Imagery of the ionosphere using dense GPS networks

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Introduction

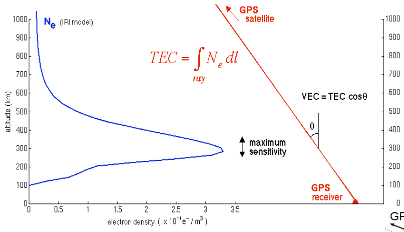
The advent of network-based Global Positioning monitoring System (GPS) represents a significant improvement in ionospheric imagery, allowing to measure the dynamic ionospheric structure over a wide range of scale sizes. The basic observable of this technique is the additional delay due to the refractivity index of a signal when passing through the ionosphere which is proportional to ionospheric electronic density. Dual-frequency GPS gives access to the Total Electron Content (TEC) which is the integral of the local electron density along the path between the satellite and the receiver. These integrated measurements provide two-dimensional cross-section maps of the ionosphere's electron density.

We present here our approach to monitor the TEC using a dense ground networks of GPS receivers and to estimate the instrumental biases (the biggest error source in the estimation of TEC using GPS observations). The maps of the electronic content in the ionosphere are shown for the Japanese (GEONET) and the Californian (SCIGN) GPS networks. The increasing number of GPS data from dense continuous networks allow a performing imagery of the ionospheric structure and to distinguish between spatial and temporal variations in details. We studied the spatial resolution obtained from these existing networks for different correlation lengths and showed that signals with amplitudes as low as 0.1 TECU can then be successfully detected. In the frequency range of 0.1-5 mHz.

The perspectives of this work are significant improvement in mono-frequency satellite measurement, and in GPS and SAR imagery of geophysical phenomena (volcano deformations or subsidence detection). Also, the precise imagery of the ionosphere make possible to detect ionospheric disturbances like geomagnetic storms, ionospheric scintillation and post-seismic perturbations such as Rayleigh waves and tsunamis.

Observation strategy : GPS and TEC measurements

GPS ionospheric sounding technique is a powerful tool for remote sensing of the ionosphere. The measured parameter is the Total Electron Content (TEC), which is the electron density N_e integrated along the satellite-receiver ray path. TEC is expressed in TEC units (1 TECU = 10^{16} e$^-$/m^2), and typical diurnal variation is in the range 10-120 TECU. GPS-based ionospheric measurement can measure TEC variations smaller than 10^{-2} TECU.



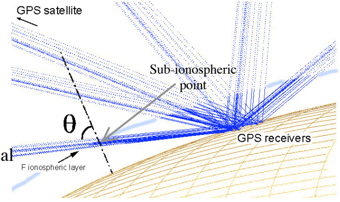
Ionospheric sounding from GPS measurements - Left part shows a typical ionospheric profile (International Reference Ionosphere). Right part shows the "thin shell" approximation made to visualize the data as vertical TEC measurements.

Data processing

In order to obtain the TEC, we process data in three stages :

1. **Decoding raw data files (RINEX format)**
2. **Geometric correction** - We define the vertical electronic content (VEC) as the TEC along a vertical profile intersecting the ionosphere at the Sub-Ionospheric Point :

$$TEC_{vertical} = TEC.\cos(\theta)$$



Geometry of GPS-based ionospheric measurements. Ray paths for 16 receivers and 6 satellites are shown. Each GPS receiver is in visibility with 6 to 10 GPS satellites and collects data with a 30 s sampling interval.

We assume that the ionosphere can be reasonably represented as a single layer at an altitude of 300 km.

3. **Inversion of the instrumental biases and the TEC**

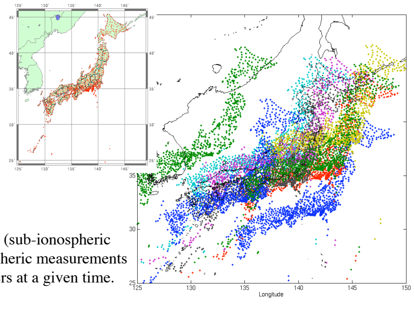
The main sources of error in the estimation of TEC using GPS observations are the differential instrumental biases in the satellites (Transmitter Group Delay - TGD) and in the receivers (Inter-Frequency Bias - IFB). The error induced in path length between the transmitter and the receiver can reach 15 m. Nevertheless, these biases present low variations and can be considered stable over short periods.

We performed a joint least-square inversion of TEC 2D large scale structure and biases, with a Kalman filter in time until a convergence of the estimated biases is obtained.

$$TEC_{rec,sat,t} = \frac{1}{\cos(\theta)}.TEC(t,x_i,y_i) + IFB_{rec} + TGD_{sat}$$

The Japanese GPS Earth Observation Network (GEONET)

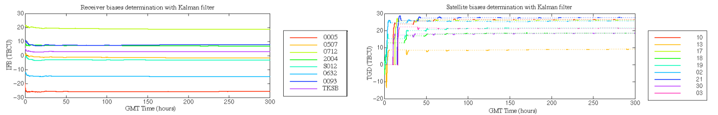
The Japanese GPS permanent network consists of about 1000 dual-frequency receivers, with approximately 25-km mean distance between receivers. TEC values are measured and recorded along more than 6000 satellite-receiver paths over Japan, every 30 seconds.



Piercing points (sub-ionospheric points) for ionospheric measurements from all receivers at a given time.

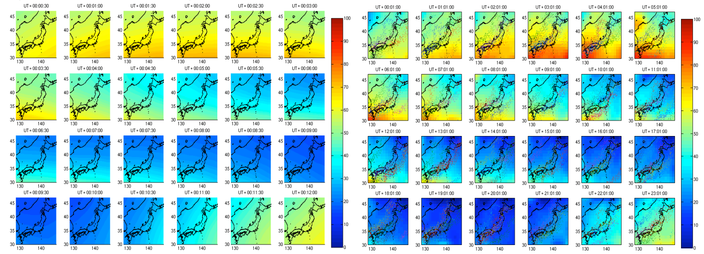
Large-scale structure of the ionosphere

Results of the large-scale inversion of the long-term variation of TEC above Japan and instrumental biases.



Temporal convergence of receiver and satellite biases obtained after inversion.

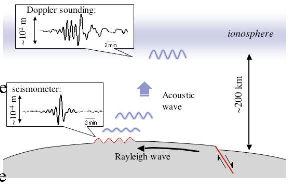
The maps represent the vertical electron content above Japan obtained using GPS data and the IRI model. The global trend seems identical. The deviation could be explained by different solar activity.



International Reference Ionosphere (March 28, 2000) GPS data (March 28, 2000)

Dense GPS networks allow to obtain a very large number of measurements even above oceans and thus to perform a imagery of the electron content in the ionosphere with a high temporal and spatial resolution.

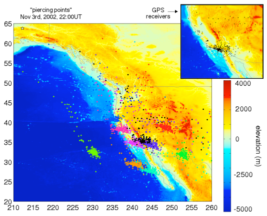
Imagery of Rayleigh surface waves in the ionosphere



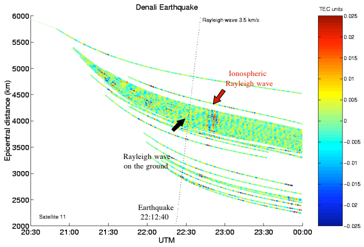
Solid Earth - atmosphere coupling at teleseismic distances.

After large earthquakes, the vertical displacement due to Rayleigh waves propagation induces upward-propagating acoustic waves in the atmosphere through continuity of displacement at the surface. The amplitude of the atmospheric wave increases exponentially with altitude, and leads to large vertical oscillations in the upper atmosphere. No significant attenuation is found below 150 km of altitude, hence the amplification of the wave can reach a factor 10^5 in the lower ionosphere. A displacement of 1 mm peak-to-peak on the ground leads to oscillations larger than 100 m at 150 km of altitude.

Signal observed after Alaska Denali fault earthquake (M_s=7.9, Nov. 3 2002)



Piercing points for ionospheric measurements from all receivers in California (SCIGN + IGS). Different satellites are shown with different colors. The black star shows the epicenter location for Denali earthquake.



Band-pass filtered TEC time series between 150 and 350 seconds from satellite 11, plotted as a function of time and distance to the epicenter. The black dashed line represent a typical Rayleigh wave on the ground.

We observe a signal two to three times larger than the noise level presenting the expected horizontal velocity and arrival time. The group velocity of the wavefront of the ionospheric disturbance is parallel to the Rayleigh wave group velocity. The time delay of 15 minutes between this line and the TEC signal corresponds to the expected propagation time of an acoustic wave from the ground up to 300 km of altitude.

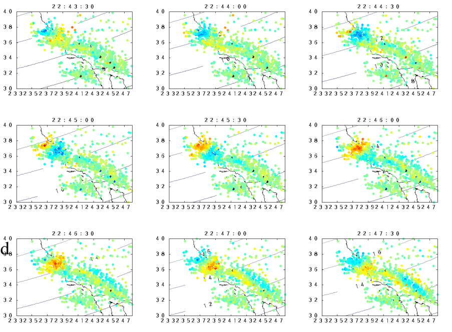


Image of the wavefront in the ionosphere (sub-ionospheric points).

Conclusion and perspectives

Our study shows that dense GPS networks enable the recording of the two-dimensional structure of the ionosphere with a sufficient resolution to detect post-seismic disturbances. The TEC observations revealed spatial and temporal evolutions of post-seismic disturbances in the ionosphere, consistent with previous observations and numerical modeling after shallow earthquakes. This work represents a significant improvement in ionosphere imagery resolution allowing investigating other sources of ionospheric perturbations (like geomagnetic storms or ionospheric scintillation) as well as the study of acoustic-gravity waves and coupling processes in the atmosphere. It is particularly suitable for space weather research and applications.