SEMEP

Search for Electro-Magnetic Earthquake Precursors

A model for the low-frequency seismo-electromagnetic turbulence

Deliverable 2.2

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SUMMARY

Task 2.1 showed evidence of an increase in the ULF wave power measured by DEMETER prior to the Sichuan earthquake. Task 2.2 investigates possible sources for this increased noise such as changes in the geomagnetic environment, the inner magnetosphere or terrestrial sources.

Results from the satellite observations of plasma turbulence induced in the Earth's ionosphere and the magnetosphere by an acoustic wave arising from man-made and natural ground sources are presented. These results include those collected from Areol 3 and Dynamics Explorer spacecraft. Theoretical qualitative models of the phenomena are developed. It is argued that acoustic waves may be a source of ionospheric turbulence that can give rise to various plasma micro-instabilities and the generation of EM waves.

1 INTRODUCTION

The results of Task T2.1 showed that there was an increase in the level of ULF plasma waves observed by the DEMETER satellite as it flew in the vicinity of the Sichuan and l'Aquila earthquake epicentres. Whilst this increase may be related to the enhanced levels of seismic activity it is important to investigate and eliminate as far as possible other potential sources of the disturbances. In Task 2.2 three other potential sources for the increase in ULF wave noise were considered, namely two magnetospheric sources - changes in geomagnetic activity and a general increase in ULF wave activity in the inner magnetosphere, and one terrestrial source – the generation of acoustic waves.

2 MAGNETOSPHERIC SOURCE

Plasma waves in the inner magnetosphere may result from effects such as magnetic storms and substorms. Therefore it is important to eliminate these as sources for the increase in wave activity discussed in Task 2.1. The state of the magnetosphere

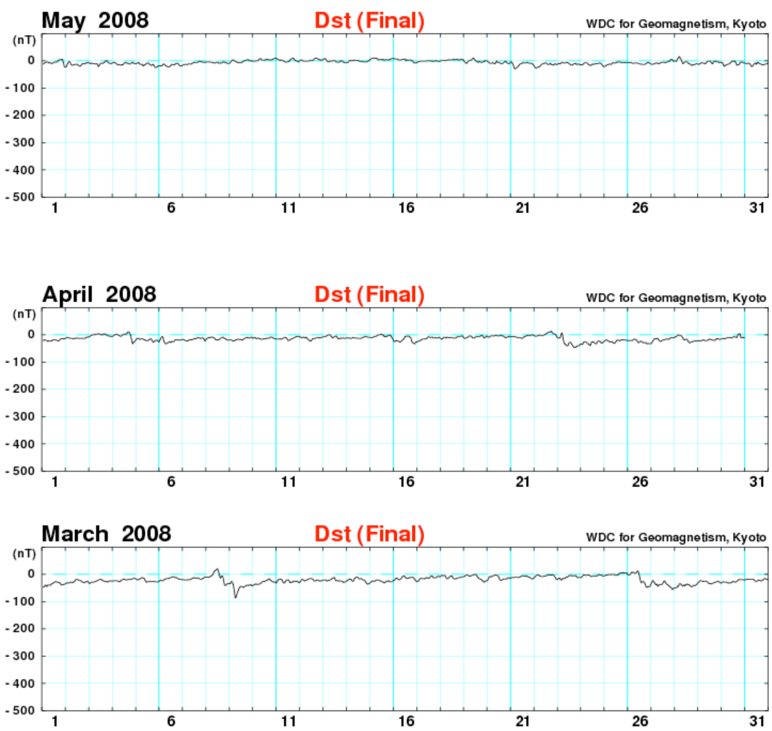

Figure 1: Variation of the geomagnetic Dst index in the run up to the Sichuan earthquake (May 12th, 2008).

maybe quantified by a set of geomagnetic indices, in particular the Dst index. Magnetic storms and substorms result from the interaction between the terrestrial magnetosphere and the solar wind. Processes on the surface of the Sun such as Coronal Mass Ejections and solar flares may result in the expulsion of large clouds of particles travelling at high speed. These particle clouds propagate through the inner solar system and, depending upon the direction of propagation, may collide with the Earth's magnetospheric cavity. This increase in the pressure of the solar wind will compress the Earth's magnetic field and, depending upon the orientation of the magnetic field within the partible cloud, inject particles into the magnetosphere via processes such as reconnection. Both of these interactions cause increased electric fields, which result in an increase in the transport of plasma within the magnetosphere via electrical currents. These increased currents will also add to the changes observed in the magnetic field at the surface of the Earth. The magnitude of these changes is usually quantified through the use of geomagnetic indices and in particular the Disturbance Storm Time index (or Dst) (Sugiura 1991). This index is typically around ±20nT during quiet periods. However, during a magnetic storm it may take values in the range -100nT and below, possible reaching -400nT in the case of a severe storm. In addition to indicating the onset of the storm the Dst is also useful in showing how the magnetosphere recovers after such an event.

Figure 1 shows the variation of the Dst index during the two-month period leading up to the Sichuan earthquake (May 12th, 2008). Throughout this period Dst stays above -100nT. This value indicates that the magnetosphere is geomagnetically quiet with no storms/substorms occurring. Hence it appears that it is highly unlikely that the increase in ULF electric field strength is due to geomagnetic sources.

A second possibility for the source of these waves may be due to a general increase in the level of plasma waves in the inner magnetosphere due to the natural occurrence of instabilities within the plasma that result in the generation of waves that may then propagate to lower altitudes. This idea was investigated by analysing changes in the electric field measured by the Cluster satellites. During the period in question (March-May) the apogee of the Cluster satellites lay on the night side, mainly in the pre-midnight sector at a distance of around 2-3Re.

Error! Reference source not found. shows the electric field measured by the EFW (Gusthafsson et al., 1997) instruments on board the Cluster satellites (Escoubet et al., 1997) 1-4 (coloured black, red, green and blue respectively). These measurements represent the mean (top) and standard deviation (bottom) of the electric field measured in the nighttime sector inside a distance of 5Re measured from the beginning of February to the end of May 2008. As can be seen from this figure, the mean and variance vary from orbit to orbit and in some cases between the different satellites on the same orbit. For most of this period, the means were fairly constant, around a level of $6mVm^{-1}$ until a few days before the earthquake at which point the means reduce to around $2mVm^{-1}$. This effect may be due to the earthquake precursory activity or could easily represent the general variability of this parameter. In order to provide a comparison for the results shown in Figure 2 similar plots were calculated for the same periods for the previous (2007) and following (2009) years. Data from the same period in 2007 showed that the mean fluctuated around $4mVm^{-1}$ for the whole period with a typical standard deviation of $3mVm^{-1}$. In contrast, this period in 2009 proved to be particularly quiet with mean electric fields of $1mVm^{-1}$ and standard deviation of $0.5mVm^{-1}$ until the beginning of May after which the results were similar to those shown in previous years.

Thus, there is no evidence that the average level of the electric field within the

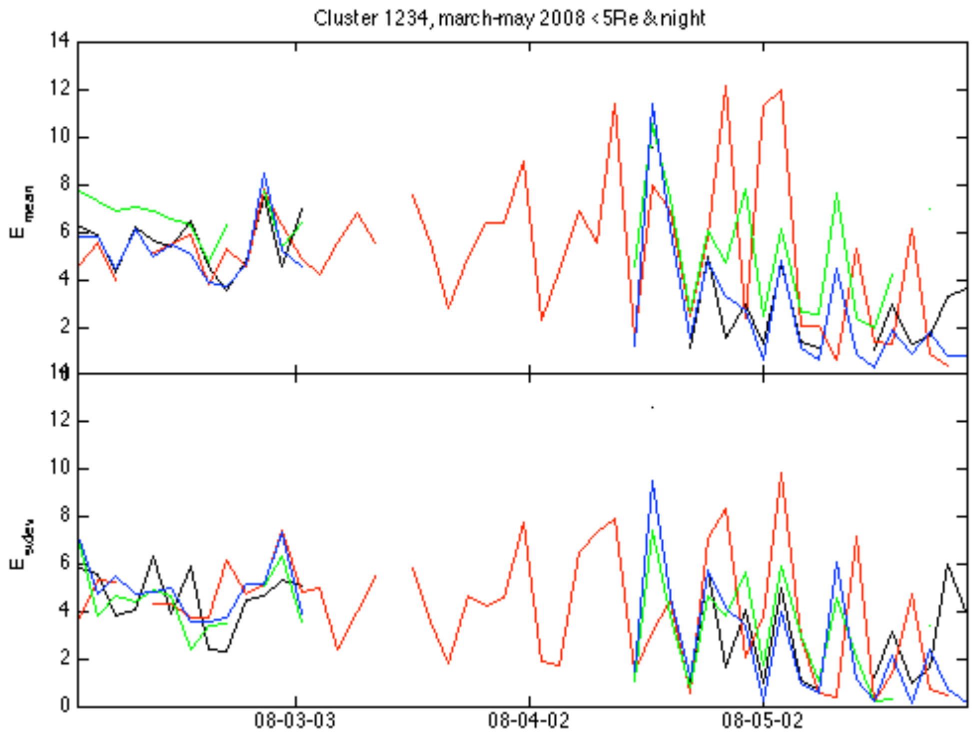

Figure 2: Orbital averages of the electric field measured by the EFW instrument on Cluster 1 (black), 2 (red), 3 (green), and 4 (blue) during the period leading up to the Sichuan earthquake.

inner magnetosphere undergoes a steady increase in the period leading up to the Sichuan earthquake and so it appears that the wave energy observed by DEMETER does not correspond to waves observed further out in the magnetosphere.

It should also be pointed out that due to its orbit Cluster and Sichuan were rarely collocated at the same local time. Therefore, no changes localised observed in the electric fields could be attributed to the increase in ionospheric electric fields observed by DEMETER.

3 TERRESTRIAL SOURCES

As far as terrestrial source of these ionospheric perturbations are concerned, there are two possible sources – Internal (or Atmospheric) Gravity Waves and Acoustic

Waves. Since the properties of gravity waves are discussed wthin the reports of other workpackages we will concentrate here on the possibility of Acoustic Waves as being the source of the observed ionospheric perturbations.

3.1 Acoustic Waves

The effects of ionospheric turbulence triggered by man-made and natural sources of acoustic waves have been widely studied. These events, which can result in the emission of a substantial amount of wave power, can be triggered by either man-made (explosions, rocket launches) or natural (earthquakes, volcanic eruptions, hurricanes, magnetic storms) sources. Such effects have been reviewed in several articles (e.g., Blanc and Rickel, 1989; Liperovsky et al., 2008). Although there are many studies dealing with the influence of large-scale disturbances due to man-made impacts upon the ionosphere, observations of ionospheric turbulence stimulated by such events are rather scarce. In what follows we describe the experimental data that provide support for their role in the generation of turbulence in the Earth's ionosphere and magnetosphere.

In the acoustic range of spatial-temporal scales, the level of natural ionospheric turbulence is considerably lower than that due to IGW (internal gravity waves) and therefore the effects due to any man-made sources will be more pronounced. A key step in the investigation of ionospheric turbulence stimulated by an acoustic wave came about as the result of a series of experiments using powerful explosions in Russia and the USA. The data used to characterise the turbulent processes occurring within the ionosphere during explosions come from two sources, either ground-based radio sounding of the lower ionosphere or satellite observations of the upper ionosphere.

The largest volume of data relating to the modifications of ionospheric turbulence due to acoustic waves was obtained during the Minor Scale experiment in New Mexico on June 21st, 1985 (Blanc and Rickel, 1989). This experiment used two explosions, the first a weak 1T yield was then followed by a second 4.8 kT yield explosion, the largest since the nuclear test ban was introduced. This pair of explosions enabled a comparison between the linear and nonlinear responses of the ionospheric plasma. Radio sounding of the ionosphere at different distances from the source was performed using a network of stations employing slightly oblique Doppler sounding and vertical pulse radio sounding units operating simultaneously at four frequencies. The experiment demonstrated that the acoustic front generates small-scale turbulent structures. The excitation of ionospheric turbulence was observed both at the location above the explosion point and at distances of the order of several hundreds of kilometres from it. At heights corresponding to the sporadic E-layer one could observe fragmentation of the inhomogeneities with typical spatio-temporal scales of 2-10 km and 1-2 s.

Plasma turbulence was also detected in the lower part of the F-layer. The mechanism for the formation of turbulence in the F-layer is still not clear. In fact, two processes are plausible. The first is associated with turbulence of the neutral component of the ionosphere. The most probable region for its generation could be at heights at which nonlinear acoustic beams are focused. The second mechanism involves the transfer of turbulent motion in the dynamo-region by vertical currents. These experiments confirmed that there was a possibility for part of the wave front to propagate horizontally along the ionospheric E-layer within in the inhomogeneous upper atmosphere. The propagation also occurred with supersonic speed. Indirect evidence for the effects of ionospheric turbulence above the regions of acoustic activity can be given by the correlation between the occurrence of increased radio signal fading and the earthquakes whose epicentres lie close to the radio propagation path (De and Sarkar, 1984).

3.2 Satellite Observations Of Ionosperic Turbulence

A most convincing argument in favour of the possible transformation of acoustic disturbances into electromagnetic oscillations was given by the results obtained from the Russian series of MASSA (**M**agnetosphere-**A**tmosphere Coupling during **S**ei**s**mic Imp**a**ct Alperovich et al., 1983) experiments. These experiments were carried out with the aim of studying the effects of industrial impacts upon the ionosphere. The MASSA experiment provided experimental evidence that, in addition to generating acoustic and internal gravity waves, magnetohydrodynamic (MHD) modes can also be excited in the ionosphere. However, the most striking and unexpected effects were recorded by the Aureol-3 satellite (Galperin et al., 1985). Around 298 s after a ground explosion Aureol-3 recorded an anomaly in the electromagnetic field whose magnetic field component registered an amplitude of 120 nT whilst at an altitude of 800 km and distance 700 km south of the explosion site. The polarization characteristics of the anomaly corresponded to an Alfven mode. The satellite also recorded a short pulse of noise in the range 10-450Hz lasting for 1.5s simultaneous with the Alfven pulse. This pulse consisted of electrostatic oscillations limited from above by a frequency of 500 Hz (the proton gyrofrequency at that location was 520 Hz). At higher, ELF frequencies (0.1-1 kHz) an increase in the intensity of electrostatic noise with a longitudinal component of the electric oscillations was observed over an extended region of around 100 km. This pulse was not observed at frequencies in the range 450-1000 Hz.

Whilst the satellite was crossing field lines magnetically connected to the site of the explosion a localised region of intense electrostatic turbulence in the frequency range 50-5000 Hz was encountered. Similar results were obtained from observations of electromagnetic noise in the frequency range 0.1-1 kHz by the Aureol-3 satellite during a series of subsequent active experiments employing powerful industrial explosions. Thus, these observations confirmed the original conclusion of the emergence of a “noisy” spot in the upper ionosphere as the satellite passed within 200km of the magnetically connected field lines (Galperin et al., 1985). Since the magnetic components of these oscillations were negligible, these perturbations could be considered as being electrostatic. According to measurements, these oscillations persisted up to 35 min after the explosion. It was concluded that the ionospheric region in which these intense electric field oscillations were observed was extended due to the propagation of waves at the acoustic wave speed (0.6 km/s) in the E-layer.

Thus, the MASSA experiments demonstrated the possibility for the occurrence of several cascades which transform the acoustic oscillations into different types of electromagnetic waves together with a redistribution of their energy into the higher frequency part of the spectrum. Constructing physical models for such processes is very difficult due to the complexity involved in the theoretical problems as well as to the fact that all the recorded effects were practically unique events.

Another interesting response to ground based explosions comes from observation by the satellite DE-2. The experimental program of this satellite was focused on plasma and electromagnetic measurements at auroral latitudes in the ionosphere and magnetosphere. During its period of operation, underground nuclear explosions were regularly conducted at the Nevada test site (Gokhberg et al., 1990), providing a source of acoustic noise. DE-2 performed electromagnetic measurements as it crossed flux tubes conjugate with the explosion location within one hour after the explosion. The analysis of the DE-2 magnetometer data did not reveal the existence of any magnetic pulses whose amplitudes exceeded the instrument interference level (10 nT) during periods when it was magnetically connected to the site of the explosion, a result similar to that of Aureol-3 during the MASSA experiment. This seems rather natural if one takes into consideration that the magnetic pulse would propagate at the Alfven speed away from the generation region. In addition, no anomalies were detected in the data from the measurements of the large-scale ionospheric potential or in the recording by the wave spectrometer in the VLF range (1-512 kHz).

The single events described above cannot be considered to be a final proof of the existence of electric field oscillations generated by acoustic wave sources.

Nevertheless, these investigations are of a certain value since they can show possible trends in future specialized satellite experiments.

3.3 Model Of The Electromagnetic Turbulence In The Upper Ionosphere

The model described below assumes a scenario in which a series of consecutive processes occur. The intense acoustic pulse reaches the current-carrying ionosphere E-layer 5-6 min after the acoustic impact. This pulse induces localized ionospheric currents that are closed by the field-aligned currents in the conjugate region of the ionosphere. In the magnetosphere the disturbance propagates along the field lines at the Alfven speed. At heights where the total electric current exceeds the threshold value necessary to excite a high-frequency instability, the traveling magnetic pulse will leave behind a "spot" of electrostatic noise that slowly dissipates due to diffusive processes.

Different aspects of the generation of the electric currents and geomagnetic disturbances due to acoustic impact upon the ionosphere have been considered in a number of papers (e.g., Sorokin and Fedorovich, 1982 and references therein). These authors examined a set of equations for three-fluid hydrodynamics with a pre-assigned oscillatory motion of the neutral component both in the IGW and the acoustic frequency range. The results of these studies may be reduced to a simple conclusion that originates from general physical concepts, namely that the motions of the conducting medium lead to disturbances in the magnetic field b whose value depends on the effective magnetic Reynolds number Re_m and over pressure parameter $\Delta p / p$, i.e. $b / B \approx \Delta p / p$.. Based on this relationship, disturbances of the ionospheric magnetic field may be of the order of several nT. One might think that this value is too small for an appreciable electromagnetic response in the ionosphere due to acoustic impact. Nevertheless, the particular properties of the Earth's ionosphere may lead to a considerable amplification of the observed electromagnetic effects.

These effects do not cover all the possible plasma mechanisms for high-frequency turbulence excitation due to external sources. The plasma micro-instabilities generating small-scale inhomogeneities with a size of the order of, and smaller than, the ion gyroradius, result from the density gradients which could be formed under the action of the acoustic waves. This may result in instabilities such as the universal drift mode, the drift-cyclotron mode or the lower-hybrid drift mode. If the external quasi-static electric field together with a field-aligned electric current are large enough, a gradient drift or current-convective instability can develop.

Another source for microinstabilities is the velocity shear of the plasma flows across and along the magnetic field. Instabilities related to the anisotropy of the distribution function can also result in small-scale fluctuations. In looking for the sources of the excited VLF-surges observed in the vicinity of a flux tube magnetically connected to the source of the acoustic wave, one has also to consider nonlinear mechanisms (Onischenko et al., 2011, 2012; Pokhotelov et al., 2011).

In order to study the interaction of acoustic disturbances due to ground-based impacts and electromagnetic fluctuations in the ULF, ELF and VLF frequency ranges in the lower and upper ionosphere, it is necessary to undertake specialized experiments aimed at producing a comprehensive set of diagnostics of the plasma and the wave fields at different heights to establish the whole coupling chain between the acoustic and the electromagnetic waves.

4 CONCLUSIONS

The experimental data presented in this report show that there is additional turbulence and low-frequency electrostatic noise over locations at which large explosion have occurred. The effects are observable at the heights from the E-layer up to the upper ionosphere (of the order of 1000 km). Experiments employing ground explosions are convenient for simulating natural sources of infrasound such as hurricanes, storms, earth-quakes etc.. The most likely physical mechanism for turbulent noise excitation is the generation of localized field aligned currents by the acoustic oscillations and the subsequent development of current instabilities in the ionospheric plasma. If the experimental data that points to the generation of ionospheric turbulence over a region of acoustic activity and also at its magnetically conjugate region can be confirmed in further investigations, it will imply that there is a much closer relationship between atmospheric phenomena and processes occurring in space plasma than has been believed until now.

Future launches of space vehicles will influence the electromagnetic ecology in the near-Earth geomagnetic medium. Along with powerful acoustic emissions, the engines of launched rockets affect the ionospheric plasma causing “water holes”. This effect can also be accompanied by the emergence of rather long-lived (of the order of 1 h) electrostatic noise in the upper ionosphere. These effects can disturb distant space radio communications due to refraction and scattering of radio waves from the plasma inhomogeneities. Furthermore, it is rather possible that by-product effects of man-made activities can also affect the global processes developing in the Earth's magnetosphere and ionosphere.

5 REFERENCES

Blanc, E. and Rickel, D., Radio Science 24,279 (1989).

De, B.K. and Sarkar, S. K., Ann. Geophys. 2,505 (1984).

Alperovich, L. S., Vougmeister, B. O., Gokhberg, M. B., Pokhotelov, O.A. and Fedorovich, G. V., Dokl. AN SSSR 269,573 (1983).

Escoubet, C.P., Schmidt, R., and Goldstein, M.L., Cluster – Science and Mission Overview, Space Science Reviews 79, 11-32, 1997.

Galperin, Yu. I. et al., IN. AN SSSR (Earth Physics) 11,88 (1985).

Gokhberg, M. B., Pilipenko, V. A., Pokhotelov, 0. A. and Parthasarati, S., Doklady AN SSSR 313,568 (1990).

Gusthafsson et al., The Electric Field and Wave Experiment for the Cluster Mission, Space Science Reviews 79, 137-156, 1997.

Liperovsky, V. A., O. A. Pokhotelov, K.-V. Meister, E. V. Liperovskaya, Physical models of Coupling in the Lithosphere-Atmosphere-Ionospere System before Earthquakes, Geomagn. Aeronom., v. 48(6), 831-843, 2008.

Onishchenko O. G., O. A. Pokhotelov, L. Stenflo, and P. K. Shukla, The magnetic Rayleigh--Taylor instability and flute waves at the ion Larmor radius scales, Phys. Plasmas, v. 18, 022106, 2011.

Onishchenko O. G., O. A. Pokhotelov, L. Stenflo, and P. K. Shukla, J. Plasma Physics, Stabilization of magnetic curvature-driven Rayleigh-Taylor instabilities, v. 78(1), pp. 93-97 DOI: 10.1017/S0022377811000444, 2012.

Onishchenko O. G., Pokhotelov O. A., Stenflo L., Shukla P. K., Finite Ion Larmor Radius Effects in Magnetic Curvature-Driven Rayleigh-Taylor Instability, Joint ITER-IAEA-ICTP Advanced Workshop on fusion and plasma physics, Book Series: AIP Conference Proceedings, v. 1445, doi: 10.1063/1.3701887, 2012.

Pokhotelov O. A. and O. G. Onishchenko, Magnetic curvature driven Rayleigh-taylor instability revisited, Annales Geophysicae, v. 29, pp. 411-413, 2011

Sorokin, V. M. and Fedorovich, G. V., "Physics of Slow MHD Waves in the Ionosphere" ("Energoizdat", Moscow 1982).

Sugiura, M. http://wdc.kugi.kyoto-u.ac.jp/dstdir/dst2/onDstindex.html.