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A REVIEW OF SEISMO-ELECTROMAGNETICS (SEM), AND PROSPECTS FOR SHORT TERM EARTHQUAKE PREDICTION

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SİSMOELEKTROMANYETİK (SEM); BİR TARAMA VE KISA DÖNEM DEPREM KESTİRİMİ DEĞERLENDİRMESİ

ÖZET
Deprem veya yanardağ patlaması gibi büyük bir sismik olayın, birkaç saatten birkaç haftaya varan bir süre öncesinde başlayan ve olaydan sonra benzer sürelerle devam eden bölgeden elektromanyetik dalga yayınımı sismoelektromanyetik (SEM) olarak bilinir. SEM olayları, yüzyılı aşkın bir süredir çeşitli biçimlerde görülmekte ve rapor edilmektedir. Son 20-30 yıldır Dünyadaki çeşitli araştırmacıların daha güvenilir ve bilimsel gözlemleri kayıtlara geçmekte, ancak henuz bütünleşik yeterliğe gözlemleri kayıtlara girmaktedir. Ancak bu veriler henüz bütünleşik ve sistematik yeterlilikten uzaktır. SEM gözlemleri, hem yer ölçümlerini ve hem de roket ve uydulardan elde edilen atmosferik ve iyonosferik ölçümleri kapsamaktadır. SEM olgusunu uzaydan incelemek amacıyla bir uydu yakında fırlatılmış olup iki tanesi daha bir yıl içinde fırlatılacaktır. SEM olgusunun daha organize ve sistematik araştırılması Litosfer-Atmosfer-İyonosfer-Manyetosfer (LAIM) etkileşiminin daha iyi anlaşılmasına yol açacak, ancak bundan daha önemli olarak, oluşması yakın bir depremi birkaç saat veya birkaç gün önceden tahmin etme yeteneğimizi önemli ölçüde gelştirecektir. Mevcut veriler bol da olsa gözlem koşulları arasındaki farklar ve kontrol eksikliği aralarında ilişki kurmayı zorlaştırmaktadır. Verileri açıklamak için bazı modeller önerilmişse de henuz bunlar arasında geniş kabul gören yoktur. Bu yazı konuyu gözden geçirecek ve yakın zamandaki bazı gelişmeleri rapor edecektir.
Anahtar Sözcükler. Sismoelektromanyetik (SEM), deprem önkestirimi, litosfer – atmosfer – iyonosfer – manyetosfer (LAIM) etkileşimi

ABSTRACT

The phenomena of different types of electromagnetic emissions from the Earth, starting a few hours to a few weeks before a major seismic event, i.e. an earthquake or a volcanic eruption, and continuing for a similar duration afterwards, is known as seismo-electromagnetics (SEM). Different manifestations of SEM have been reported for over a hundred years. More scientific, albeit fragmentary, observations have been recorded by researchers from different parts of the World, in the last two or three decades. These include ground measurements as well as atmospheric and ionospheric data obtained from satellites and sounders. One satellite has recently been launched and two others are under construction, specifically for the purpose of investigating SEM from space. More organized and systematic research in SEM is expected to lead to not only a better understanding of the lithosphere – atmosphere – ionosphere – magnetosphere (LAIM) interactions, but more importantly, to contribute significantly to the development of an ability to predict imminent (few hours to a few days) earthquakes. Although several models have been proposed to explain the physical basis of the observations, none has gained widespread acceptance. The available data seems to be abundant but difficult to correlate due to wide differences in the means of collection and control of variables. The paper will review the subject and report on the recent developments in the field.

Keywords: seismo-electromagnetics (SEM), earthquake prediction, lithosphere – atmosphere – ionosphere – magnetosphere (LAIM) interactions

1. INTRODUCTION

As the term implies, seismo-electromagnetics (SEM) has been coined for the often-observed phenomena of electromagnetic emissions from the Earth, before, during and after a major seismic activity, i.e. an Earthquake or a volcanic eruption. SEM emissions have durations varying from a few hours to a few days, or even weeks, either way of the seismic event in time. Much of the early and significant developments in the subject have occurred in the Soviet Union starting in the 1950s. Starting in the early 1990s, Russia has been joined in SEM research by Japan, France, China, Ukraine and to a certain extent Greece, US and India as well.

Earthquake prediction studies have involved, seismology, geophysics, electromagnetic theory, geology, geochemistry, hydrology, atmospheric physics, and near-Earth space physics. In addition astronomical factors and animal behavior have been considered as having possible links. SEM certainly is closely tied to all the geosciences and recent developments indicate it carries a good potential for developing short term earthquake prediction capability. A review of the literature on SEM shows that most of the recent publications on the subject appear, naturally enough, in geophysics literature but quite significantly, in space research journals as well. It is worth noting that the author could not come across any papers on SEM in remote sensing focused literature, although sensing of deep underground phenomena by electromagnetic signals is certainly a form of remote sensing. This paper will restrict itself to SEM's role in earthquake prediction.

Several special international workshops specifically covering the subject were held in recent years i.e. in Paris, July 1999, in Boston July 2000, in Tokyo, September 2000, and Bangalore, December 2000, in addition to special sessions in wider scoped international conferences. The first phase of the Japanese Earthquake Remote Sensing Frontier Research Project has been concluded with the final report published in March 2001 [1]. The observations in the 1990s have constituted sufficient evidence for at least three orgnizations in Russia, France and USA to build satellites specifically for investigating the phenomena [2], [3],[4]. The Russian KOMPASS has been launched in December 2001, the French DEMETER satellite and the US QuakeSat are to be launched in 2003. It is interesting to see that the near-Earth space community has joined the geophysics community to spearhead SEM research.

The subject of SEM carries special significance outside of the scientific domain. An understanding of the lithosphere – atmosphere – ionosphere – magnetosphere (LAIM) interactions, is a worthwhile scientific endeavor in itself. But a quantitative model relating the SEM observations to the physical and seismic processes involved, may actually lead to the development of the ability to predict imminent earthquakes. Needless to say, warning times of a few hours to a few days prior for a major earthquake, would save many lives and some property too, by allowing time for precautionary measures such as cutting off gas, electricity, flow of chemicals, securing loose items etc.

Several factors have contributed to a delay of more comprehensive studies toward a better understanding of SEM phenomena. First is the difficulty of gathering dependable data, i.e. instrumenting the right place (close enough to the expected earthquake epicenter) and having to wait a long time for a major earthquake to strike. Together with it comes the impossibility of duplicating the same set of conditions for a repeat measurement to increase the confidence in data. Data, which are actually collected, are dispersed in location all over the World, by several years in time, and collected with differing methods, making cross correlation difficult. The uncontrollability of other factors strongly affecting the recorded measurements such as solar flares and thunderstorms, adds to the difficulty. Dependence of the observations on the local subterranean conditions may mean different models to be developed peculiar to each geographic region. Thus, whatever data is available, and there is plenty, has proved to be complex, intriguing and rather difficult to correlate and interpret.

A more basic impediment has been the long held belief that seismic activity is purely a mechanical one. This assumption may have led to the dismissal as hearsay or creations of the mind under distress, of the reports by the ordinary people in the media, of such happenings as atmospheric lights or short-circuiting electrical equipment just before an earthquake. It also led to SEM phenomena being taken as pseudoscience for a while by some established scientific centers. It is the author's impression that this attitude may have delayed earlier research initiatives. The recent experimental findings, especially coming from the Japanese frontier research initiative and theoretical propositions coming from several sources since the mid 1990s, have produced substantial credible evidence in favor of SEM as a potential earthquake precursor. So a review of the subject is considered well warranted at this time. The reader is advised to consult the NASDA 2001 report [1] for an extensive review.

2. OBSERVATIONS

Reports of strange atmospheric phenomena just preceding a major earthquake have been reported all around the World for centuries going back to ancient times. Sightings of atmospheric lights, air glow and even lightning in clear weather, are just specific manifestations of the SEM phenomena. Numerous other SEM observations are in the form of electromagnetic emissions from the ELF/ULF, through the VLF / LF up to the HF frequencies. In addition to ground measurements of EM emissions, there is plenty of SEM related data from ionospheric measurements obtained either from ground sounding or from satellites. Accounts of these observations can be found in the many articles and three books on the subject, appearing from the 1980s on [5], [6], [7]. This paper will mention only some well known representative observations, and some significant recent ones that point to new research directions.

2.1. Ground Based Observations

Invention of the telegraph in the 19th century also brought to the attention of engineers and scientists, occasional large anomalous currents in the telegraph lines originating from the potential difference between different points on Earth. Among the first explanations for these telluric currents, were hints that they could be related with earthquakes. Gokhberg [7] writes that perhaps the first reported observation of an SEM effect was in 1894 by Bahmetyev who was making measurements of electromagnetic fields near the city of Sofia, Bulgaria, and noted an unusually large variation on the day of an earthquake at the city of Ruschuk 270 km away.

The first systematic study, which explicitly linked Earth currents with earthquakes, was published in 1954 in Russia by Tikhonov, as reported in Gokhberg [7]. Based on a detailed analysis of telluric disturbances recorded by a network of receivers spaced hundreds of kilometers apart, one of the conclusions made was that some telluric currents were related to the slow mechanical movement of tectonic plates.

Japanese research under Rikitake in the 1965-1967 period over the Matsushira cluster of earthquakes showed the complex nature of the phenomena, but led to no conclusive results,. No distinct correlation could be found between seismic events and electromagnetic measurements, as some weak events could have associated EM manifestations while stronger ones would sometimes not [6]. The skepticism in Japan was countered by the well-known successful prediction by Chinese researchers of the Hay – Chang earthquake on February 4th 1975. The prediction of the M=7.3 earthquake, which resulted in the evacuation of a medium sized city, was based on a number of prognostic data including SEM related observations [7].

Several institutions in the Soviet Union have performed leading research in SEM starting in the 1950s and 1960s with the aim of discovering earthquake precursors. Two of these institutions are the Institute of Physics of the Earth (IPE) and Institute of Geomagnetics, Ionosphere and Radio Propagation (IZMIRAN). In some early research on strong earthquakes, anomalies were observed at nearby stations spaced as much as 100 km apart, but they were recorded with some delay. It was therefore believed that the anomalies were migrating in space, which was considered as evidence of the migration of the mechanical stress - strain state of the rock mass prior to an earthquake. Gokhberg [7] gives a record of the earlier findings of these centers. A number of presentations at the *First Eurasian Symposium on Space Science and Technologies* at Gebze, Turkey in December 1993, were dedicated to that topic, almost all coming from Soviet research. Some of them appeared in print in the Turkish Journal of Physics, [8], [9], [10], [11], 12].

Perhaps the most widely publicized and well-documented observations of seismic related ULF magnetic field anomalies occurred following the two earthquakes of Spitak (M=6.9) in Armenia in 1988 and Loma Prieta (M=7.1) in California in 1989. Kopytenko et. al. [13] report about the ULF emissions recorded at Dusheti situated about 130 km from the Spitak epicenter, during the time of observation, starting about three weeks before the earthquake and continuing until about three months after. The three-component magnetic field data were filtered at two frequency bands of 0.005-1.0 Hz and 0.1-5.0 Hz. A noise-like burst of ULF emission was observed a few hours before the main shock and each aftershock with M>5.0. The emission continued for about an hour in each case, but precursor times varied between two to five hours (Figure 1a). There were other anomalies. Averaged daily intensity of the magnetic field variation started a sharp increase several days before the main shock and continued at a high level for about a month (Figure 1b). Measurement of the burst spectra showed a peak around 0.3 to 0.5 Hz. Amplitude of the vertical (Z) component was comparable to the horizontal components unlike the natural geomagnetic components.

In the fall of 1989, a group from Stanford University was engaged in remotely monitoring magnetic fields in the Santa Cruz Mountain Range as part of an unrelated project [14]. Data were recorded around the time of the magnitude 7.1 Loma Prieta Earthquake using a one-component magnetometer, in a 10-channel recorder with filters covering the frequency range of 0.01 to 10Hz. The results show two very interesting features:

1. About two weeks before the earthquake the ULF magnetic field signal levels increased about 10-20 times from their background level; and

2. About three hours prior to the earthquake these signals increased again to a level about 60 times their normal background level. The amplitude at the lower frequencies remained high for several days after the shock and it took a few months for them to settle to their background levels

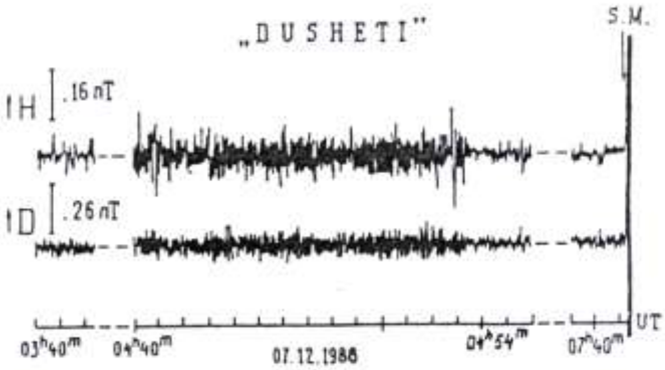

Figure 1a. Section of a chart recording showing ULF magnetic field burst emissions recorded at Dusheti about a day before the Spitak Earthquake of 8 Dec 1988.

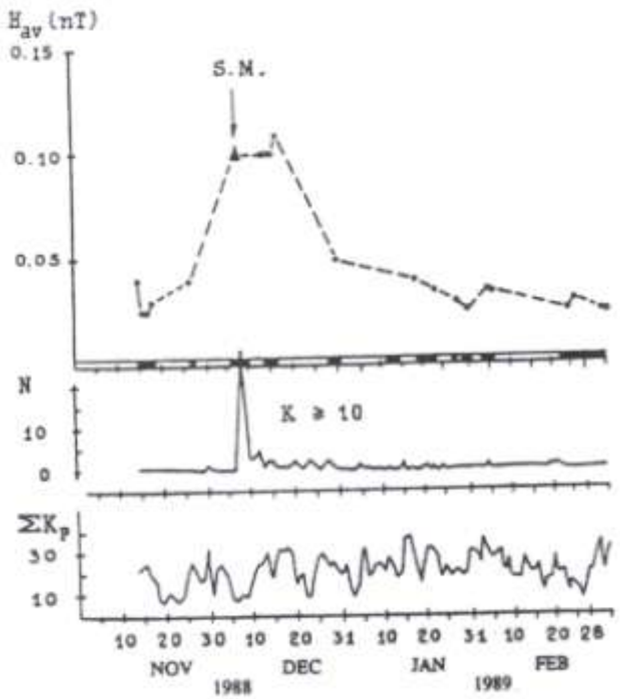

Figure 1b. (Top) Mean daily values of the H component of the ULF emissions recorded at Dusheti in the 0.1 to 1Hz range, from 14 Nov. 1988 to 5 March 1989. (Middle) Number of shocks with energy K => 10. (Bottom) Σ K p index values in the same time period.

Molchanov et. al. [15] compared the characteristics of Spitak and Loma Prieta earthquakes based on ULF observations and found many similarities between the two. These included the precursor times, and the characteristic frequencies. There were also some differences such as the duration of the bursts and correlations with the aftershocks. Some differences in the data of the two earthquakes could be explained by the different distances to the epicenters.
Anomalies in ULF magnetic field measurements prior to other major earthquakes have been reported and discussed in several other publications [16], [17], [18], [19]. Hayakawa et. al. [19], reporting on their analysis of the Guam earthquake of 1993 (M= 8.0), show convincing evidence of a ULF signal preceding that earthquake. Among their conclusions are:

1. The ratio of the vertical to the horizontal (Z/H) component of the field is a good discriminant of the emissions presumably of seismic origin and those from space plasma waves,
2. The temporal evolution of this ratio showed a maximum about one month before the Guam earthquake,
3. The same ratio showed a maximum 10 days to 2 weeks before the Loma Prieta earthquake, and
4. This Z/H ratio is likely to be a precursor of large earthquakes.

On the other hand, Fraser-Smith et. al. [16] could not find any large precursor signals associated with the Northridge earthquake (M= 6.9) occurring in Southern California from their measurement point in Northern California. This lack has been attributed to the large distance between the epicenter and the measurement site.
The ULF electromagnetic emissions associated with a large (M=8.2) earthquake occurring at Biak Indonesia, were analyzed by Hayakawa et. al. [20] as recorded at two sites, one 100 Km to the epicenter and the other at Darwin Australia 1200 Km away. There was no obvious and significant effect of the quake on ULF at first sight. The data from the two stations were similar and were dominated by the general global geomagnetic activity ΣK_p. However treating the data separately showed an enhanced ULF activity (both Z and H components) at the closer station just before the quake, although it is closer to the equator where normally reduced ULF emissions are expected. Figure 2.
Nickolaenko, et. al. [21] report on their analysis of the ULF/ELF records from the Uzbekistan Institute of Seismology near Tashkent, in the period from August 23 to September 30 1984, during which a number of minor earthquakes occurred as well as one with a magnitude of 6.2. They report an increase of the level and variability of the vertical electric field component of the radio signals in the 1, 3, and 5 Hz bands, prior to the earthquake shocks. ULF/ELF spectral indices were used to evaluate the slope of the amplitude spectrum. The authors conclude that both the frequency decay of the noise spectra in the 1-3 Hz region and the rise between the 3-5 Hz region tend to grow simultaneously prior to the earthquake.

A more recent publication on ground based SEM observation [22], comes from Northern India, where a major fault line, existing between two tectonic plates, is the source of much seismic activity. A borehole antenna has been used to measure the subsurface (120 m deep) vertical electric field at Agra since February 1998. Analysis was done after dividing the data into two groups, one for the months of calm atmosphere (May to September) and the other when thunderstorms and lightning are more prevalent (October to April). Noise bursts in different VLF bands were found to correlate with recorded earthquakes for both groups. Noise burst occurrence numbers increased considerably on the days preceding or following a major earthquake (M>5). In 60% of the cases, noise bursts occurred as precursors with periods ranging between 1 hour and 2.3 days. In the rest of the cases increases were observed either both before and after, or just after the earthquakes. However correlations of noise bursts with earthquakes, becomes more difficult in the presence of other noise sources like thunderstorms.

Not only magnetic but also electric field variations have been recorded associated with earthquakes. Varotsos and Alexopoulos [23] called these signals SES (seismic Electric Signals) and first gave a large account and a comprehensive explanation of the observations. SES signals show an increase in the intensity of the electric field, some 6 to 115 hours before the earthquake and continue for a duration of up to 90 minutes. Earthquake lights (EQL) are another phenomena that could be tied to SEM effects. EQL have been reported just above the ground, on top of mountains, in the sky or even above the sea associated with many strong earthquakes [24], [25].

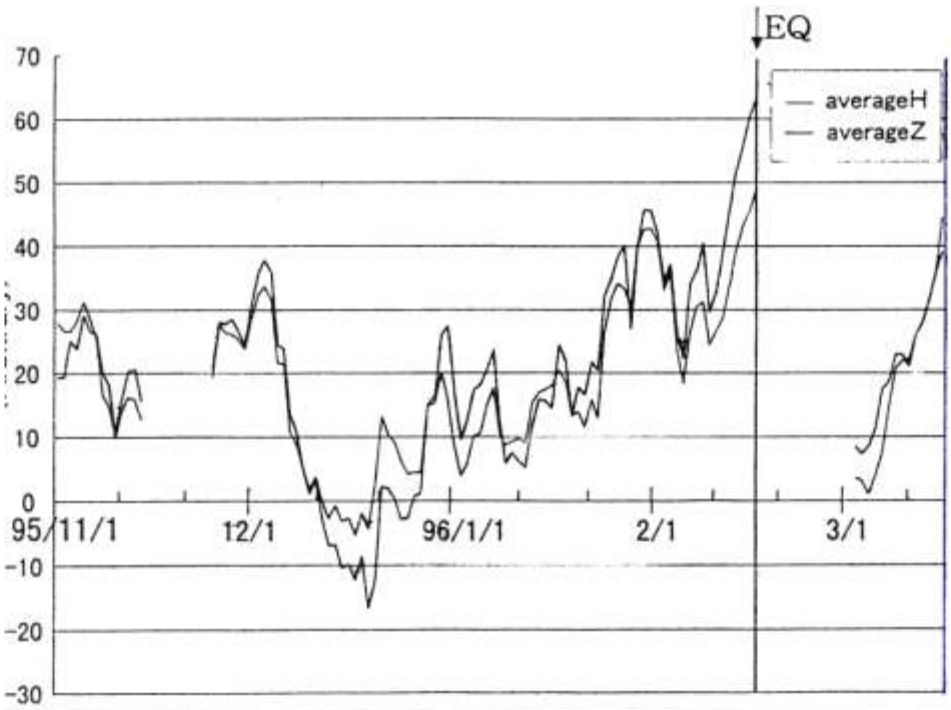

Figure 2. Temporal evolution of the ULF magnetic activity at Biak station (Indonesia) around 17 February 1996

2.2. Observations Related to the Ionosphere

Seismic related physical changes at the lithosphere show up not only as measurable electromagnetic field changes at the surface of the Earth, but also as perturbations of the ionospheric characteristics which can be measured from sensors on satellites or detected from the Earth using radio sounding techniques. Variability in ionospheric

parameters has been attributed to seismic activity through lithosphere-ionosphere coupling mechanisms, after being accounted for and separated from the solar, geomagnetic, geoelectric, atmospheric, cosmic or other known sources.
Ionospheric variations prior to or following an earthquake were first reported in the 1960s following the Chilean (M=8.5, 22 May 1960) and Alaskan (M=8.3 28 March 1964) earthquakes [26], [27]. These were very long distance observations, recorded at Boulder Colorado 4500 Km away, as Doppler shifts in the frequencies of 4 MHz, 5 MHz and 10 MHz. Two hours before the quake the 5 MHz signal underwent irregularities but the 4 MHz and the 10 MHz signals did not show any shifts. All three signals showed disturbances about seventeen minutes after the quake. The authors believed that the infra-acoustic waves with a 30 s period should be regarded as the source of the ionospheric irregularities.
Gokhberg et. al. [7] cites many similar observations, studies and publications in the Soviet Union following the Tashkent earthquake of April 1966. **Figure 3** shows the daily average value of the ionospheric value, $\Delta f_0 E_{av.}$ recorded around the Tashkent earthquake for the month of April 1966. It is seen that this figure rises to three times its standard deviation one day before the earthquake. In various other studies monitoring the different parameters of the ionosphere, inconclusive results were obtained. It should be noted that the ionosphere is characterized by a number of standard parameters, among them f_{min}, $f_0 E_1$, $f_0 E_2$, $h'f_1$ and $h'f_2$. Gokhberg [6] lists and gives details of other later observations and investigations of ionospheric perturbations linked to seismic events. Gokhberg points out that although analysis of vertical ionospheric sounding data reveals anomalies in one parameter or another prior to almost all non-minor earthquakes, any single event is often unrepresentative of a general pattern. A claim made by Birfeld in 1979 is reported in Gokhberg as "*the discoveries have made it possible to use measurements of ionospheric parameters for earthquake prediction purposes*". The extent to which that claim is valid today, is open to discussion.

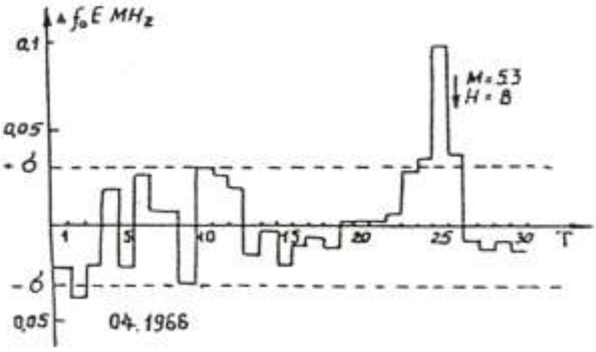

Figure 3. Daily $\Delta f_0 E_{av.}$ values, prior to the Tashkent earthquake of 26 Apr 1966.

Within the last decade or so Russian and Japanese researchers have made extensive use of VLF radiophysical sounding as a common and relatively easy way of monitoring ionospheric change. With the VLF radiophysical method, phase and amplitude of radio signals from navigational transmitters propagating inside the earth – ionosphere waveguide are measured and analyzed at some distance [1]. If transmitter frequency and receiver distance are fixed, then the observed VLF signal parameters are mainly dependent upon the reflection height of the ionosphere boundary, which is a function of the values and gradients of the electron density in that region. Thus VLF signal parameters can be used to deduce the electron density at the atmosphere – ionosphere boundary.

Hayakawa et. al [28] noted the anomalies with VLF signals observed during the 1995 Hyogo-ken earthquake. In following studies by the same group, Molchanov et. al. [29] reported encouraging results from the analysis of VLF signals related with the Kobe earthquake (M_g = 7.2) of January 1995. They analyzed the VLF Omega signal (10.2 KHz) transmitted from Tsushima Japan, and received at Inubo near Tokyo 1000 Km away, for a period of 8 months centered around the 17 January 1995 earthquake date, noting that the epicenter was located inside the Fresnel zone of the VLF path (Figure 4). They developed a method first suggested by Gokhberg [30], which may accentuate the expected effect of a possible change in the ionosphere. The method analyzed the variations in the terminator times occurring in the morning and evening. The two terminator times t_m and t_e are defined as the times where a minimum in phase takes place around sunrise and sunset respectively. Analyzing the data around the Kobe earthquake, a statistically significant change in terminator times was discovered, which began 2-3 days before the main shock. The change continued for a few weeks afterwards, as a transient oscillation with a period of about 10 days. Based upon simple ionospheric modeling, that implies the lowering of the reflection boundary by 1-2 km, which may be a result of seismically induced electric field increase (Figure 5 and Figure 6).

Figure 4. Map of Japan showing the locations of the VLF transmitter at Tsushima, receiver at Inubo and the site of the Kobe earthquake marked X.

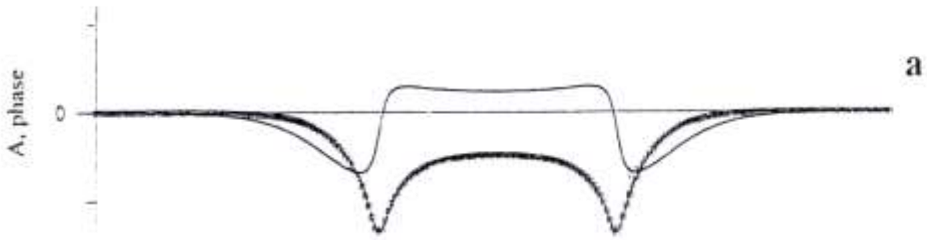

Figure 5. Theoretically computed values of the expected diurnal changes of phase.

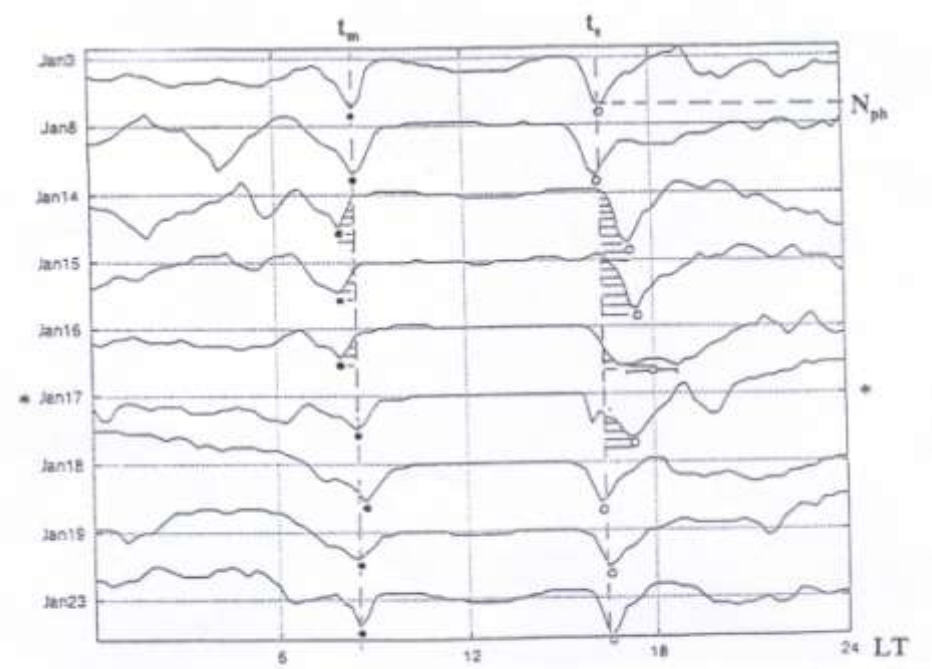

Figure 6. Sequential plots of the daily VLF signal phase changes recorded at Inubo. The shift at the morning and evening values of the termination times prior to the 17 January earthquake is taken as a precursor.

Encouraged by the results of Kobe data, further work was done by the authors with data from 10 other major earthquakes, with magnitudes between M=6.0 and M=7.6, and occurring between the years 1978 and 1993 [31], [32]. Again the source of the data was the Inubo radio observatory as the receiver and the 10.2 KHz Omega transmitter at Tsushima. The results of the 11 earthquakes as given in Table 1, have important implications.

Table 1. Parameters of 11 large earthquakes analyzed with respect to VLF termination times:(after Hayakawa and Molchanov [32].

Number	Magnitude	Depth	Distance to VLF path	Significant correlation
1.	7.0	0 Km	70 Km	present
2.	7.6	440	450	absent
3.	6.1	0	10	present
4.	6.7	10	40	present
5.	6.1	80	30	uncertain
6.	6.0	56	10	absent
7.	6.5	6	30	present
8.	6.4	368	10	present
9.	6.2	364	40	absent
10	7.1	390	390	absent
11	7.1	10	70	present

The conclusions are, that considering the terminal time variations:

1. Probability of finding seismo-associated VLF signature is high for shallow earthquakes: 5 out of 5 earthquakes with focal depth less than 30 Km had significant correlation;
2. Probability of finding seismo-associated VLF signature is low for deep earthquakes: only 1 out of 4 for earthquakes with focal depth greater than 100 Km showed significance;
3. No VLF signature found for earthquakes outside the sensitivity zone, that is distance to VLF path greater than 100 Km in this case.
4. Evening terminator times give more significant results than morning times.

In other words, the likelihood of detecting an imminent earthquake is very high for shallow earthquakes, if on the VLF transmission path.

These conclusions resulted from data from a fixed VLF transmitter-receiver set. Similar studies were performed using other transmitter-receiver pairs operating in other VLF as well as LF frequencies. In one study, signals transmitted from the Australian NWC VLF transmitter at f =19.8 KHz were monitored at Kasugai in Japan several thousand Km away for a period of seven months during 1998 and 1999 [1]. Again termination time anomalies could be observed using the 2-sigma threshold value, for relatively moderate (M>3.5 up to 5.9) and shallow earthquakes, occurring at Tokai Japan. Tokai area is close to the receiver (60 Km) and close to the VLF path, which is part the great circle connecting the

points of transmission and reception. The anomalies showed up again a few days before the quake. Deeper earthquakes and those away from the VLF path did not produce any terminator time anomalies.

The demonstration of the sensitivity of termination times to seismic activity prompted several other studies using LF as well as VLF frequencies and larger transmitter-receiver distances. In one study based on LF receptions in central Italy from transmitters in Monte Carlo (216 KHz) and Czech Republic (270 KHz) and in another study following the October 2000 Tottori earthquake in Japan, the preliminary results [1], [33], [34] all point to similar conclusions, that LF and VLF termination times show anomalies starting a few days to a few weeks before an earthquake, if they are located

on or close to the direct transmission path. But for long paths of several thousand Km, earthquakes not near the receiver site may have smeared or subdued effects.
While changes in LF and VLF termination times show a lowering of the lower ionosphere boundary, Global Positioning System (GPS) signals can and have been used to infer changes in the upper layer as well, through monitoring variations in the Total Electron Content (TEC) of the ionosphere. TEC values as deduced from a network of GPS receivers have been shown to be a precursor of several recent earthquakes. Liu et. al. [35] report significant TEC value perturbations 1 to 5 days before three major Taiwan earthquakes. Smirnov, Alpatov and Namazov [36] report that analysis of the GPS signals received in Moscow and in Ankara, showed significant anomalies 24 to 27 hours before the M=7.4 Izmit earthquake of 17 August 1999. TEC figures following the 6 October 2000 Tottori Japan quake, indicate anomalies during the one week before the quake [37], meaning that the upper boundary of the ionosphere is affected as well as the lower boundary. Suganuma and Isezaki [38] investigated how the Hyogo-ken Nanbu earthquake (M=7.2) of 17 Jan 1995 affected GPS signal reception at the 18 GPS stations set up for this purpose. They report that the short term component of the TEC variation showed strong amplitude signals appearing three times for each station some 20 to 80 minutes before the quake. No post-seismic perturbations were detected at that study.
The capability that GPS signals provide in measuring millimeter range displacements for tectonic monitoring, is well known. In addition the value of GPS signals as possible earthquake precursors is now also recognized. Dense networks of GPS receivers have been installed in recent years in Japan, California and Taiwan, which may yield important data to help explain seismological effects on the ionosphere and develop more reliable methods of earthquake prediction. .
Another interesting anomaly is the recent observation of over-the-horizon transmission of FM signals. It is reported in [1] that observations on reception of signals from an FM (77.1 MHz) transmitter 80 Km away (direct distance) during the 01 February to 30 June 2000 period, showed unexpected variation. Analysis showed a crosscorrelation with several earthquakes with M>3.5, and that such signals, normally not receivable, were received about 7 days before an earthquake. The received signals had small elevation angle (<10 0) and rather large amplitudes, which point to favorable conditions in the troposphere rather than the atmosphere.

2.3. Satellite Observations

The first satellite observation of SEM phenomena goes back to the flux-gate magnetometer measurements aboard a Soviet satellite launched into LEO orbit in May 1969. The OGO-6 magnetometer was designed to detect three component magnetic field emissions in seven bands centered around 10, 22, 47, 100, 216, 550 and 1000 Hz. Data from orbits, that passed over sufficiently close to the epicenters (R<900Km) of earthquakes with magnitudes of M>5.5, were processed from one day before to one day after the earthquake. In three of the six cases studied, significant electromagnetic emission was registered above the seismic region a few hours before the shock as shown for one case in Figure 7. The emissions occurred at frequencies above 100 Hz and there was no difference among the three components of the magnetic field [39], [40], [7].
Other satellites were used by the Soviet Union to measure other ionospheric characteristics. The AE-C satellite provided information on the ion and neutral content of the ionosphere, density and temperature of the neutrals and positive ions, energy spectra of photo-electrons, and fluxes of charged particles with energies up to 25 KeV.

Again data collected over earthquake epicenters, no more than one day before the earthquake, were analyzed. Of the several parameters measured only ion density showed anomalous variations. Similar data came from the ISIS-2 satellite also operating in the early 1970s as the AE-C satellite.

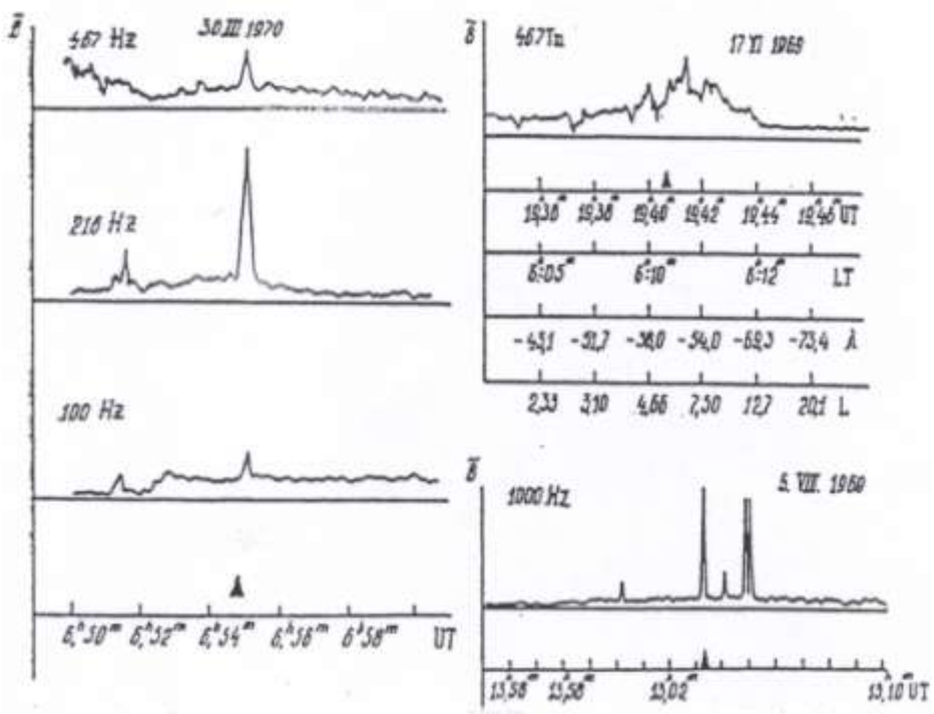

Figure 7. Electromagnetic emissions recorded by the OGO-6 satellite above seismic areas at different frequencies and times.

Gokhberg [7] gives data from the Intercosmos 19 satellite recorded on 9 July 1979 as a striking evidence of seismically induce EM field anomalies. The satellite measured electric and magnetic fields in the 0.1 to 16 KHz region. Data from the satellite obtained only during magnetically quite times and over strong earthquakes (M>6) were analyzed. For 15 hours prior to the earthquake and 18 hours afterwards, K_p was less than 1^+ indicating very normal (quiet) magnetic conditions. Yet 42 minutes before the earthquake when the satellite was passing overhead, intense emissions drove all the on board ELF-VLF instruments off scale. On subsequent orbits the emissions were reduced but the electric field remained high for a while after the magnetic field died off.
The Russian Intercosmos-24 satellite measured ELF-VLF emissions during its 3000 orbits in 1989 – 1991. Molchanov et. al. [41] analyzed data from 180 orbits during November and December of 1989, in which twentyeight rather strong earthquakes took place (5.2 < Ms < 6.1). Among their main conclusions are that::

1. ULF-VLF (f < 1000Hz) and VLF (10KHz < f < 15KHz) emissions are typically observed as bursts above the earthquake epicenters,
2. Only VLF emissions are observed far from the epicenter,

3. These emissions may start several days before but emission ocuurence probability is at a maximum at 12-24 hours before the earthquake.

Hayakawa, [42] further analyzed a larger database of plasma densities recorded in the 3000 orbits of the Intercosmos 24. They report a reliable correlation between global distribution of seismic activity and ion density variations in the ionosphere, as measured by the normalized standard deviation (NSD) and the relative normalized standard deviation (RNSD). However a clear correlation was found only during daytime measurements (10-16 hours local time), quiet magnetic conditions and altitude range of 500 to 700 km. The correlation disappeared during magnetic storms.

Parrot [43], [44] performed a statistical analysis on the data from the GEOS-2 satellite which is a geostationary satellite as opposed to the low earth orbit of other satellites investigating the ionosphere. GEOS-2 data as well as the data from the AUREOL-3 low orbit satellite show positive correlations between ELF/VLF electric and magnetic field recordings and proximity to earthquake epicenters. It was also observed that anomalies could be observed for a long distance along the magnetic meridian passing over the epicenter of the earthquake corresponding roughly to North-South direction. Only the data recorded between the +45 ^{0} and –45 ^{0} latitude was considered, to avoid high levels of natural noise closer to the poles.

Based on other statistical analysis of high apogee (APEX) and low apogee (COSMOS-900) satellites, Afonin et. al. [46] conclude that dramatic changes in ion density distribution pattern occur over earthquake epicenters at night (quieter environment) and at 450 to 500 Km satellite altitude. More importantly these changes are of precursor type. They start to be observed about 7 days before a strong earthquake and last for about 7 days afterwards. The effects are more pronounced within + or - 40 ^{0} of magnetic latitude.

Critical analyses of satellite data were the subject matter of papers by Henderson et. al. [47] and Roger et. al. [48]. The former paper analyzed ELF/VLF emission data from DE-2 satellite passing over earthquake epicenters and could not find any significant anomalies. The latter also could not find positive conclusions after analyzing wide band ELF/VLF data from an ISIS satellite. However analyzing those two papers and other data, Galperin and Hayakawa [49] concluded that methodological differences can account for the observed differences, considering differences in single-pass vs. multi-pass, wide-band vs. narrow-band filters, antenna configuration, instrument configuration (sensitivity, operating mode, bandwidth), data selection (regarding times), processing, and differences in other environmental conditions.

A recent type of earthquake related anomaly, which is observed from satellites, is the rise in thermal infrared brightness temperature at the epicentral area. Tronin [50] and Zuji [51] Hayakawa [1] report correlations between earthquakes and IR temperatures as measured from such satellites as NOAA series, up to three weeks before an earthquake. China seems to be the center of most research on any possible Earthquake and IR temperature links [51].

3. EXPLANATIONS FOR THE PHYSICAL BASIS OF THE OBSERVATIONS

Studies to explain and model the seismo-electromagnetic observations have involved the modeling and interactions of the lithosphere, atmosphere and ionosphere. Research work on the possible physical models to explain SEM data can be roughly divided into two groups:

- **Research on subterranean physical models,** that is, how seismic activity produces the electromagnetic fields that affect the atmosphere and ionosphere;

- **Research on atmospheric and ionospheric processes,** that is, how subterranean EM electromagnetic fields produce the observations in the atmosphere and ionosphere.

Short qualitative explanations of some modeling studies will be given below. The reader is referred to the many references given, such as [52], [5], [7] and [1].

3.1. Subterranean Physical Models

Two or three basic qualitative mechanisms have been proposed for the subterranean generation of EM fields and emissions from seismically active areas. The first hypothesis is based on the well-known piezoelectric effect and the triboelectric effect, which concern direct EM wave production by rocks under compression and friction producing motion. These effects are well supported by laboratory experiments [53], where rock samples under large compressive and friction forces are observed to emit EM energy in a very wide frequency range. The actual emissions depend on the rock types and experimental conditions, such as external temperature, surrounding gas or liquid, and force applied. However scaling up of data from laboratory experiments to large subterranean structures is a matter that has not been satisfactorily explained and is a subject for further research.

The second mechanism for subterranean EM wave production is transportation of electric charges usually by underground water [54]. Electric charges can be produced by rock fracturing where charges appearing on the cracks can be carried by underground water starting to flow through the cracks. The formation and propagation of cracks prior to an earthquake, and fluid motion in these regions carrying charges, thus is claimed to be the source of an EM anomaly. Radon diffusion through the cracks is also believed to be a source of EM anomalies.

Still a third model has recently been proposed for subterranean EM energy, which is based on peroxy in rocks [55], [56]. Peroxy, which is known to be present in all rocks, can be viewed as representing positively charged electron-hole pairs. Until recently though the amount of peroxy in most common rocks was thought to be around 100 to 1000 ppm. But recent laboratory techniques put that figure around 1% for MgO crystals and similarly high figures for granite, andesite, labradorite and other natural rocks that make up mid to lower crustal environments. Important implications follow concerning the generation of highly mobile charge carriers when rocks are stressed prior to an earthquake and undergo microfracturing. It is conjectured by Staple et. al. [55] and Freund [56] that "*the acoustic waves emitted during microfracturing are believed to cause spontaneous dissociation of peroxy (or positive hole pairs) leading to clouds of positive hole charge carriers that propagate outward from the stressed volume and may be the cause of preseismic electrical signals*". This hypothesis brings a whole new view on the generation of seismogenic EM signals but it needs to be further supported by research.

There is little doubt that increasing seismic pressure starts rock microfracturing at some point in time before the main shock of an earthquake. This has been shown among other studies by the analysis of data from Matsushira station in Japan (1998) [1]. How the microfracturing leads to the observed ULF magnetic field measurements has been the subject matter of more detailed quantitative models. The models start with microcracks of length varying between 10^{-2} and 10^{+3} meters, with homogeneous distribution at certain given depths. The EP or Electric Pulse model proposed by Fenaglio in 1994 and as explained by Molchanov [57], [58] builds on electro-kinetic excitation of potential electric field pulses just after opening of the microcracks in a water-saturated environment. The magnetic pulse model assumes excitation of magnetic field pulses by seismic/acoustic waves. A third model, called the Volume Current Density Model, [58], characterizes the rock medium with a certain dielectric permittivity ε_g and conductivity σ_g. Assuming approximate time constants for microcrack formation, seismic stress propagation, and some charge production in or on the microcracks, Maxwell's equations are used to obtain the Fourier transforms of EM fields produced at depths and at ground level [58], [1].

Difficulties of collecting reliable ULF data are addressed in the paper by Koons et. al. [59], where ULF data from a Seikoshi station in Japan is statistically analyzed to separate real signals of seismic origin from the background of natural and man-made sources. That data is compared with data from three US stations. Similarities and differences are given as well as apparent data dependence on local time.

In another modeling effort on electromagnetic seismic interactions, Şengör [60] [61] [62], notes the shortcomings of classical electromagnetic theory and extends it to handle the non-uniform, non-smooth case, which should be more appropriate regarding the motion of large masses during a significant earthquake. He derives the wave equation and extends the continuity equation to apply to such cases. He compares experimental data from the major Turkish earthquakes of 1999 with his derivations and concludes that the results are useful in predicting the unexpected behavior of random phenomena such as in upcoming earthquakes.

Still other models propose explanations for the seismo-electric field observations. Again it seems there is a major difficulty in explaining the original physical production of charges. Varotsos [23] lists a number of properties deduced from many observations regarding seismo-electric signals (SES), before proceeding with a proposed model. These properties are briefly:

1. SES is usually a purely electrostatic field, not accompanied by magnetic field variations.
2. Amplitude of SES is of the order of 5 – 20 microvolts per meter.
3. Duration of SES is between 0.5 min and several hours.
4. SES precedes the main shock by a period of several hours to 10-11 days, or even longer periods for isolated cases.
5. There is an intriguing selectivity of SES, which is that a given station may detect signals from certain areas while remaining insensitive to closer seismic areas. The detection range may reach 100- 200 Km but may be blind to events within 30-50 Km.
6. Polarity stability: A given station for a given seismic event may record an increase or a decrease in the electric field, but it is always one or the other and never a reversal.
7. Most importantly, Varotsos gives an empirical relation between the SES amplitude E_v and earthquake size M which is:

$$\text{Log } E_v = a M + c$$

where c is a constant peculiar to the observation site, but the value of a is common to all sites and is in the range of 0.34 to 0.37. Varotsos later revised and developed his model further in [5] and [63].

Models explaining SES phenomena again start with microfracturing as the original source of signals and explain almost all the properties except the selectivity property, which has to do with the different crustal composition materials at different regions of the Earth. Detailed mathematical presentations of the different models can be found in [1].

3.2. Models on Lithospheric Coupling with the Atmosphere and Ionosphere

First publications of seismic influences on the ionosphere came after the observations following the major earthquakes at Chile (M=8.5) on 22 May 1960 and at Alaska (M=8.3) on 28 March 1964, [26], [27]. But the authors could not give any detailed explanations other than that some ionospheric perturbations caused the observed HF Doppler shifts.

It is a well-shown and well-accepted fact that anomalous perturbations do occur in the ionosphere some 3 to 7 days before an earthquake. However there is hardly any agreement on the factors responsible for the seismo-ionospheric coupling. Proposed possible mechanisms have included acoustic gravity waves, infra-acoustic oscillations, magnetic field disturbances, static electric field anomalies, VLF emission, radioactive emanations and changes in the composition of the atmosphere. [64], [65], [66], [67] [1]. No single parameter has yielded a satisfactory explanation, which is based on measurements on the ground and extended to the ionosphere. The most plausible among them has probably been based on the assumption of a DC electric field on the Earth's surface for some seismic reason underground. The main problem here has been the lack of ground measurements that would theoretically give the ionospheric disturbances based on a standard understanding of the atmosphere. Such DC electric fields are many orders of magnitude higher than the quiescent values and higher than the required levels to produce the observed ionospheric changes.

Models based on different mechanisms of electromagnetic field transmission from subterranean seismic sources up to the upper ionosphere have been proposed and analyzed in several publications [68], [69], [65], [70], [71], [72], [73]. The basic approach is to use Maxwell's equations to evaluate transmission coefficients of the EM energy produced at different source depths and configurations, taking into account different conductivities of ground, atmosphere, ionosphere and magnetosphere and the equations of continuity at the edges of these media. Details of any quantitative modeling will not be given here.

Pokhotelov et. al. [65] explain the influence on the ionosphere, of various acoustic waves in the atmosphere or near-Earth space. The source of acoustic waves could be natural or man-made, such as hurricanes, earthquakes, meteorites, rocket launches, explosions (chemical or nuclear), or even supersonic jets. These waves, more generally called acoustic-gravity waves or AGW, are shown to transport the energies formed in the atmosphere to the ionospheric layers, in particular contributing to the formation of E-layer perturbations.

Ionospheric behavior as a result of electric fields originating at the ground level is modeled in Pulinets et. al. [67], [71]. Pulinets assumes that the effects start with emanation of different chemical substances from the epicentral region such as radon, light gases (hydrogen and helium), and submicron aerosols with high metal content. This leads to changes of the electrodynamic properties of the atmosphere resulting in the modification of the vertical atmospheric electric field at the near ground levels of the atmosphere. The electric fields there are amplified due to the "electrode effect" as they extend to upper levels of the atmosphere, reaching several kV/m levels just below the ionosphere. The anisotropic conductivity in the ionosphere transforms the vertical fields into horizontal fields, which then increase the electron temperature of the E-layer due to joule heating, resulting in ionospheric irregularities. Model calculations are consistent with the 5-7 day precursor periods observed. Pulinets contends that the irregularities are larger when observed by topside sounders as from satellites. Pulinets also contends that the VLF noise observed on satellites is not a direct outcome of the seismic radiation but a result of large plasma irregularities.

Liperovsky et al. [69] review some of the ionospheric work done in the Soviet Union and Russia, underlining the importance of the sporadic E-layer formations before and during strong earthquakes. They propose a model of lithosphere – ionosphere coupling, taking into account various surface effects such as electric charge generation, emanation of radioactive gas, temperature variation and surface vibration. The model is used to explain certain SEM observations through the formation of sporadic E-layers in the ionosphere. No attempt is made to extend that to the F-layer.

Ionospheric parameters depend on a number of external factors which must be well accounted for, in order to isolate effects due to seismic sources. Electromagnetic noise is generated at the ground level and in the ionosphere by a number of natural and man made sources, covering a wide frequency range. These include solar and cosmic sources, atmospheric sources like thunderstorms and cyclones, dust and sand storms, contaminants in the troposphere, power line noise, and industrial noise. Any monitoring of ionospheric parameters must show extreme care in accounting for the influences of the these external effects in the effort to isolate any seismic influences.

Gokhberg [7] comments that although there is convincing evidence of the interrelations among the earthquake preparation phenomena and near-Earth environment, finding an explanation for the interrelations is a far more difficult task.

4. CONCLUSIONS AND RECOMMENDATIONS

Some comments are in order regarding what is meant by prediction. Short-term earthquake prediction would include the ability to predict (1) the time (a few hours to a few days accuracy), (2) the epicenter and (3) the magnitude of an impending earthquake. Present data suggests that the time could be the first variable to be predicted with a good degree of confidence. Epicenter information would probably be attainable with a sufficiently dense network of measurement points, perhaps in the order of a few kilometers. Most eluding variable at this time seems to be the magnitude. There is no study or publication yet known to this author linking magnitude of the impending earthquake with the shape, amplitude or any characteristic of the precursory signal. In other words we may soon be able to say that an earthquake will be occurring in a certain time and at a certain place, but we are in no position yet to say whether it will be an M=4 or an M=7 earthquake.

It should also be made clear that seismo-electromagnetics is not the only basis for earthquake prediction. Other seismic, geodetic, hydrological geochemical and biological effects are all expected to play their roles in an eventual model.

A brief summary of the recent SEM developments, which also point to the recommendations for promising near-future research, can be given as follows:

1. **Ground based EM field monitoring**: Numerous studies have shown the precursory nature of data from ground based monitoring of the electric and magnetic fields at ULF through acoustic (up to a kilohertz or so) frequencies, for impending earthquakes. These emissions are believed to be direct manifestations of the microfracturing occurring at the focus, prior to an earthquake. A ground network of such monitoring stations would be recommended with spacing distances of 10 - 30 km. These distances could be reduced to 3 - 5 km for finer resolution in epicenter location estimation.
2. **VLF and LF radio techniques to detect ionospheric perturbations:** Recent discovery of the shift in diurnal terminator times is very significant. Availability of VLF and/or LF transmitters in wide geographic areas should make it relatively easy to put detectors worldwide in the line of expected earthquakes. In Turkey for example, the LF transmitters of TRT in Ankara which is more or less centrally

located, can be used as the signal source for detectors to be located close to the borders around the country for phase and amplitude monitoring.

3. **Ground based HF radar to detect ionospheric perturbations**: Another technique for detecting the ionospheric conditions is by using special HF radar.
4. **Over the horizon FM station monitoring**: This is again a recent phenomenon which is relatively easy but potentially misleading way to look for precursory signals.
5. **GPS monitoring of the ionosphere:** A network of GPS receivers over a seismically active region can be used for two different purposes. Separate from and in addition to the other established use of GPS in earthquake studies, that is, for measuring tectonic plate movements, another use of GPS signals is for monitoring the ionosphere for perturbations. It is known that a network of GPS stations have been already established in Japan, California and Taiwan.
6. **Satellite observation of ionosphere:** Reliable correlations have been shown between seismic activity and such ionospheric parameters as ion density and TEC (total electron count). Top sounding of the ionosphere from satellites gives a view not available from the ground [67]

Further words on the use of satellites in SEM and earthquake research are in order. Already there is plenty of SEM related data from satellites, as noted earlier, but these have come as by products of some other satellite missions. The data is either not comprehensive or not fully meaningful for specific SEM related purposes, which points to a requirement for satellites specifically built for SEM. Again as noted above, one such satellite has been recently launched and two more are scheduled for launch in 2003. There are proposals for other satellites with varying sensors [74], [75], [76].

A very important point about satellite observations is that the satellites mentioned are at LEO (Low Earth Orbit) and at fairly high inclination angles or even polar orbits, which means data is collected from all over the Earth’s surface. So all seismic activities in any region of the Earth have the potential to contribute meaningful data as long as revisit times and characteristic space-time relationships are not very unfavorable. Therefore satellites should enable much faster data collection than earth-based methods, which are necessarily confined to a specific area or region. Considering that satellite observations need to be correlated with ground-based measurements, international cooperation also becomes a necessity.

International cooperation becomes especially important in SEM research because actual data may be hard to obtain at a specific place in timely fashion, because its availability is left to the discretion of nature. So sharing of data and information among researchers becomes very valuable not only at workshops but also on a more regular basis in the framework of international projects.

Some words about a specific earthquake prone country, i.e. Turkey, should be mentioned. Following the disastrous earthquake of 17 August 1999, many have asked if it would not have been possible to predict the earthquake given the many anomalous signs reported in the media. The answer from the official seismological community has naturally been negative. This is certainly correct and true at the present state of the art. However, it is also very interesting and eye opening to note some later publications about that earthquake, [77], [78], [79], [80], [36]. These all report, although in hindsight, that the earthquake of 17 August 1999 (also known as Marmara, Golcuk or Izmit Earthquakes), actually had plenty of precursors. Taken together, it would not have been difficult to predict the coming disaster, had methods been developed to do so.

A Turkish newspaper ***Akşam*** reported from Japan on its January 16th 2001 issue, [81] a speech made at the remembrance ceremonies on the occasion of the sixth anniversary of the Kobe earthquake. According to the report, Professor Naoshi Hirata predicted in his speech that in 10 to 20 years, prediction of earthquakes would be as routine as predicting the weather.

We are not there yet, but evidence has been accumulating in the last few years to be optimistic. Years of Soviet and Russian research and the more focused efforts of the Japanese Earthquake Remote Sensing Frontier Research Project 1996 to 2001, have produced promising new findings as the basis for further work which may well enable short term earthquake prediction in the time period given above.

These optimistic comments should be contrasted with a few other publications which are strongly critical and pessimistic about short term prediction. The message of the two articles published in 1997 are straight in their titles. The article by Geller et. al. [82], entitled "**Earthquakes cannot be predicted**", almost totally rejects the idea and warns authorities not to fund such project proposals out of social concerns. The other publication is actually a RAS (Royal Astronomical Society) press release summarizing the proceedings of a special meeting of the RAS entitled "Are Earthquakes Predictable" [83]. The press release is entitled "**Dismal Prospects for Short-Term Earthquake Prediction**". As the title says the major conclusion of the meeting was quite negative; that prediction is inherently impossible due to the chaotic and highly nonlinear nature of earthquake preparation process.

The article by Geller is criticized by Zuji [51] as being too narrowly focused. The negative tone of the two US and UK sourced publications is the subject of an excellent article by Morgunov [84], where he first questions whether our incapability for prediction is inherent in the nature of earthquakes or it is a result of lack of sufficient knowledge which could be developed by research. He asserts that a lack of knowledge cannot serve as a proof of impossibility. Morgunov joins the criticism on the lack of an understanding of earthquake mechanisms, how it all starts at the root, that is, the rock fracture mechanism. Critically reviewing the existing knowledge, he proposes possible types of precursors. Morgunov concludes with reserved optimism and recommendations for careful further research.

In one sense the issue can be divided into empirical (prediction related) and theoretical parts. Such a division is certainly not a mutually exclusive one but it is made for the practical purpose of focusing the study effort. Naturally the ultimate objective would be a comprehensive LAIM model, based on a good quantitative understanding of the underlying physical phenomena as manifested by physical observations, and one which will also allow us to predict earthquakes fairly reliably. However that should not preclude the development of empirical models, which may not be based on strong theory but nevertheless bring some degree of success in prediction. Saving of thousands of lives is a sufficiently good reason.

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