Further, although the fault-plane solutions of the aftershocks show different mechanisms, reverse faulting with right-lateral as well as left-lateral strike-slip movement, the shocks show different mechanisms, reverse faulting with stress measurements. The P-axis and the observed GPS displacement vectors in the area are in good agreement. The KRB, which is developed due to dominant tensile plate and back push thrust force from the Himalaya. This observation is similar to that of the Narmada Rift Basin (NRB) earthquakes. The 1997 Jabalpur earthquake in the NRB was also generated by left-lateral reverse faulting; a NNE–SSW compressive stress (P-axis) is dominant in the NRB.

The GPS results of temporal and spatial variations of the horizontal crustal movement in the Bhuj area possibly indicate post-earthquake adjustment, which is also evident from the ongoing aftershock activity. These results encourage further investigations and to increase stations to the northwest in the area.


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Observation of seismogenic ultra low frequency electric field fluctuations detected as a burst in the ionosphere during tsunamiis over the Andaman and Nicobar Islands

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Natural ultra low frequency (ULF) geomagnetic pulsations are mainly caused by wave plasma processes in the terrestrial magnetosphere and ionosphere. Earth crust processes may influence the parameters of geomagnetic noises and pulsations owing to the generation of additional noise or variation of local geo-electric properties. Electromagnetic disturbances of lithospheric origin observed before earthquakes are believed to become a physical background for short-term forecasting of seismic hazards. Among a large variety of seismo-electromagnetic phenomena, considerable in-

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Here, electric field fluctuations recorded in the ULF frequency range on 25 and 26 December 2004, as a precursor to the series of seismic events that occurred after the disastrous tsunami hit the Andaman and Nicobar Islands, using DEMETER micro-satellite have been discussed. Since geomagnetic activity during the period was found to be moderate, the significant electric burst recorded in the early morning of 26 December 2004 around 04:05:00 UTC, could be attributed to the frequency of occurrence of earthquakes, including two major events (Mw = 7.3, depth = 10 km and Mw = 7.1, depth = 39 km) that occurred a few minutes later around 04:21:00 UTC and 04:21:29.8 UTC on the same day. From the recorded observations, it is clear that the intensity of the electric fluctuations varies with the number of earthquakes and diminishes as the number decreases. The pattern of electric field fluctuations recorded could be used for a precursory study of earthquake occurrences.

**Keywords:** Earth crust, seismo-electromagnetic phenomena, seismic hazards, ULF electric field.

Natural hazards like earthquakes, tsunamis and volcanic eruptions are inevitable. In the scenario of fast-developing scientific technologies related to the welfare of human society, early warning of any kind of disaster is required in order to provide immediate safety. One of the essential approaches is to encourage detailed study of the earth system processes using space and ground-based techniques. Earthquake preparation is usually accompanied by electromagnetic phenomena in different frequency bands, starting from DC up to VHF radio emissions. Seismoelectromagnetic effects are the electric and magnetic phenomena observed at the time of earthquakes. They include: variation of magnetic fields, variation of telluric currents, ionospheric perturbations, night airglow observations and emission of electromagnetic waves. Many hypotheses concerning the mechanisms by which these waves are generated have been investigated. They are mainly related to a redistribution of the electric charges in the crust or in the earth’s atmosphere. Seismo-electromagnetic effects can thus be considered as short-term precursors and the conditions for triggering these precursors, have not been extensively studied because such studies need many observations. Due to the ability of electromagnetic emissions to propagate in the ambient environment up to the ionosphere, these emissions are registered using space-borne techniques at different distances from the earthquake’s epicentre for a few days or hours/minutes before or after the seismic shock. Now, it is an established fact that low-frequency electromagnetic emissions and ionospheric disturbances are one of the growing methods to monitor the crustal activity as ultra low frequency (ULF) emissions, which are typically observed as a burst in the ionosphere above the earthquake epicentres. Similar bursts in ELF/VLF amplitude were observed using the Interkosmos 19 satellite. The present study deals with data showing variations in the intensity of the ULF electric field emissions studied on 25 and 26 December 2004 using data from Detection of Electromagnetic Emissions Transmitted from Earthquake Region (DEMETER) micro-satellite to attempt positive identification of the spectra of seismo-active events.

**Table 1.** Earthquakes that occurred in the Andaman and Nicobar region on 26 December 2004 (source: [http://www.imd.ernet.in/section/seismo/dynamic/last-monthdecember.htm](http://www.imd.ernet.in/section/seismo/dynamic/last-monthdecember.htm))

<table>
<thead>
<tr>
<th>Date</th>
<th>Time in UTC</th>
<th>Latitude (deg. N)</th>
<th>Longitude (deg. E)</th>
<th>Magnitude (Mb)</th>
<th>Depth (km)</th>
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<td>6.1</td>
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</table>
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Figure 1. **a**, Tsunami generating area (source: [http://iri.columbia.edu/~lareef/tsunami](http://iri.columbia.edu/~lareef/tsunami)); **b**, Track of DEMETER orbit on 25 and 26 December 2004. ‘*’ denotes position of epicentres.

tiales (CNES), France and launched on 29 June 2004 from Bakanoor. The measurements made using the DEMETER experiment are intended to study emissions of electromagnetic waves observed during earthquakes and volcanic eruptions in the ionosphere, the upper atmosphere and the corresponding precipitations of particles, systematically. The disturbances taking place on the surface of the earth are measured using several types of experiments on-board, e.g. IMSC (measuring the magnetic components of waves), ICE (measurement of quasi-continuous electric fields and the electric components of waves), IAP (measurement of plasma parameters), ISL (measurement of the characteristics of thermal plasma) and IDP (measurement of energetic particle spectra). Data recorded at noon on 25 December 2004 and early morning of 26 December 2004 have indicated the precursory effect of earthquakes. The pattern of electric field fluctuations recorded at ULF was unique. Such identification would help in understanding the earthquake events which contribute to electromagnetic activity in the ionosphere. It could also provide better understanding of its application as a precursory warning to imminent shock.

The observations reported here have been made through detection of ULF (0–15 Hz) electrical signals associated with seismic activity in the ionosphere, using measurement of quasi-continuous electric fields and the electric components of wave (ICE) sensors on-board the DEMETER satellite, which consists of four electrical sensors.\(^1\) The basic motive of the study is to verify ULF emissions as precursors to earthquakes and to understand the nature of the relationship likely to be established between the intensity of the detected ULF emissions and the number of earthquakes that have occurred during a particular period and further, to verify the relationship existing between the intensity of detected ULF emissions and that of the magnitude of the earthquakes.

The earthquake events covered under this study specifically deal with the identification and examination of
Date: 25 December 2004, Orbit no. 02562_1, Time scale: 15:31:30 UTC to 16:05:56 UTC and 26 December 2004, Orbit no. 02570_0, Time scale: 3:48:00 UTC to 4:23:26 UTC

Figure 2. a, Spectrum of ULF emissions recorded on 25 and 26 December 2004. The portion where the probability of seismogenic signal is more has been encircled. b, Magnified spectrum of encircled portion for the corresponding timescale 15:42:07UTC to 15:57:00UTC and 3:55:00UTC to 4:17:02UTC respectively.

Figure 3. a, Average number of signal samples received each day, gap indicates the period during which the satellite was in safe mode and so no data were available. b, Line plot of the range of ULF electric field samples distributed corresponding to the latitudinal range (Andaman and Nicobar Islands) on 25 and 26 December 2004, orbit number 02562_1, 02570_0 and 02576_1 respectively.
Figure 4. FFT angular and amplitude variations in (a) north-south, (b) east-west and (c) vertical direction for 25 December 2004 (LHS panel; r denotes FFT without filter) and for 26 December 2004 (RHS panel).

Figure 5. Kp index for December 2004; Kp was found to be 3, for the entire period.

seismic signatures in the ionosphere. The DEMETER data have been downloaded from the web server (http://demeter.cnrs-orleans.fr) and have been analysed using the software SWAN (Software for Wave Analysis) pertaining to earthquakes that occurred in Andaman and Nicobar Islands on 26 December 2004 (Figure 1 a). Among the four orbits that have been analysed, significant disturbances have been detected only in two orbits: one at noon on 25 December 2004 and the other early morning on 26 December 2004 (Figure 1 b). They are found to be close to the epicentres of the series of earthquakes. Details of
earthquakes which occurred on 26 December 2004 along with the time of occurrence in UTC and corresponding latitude and longitude of the epicentres are shown in Table 1. Figure 2a shows the spectrogram of the electric field of ULF emissions detected at noon on 25 December 2004 and early morning of 26 December 2004 in the ionosphere in different timescales. The latitudinal region under observation is encircled. Figure 2b shows the spectrogram of the encircled area which gives a clear view of the observed ULF electric field fluctuations which have been detected as a burst. A sudden variation in the intensity of the observed electric burst is noticed only in the early morning of 26 December 2004 (orbit no. 02570_0), just before the series of events shown in Table 1. This indicated that when the earthquake occurred there was a significant increase in the intensity of waves in all the electric shells passing through the latitude of the epicentre. Figure 3a shows the average number of signal samples received each day. The gap indicates the period during which the satellite was in safe mode, and so no data were available. The curve shows a sudden deviation between 25 and 26 December 2004, which point towards the possibility of addition of new samples while the satellite was over the corresponding latitudinal region. It is found that the range of the difference between the maximum and minimum value of the electric field sample received in each orbit increases over the considered latitudinal region on the early morning of the 26 December 2004 (Figure 3b). This gives a clear picture of the fluctuations observed in the electric field. The waveform of three electric field components (N–S, E–W, vertical (Z)) for noon of 25 December 2004 (orbit no. 02562_1) and for early morning of 26 December 2004 (orbit no. 02570_0) respectively, are then subjected to FFT analysis (Figure 4) using windowing function (Hamming window) to measure the maximum electric field fluctuation recorded and the corresponding angular variations with respect to the frequency of the observed burst. A sudden angular fluctuation is observed in the east-west and vertical directions in the orbit taken on early morning of 26 December 2004, which is unexpected. Furthermore, to get the desired band of signal over that latitudinal range, a low pass filter of 15 Hz cut-off was used (marked by red line in Figure 4). We have observed an electric field fluctuation of approximately 15 mV/m, which is more than the expected value in the ionosphere. Thus, the main conclusion derived from the data is that an increase in electric field at frequencies less than 15 Hz is observed in the sequential trend with the number of events above the seismic regions a few minutes before the earthquakes. Further, it is observed that the $Kp$ index variation (Figure 5) for the corresponding period is moderate ($K \leq 3$). This means that detected large-scale electric field fluctuations in the ionosphere cannot be interpreted as a result of geomagnetic disturbances. It may be attributed to the occurrence of earthquakes.

Electric field fluctuations of ULF electromagnetic emissions as a burst have been detected corresponding to the events of earthquakes of 26 December 2004 over the Andaman and Nicobar Islands. A unique sequential pattern is noticed in the intensity (Figure 2a and 2b) of the detected burst with respect to the number of earthquakes, suggesting a relationship between the intensity of electromagnetic burst and the frequency of occurrence of earthquakes.


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