Geophys. J. Int. (1998) **132,** 191–202

Ionospheric signature of surface mine blasts from Global Positioning System measurements

Eric Calais,[1] J. Bernard Minster,[2] Michelle A. Hofton[2] and Michael A. H. Hedlin[2]

[1] *CNRS Géosciences Azur, Sophia Antipolis,* 250 *rue A. Einstein,* 06560 *Valbonne, France. E-mail: calais@faille.unice.fr*
[2] *Scripps Institution of Oceanography,* 9500 *Gilman Dr., La Jolla, CA, USA*

Accepted 1997 August 29. Received 1997 August 28; in original form 1997 April 28

SUMMARY

Sources such as atmospheric or buried explosions and shallow earthquakes are known to produce infrasonic pressure waves in the atmosphere. Because of the coupling between neutral particles and electrons at ionospheric altitudes, these acoustic and gravity waves induce variations of the ionospheric electron density. The Global Positioning System (GPS) provides a way of directly measuring the total electron content in the ionosphere and, therefore, of detecting such perturbations in the upper atmosphere. In July and August 1996, three large surface mine blasts (1.5 Kt each) were detonated at the Black Thunder coal mine in eastern Wyoming. As part of a seismic and acoustic monitoring experiment, we deployed five dual-frequency GPS receivers at distances ranging from 50 to 200 km from the mine and were able to detect the ionospheric perturbation caused by the blasts. The perturbation starts 10 to 15 min after the blast, lasts for about 30 min, and propagates with an apparent horizontal velocity of 1200 m s^{-1}. Its amplitude reaches 3×10^{14} el m^{-2} in the 7–3 min period band, a value close to the ionospheric perturbation caused by the $M = 6.7$ Northridge earthquake (Calais & Minster 1995). The small signal-to-noise ratio of the perturbation can be improved by slant-stacking the electron content time-series recorded by the different GPS receivers taking into account the horizontal propagation of the perturbation. The energy of the perturbation is concentrated in the 200 to 300 s period band, a result consistent with previous observations and numerical model predictions. The 300 s band probably corresponds to gravity modes and shorter periods to acoustic modes, respectively. Using a 1-D stratified velocity model of the atmosphere we show that linear acoustic ray tracing fits arrival times at all GPS receivers. We interpret the perturbation as a direct acoustic wave caused by the explosion itself. This study shows that even relatively small subsurface events can produce ionospheric perturbations that are above the detection threshold of the GPS technique. By sensing derivative signals, which can be detected over a relatively broad region, it appears that GPS might be particularly useful for source characterization within the first acoustic quiet zone where infrasound would probably be ineffective. This suggests that dual-frequency GPS monitoring could contribute to Comprehensive Nuclear Test Ban Treaty verification.

Key words: acoustic–gravity waves, GPS, ionosphere, Nuclear Test Ban Treaty verification.

INTRODUCTION

Near-surface sources causing large vertical near-field displacement of the Earth's surface, such as strong earthquakes or explosions, are known to excite atmospheric infrasonic waves (see Blanc 1985 for a review). Such a piston-like ground displacement generally excites acoustic and gravity oscillation modes that propagate laterally and upwards, away from the source (Fig. 1). These perturbations eventually reach the ionospheric layers, where the coupling between neutral atmosphere and ionized plasma results in fluctuations of the ionospheric electron density. Since the atmospheric density decreases almost exponentially with altitude, energy conservation implies that the pulse amplitude increases upwards as it propagates into the atmosphere. For a near-surface source, for instance, the amplification factor can reach 10^4 at ionospheric

© 1998 RAS

GJI000 22/1/98 13:12:34 3B2 version 5.20
The Charlesworth Group, Huddersfield 01484 517077

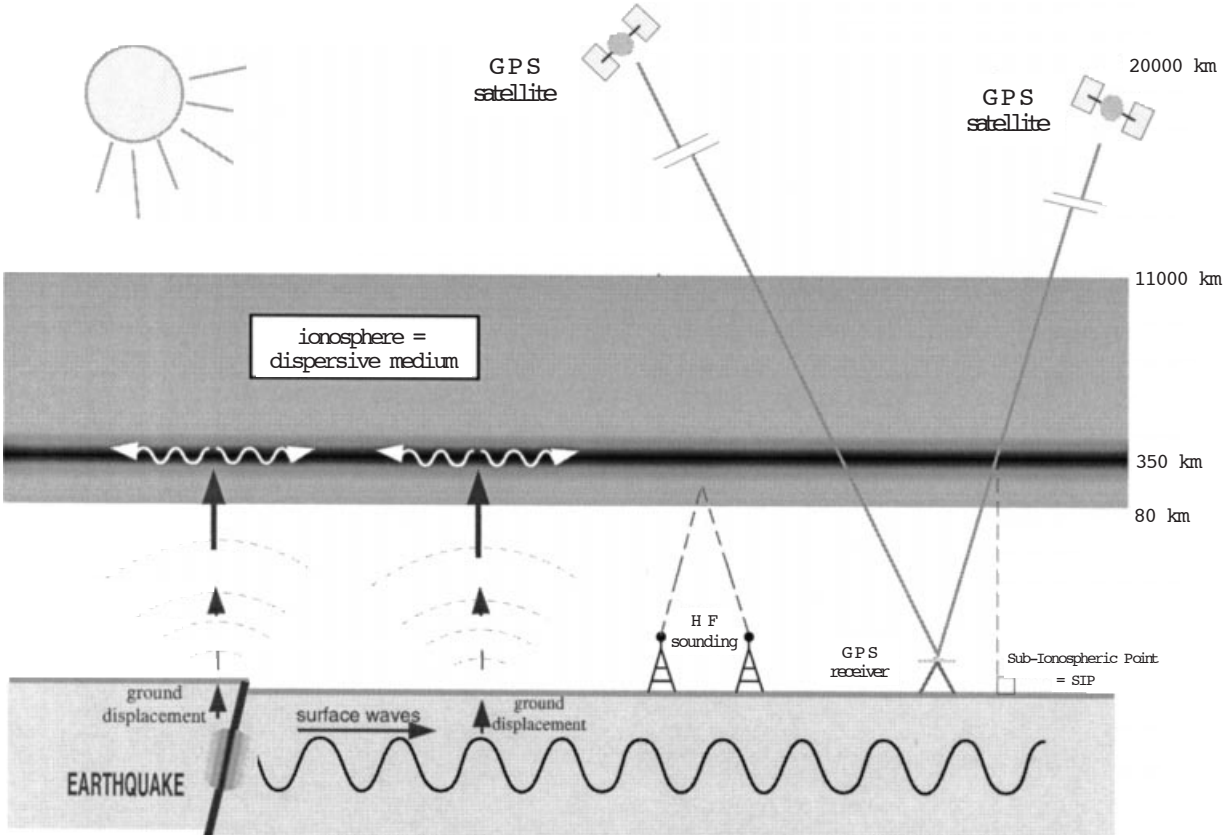

Figure 1. Schematic diagram showing the excitation mechanism of atmospheric waves caused by a near-surface seismic source (earthquake or explosion).

heights. Detection of ionospheric disturbances is generally conducted using ground-based HF sensors that probe the ionosphere below the peak electron density level (Fig. 1). The Global Positioning System (GPS) provides a way of directly measuring the total electron content (TEC) in the ionosphere (Klobuchar 1985) and, therefore, of detecting acoustic and gravity perturbations which affect the entire ionosphere (Calais & Minster 1995, 1996).

The current state of the art in GPS technology allows measurements of changes in the TEC of about 2×10^{14} el m^{-2} (Calais & Minster 1995, 1996), which corresponds to a change of the radio-signal path length of about 5 mm. Numerical modelling indicates that a 600 t surface explosion (similar to the Mill Race test) can induce TEC changes of 3×10^{15} el m^{-2}, or about 30 cm of path length change (Warshaw & Dubois 1981; Davies & Archambeau 1994). These theoretical models predict a large initial pulse that decays in amplitude with time, followed by oscillations of 3 to 5 min periods that can last for several tens of minutes (Davies & Archambeau 1994). Such a scenario is within the detection capability of the current GPS technique. Moreover, since the characteristics of ionospheric waves are a function of their source (see Table 1), one can expect to discriminate between different sources by analysing their signal characteristics as revealed by the GPS data.

Table 1. Seismic-source discrimination through the joint use of seismic-, acoustic- and indirect-atmospheric-wave sensing using electromagnetic measurements (passive or active) for events of small seismic magnitude ($m_b < 4$) with the same low-frequency *P*-wave amplitude. According to this table, a quarry blast is expected to produce an acoustic wave of larger amplitude than an underground explosion of the same seismic magnitude. On the other hand, an earthquake should produce a smaller ionospheric disturbance than an underground explosion of the same seismic magnitude (C. Archambeau, personal communication, 1994).

	Tamped nuclear test	Decoupled nuclear test	Industrial explosion	Shallow earthquake
Regional high-frequency seismic-*P*-wave signal	moderate/large	large	small/moderate	small
Near-regional acoustic signal	small/undetect.	undetect.	large	undetect.
Ionospheric electromagnetic sounding	small	undetect.	large	small/undetect.
Secondary ionospheric EM emissions	small	undetect.	large	small/undetect.

GJI000 22/1/98 13:13:21 3B2 version 5.20
The Charlesworth Group, Huddersfield 01484 517077