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Ionospheric remote sensing of the Denali Earthquake Rayleigh surface waves

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[1] Using the Global Positioning System, we have detected ionospheric disturbances associated with the long-period Rayleigh waves from the 2002 Denali earthquake ($M_s = 7.9$). The dense California GPS networks allowed us to map the ionospheric perturbations and to compute the group velocity with a high spatial resolution above the Pacific coasts. Due to a low sampling rate, a large error in the velocity determination remains. Nonetheless, it demonstrates that bi-static remote sensing measurements of seismic waves with GPS networks can be performed. Monostatic measurements with a dedicated satellite could possibly be used to record in the ionosphere surface waves originating from large earthquakes. Such a space-based remote sensing of the local group velocity of Rayleigh surface waves would effectively complement the seismic networks for high-resolution global tomography of the Earth's lithosphere. *INDEX TERMS:* 2435 Ionosphere: Ionospheric disturbances; 2487 Ionosphere: Wave propagation (6934); 7218 Seismology: Lithosphere and upper mantle; 7255 Seismology: Surface waves and free oscillations; 7294 Seismology: Instruments and techniques. **Citation:** Ducic, V., J. Artru, and P. Lognonné, Ionospheric remote sensing of the Denali Earthquake Rayleigh surface waves, *Geophys. Res. Lett.*, *30*(18), 1951, doi:10.1029/2003GL017812, 2003.

1. Introduction

[2] Tomographic images of the lithosphere and upper mantle are based generally on the inversion of surface wave group or phase velocities [e.g., *Larson and Ekstrom*, 2001]. These models are however severely limited by the non homogeneous distribution of stations and seismic sources. Only a few seismic stations have been deployed at the bottom of the oceans [e.g., *Petitt et al.*, 2002], which cover about 70% of the Earth's surface, and only a few are permanently installed on islands, where they face generally large micro-seismic noise levels. A second limitation, inherent to the phase or arrival time of surface waves, is related to the accumulation of the seismic information along the source to receiver path. A specific inversion (called regionalization) must therefore be performed in order to retrieve from the set of seismograms a worldwide map providing the velocity perturbations of Rayleigh and Love surface waves. Even if waveform inversions have the potential to retrieve with a significant sensitivity remote small scales structures, these two issues and computational requirements limit the resolution of present tomographic models of the oceans. For a review of the inversion of surface waves, see *Romanowicz* [2002].

[3] In this paper, we propose a strategy to complement the data produced by seismic networks with new measurement techniques. These measurements are based upon space remote sensing techniques, and provide a direct measurement of the local group velocity of Rayleigh waves by imaging the wavefront in space and time. Such local group velocities constrain directly the Earth structure beneath the observation locations and can provide measurements over the oceans.

[4] After large earthquakes, the vertical displacement due to Rayleigh wave propagation induces upward-propagating acoustic waves in the atmosphere through continuity of displacement at the surface (Figure 1). The amplitude of the atmospheric wave increases exponentially with altitude, and leads to large vertical oscillations in the upper atmosphere and ionosphere. These effects have been observed and described since the 1960s [e.g., *Bolt*, 1964; *Yuen et al.*, 1969]. See *Blanc* [1985] for a review. Two types of measurements can be performed: (1) Doppler sounding [e.g., *Tanaka et al.*, 1984], which provides the vertical velocity of the ionosphere [*Artru*, 2001] at the reflection altitude of the sounding electromagnetic signal; (2) Total Electron Content measurements. The latter were used by *Calais and Minster* [1995] and *Afraimovich et al.* [2001] to record the electron density perturbations near seismic sources.

[5] In order to assess the sensitivity of Total Electron Content measurements for detecting seismic wave in the ionosphere and measuring surface wave group velocity, we have used existing dense GPS networks to sound the ionosphere. We have detected the long-period Rayleigh wave signal from the November 3, 2002 Denali Alaska earthquake (Ms = 7.9) on a multitude of stations from the California GPS networks (SCIGN, BARD and IGS), covering the western United States. Although the signal is weak and limited to the low-frequency part of the seismic signal,

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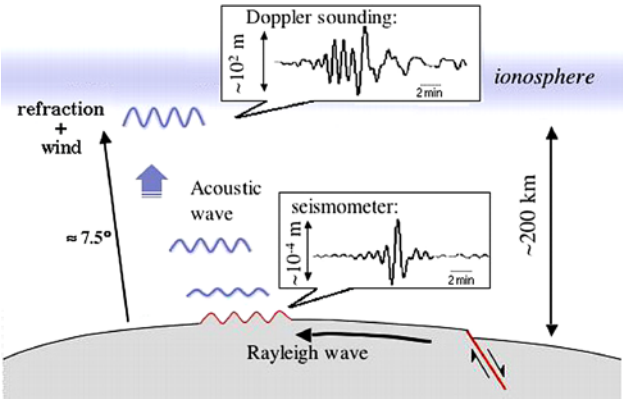

Figure 1. Solid Earth atmosphere coupling at teleseismic distances. Propagation of the signal with time, adapted from *Calais and Minster* [1995]. Data show the vertical displacement in France after the Izmit earthquake recorded on a seismometer (SSB station, Geoscope, France) and by the Francourville Doppler sounder, at an altitude of about 170 km. The refraction due to vertical variations of the sound speed as well as horizontal winds, shifts by 30–45 km the ray from its surface location.

it can be easily identified from its propagation properties. We were also able to determine, by cross-correlation, the altitude where the signal maximized and to extract from these signals the first map of Rayleigh waves obtained with ground-space measurement techniques.

2. Solid Earth Atmosphere Coupling

[6] Due to the coupling between the atmosphere and the solid Earth, Rayleigh surface waves cause atmospheric disturbances that propagate upward toward the ionosphere. The propagation of these waves is efficient down to a high pass cutoff frequency of about 3.7mHz [*Lognonné et al.*, 1998]. As for surface waves, their apparent horizontal velocity is in the range of 3–4.5 km/s. Such a velocity is much larger than acoustic waves with a sound speed reaching a maximum of 900 m/s at 400 km altitude or than gravity waves, also observed in the ionosphere with GPS [*Calais et al.*, 2003]. A main feature of the atmospheric Rayleigh signal, due to the exponential decrease of density with altitude, is an exponential increase of the perturbed velocity field. Such amplification is due to the conservation of kinetic energy. At very long periods (100 sec or more) no significant attenuation below 300 km is found and the amplification of the wave can reach a factor 10^5–10^6 [*Farges et al.*, 2002]. A 1 mm peak-to-peak displacement at the ground level leads to oscillations larger than 100 m at an altitude of 150 km and makes the perturbations observable with remote sensing techniques. Detection can then be performed at teleseismic distances for most earthquakes of magnitude higher than Ms = 6.5 using Doppler sounders [*Farges et al.*, 2002] which can detect vertical ionospheric velocities of a few m/s. Rayleigh waves have been also observed by GPS techniques, which measure the variations in the Total Electronic Content (TEC) of the ionosphere [*Calais and Minster*, 1995; *Afraimovich et al.*, 2001]. Recently, modeling of these waves, either for TEC variations [*Davies and Archambeau*, 1998] or Doppler variation [*Artru et al.*, 2001; *Farges et al.*, 2002] were successfully performed.

3. Remote Sensing Method

[7] We present here a first step toward remote sensing seismology by using the dense GPS network of California. The GPS ionospheric sounding technique is indeed a powerful tool for remote sensing of the ionosphere [e.g., *Mannucci et al.*, 1998]. The measured parameter is the Total Electron Content (TEC), which corresponds to the electron density integrated along the satellite-receiver ray path, and is given as $TEC = \int_r^s N_e(r)dx$. TEC is expressed in TEC units (1 TECU = 10^{16} el.m^{-2}) and varies daily from 10 to 100 TECU.

[8] In most of this study, offsets due to electronic biases and diurnal variations are suppressed by high-pass filters. For the determination of the TEC absolute value, we have however performed an inversion of the electronic biases [*Artru*, 2001]. We have also taken into account the zenith angle θ of the ray by using vertical TEC: VTEC = TEC $\cos\theta$ as an approximation valid for the long wavelengths of the 200 sec surface waves (about 700 km). We used mainly data from the California GPS Networks (SCIGN+BARD+IGS). Due to the oscillating character of waves, their detection with any integrated parameter, like electronic content, is challenging. However GPS-based ionospheric measurement can measure TEC variations smaller than 0.01 TECU in the frequency bandwidth of surface waves, which is equivalent, for example, to a 1% variation in the F2 peak electron density, integrated 10 km along the ray. And because a receiver is generally visible from 6 to 10 GPS satellites, we can achieve a high number of measurements throughout the western United States, including over the Northern Pacific coast (Figure 2).

4. Signal Observed After the Denali Earthquake

[9] The November 3, 2002 Alaska earthquake (Ms = 7.9) gave us an opportunity to perform a successful remote sensing of Rayleigh waves. Figure 2 shows the TEC time series for one of the GPS satellites. A band-pass filter between 150 sec and 350 sec corresponding to a central period of 225 sec close to the Airy phase of Rayleigh waves was applied. Data are here plotted as a function of time and epicentral distance. We observed a signal two to three times larger than the noise level, arriving about 660–670 sec after the arrival time of Rayleigh waves at the ground. The amplitude of the perturbation varies from satellite to satellite, but the signals are consistent and were observed on 6 others satellites in visibility. The total electron content (about 60 TECU at this local time) is found to be perturbed by about 0.1% (0.05 TECU peak to peak). The dashed line represents the arrival at the ground level of a typical seismic Rayleigh wave traveling at 3.5 km/s from the epicenter. Such propagation is also observed on the ionospheric map compiling all observations (Figure 3).

[10] In order to determine the altitude of the signal, we selected all satellite-station pairs with rays drawn closer than 100 km at a given altitude. We then computed the mean cross-correlation of these pairs for altitudes up to

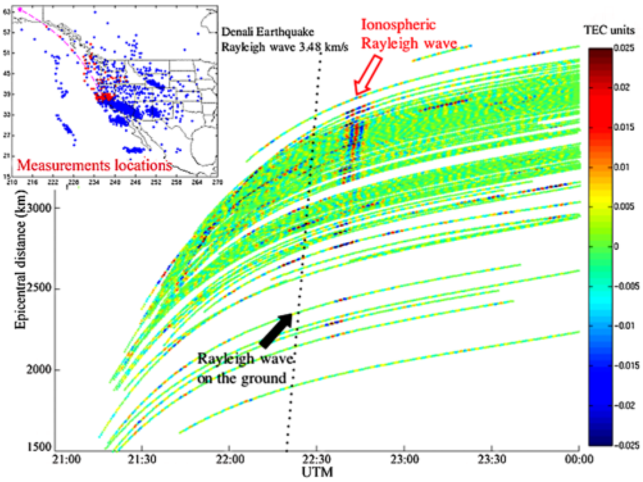

Figure 2. TEC time series from satellite 26 as a function of time and distance to the epicenter. The TEC data were obtained from the difference of the two GPS carriers propagation times and then band-pass filtered between 150 sec and 350 sec. Each trace corresponds to the TEC obtained with a given GPS station at the sub-ionospheric point. The satellite elevation is about 35–40 degrees at the time of signal observation. The positions of the sub-ionospheric point are obtained from re-processed satellite coordinates with a 30 sec sampling. The black dashed line represents the arrival time on the ground, for a surface wave propagating at 3.5 km/s. Differences in arrival times might be related to lateral variations. On the top left: Piercing points (blue dot) for ionospheric measurements from all receivers in California and all satellites. The purple star shows the epicenter location for Denali earthquake and the red dots are the position of the sub-ionospheric point shown.

400 km. A maximum correlation of 0.8 is found for an altitude of 290–300 km, which is slightly more than the modeled altitude of maximum ionization, in the range 280–285 km after IRI [*Bilitza*, 2001] at the local time of observations. However, non local effects, such as plasma transport effects along the Earth's magnetic field or ionospheric wind effects might weaken the horizontal coherency of the signals. We have estimated the atmospheric propagation time by using ray theory and the NRLMSISE-00 Neutral Atmosphere Empirical Model with wind model HWM93 [*Picone et al.*, 2002], and found values of about 630 sec to reach the maximum of ionization and 30–40 sec more to reach the altitude where the perturbation maximizes. Such a delay of about 660–670 sec is approximately found in the observed signals. The offset due to ray bending and wind is typically in the range of 30 to 45 km for these empirical models, and therefore only a fraction of the wavelength of 200 sec surface waves.

5. Remote Mapping of the Group Velocities

[11] To obtain the Rayleigh waves group velocities we determined the arrival times of waveforms. For each satellite a reference waveform was first computed and assigned with a reference time. The waveform was obtained from the stack of all traces, each of them being first re-aligned with respect to a high signal to noise ratio trace. For all traces, the group delay was then computed by a direct cross-correlation with the reference waveform. The local group velocity was then estimated by a least square fit of the arrival time versus epicentral distance (after correcting from atmospheric propagation and the movement of the GPS satellites) for all pairs of data closer than 2 degrees. Such least-squares are more noise sensitive than a classical regionalization but do not depend on the reference time or on the earthquake time.

[12] The results are shown on Figure 4, superimposed on the absolute TEC structure. The obtained mean group velocity is 3.48 km/s, about 2.5% below the PREM value at 225 sec [*Dziewonski and Anderson*, 1981]. Such value is confirmed by a global map of Rayleigh Group velocities [*Larson and Ekstrom*, 2001]. The obtained variance of GPS measurements is 0.40 km/s, too large to be related to Earth lateral variations. This is probably due to the insufficient 30 sec waveform sampling, which corresponds to a group delay of about one degree of propagation.

[13] Some distortion of the signal might also be related to horizontal variations in the ionospheric structure as well. Indeed, the group velocities show an East-West trend,

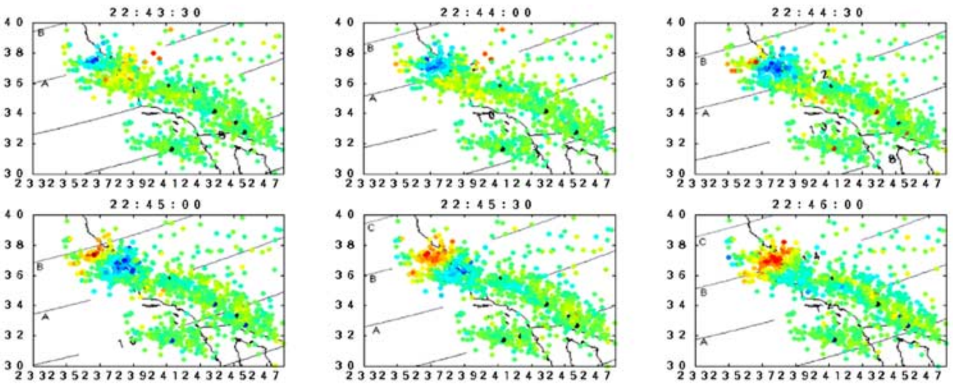

Figure 3. Images of the wavefront in the ionosphere every 30 sec. The solid lines A, B and C are at a constant epicentral distance from the epicenter and propagate at 3.5 km/s. 225 sec surface waves have a wavelength of about 7 degrees and about half a wavelength is observed on the north-western portion, corresponding to the ionosphere sounded by SCIGN stations with a low elevation GPS satellite. With the oscillating character of the acoustic waves and the TEC integration along ray, the signal is weaker for vertical elevation and therefore above the South California Network.

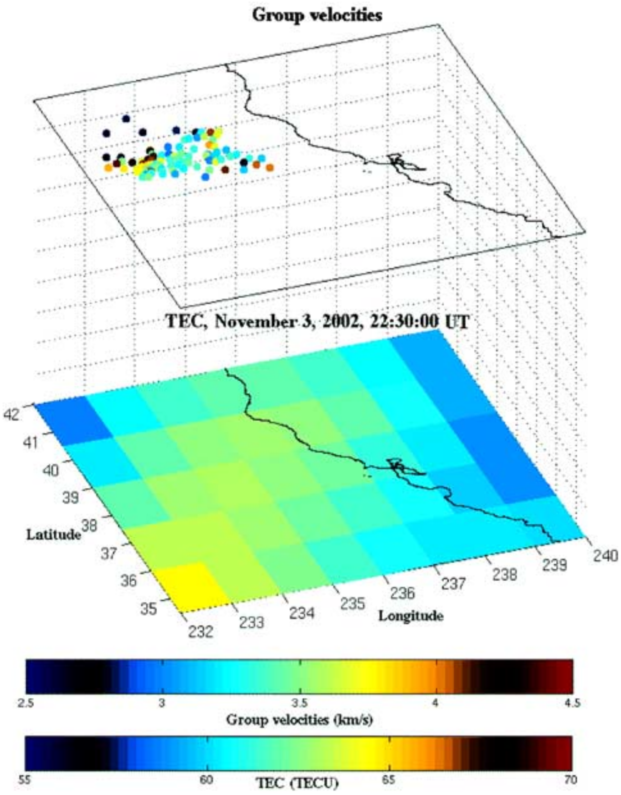

Figure 4. Group velocities found for cluster of measurement over the northern Pacific Ocean. Below is the TEC structure of the ionosphere, obtained by TEC tomography when the surface waves reach the ionosphere.

observed not only on regional tomographic models, but also, due to coincidence in the local time of observation, in the ionospheric structure.

6. Conclusion

[14] After the Denali earthquake, dense GPS networks in California detected an ionospheric perturbation related to the atmospheric acoustic waves associated with Rayleigh waves. The signal observed on ionospheric maps has a group velocity consistent with seismic tomographic models of the Earth even if noise, related to the low sampling rate of GPS receivers and the likely ionospheric distortion, make the obtained group velocity maps useless for lithospheric tomography purpose. We however believe that higher density GPS networks, especially with 1 Hz sampling rates, can image more efficiently the ionospheric perturbation produced by the Rayleigh wavefronts. These data might be used in the future to obtain the local group velocity over the oceans and could then constrain the velocity lateral variations of the Pacific lithosphere near California and Japan. Mono-static TEC measurements (i.e., with a sounding signal not only emitted but also received by the satellite) are already performed from space, for example with the Topex-Poseidon satellite. A mono-static TEC imaging satellite with a kilometer scale resolution in the ionosphere surface will be a major step toward a global imaging of these waves. This would allow a remote sensing from space of the electron density perturbations related to the Rayleigh waves of large Earthquakes and, after data processing, global high resolution maps of the shear modulus of the Earth's lithosphere.

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