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

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 propagating 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 (f1) and 1575.42 MHz (f2) 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:

\[ TEC = \int_{\text{ionosphere}} N_e \, ds \]

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.

Data processing

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

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

\[ \Delta TEC = TEC_{\text{true}} - TEC_{\text{model}} \]

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

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 analysis 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.

References: