiver's velocities

$\hat{k}_t$, $\hat{k}_t$: the unit vectors in the direction of the transmitted and received signal

$\hat{k}$: is the unit vector in the direction of the straight line connecting the transmitter to the receiver.

Abel transform

The spherical symmetry assumption can also be used to relate the signal's bending to the medium's index of refraction, *n*, via the relation

$$\alpha(a) = 2a\int_a^{\infty} \frac{1}{\sqrt{a'^2 - a^2}} \frac{d\,\ln(n)}{da'} da'$$

where

$a = nr$ and r is the radius at the tangent point.

This integral equation can then be inverted by using an Abel integral transform given by

$$\ln\,(n(a)) \;=\frac{1}{\pi}\int_{a}^{\infty}\frac{\alpha(a')}{\sqrt{a'^2-a^2}}da'$$

Refractivity *N*, is related to atmospheric quantities:

$$N=(n-1)\times10^6=77.6\frac{P}{T}+3.73\times10^5\frac{Pw}{T^2}-40.3\times10^6\frac{Ne}{f^2}$$

where

$$P=\frac{\rho RT}{m} \qquad\qquad \frac{\partial P}{\partial h}=-g\rho$$

P, T : total pressure and temperature
Pw : water vapor partial pressure
Ne : electron density
f : operating frequency
ρ : density
R : gas constant
m : gas effective molecular weight
h, g : height and gravitational acceleration.

We highlight some GPS occultation features:

- Due to the nature of the measurement, the technique has a much higher vertical and across - beam resolution than horizontal.

- The vertical resolution of the technique is essentially set by the physical width of the beam where geometrical optics is applicable.

The main observable used in an occultation geometry is the phase change between the transmitter and the receiver. This phase change is due to the relative motion of the SAC-C with respect to the GPS, clock drifts of the GPS and SAC-C and delay induced by the atmosphere. In order to derive the excess atmospheric Doppler shift, one must remove the contribution of the first two effects.

Results of GPS Occultation to Atmospheric Science

The radio occultation technique holds the promise of providing atmospheric sounding which combines the high-resolution vertical profiling characteristic of radiosondes and the global coverage usually provided by passive remote sounders. The technique depends on the proven ability to measure the time delay of transmitted radio signals with high precision and stability as they traverse the atmosphere. Improving the Abel inversion by adding ground GPS data to SAC - C radio occultations in ionospheric sounding. The procedures used to obtain ionospheric profiles can be classified in two main groups. First, Tomographic approach which involves using a set of orthogonal functions to describe the electron density, Leitinger et al., 1997 and the Abel Tranform which provides directly the electron density from either the bending angle or the excess of phase data of signal, Hajj, et al., 1994, Schreiner et al, 1999.

We use the technique given by Hernandez Pajares et al., 2000 and suppose that the electron distribution must present spherical symmetry (i.e. the electron density only depends on height) and the electron density above the SAC-C can be neglected.

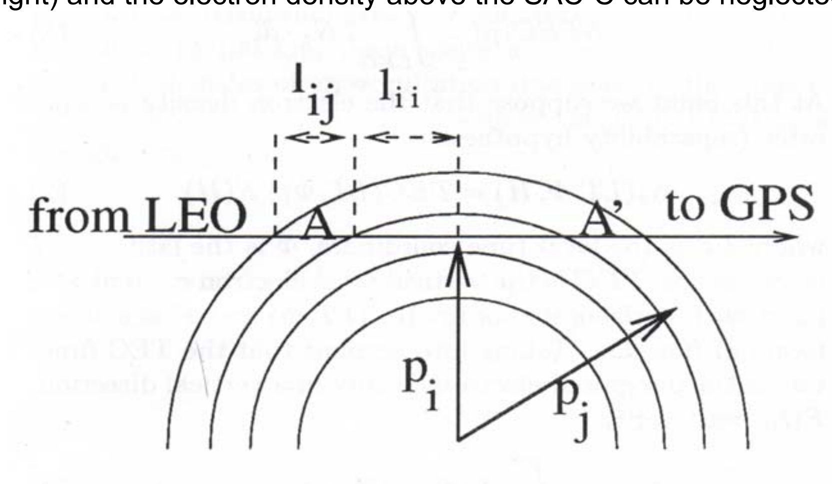


Fig.7 Layout of the Inversion model geometry

The Inversion algorithm

STEC (Slant Electron Content) is realted to electron density Ne by

$$STEC(p) = \int_{SAC-C}^{GPS} N_e \, . dl$$

We suppose that Ne is separable

$$N_e(LT, \Phi, H) = TEC(LT, \Phi) \, . \, F(H)$$

where LT: local time ; H : height and F : Shape function is defined by:

$$\int_0^{\infty} F(H) \,.\, dH = 1$$

Starting from the outer ray, for a given ray i, where i = 1, … impact parameter pi, its STEC can be written by:

$$STEC(p_i) = 2.l_{ii}.TEC(LT_{ii},\Phi_{ii}).F(p_i) + \sum_{j=1}^{j=i-1} l_{ij}[TEC(LT_{ij},\Phi_{ij}) + TEC(LT'_{ij},\Phi'_{ij})]F(p_j)$$

where

> LT_{ij} , LT'_{ij} and Φ_{ij} , Φ'_{ij} : horizontal ccordinates of two intersection points between the ray "i" and layer "j".

This is a triangular linear equation system that could be solved recursively for the shape function. We will use as data the differences between L1 and L2 GPS carrier phases that are related with the STEC by:

$$L_I = L_1 - L_2 = \alpha \,.\, STEC + b$$

where α = 0.105 m/TECU and b is a bias term

Equation for $STEC(p_i)$ is completed with the contribution to the STEC of the ionosphere above the SAC-C. Then equation for L_I and STEC can be written as follows:

$$\alpha^{-1}.[L_I(p_i) - L_I(R)] = \sum_{j=1}^{j=i-1} l_{ij}[TEC(LT_{ij},\Phi_{ij}) + TEC(LT'_{ij},\Phi'_{ij})]F(p_j) + 2.l_{ii}.TEC(LT_{ii},\Phi_{ii}).\,F(p_i) + STEC_A(p_i) - STEC_R$$

where

> $L_I(R)$ is the datum of the reference observation, $STEC_R$ is its STEC and $STEC_A$ is the portion of STEC above the SAC-C orbit.

Results

In the figure we show the results of two recovering of the model profiles, in a typical ionograma obtained by the digisonda of Tucumán, for the day a hours. The improvement of separability hypothesis is clear, particularly at low latitudes.

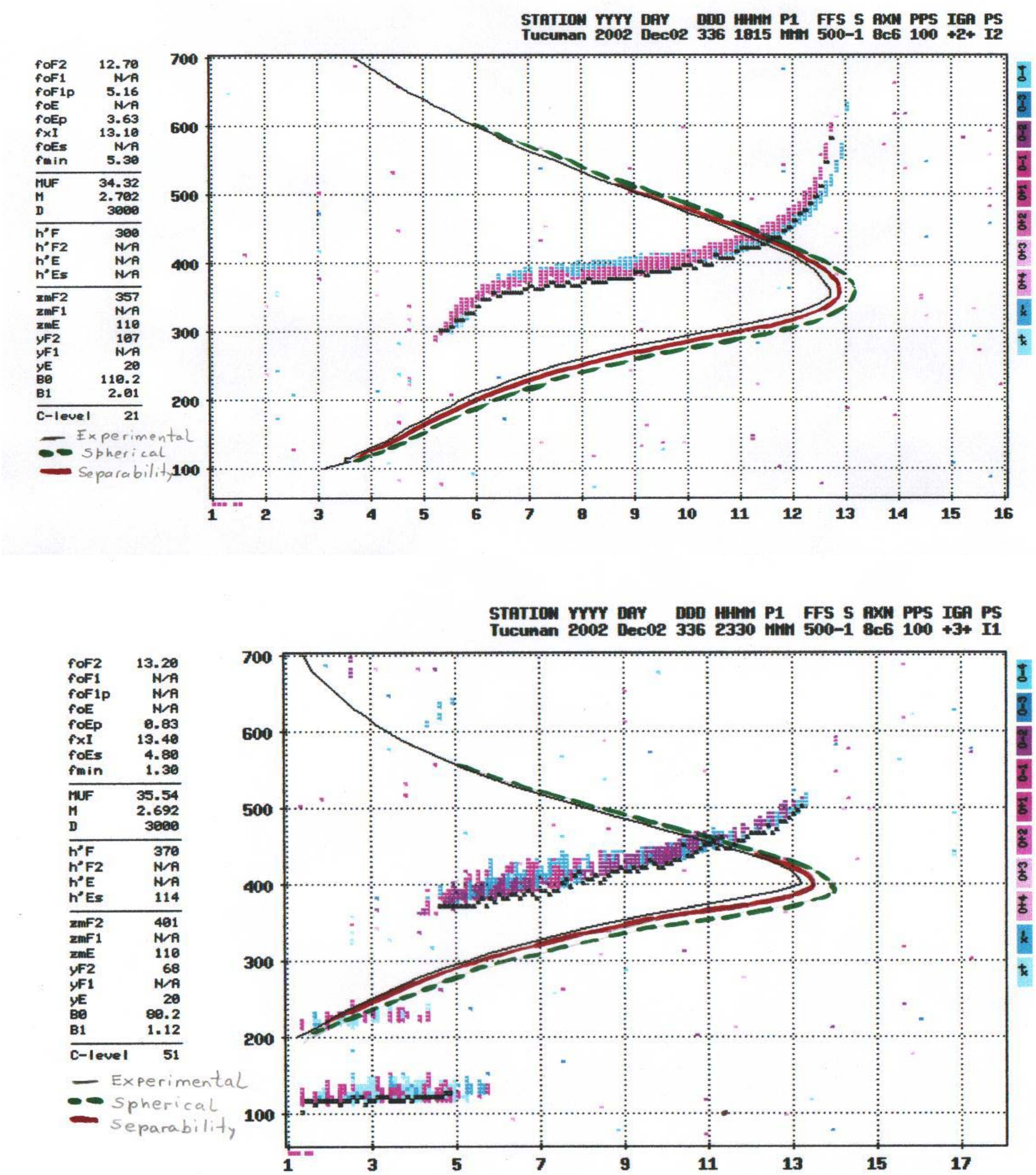


Fig. 8 Electron density retrieval with simulated STEC and obtained by Digisonde of Tucumán

Conclusions

From the comparison of ionosonde of Tucumán for two occultations the electron densities in general we have a good results. From these results it is clear that the addition of TEC information improves the results of the inversion procedure. In all cases the separability assumption provides better statics than the traditional Abel inversion algorithm assuming spherical symmetry. This improvement is generally close to 38% in rms when digisonde and occultation results are compared. The results obtained in this work show the TEC suitable as a priori information.

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