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Could ionospheric variations be precursors of a seismic event? A short discussion

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Abstract
A short review of published papers on the perturbations in the ionosphere due to seismogenic effects is reported. The method to correlate different classes of phenomena as ionospheric variations and subsequent seismic events is discussed. Even if the theoretical attempts to understand or to explain the electromagnetic phenomena in the ionosphere, as precursors of earthquakes are not satisfactory, the reported results encourage further investigations.

Key words *ionosphere – seismic precursors*

1. Introduction

During the last 20 years the study of geophysical phenomena which appear prior to a seismic event is the subject of research of many scientists from different disciplines like geophysics, hydrology, geomagnetism, atmospheric physics, geochemistry, radiopropagation and of course seismology. The result is that many articles dealing with electromagnetic effects and ionospheric effects, associated with earthquake precursors, have appeared in different international journals. Even if this report is mainly related to the possible ionospheric precursors many interesting collections of papers on the electromagnetic effects can be found in special issues as, for instance in *Review of Radio Science* of 1992 and 1996 (Molchanov, 1992; Hayakawa, 1996). We mention, as an example of this large class of studies, the first important paper by Gokhberg *et al.* (1982). This paper reports that a wide band electromagnetic radiation occurred just prior to an earthquake of 7 degree magnitude. After a period of relatively quiet level of the radio noise at 81 kHz, an anomalous amplitude increase of 15 dB higher than the normal level was recorded about one-half hour before the main shock in Japan on 31 March 1981. The amplitude of the radio-noise went to its normal level just after the event. The authors state that the intensity of the electromagnetic radiation is different for different earthquakes because of the dependence of the characteristics of the electromagnetic radiation on various factors like the magnitude of the earthquake, the depth of focus, the geology of the earthquake region, the distance between epicenter and point of observation and the condition of ionospheric propagation. Concerning the anomalous variation of VLF emission associated with strong earthquakes, see also Morgounov *et al.* (1994) and references therein.

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More recently, many publications refer to the modification of the ionosphere parameters due to seismic activity (Pulinets, 1998; Liperovsky *et al.*, 1998; and reference therein. These anomalous modifications within the ionosphere could be registered both by ground-based measurements and onboard satellites. According to Pulinets (Pulinets,1998; Pulinets *et al.*, 1997, 1998, 1999), certain irregularities occurring in the ionosphere are apparently caused by seismic activity and appear prior to the main seismic event. However, variations in electron density, as at the F_2-layer peak heights, seem to be recorded every day and also within-the-hour (Kouris *et al.*, 2000) and can be attributed to different mechanisms (Rodger *et al.*, 1989; Davies, 1990) like tides, winds, gravity waves, travelling ionospheric disturbances and so on. Thus the question arises how to distinguish the variations stimulated by the seismic activity from the other kinds of ionospheric variability. This leads to the important problem that for using ionospheric variability as a precursor of earthquakes, a reliable knowledge of the different kinds of irregularities that appear within the ionospheric plasma is needed to emphasise the typical shape of a seismoionospheric variation.

This paper aims at a short review of the published papers on the perturbations in the ionospheric plasma due to seismogenic effects and discusses the scientific method to correlate different classes of phenomena like variations of some ionospheric parameters and subsequent seismic events.

2. The ionosphere and its measured parameters

The methods and instrumentation used to measure ionospheric electron densities are based on the principle that an electromagnetic wave, propagating vertically into the ionosphere, will be reflected when the refractive index becomes zero

$$n = \sqrt{1 - \frac{80.5\,N}{f^2}} \cong \sqrt{1 - \frac{81\,N}{f^2}} = 0 \qquad (2.1)$$

where N is the electron density at a certain

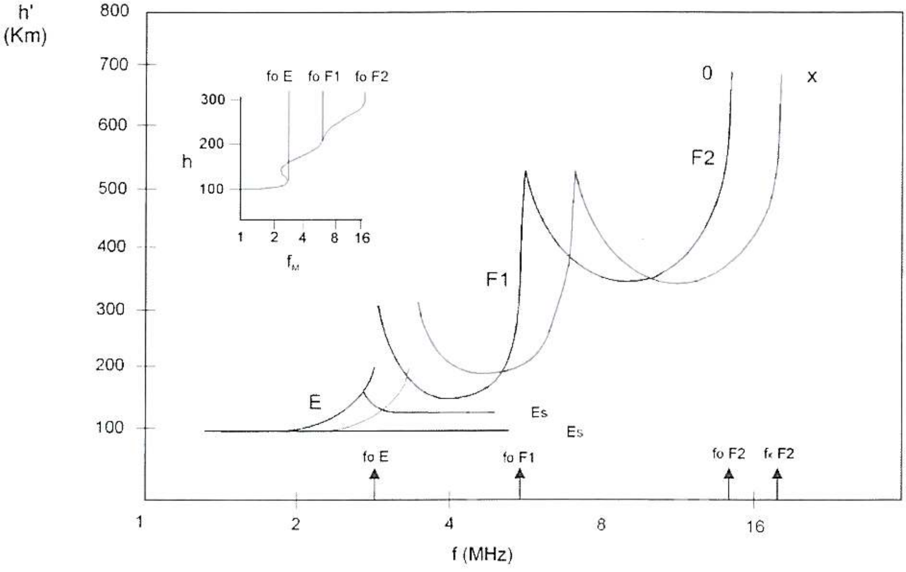

Fig. 1. Sample ionogram: ordinary and extraordinary traces and derived ionospheric parameters. On the upper left corner the reconstructed real electron density profile.

altitude in electrons m^{-3} and f is the incident wave frequency in MHz. The electron density profile *versus* the altitude may be measured using increasing radio-frequency pulses. The frequencies f_0, corresponding to absolute and relative maxima of the electron density N, see fig. 1, called critical frequencies or sometimes plasma frequencies are given by

$$f_0 = 9\sqrt{N_{\max}}\,. \tag{2.2}$$

Each of the ionospheric layers has a specific $N_{\max}$ at a given location and time, and the maximum frequencies at which reflection occurs by the various layers are labelled f_0E, f_0F_1 and f_0F_2 respectively. These critical frequencies are not constant but vary diurnally, seasonally and with the 11-year solar activity. Only monthly median variations are typical and can be modelled and in some instances predicted.

The ground vertical radio-sounder, the ionosonde, is based on radar techniques to detect bottom side electron densities of ionospheric plasma by scanning the transmitting frequency from 1 MHz to about 20 MHz and recording the time delay of any received echo (see fig. 1).

The ionosphere may be also observed by ionosondes boarded on satellite providing profiles above the peak. Satellite measurements are also used to determine the integral of the electron density, along the ray path between the satellite and the receiver, called Total Electron Content (TEC). Profiles of electron densities may be evaluated from TEC using tomography and occultation.

3. Seismogenic effects on ionosphere

The effects on the ionosphere once an earthquake has occurred have been well known for some decades. A first example of the seism ionospheric coupling was the disturbance of the ionosphere caused by the earthquake at Kurile Islands on August 1969. The vertical component of the longitudinal pressure waves, caused by the seismic waves, moved the contours of constant electron density layers (Weaver *et al.*, 1970). These acoustic gravity waves, that propagate upward, present an increasing amplitude as the density of the neutral atmosphere decreases, so that displacements of the order of millimetres on the Earth's surface grow into displacements of the order of kilometres at ionospheric heights.

To evidence precursor phenomena in the ionosphere, the investigation methods proposed in most papers published in the recent past are based on *a posteriori* statistical analysis of the variations of one or more ionospheric parameters, for example the critical frequency of the F_2 layer, anomalous behaviours of the lower layers as the E layer and even the sporadic E layer (Liperovsky *et al.*, 1998; Pulinets, 1998; Pulinets *et al.*, 1998; Krasnov and Chshyolkova, 1999; Chen *et al.*, 1999). These variations of the ionospheric parameters are considered in comparison with a given «normal» or «quiet» ionosphere in a period of time associated with an earthquake.

Recently, Liperovsky *et al.* (1998) analysed many vertical ionograms taken at a distance of 220 km from the epicentre of the Kairakkum earthquake of 1985. This case study seems to confirm previous observations of the authors on the disturbed conditions of the sporadic E-layer parameter *fbEs*, that is the frequency at which the sporadic E layer becomes semitransparent. Such events have been observed two or three days before a strong earthquake of magnitude greater than 5 occurred. The physical mechanisms of the seismoionospheric coupling, used to explain the «anomalous» behaviour of an unpredictable layer like the sporadic E, are very complex. In fact, small turbulences and temperature variations in neutral components generated by acoustic gravity waves caused by seismogravitational vibrations or other electromagnetic phenomena, like electrostatic fields generated by piezoelectric effects, are taken into account in order to explain the variations.

Very promising studies have been performed in the last few years by Pulinets *et al.* (1997, 1999) and Boyarchuk *et al.* (1997), who proposed the following mechanisms to explain the lithospheric-ionospheric coupling:

1) The emanation from the ground of different chemical substances like radon, light gases like helium, hydrogen or submicron and metallic aerosols changes the electrodynamics prop-

erties of the atmosphere over a region originating an earthquake.

2) The generation of an electric field due to an electrode effect in the atmosphere at ground level, in the presence of metallic aerosol emanations, leads to large scale atmospheric electric fields of the order of kV/m.

3) The vertical fields reach the ionosphere and increase by joule heating the electron temperature, generating small scale irregularities in the *E* layer and large scale irregularities in the upper part of the ionosphere, perhaps through acoustic gravity waves, fig. 2 .

They analysed measurements both from topside and ground-based ionosondes and apply mapping techniques to show variations in the ionospheric parameters. Thus, the Kriging (Oliver and Webster, 1990) mapping technique was applied to f_0F_2 data, measured at several ionospheric stations in Europe and f_0F_2 data from satellite, marking anomalous variations in the f_0F_2 frequency in the geographic area close to the epicentre of the earthquake (Pulinets, 1998). Positive or negative variations of the order of 1 to 5 MHz from quiet condition values are observed during night or early morning, two to five days before the first shock occurs.

Finally, Chen *et al.* (1999) presented during the last URSI general assembly a large statistical analysis of strong seismic events preceded by ionospheric precursors by using the above mentioned physical mechanism and different definition of ionospheric variation.

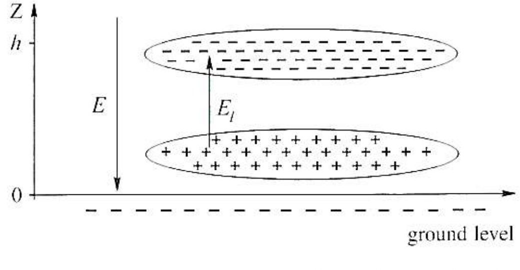

Fig. 2. Schematic representation of the seismic-ionospheric coupling model. *E* is the natural atmospheric electrostatic field which generates a different distribution of the positive and negative ions near the surface and E_l is their electrode field.

4. Ionospheric variability

It is worth mentioning here some results and definitions regarding ionospheric variability. The «median» ionospheric electron density of the different layers and thus their critical frequencies depends strongly on the 11-year solar-cycle variation and the position of the sun and therefore on the hour of day and the season of the year. Changes in ionospheric electrodensity due to various causes not yet well established are also observed.

It is well known that the ionospheric electron density varies from day to day, from hour to hour and within the hour. On the other hand, many physical mechanisms, some of which not well known, are responsible for the ionospheric variability (Rodger *et al.*, 1989). Considering that the ionosphere is never quiet, the definition of a given variation from its «normal» behaviour is very important in these studies (Wilkinson, 1995).

For prediction studies and telecommunication purposes (Kouris *et al.*, 1998) the ionosphere has been defined as «disturbed» when the absolute value of the 3-h average of the relative deviation of f_0F_2 exceeds 0.3 at least once. Periods of time that are not disturbed in this sense are considered «quiet». The end of the duration of a disturbance is assumed to be reached when the absolute value of the 3-h average of the relative deviation of f_0F_2 with respect to the corresponding monthly-median value is not greater than 0.2 and remains so for at least two consecutive three-hour periods (Kouris *et al.*, 1999). However, it is shown (Kouris and Fotiadis, 2000) that for about 40% of the time the variability of f_0F_2 is greater than 10%.

In addition to this natural ionospheric noise, there exist other kinds of intense ionospheric disturbances characterised by various durations and various amplitudes of ionospheric density variability. For example, ionospheric storms are a strong source of ionospheric variability especially in the F_2 layer, lasting from a few to many hours. They are usually associated with magnetic storms even if they can develop independently of each other or occur in unpredictable sequence. In fact, ionospheric storms may have no

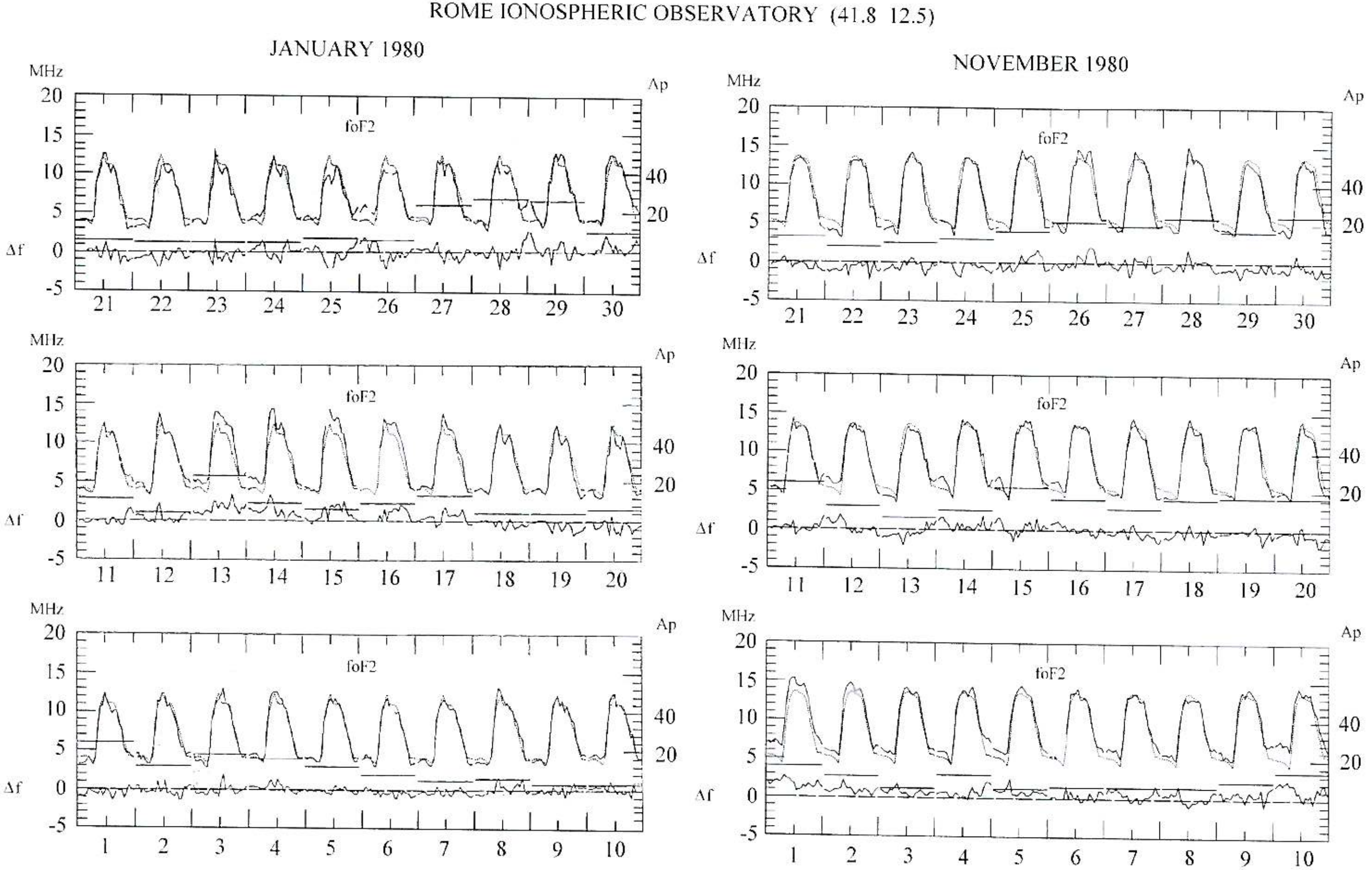

Fig. 3. Hourly values of f_0F_2, continuous line, the monthly median (dotted line) as well as their differences are reported for January and November 1980, when a strong earthquake on 23rd November occurred in Southern Italy close to ionospheric measurements. The magnetic parameter A_p is also drawn to indicate the level of magnetic activity.

relationship with the intensity of magnetic storms and may also occur during magnetically quiet conditions. Ionospheric storms may be different in the same location during similar magnetic storms.

Ionospheric conditions similar to those of the «median» ionosphere of the F_2-layer are actually present only for a small percentage of time in each month (Davies, 1990). Figure 3 reports the hourly values of f_0F_2 (continuous line) the monthly median (dotted line) as well as their differences for January and November 1980, when a strong earthquake on 23rd November occurred in Southern Italy close to the locations where ionospheric measurements were made. The magnetic parameter A_p is also drawn to indicate the level of magnetic activity. In the figure many of the above described cases of variability are present.

5. Discussion and conclusions

Based on a general survey of the various already mentioned papers on electromagnetic and ionospheric phenomena associated with earthquakes, we denote that there exists much experimental evidence on anomalous variations of some ionospheric parameters, alleged to be associated with earthquakes of a given magnitude that are consistent with the generation of a strong electrostatic field. The mapping technique describing the ionospheric variations points out a regional anomaly near in space and time to the epicentre area, while some nuclear weapons tests confirm the major features of the physical mechanism proposed by Pulinets *et al.* (1998).

However, in general it is important to consider the following problems:

a) Many statistical analyses have been performed considering the variations from the median hourly values. This means that the median conditions are considered the normal or quiet ionosphere. Nevertheless this is not completely true because median values were introduced in the past mainly to solve radio propagation links problems but they have a disputable geophysical meaning.

b) Magnetic quiet conditions do not always mean quiet ionosphere. The statistical analysis often refers, except for the last URSI presentation, to case studies or a poor number of seismic events. Many different effects have been considered separately, such as the depletion of f_0F_2, the anomalous behaviour of *Es*, variations in TEC and hmF_2, the height of the maximum electron concentration.

c) Are the effects observed so strong as to overlap «the normal» ionospheric variability caused by many internal or external mechanisms?

d) Considering the large number of earthquakes occurring every year in the planet, may they be considered an important source of the natural ionospheric noise?

e) The physical and chemical mechanisms are very complex so they need a clearer explanation especially where the cause-effect chain is too vague.

f) It is not enough examined the important problem of the history of the ionospheric measurements in a given place. This leads to the usual question for a seismic precursor: how many similar «ionospheric effects» occurred in the past or will occur in the future without any following seismic event?

g) The results reported by the various researchers are of course fascinating and interesting, but it is not clear, for example, how the seismogenic variability can be selected from other non-seismic variations. It is well known that the ionosphere and especially *F*-layer presents a great variability from hour to hour and day to day. Therefore a method of selecting the seismogenic effect should be developed, otherwise the obtained results may be criticised as a sort of «retrospective predictions».

A rigorous statistical method at least implies:

1) Univocal definition of the hypothesis and clear definition of the model, characterising the concerned anomaly or precursor for them to be well recognised in any circumstances by any observer.

2) Observation of a sufficient number of past cases to determine the rate at which the precursor has been followed or not followed by the

target seismic event, or the rate at which a target event has been preceded or not preceded by the precursor.

3) Definition of parameters that maximise successes and minimise false alarms. See the approach to apply the Bayes' criterion as described by Console (1998).

Concluding, it is now clear that the seismic precursors of electromagnetic nature and the possible effects in the ionosphere cannot be neglected and need more investigations in the future. In spite of its interesting physical mechanisms, the ionospheric effect still appears to be one of the numerous precursors that are well recognised only *a posteriori*. This is because the statistical analysis of the ionospheric history of the seismogenic region is not yet convincing. It seems up to now not enough to distinguish those variations caused by a seismogenic action (then really followed by an earthquake) from the very large series of natural variations, given by many unknown causes. An interesting method to define the normal ionosphere has been recently proposed by Belehaki *et al.* (2000). A strong mathematical approach is necessary to compare the two classes of events in order to test their univocal relation. Of course this is valid for every kind of precursors.

Finally, considering the interdisciplinary subject, extreme care should be given to the interpretation of the measured parameters. Data from satellites should be validated by ground-based measurements, and these should be studied by the same people who made the measurements in order to avoid misunderstanding due to instrumentation problems.

Studies and methods, mainly based on complex astronomical phenomena, applied at the beginning of the 18th century, to solve the problem of finding the longitude of a ship a long time after it left the harbour of origin, have been told in a book entitled «Longitude» recently published (Sobel ,1995). Even if much money was given to astronomers and to the British Royal Society, the problem was finally solved by a watchmaker who was able to build watches with no or only very small drift of time.

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