Detection of ionospheric shaking and heating after the Hector Mine earthquake

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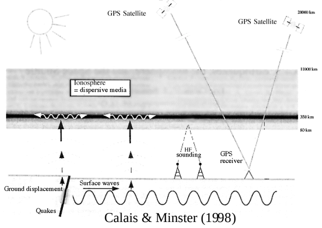
Introduction

Various ground-based or satellite observations have shown strong perturbations of the ionosphere after earthquakes.

The observed signals can be explained by the propagation of pressure waves in the atmosphere, generated by the ground displacement near the source or due to Rayleigh waves. Since the atmospheric density decreases exponentially with altitude, the wave amplitude increases exponentially as it propagates towards the ionosphere, and can reach several tens of meters for M > 6 earthquakes.

At ionospheric heights, these low frequency acoustic waves interact with the ionospheric plasma and induce variations in the electronic density.

Calais & Minster(1995) have observed post-seismic disturbances on TEC (Total Electron Content) measurements, obtained from dual-frequency GPS sensors.



Calais & Minster (1998)

Dense networks provide an opportunity to image ionospheric perturbation with high space and time resolution. We developed a data processing technique in order to take advantage of two dense networks deployed in California and Japan.

We present here the first results for the Southern California network, after the M 7.1 Hector Mine earthquake (October 16, 1999), showing perturbations of TEC above the epicenter due to a direct effect of the wave and long-term heating.

- **Ionospheric perturbations**

The post-seismic effects are of two types in the ionosphere :

– The direct perturbation in electron content due to the wave. The induced perturbation has the same characteristics as the seismic pressure wave (horizontal and apparent velocity similar to the Rayleigh wave, whereas vertical parameters are those of an upward propagation acoustic wave. For a 100 s period wave, the vertical wavelength will be about 30 km and the horizontal wavelength will be 300 km.

– Heating related perturbation due to energy dissipation - attenuation of seismic pressure waves in the upper atmosphere and ionosphere should lead to an increase of thermal energy, mostly above the epicenter.

- **Observation strategy : GPS and TEC measurements**

The radio signals transmitted at 1227,60 MHz (f_2) and 1575,42 MHz (f_1) by the GPS satellites are dispersively delayed by the propagation through the ionosphere. In geodetic applications, we use this property to remove the ionospheric delay from GPS data.

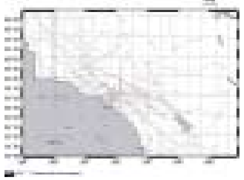
Conversely, using the phase and group delay recorded at both frequencies by GPS receivers, we construct an observable to measure the TEC (Total Electron Content) in the ionosphere :

$$TEC = \int_{satellite}^{receiver} N_e . ds$$

where N_e is the local electron density. The TEC is measured in units of TECU. 1 TECU represents 10^{16} electrons per square meter.

- **The Southern California Integrated GPS Network (SCIGN)**

The Southern California continuous network consists of about 250 dual-frequency receivers. Each GPS receiver tracks about 5 to 12 satellites at each time over a site, and collects data with a 30 second sampling interval.



Dense GPS networks allow to obtain a very large number of measurements over a given area with a high temporal resolution, and thus to perform real-time cartography of the electron content in the ionosphere. Such dense coverage of continuous GPS receivers should provide a sufficient space resolution to detect small scale ionospheric perturbations as those produced by earthquakes.

Data processing

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

1. ***Decoding raw data files (RINEX format)***
2. ***Geometric correction***

$$TEC_{vertical} = TEC_{slant} * m = TEC * \cos(\theta)$$

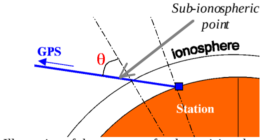


Illustration of the geometry for determining the vertical electron content

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 (*Mannucci et al.*, 1998).

The receiver and satellite instrumental biases are estimated simultaneously with the TEC by inverting the following observable :

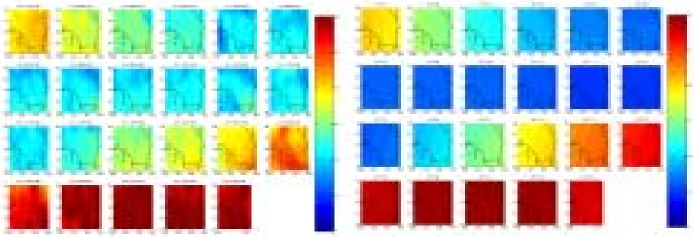
$$d_{rec,sat,t} = TEC_{slant}(t) + IFB_{rec} + TGD_{sat}$$

and by applying a Kalman filter which is an iterative process of inversion/prediction.

- **Hector Mine earthquake (M 7.1 , 9:46 GMT, October 16, 1999)**

Long-term validation

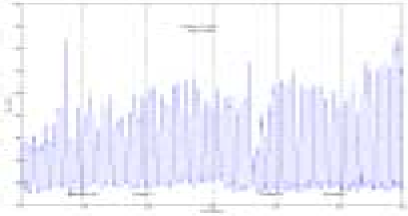
By using dual-frequency GPS, and after geometric corrections we obtain the TEC computation for October 16, 1999.



(a) GPS data (b) International Reference Ionosphere (IRI)

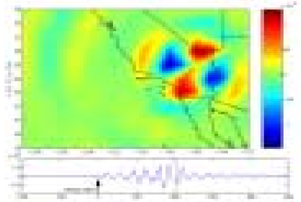
The maps represent the vertical electron content over Southern California obtained by using GPS data and the IRI model. The global trends seem to be identical.The deviation could be explained by different solar activity.

The opposite figure shows the diurnal variation of the vertical electron content during two months (Sept. 16 - Nov. 16 1999).The diurnal profile is associated with the solar radiation (maximum TEC value during the day and minimum during the night).



Modeling of expected signal

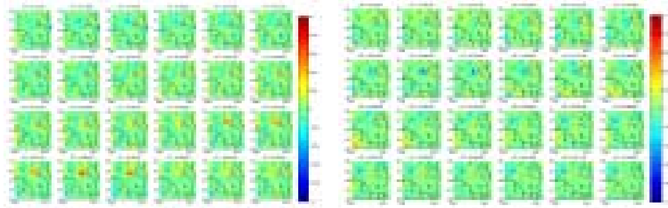
In order to quantify the TEC perturbation that we can expect after Hector Mine, we used normal modes modeling to compute synthetic seismograms in the atmosphere, following Artru et al.We can deduce the variation of TEC by assuming that the electronic density perturbation is proportional to neutral density variation. An integration of the electronic density up to 100 km leads to the TEC perturbation showed on figure.



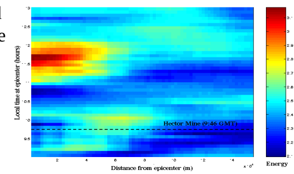
Residuals and energy

$$TEC_{syn}(x,y,t) = \int N_e(z) \frac{\delta\rho(r,t)}{\rho_0(z)} dz$$

To detect small scale perturbations, we have to remove the diurnal variation and the instrumental biases previously determined from TEC measurements and to analyze the residuals. An anomalous signal appears near the epicenter several minutes after the earthquake. This perturbation has a period of about 10 minutes. We didn't identify such perturbation the days preceding and following the earthquake.



We attempted to isolate a signal which propagates from the epicenter by integrating the TEC around concentric circles.The first signal associated to the direct wave appears approximately 20 min after the quake.The second signal, appearing later, corresponds to the long term-heating due to energy dissipation.



- **Conclusion and perspectives**

This work represents a significant improvement in TEC tomography resolution. The Californian continuous GPS networks provide a sufficient coverage to image small scale perturbations as those produced by earthquakes.To determine the characteristics of the post-seismic disturbances in the ionosphere we will apply a spectral analyzes in the k-w domain.These studies will provide new constraints on seism-ionospheric coupling, in the frame of DEMETER mission preparation which objectives are the recording of natural and artificial ionospheric disturbances.
This data processing technique will be applied to the Japanese GPS network.

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