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TEC MEASUREMENTS WITH GPS DATA

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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 TEC measurements are made mostly using GPS data, 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).



GLOBAL POSITIONING SYSTEM (GPS)

- 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.
- 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.
- GPS 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
- There are today a great number of GPS receiving stations able to provide TEC measurements. The International GPS Service has 379 stations (15 August 2006), being 3 in Brazil. Besides those, in Brazil there is the local GPS stations network RBMC (Rede Brasileira de Monitoriamento Contínuo) with 23 stations.

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

$$L1 = 1575.42 \text{ MHz (} 154 \times 10.23 \text{ MHz) } \quad \lambda = 19 \text{ cm}$$

$$L2 = 1227.60 \text{ MHz (} 120 \times 10.23 \text{ MHz) } \quad \lambda = 24 \text{ cm}$$



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

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

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

$\Delta i_{iono} = 40.3 \text{ TEC}/f_i^2$ is the ionospheric delay

TEC is the Total Electron Content

f_i is the carrier frequency L_i

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 L_i integer carrier phase ambiguities

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



OBSERVATION DATA IN RINEX FORMAT

```
2          OBSERVATION DATA      G (GPS)          RINEX VERSION / TYPE
RGRINEXO V2.4.5 UX  GODC          21-JAN-97 09:23      PGM / RUN BY / DATE
BIT 2 OF LLI (+4) FLAGS DATA COLLECTED UNDER "AS" CONDITION COMMENT
      .000000000000          HARDWARE CALIBRATION (S)      COMMENT
      -.000000371832          CLOCK OFFSET (S)            COMMENT
FORTALEZA          MARKER NAME
41602M001          MARKER NUMBER
AM                INPE          OBSERVER / AGENCY
T119              ROGUE SNR-8000      2.8          REC # / TYPE / VERS
119              DORNE MARGOLIN T    ANT # / TYPE
      4985390.4497 -3955001.1230 -428426.5905      APPROX POSITION XYZ
      .6430          .0000          .0000          ANTENNA: DELTA H/E/N
      1      1          WAVELENGTH FACT L1/2
      5      C1      L1      L2      P2      P1          # / TYPES OF OBSERV
      30          INTERVAL
      1997      1      13      0      0      .000000      TIME OF FIRST OBS
          END OF HEADER

97 1 13 0 0 .0000000 0 7 14 22 29 16 03 27 31
20998973.578 -19349866.573 9 -15077798.42147 20998974.8504
23116684.903 -10567434.129 7 -8234344.22445 23116685.7924
23066692.498 -12363829.552 7 -9634131.50145 23066694.7544
22459576.598 -11205991.079 8 -8731933.69845 22459578.1684
24824781.819 152225.509 6 118616.45545 24824780.6914
24118650.221 -3146122.094 6 -2451517.93445 24118653.5184
23867924.442 -5326201.306 6 -4150259.06045 23867925.2474
```

TEC calculation

Combining the pseudorange observations P_i , a TEC value is obtained

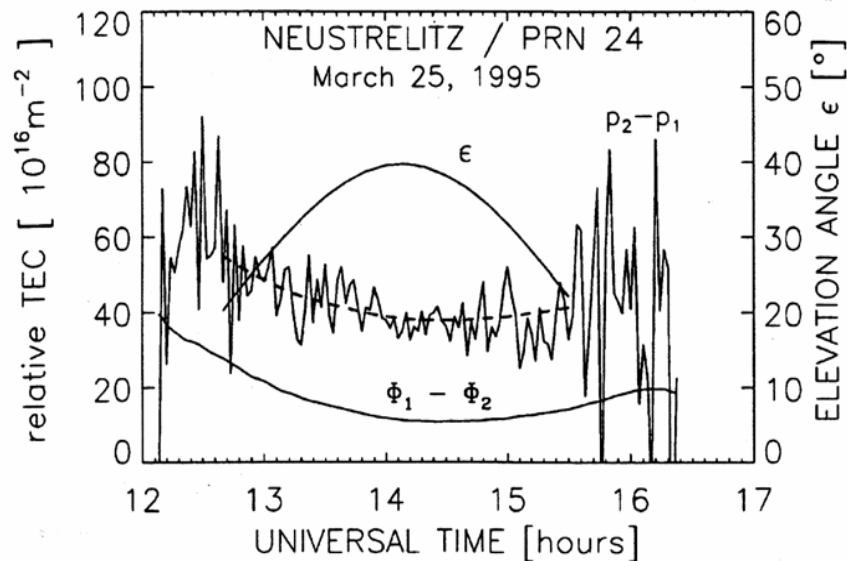
$$TEC_p = 9.52 \cdot (P_2 - P_1) + \text{instrumental delays} + \text{multipath} + \text{noise}$$

which is very noisy.

And after combination of carrier phase observations Φ_i we get:

$$TEC_\phi = 9.52 \cdot [(\Phi_1 - \Phi_2) - (N_1\lambda_1 - N_2\lambda_2)] + \text{instr. delays} + \text{multipath} + \text{noise}$$

which is less noisy than TEC_p , but ambiguous.



Example of TEC_p and TEC_ϕ measurements [$(\Phi_1 - \Phi_2)$ and $(P_2 - P_1)$] together with elevation angle ϵ of the satellite with time. The noise of TEC_p increases as elevation angle is less than 20° . (Jakowski, 1996).



CYCLE SLIP

The carrier phase observations have sometimes a sudden jump, that is removed ("cycle slip correction") by adjusting the continuity of $(\Phi_1 - \Phi_2)$.

This can be done by adjusting a polynomial to some data before and after the cycle slip occurrence.

PHASE LEVELING (AMBIGUITY)

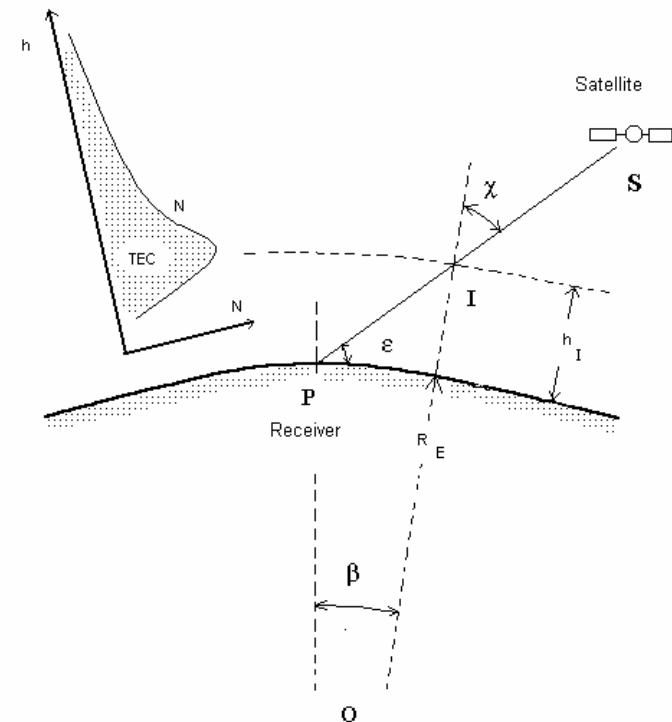
The ambiguity is removed by averaging $(TECP - TEC\phi)$ over a satellite pass (phase connecting arc)

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

This "levels" the TEC to the unambiguous $TECP$, has the TEC information of the less noisy $TEC\phi$, but includes the instrumental delays, multipath and noise.

VERTICAL TEC

It is of geophysical and applications interest a "local" TEC, the vertical TEC (*TECV*), 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 $M(E) = 1/\cos\chi$, 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).





Absolute TEC and TEC Mapping

To study perturbations in the ionosphere, the $TECV = TECL \cdot \cos\chi$ 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 $TECL$ measurement $Trs(t)$ 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

$I(\theta, \varphi, t)$ is an ionospheric TEC model

θ, φ are latitude and longitude

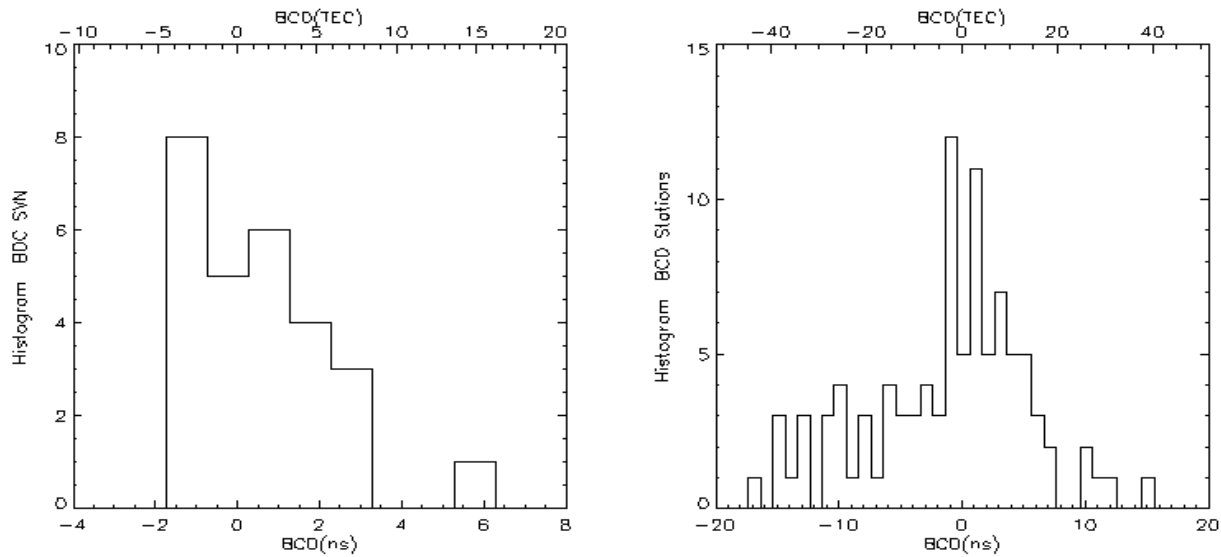
t is the measurement epoch

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 $TECL$ measurements, the b 's and the parameters of the ionosphere TEC model $I(\theta, \varphi, t)$ 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.

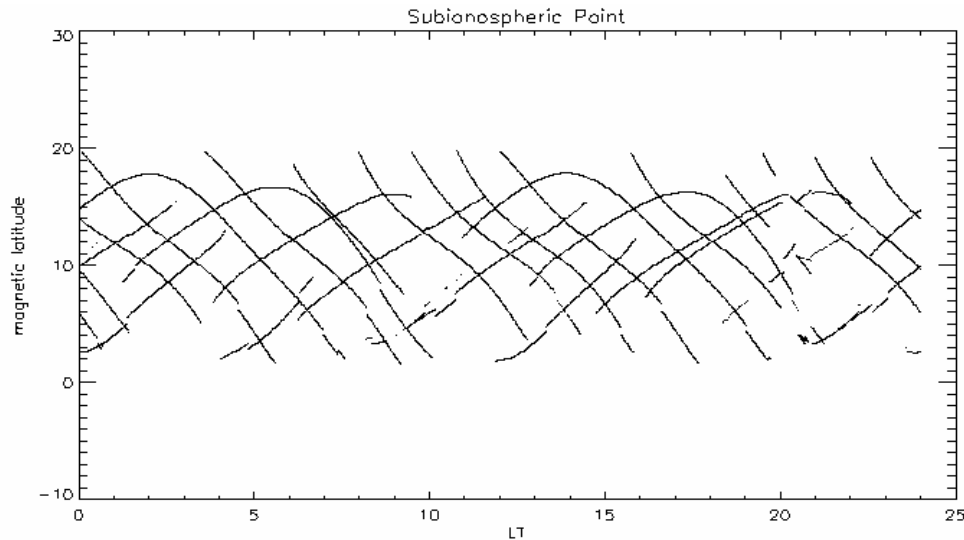
Pre-calculated biases b 's are available in CDDIS (Crustal Dynamics Data Information System) at the Internet. Simpler methods to obtain the biases are to assume TEC of about 3-5 TECU at vertical nighttime data (about 4 AM local time), or, to assume no TEC gradients (fixed zenith TEC value) over an arc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

SATELLITE AND RECEIVER INSTRUMENTAL DELAYS



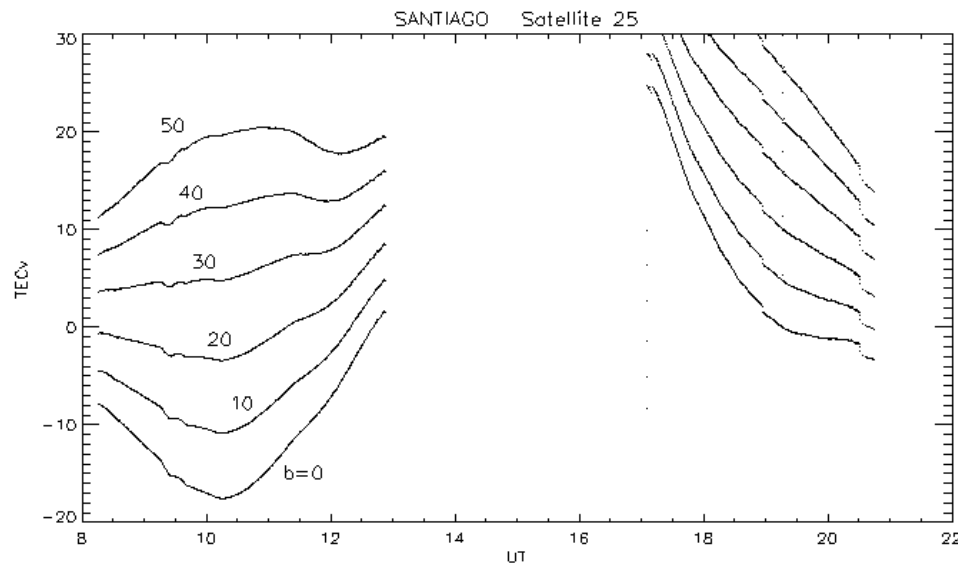
Histogram of satellite and receiver instrumental delays in nanoseconds and in UTEC (10^{16} electrons / m²).

SUBIONOSPHERIC POINT



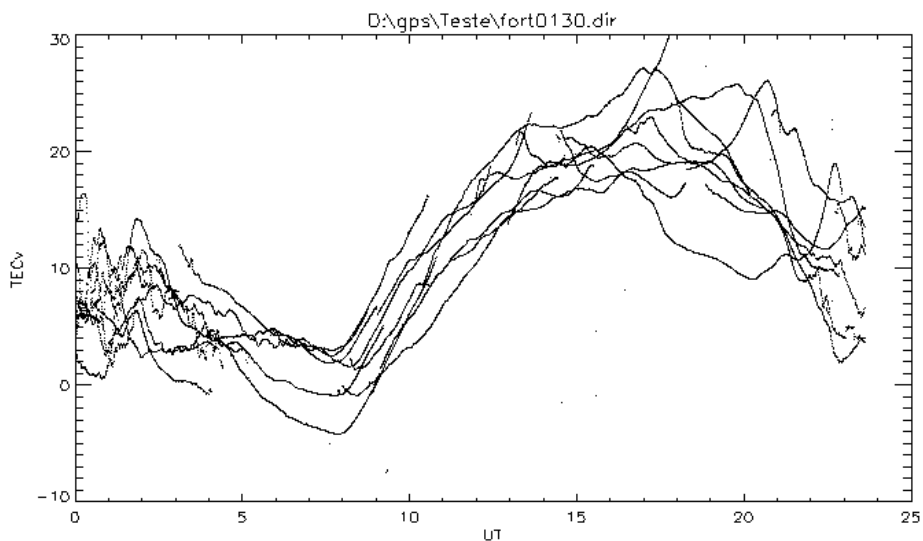
Trajectory of the subionospheric point for all satellites with magnetic latitude and local time for Kouru station.

Other Methods for obtaining Satellite Instrumental Delays

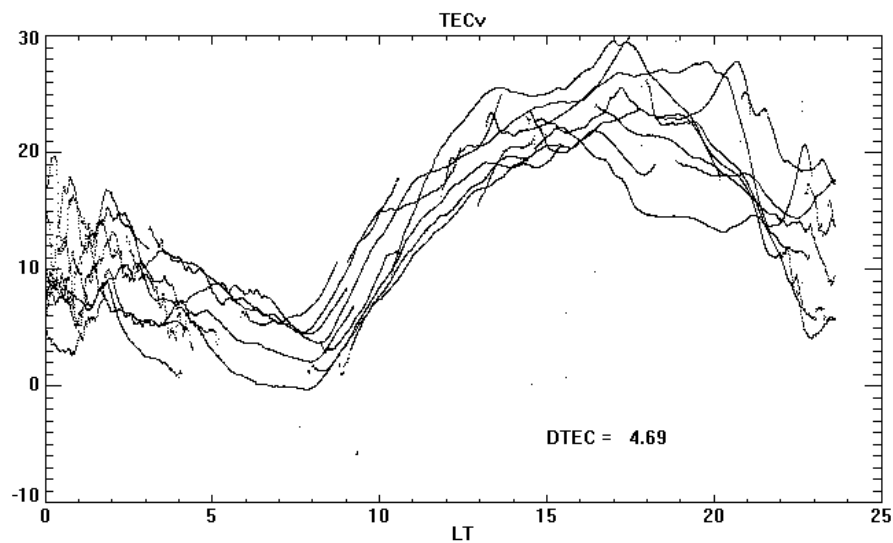


Variation of TEC if b would change, presenting U shape variation. Varying the delays b 's, vertical TEC curve will vary its shape from \cap to \cup (U-shape variation).

Plot of $I_{r,s}(LT)$ for several satellites. Fortaleza 13 January 1997



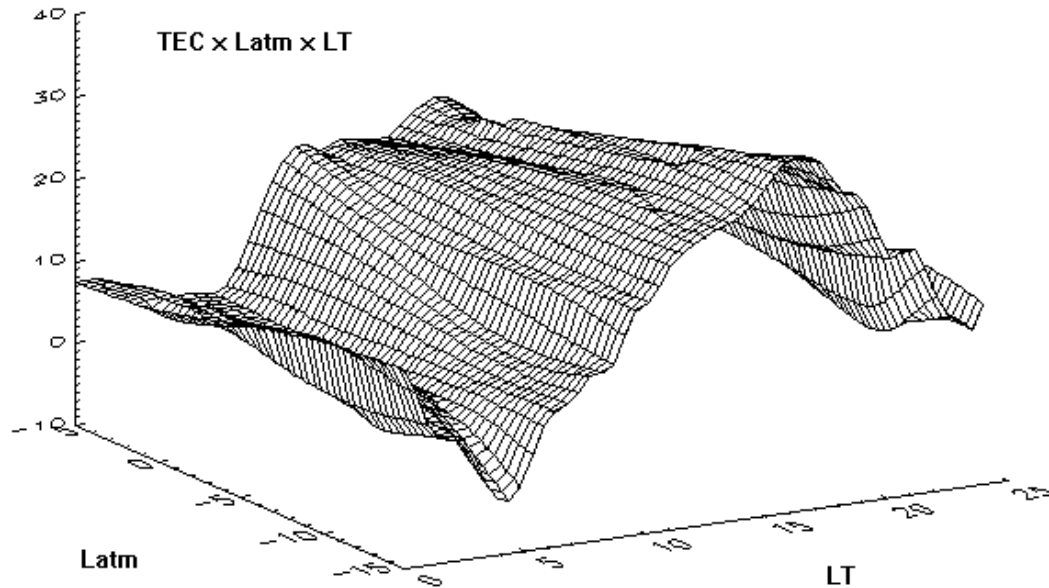
Instrumental delays, $br + bs$ are not included.



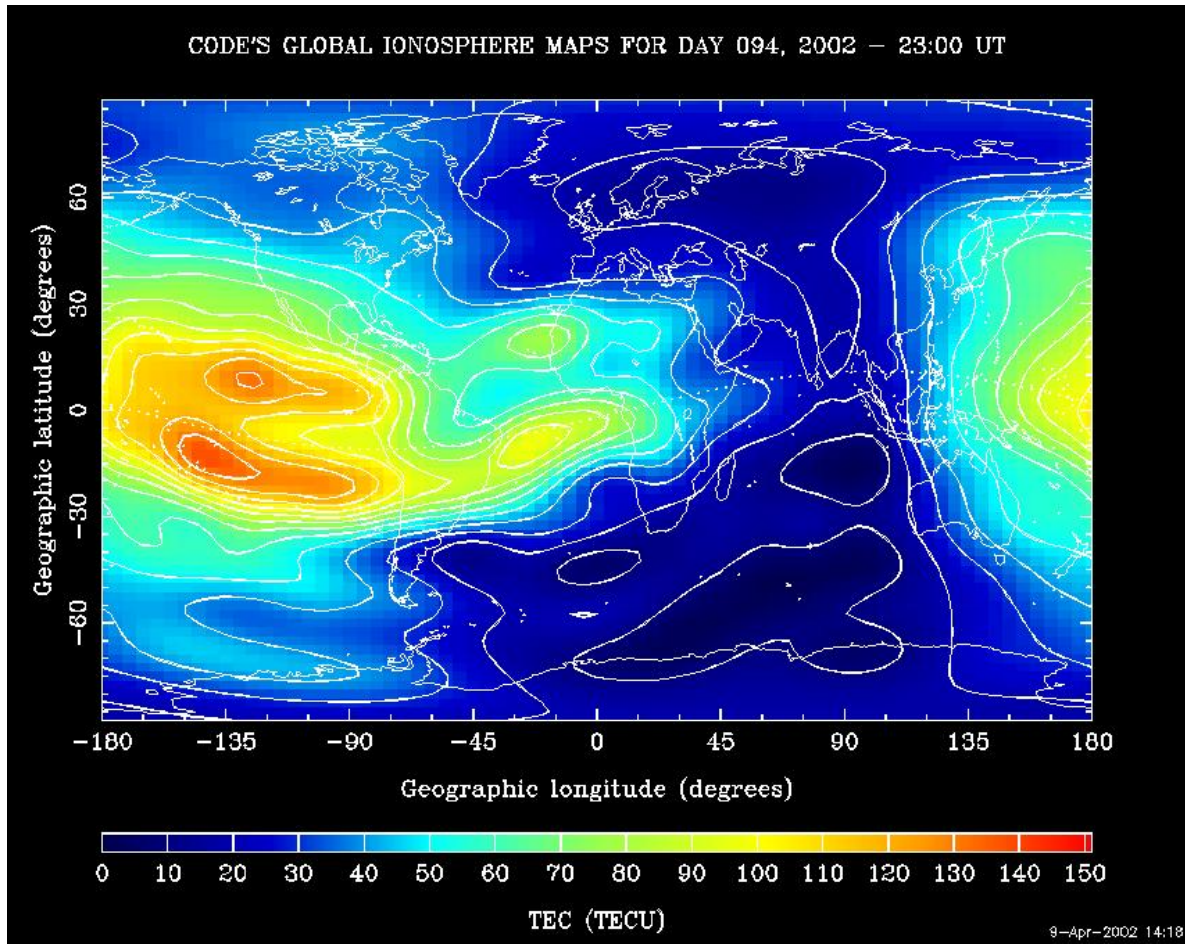
Instrumental delays, $br + bs$ using "similitude" are included, showing smaller dispersion of data and values above zero.



Plot of TEC (magnetic latitude, local time)
around Fortaleza (13 January 1997),



Example of a TEC contour map of CODE's Global Ionospheric Map, in geographic latitude and longitude. Day 094, 20:02 - 23:00 UT





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