

A study of ionospheric response to regional seismic activity by VLF radio sounding

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Abstract

Electric field strength nighttime fluctuations in subionospheric signals of very low frequency (VLF) on Omega, Tsushima-Chofu (Tokyo) and NWC, Australia-Chofu propagation paths recorded during March–August, 1997 were studied for searching for correlation with seismic activity. Wave-like anomalies in VLF Omega signal with periods of a few hours were observed 1–3 days before or on the day of moderately strong earthquakes of magnitudes 5–6.1. Analysis of the correlation between regional seismic activity around Tokyo and dispersion of VLF fluctuations revealed that maximal correlation was observed during pre-seismic periods for shallow earthquakes (focal depth less than 40 km) that occurred at distances up to 350–400 km from receiving place. Spectral analysis of the earthquake catalogue has shown rhythmical variations of seismic activity integrated over large areas with periods of 4–14 days. Similar periodic components are observed in fluctuations of VLF signals propagating over the NWC-Chofu path. For both VLF propagation paths, a 27-day periodicity was found in fluctuations of signals that can be referred to as tidal or solar rotation influence.

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1. Introduction

VLF subionospheric radio sounding has been discussed in a number of recent publications as a prospective tool for remote detection of perturbations in the lower ionosphere connected with seismic processes (Gokhberg et al., 1989; Gufeld et al., 1992; Gufeld et al., 1994; Morgounov et al., 1994; Hayakawa et al., 1996; Molchanov et al., 1998; Ohta et al., 2000).

Subionospheric VLF propagation between the transmitter and a receiver are mainly determined by the state of the lower ionosphere. A single normal waveguide mode forms a stable day-to-day signal under sunlit conditions in the ionosphere along a propagation path. Regular variations in amplitude and phase in daytime are determined by the zenith angle of the Sun, and perturbations in a signal can be caused only by

sufficiently large irregularities in the lower ionosphere produced by such phenomena as solar flares.

Under nighttime conditions, stochastic fluctuations in VLF signals intensify as a result of both loosening of the lower ionospheric fringe and multimode interaction. Due to smaller losses at heights of about 85–90 km that are characteristic of the nighttime ionosphere, the higher-order normal modes propagate in the earth-ionosphere waveguide with their own amplitudes and phases. So, we can observe either amplification or decay of average nighttime levels of VLF signals depending on the propagation path configuration. In particular, when a receiver is placed near an interference minimum point, the amplitude decreases at night due to multimode interaction; and the sensitivity of VLF propagation to irregularities in the lower ionosphere increases, which leads to increased signal fluctuations (Bezrodny et al., 1984).

In this study we consider spectral representation of nighttime fluctuations in signals synchronously received by two (Omega and NWC) out of four VLF stations

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(Hayakawa and Molchanov, 2002). This choice was made due to the proximity of the observation point to the interference minimum and expected increased sensitivity to ionospheric perturbations of signals propagated over chosen paths. We also expect an increased response of VLF signals to seismicity because essential parts of chosen propagation paths overlap seismo-active areas.

Nighttime fluctuations in amplitude of signals of frequencies 12.8 and 19.8 kHz transmitted respectively by the Omega (Tsushima, 34° N, 129° E) and NWC (Australia, 21° 48' S, 114° 09' E) stations received in Chofu, Tokyo (35° 39' N, 139° 32' E) during March–August 1997 are analyzed in this study. The VLF measurements were started and performed in the framework of the Earthquake Remote Sensing Frontier Project of the Earth Observation Research Center (EORC) NASDA of Japan.

2. VLF data acquisition and processing

A VLF digital receiver OmniPAL (Dowden and Adams, 1988) with a vertical electrical antenna rod installed on the roof of the laboratory building of the Electronic Engineering Department of the University of Electro-Communications (Chofu, Tokyo) was used to obtain round-the-clock VLF data. To remove regular strong variations in the amplitude of VLF signals caused by day–night transitions in the ionosphere, we analyzed the difference between current and 17-day running average diurnal runs of the VLF amplitude calculated over the period immediately preceding a current day:

$$dA_k(t) = A_k(t) - \frac{1}{N} \sum_{i=k-N+1}^k A_i(t) = A_k(t) - \langle A(t) \rangle_k, \quad (1)$$

where k is a current day number; N is the number of averages; $A_k(t)$ is the amplitude diurnal dependence for

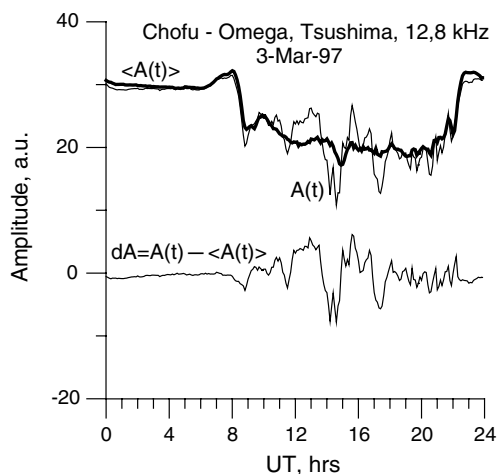


Fig. 1. An example of diurnal runs of amplitude variations in VLF signal.

the k th day; and t is the time during a particular day. Fig. 1 shows an example of current $A(t)$, average $\langle A(t) \rangle$, and differential $dA(t)$ diurnal runs of amplitude. We can observe a decrease of average amplitude $A(t)$ for the signal during the nighttime due to modal interference.

3. Spectral properties of nighttime VLF amplitude fluctuations

In accordance with the theory proposed by Bezrodny et al. (1984), the frequency spectrum of nighttime fluctuations in VLF signals is defined by spatial scales of advanced inertial turbulence in the upper atmosphere. Time variations in VLF signals arise from wind transportation of turbulent structures as a single whole as it is considered in the frame of the commonly adopted “frozen turbulence” hypothesis. The spatial spectrum of turbulence is defined by power law, with spectral index r close to 11/3. The corresponding frequency dependence of amplitude and phase VLF fluctuations is described by power law $S \sim F^{-p}$, with spectral index $p = r - 1 = 8/3$.

A power spectrum of nighttime amplitude fluctuations in the Omega signal averaged over the full period of our observations (spring and summer of 1997) is presented in Fig. 2. Approximation of the experimental spectrum with the power of frequency dependence $S \sim F^{-p}$ reveals $p \approx 2.21$ for the 0.0001 to 0.0015 Hz frequency range. This is slightly less than the value of 8/3 predicted by the theory of turbulence, and it is in good agreement with different experimental works (Bezrodny et al., 1984, and references therein).

Less steep slope is obtained for the lower frequencies in the spectrum (below 0.0001 Hz or above 2.8 h). This is

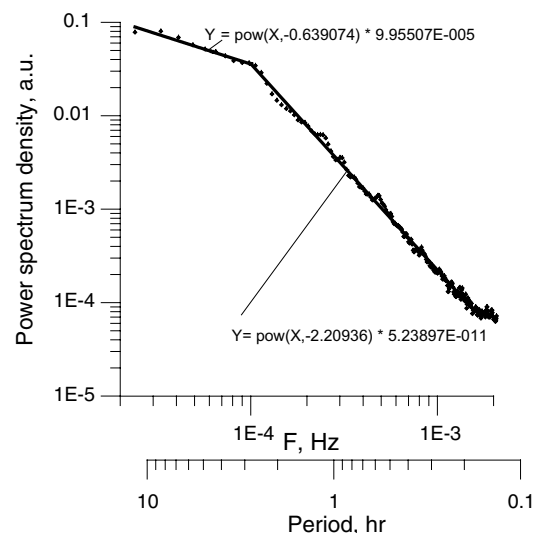


Fig. 2. Average spectrum of amplitude fluctuations in the Omega signal and its approximation with power law.

possibly connected with the limited length, from 9 to 12 h, of the processed time series that we chose depending on seasonal variations of night duration during the observation period.

4. Anomalies in spectra of nighttime VLF fluctuations associated with seismic events

Choosing VLF signal parameters to find anomalies associated with seismic influence is a problem. Different authors (Gokhberg et al., 1989; Gufeld et al., 1992; Gufeld et al., 1994; Morgounov et al., 1994; Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Ohta et al., 2000) used for this purpose day-to-day average nighttime phase variations, the occurrence of specific shape (bay-like) disturbances in diurnal runs of phase or amplitude, and tracing for position of characteristic minima in diurnal runs appearing at sunset or sunrise moments.

The selection of seismic events that could influence the properties of a chosen VLF propagation path is another problem. Earthquakes that occurred within the first Fresnel zone for a chosen great circle VLF propagation path are usually considered for analysis (see e.g., Gufeld et al., 1994; Hayakawa and Sato, 1994, 1996). This method was used when the earthquakes considered occurred rather far from the transmitter and receiver points.

In our case, the receiver was placed directly in a seismo-active area where the first Fresnel zone ellipse has a minimal extension of the order of a wavelength (<30 km). However, the scale of ionospheric disturbance sufficient to induce the observed effects in VLF propagation is believed to be of the order of a few hundred kilometers (Gufeld et al., 1994; Martynenko et al., 1996). So, in the present study we use the fifth Fresnel zone combined with a circle area of 350 km radius around the observation point, the size of which is comparable with above-estimated spatial scale of ionospheric perturbations, to investigate the possible correspondence between seismic activity and the fluctuations in VLF signals. The chosen areas and corresponding geographical distributions of earthquakes of a magnitude $M \geq 2$ within these areas are demonstrated in Fig. 3 for the Omega-Chofu VLF propagation path and in Fig. 4 for the NWC-Chofu VLF propagation path.

4.1. Omega-Chofu VLF propagation path

We chose the strongest earthquakes ($M \geq 5$) to search for possible associations of VLF anomalies with seismic events. The parameters of the 10 seismic events that included earthquakes answering the above selection criteria are presented in Table 1. An event can include a few earthquakes occurring approximately at the same

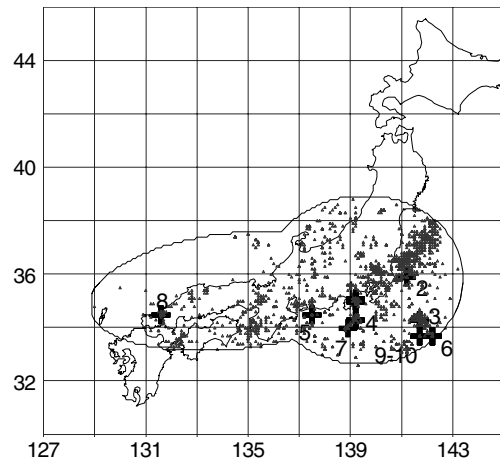


Fig. 3. Geographical distribution of earthquakes within the analyzed area combined of the 350 km radius circle around Tokyo with the fifth Fresnel zone for the Omega-Chofu VLF propagation path. The strongest 10 seismic events with magnitude ≥ 5 are marked with bold crosses labeled with the corresponding numbers from Table 1.

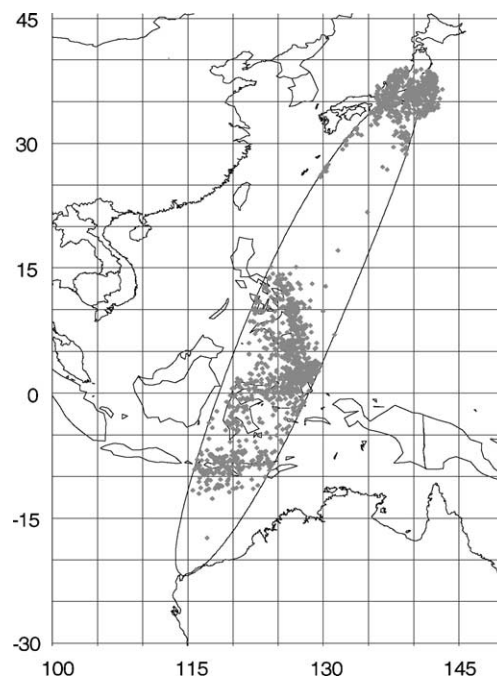


Fig. 4. Geographical distribution of earthquakes within the analyzed area (350 km radius circle around Tokyo and the fifth Fresnel zone) corresponding to the NWC-Chofu VLF propagation path.

place at the same time, as indicated in the IRIS catalogue. The selected events labeled by corresponding numbers from Table 1 are marked with bold crosses on the map in Fig. 3.

The dynamic FFT spectrum presented in Fig. 5 smoothed with a 9-day running mean demonstrates day-to-day variations of spectral content of nighttime

Table 1

Seismic events including shallow earthquakes (focal depth <40 km) of $M \geq 5$ in the vicinity of the monitored Omega-Chofu VLF propagation path

#	Date, Y/M/D	Latitude (deg)	Longitude (deg)	Depth (km)	Max magnitude
1	1997/3/3–1997/3/5	34.9	139.2	2–22	5.7
2	1997/5/9	35.8	141.2	16	5.3
3	1997/5/19	34.2	141.7	27.5	5.4
4	1997/5/21	34.2	139.2	8	5.6
5	1997/5/23	34.4	137.5	27.8	6.1
6	1997/5/24	33.6	142.2	18	6.1
7	1997/6/11	33.9	138.9	10.3	5.1
8	1997/6/25	34.4	131.6	13.1	6.3
9	1997/7/6	33.6	141.7	0	5.3
10	1997/7/19	33.6	141.7	0	5.1

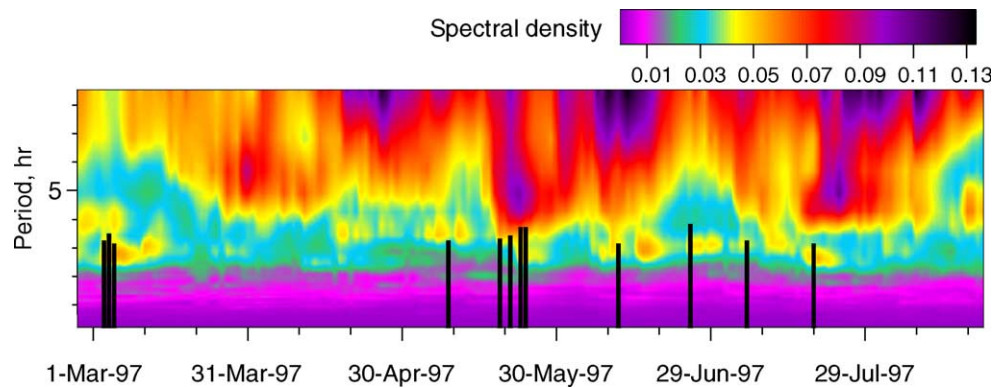


Fig. 5. Dynamics of power spectra of nighttime amplitude fluctuations in the Omega signal.

fluctuations in the amplitude of the Omega signal. We noted a frequency range around the inflection point in the average spectrum (see Fig. 2) corresponding to approximately 2.8 h. A tendency of leakage of energy of fluctuations from lower frequencies to isolated peaks in this band was observed. Such periodicities in VLF signals can be induced by periodical structures in the lower ionosphere with a characteristic size of the order of a few hundreds kilometers transported by wind with a speed of tens of m/s that is typical for heights of 80–90 km where VLF radio waves reflect from the ionosphere at night.

The selected strongest events are marked by vertical bars of a length that is proportional to its maximal magnitude. These are superposed on the dynamic spectrum of the VLF fluctuation shown in Fig. 5. We can see from the graph that most of the selected earthquakes are accompanied by intensification of spectral components of VLF fluctuations with periods ranging from 2 to 4 h a few days before or after an event.

An example of a specific wave-like anomaly in the nighttime signal that was associated with Case no. 1, the earthquake swarm at Izu peninsula, is shown in Fig. 1. Evolution of daily runs of the Omega amplitude (left graph) and the corresponding spectral contents of nighttime fluctuations (right graph) around the dates of

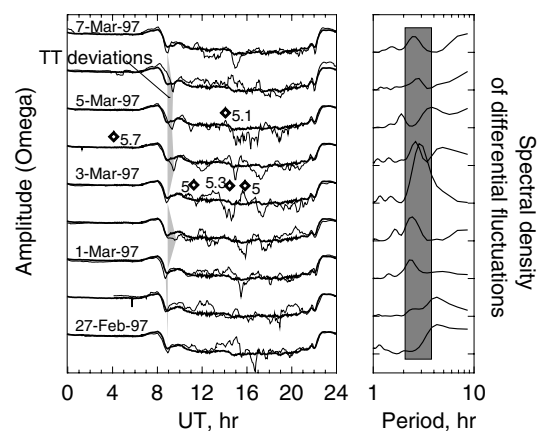


Fig. 6. Evolution of daily runs of the Omega amplitude (left graph) and corresponding spectral contents of nighttime fluctuations (right graph) around the dates of earthquake swarm at Izu peninsula. Shaded area in the left graph shows anomalous terminator time deviations associated with this seismic event.

Event no. 1 are shown in Fig. 6. Separate earthquakes included in this case are marked in Fig. 6 with rhombs placed at corresponding dates and times. We can see the appearance of an anomalous peak with ~ 3 h period in the spectrum of Omega signal fluctuations during the night of March 3, 1997, which coincides with the date of

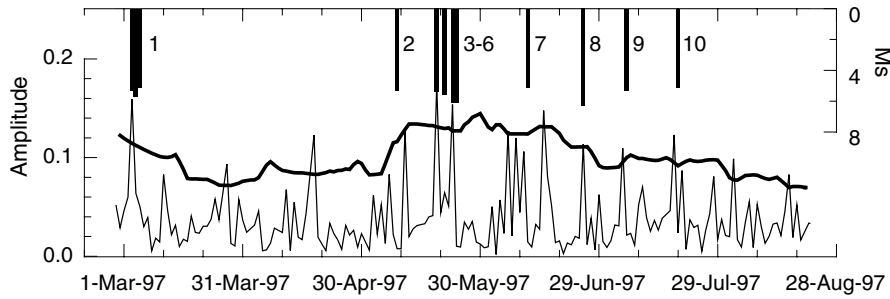


Fig. 7. Correspondence of peak amplitude in spectra of nighttime fluctuations of the Omega signal (lower thin curve) and shallow (focal depth ≤ 40 km) earthquakes with $M \geq 5$ occurred around Tokyo and in the vicinity of the monitored VLF propagation path (upper descending bar chart). The thick curve is ± 12 day running average of $\langle A \rangle + 2\langle \sigma \rangle$ level of the amplitude of VLF oscillations.

the beginning the earthquake swarm. Hayakawa (2002) observed anomalous deviations of the evening terminator times (TT) in the Omega signal associated with this event. The shaded area in the left graph demonstrates these anomalous TT deviations during March 2, 4, 5, and 6. As we can conclude from this graph, the TT deviations can be interpreted as a superposition of a terminator minimum with the succeeding fading of amplitude during transitional time.

For a more detailed analysis, we considered a narrow band of periods from ~ 2 to ~ 4 h (shaded area in the right graph in Fig. 6) in which essential leakage of fluctuation energy was observed as seen in Fig. 5. To recognize wave-like patterns used for characterization of anomalous deviations in the VLF signal, the amplitude of maximal spectral peak within the narrowband range for a 3-h period was determined for each day. The lower curves in Fig. 7 represent a time series of the amplitudes of 3-h oscillations, and a corresponding monthly averaged $\langle A \rangle + 2\sigma$ level. The upper descending bar chart

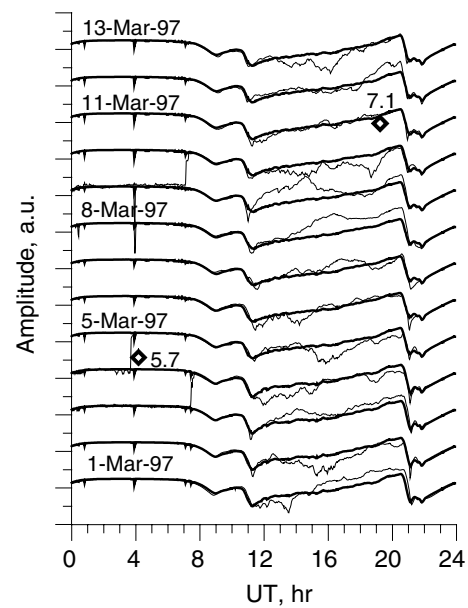


Fig. 9. Amplitude diurnal runs (thin lines) for NWC signal from 1 to 13 March 1997. Anomalous deviations from current average diurnal runs (thick lines) appeared during nighttime in March 7 and 8 2–3 days before the earthquake at Mindanao Island.

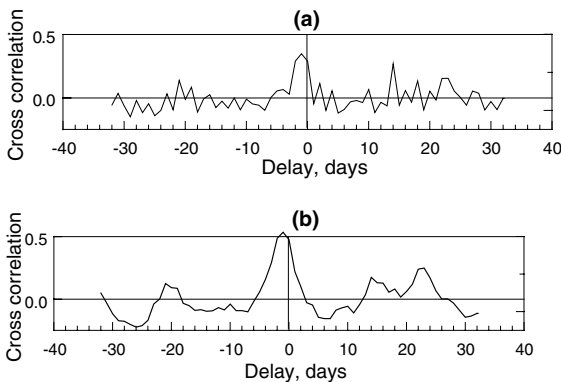


Fig. 8. (a) Cross-correlation coefficient between the variations of VLF amplitude within narrow band of periods 2–4 h and selected strong earthquakes ($M_s \geq 5$); (b) the same calculated for smoothed with 3-day running mean time series. Negative delays correspond to the pre-seismic period.

indicates the daily maximal earthquake magnitudes with the scale shown along the right Y-axis.

We applied a cross-correlation analysis of the considered processes to estimate the average time delay between anomalies in VLF signals and earthquakes. The cross-correlation coefficient between VLF anomalies and the selected strong earthquakes is shown in Fig. 8a. The cross-correlation coefficient is very unstable due to a lack of statistics. As shown, the principal positive maximum is observed at $-2-0$ days. This means that a VLF anomaly typically occurs 1–2 days before or on the date of an earthquake. For clarity we give in Fig. 8b the cross-correlation coefficient calculated for a time series of earthquakes and VLF anomalies smoothed with 3-day running mean. It demonstrates a pronounced peak in the vicinity of negative delay, -1 day.

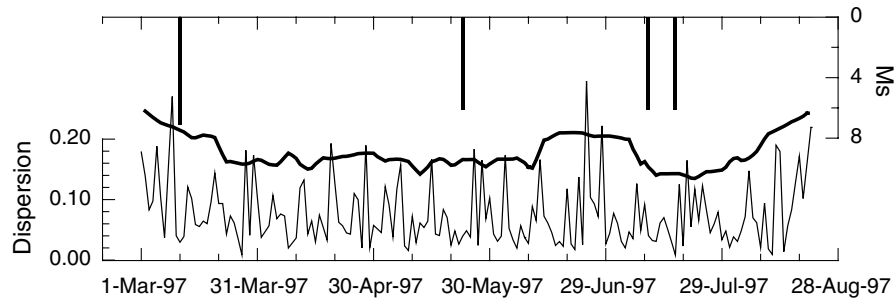


Fig. 10. Day-to-day variations of dispersion of NWC signal within a range of 1–9 h (lower thin curve) and earthquakes $M \geq 6$ occurred within the studied area corresponding to the NWC-Tokyo VLF propagation path (upper descending bar chart). The thick curve is ± 12 day running average of $\langle A \rangle + 2(\sigma)$ level of the amplitude of VLF fluctuations.

4.2. NWC-Chofu VLF propagation path

The largest event within the fifth Fresnel zone for the NWC-Chofu propagation path occurred on March 11, 1997 at 19:22 UT near the east Coast of Mindanao Island ($7^{\circ} 47' N$, $127^{\circ} 42' E$) at a depth of 8.5 km. It included 11 shocks of magnitudes ranging from 5.7 to 7.1. Anomalous deviations in NWC signals were observed 2–3 days before this event. This can be seen in the detailed diurnal runs of changes of amplitude for March 1–13, 1997 shown in Fig. 9. Strong deviations from current average diurnal runs occurred during nighttime on March 7 and 8. The moment of the seismic event is marked in the graph by a rhomb sign.

Not so prominent but essential deviations in the March 1–5 period can possibly be associated with the earthquake swarm on the Izu peninsula. The strongest earthquake of a magnitude of 5.7 for this event is marked by a rhomb in the graph.

We could not find pronounced effects of intensification of quasi-periodical oscillations in fluctuations of the NWC signal-like those observed in the Omega signal. This is possibly connected to the averaging of propagation properties over a much longer path than was done with the Omega case.

Variations of dispersion of NWC fluctuations in a range of 1–9 h are presented in Fig. 10 together with those averaged over ± 12 days at a current level of 2σ deviations. Selected seismic events of $M_s > 6$ and focal depths less than 40 km within the fifth Fresnel zone are shown by descending bars in the graph.

5. Correlation between VLF perturbations and regional seismic activity

As our next step we examine the response of VLF fluctuations to variations of integral parameters of regional seismicity. Shvets et al. (2002) considered the following parameters to be integral characteristics of regional seismicity:

- Daily cumulative EQ energy.
- A common logarithm of the sum EQ energy released during a particular day (cumulative class). A class of earthquake K is defined as a common logarithm of earthquake energy and can be related to magnitudes from an empirical equation (Kanamori and Anderson, 1975): $K = 4.8 + 1.5M$.
- Daily maximal EQ magnitude M_{\max} .
- Daily EQ rate.

It was found that variations of the cumulative class and maximal magnitude reveal practically identical behavior because M_{\max} mainly determines daily energy liberation.

The other integral seismic parameters listed above, such as daily earthquake energy and earthquake rate, have a much larger dynamic range. The results of correlation and Fourier analysis discussed below are determined by a few of the largest events (or even a single event) that occurred during an analyzed time interval.

Therefore, a daily maximal EQ magnitude M_{\max} is used for analysis in this paper as an integral parameter characterizing seismicity in a large area.

Earthquakes within a circular area centered at the observation point were encountered. With variation by area sizes and the maximal focal depths D_{\max} of selected earthquakes, we can estimate some effective volumes for which maximal ionospheric responses to seismic activity are observed by maximizing the cross-correlation coefficient between the intensity of VLF fluctuations and integral seismic parameters.

5.1. Omega-Chofu VLF propagation path

Presented in Fig. 11 are smoothed series (with 3-days running mean time) of daily maximal magnitudes and dispersion of Omega VLF fluctuations in a range of periods from 1 to 9 h.

The cross-correlation function is demonstrated in Fig. 12a. We can see that the maximal cross-correlation

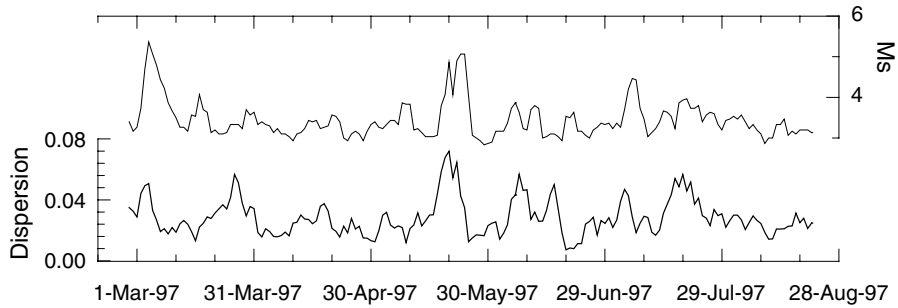


Fig. 11. Comparison between the variations of regional seismicity around Tokyo and along the Omega-Chofu propagation path ($M_s > 2$, focal depth $D < 40$ km) and dispersion of nighttime amplitude fluctuations in the Omega signal in a range of periods 1–9 h smoothed with 3-day running mean.

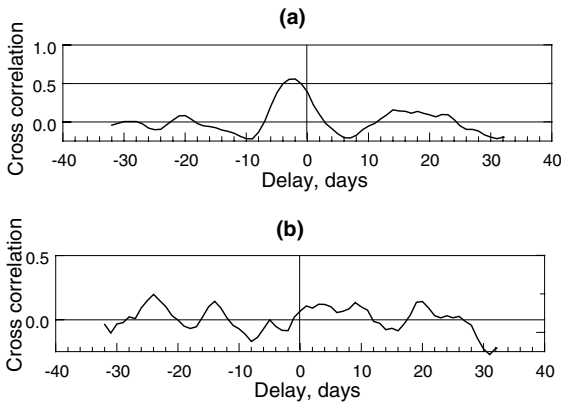


Fig. 12. (a) Cross-correlation coefficient between daily maximal magnitude and dispersion of the VLF signal. Maximal value of cross-correlation reaches ~ 0.5 at delay of -2 days that indicates intensification of fluctuations in VLF signal in the pre-seismic period. (b) Cross-correlation coefficient between dispersion of the VLF signal and maximal daily magnitude for deep earthquakes ($D > 40$ km).

value reaches approximately 0.5 at negative delay -2 days and corresponds to the pre-seismic period. Maximization of this value had been provided for relatively shallow ($D_{\max} < 40$ km) earthquakes distributed within a circle area of 350 km radius.

For comparison, a cross-correlation function calculated for the same area as above but only accounting for deep earthquakes ($D_{\max} > 40$ km) is demonstrated in Fig. 12b where we cannot observe any dominating peak.

5.2. NWC-Chofu VLF propagation path

As in the case of the Omega-Chofu propagation path, we selected shallow ($D_{\max} < 40$ km) earthquakes within the fifth Fresnel zone combined with a circle area of 350 km around the receiving point for analysis of seismic influence for the NWC-Chofu propagation path. In

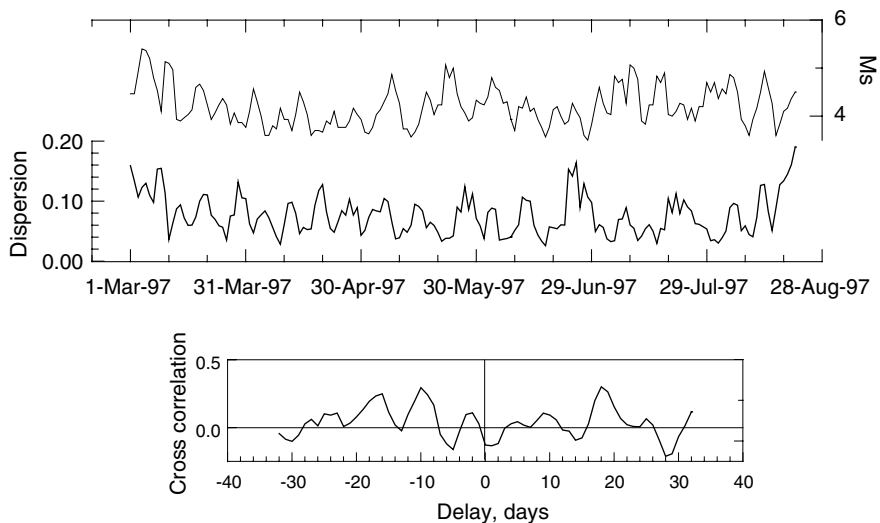


Fig. 13. Smoothed time series of daily maximal magnitude and dispersion of fluctuations in the NWC signal in the range of periods 1–9 h (upper graph). The corresponding cross-correlation function (lower graph) demonstrates an oscillating behavior that is following from quasi-periodic character of the compared time series.

addition to the area around Tokyo, this path covers a seismically very active region in the Pacific Ocean and Philippines Archipelago. The analyzed area and corresponding geographical distribution of earthquakes are presented in Fig. 4. A set of smoothed time series of daily maximal magnitude and dispersion of fluctuations in NWC signals in the range of periods from 1 to 9 h is presented in Fig. 13. The corresponding cross-correlation function (lower graph in Fig. 13) demonstrates oscillating behavior. For this case, it is impossible to definitely indicate any dominating peak-like the case of the Omega-Chofu propagation path.

6. Rhythms in regional seismic activity and nighttime fluctuations of VLF signals

An earthquake occurring at one place could trigger one or more earthquakes at other remote places (Tverskoy, 1939; Nikolayev and Vereshchagina, 1991; Beresnev and Wen, 1995). Because of this, we considered a sufficiently large seismically active region to cover an area of possible collective features in the behavior of seismic activity. Quasi-periodic oscillations in VLF propagation parameters coming into the frequency range of planetary waves with periods of 5–10 days and intensifications connected with strong earthquakes have been discovered and discussed in recent papers (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Hayakawa and Molchanov, 2002). In this chapter we analyze series of data on earthquakes from the IRIS catalogue to search for periodical behavior of the same frequency range previously found in VLF data.

We considered parameters that characterize large seismically active areas to search for periodicities in seismic activity. Peaks in seismic activity that tend to form periodical patterns are produced by earthquakes occurring at different places within a studied region. Regional activity was investigated previously within much smaller areas $\sim 2 \times 2^\circ$ (Rikitake, 1976). This is possibly why patterns with quasi-periodical behavior in seismicity were not revealed.

We are looking for a hidden periodicity by application of Fourier transform to autocorrelation functions calculated for time intervals of 64 days and averaged over an entire period of observations broken in three pieces to minimize the influence of the nonstationarity of the analyzed processes.

6.1. Omega-Chofu VLF propagation path

An area of 350 km radius around Tokyo combined with the fifth Fresnel zone for the Omega-Chofu VLF propagation path was analyzed during the interval of our observations. This was done for comparison of spectral contents of VLF fluctuations in the Omega

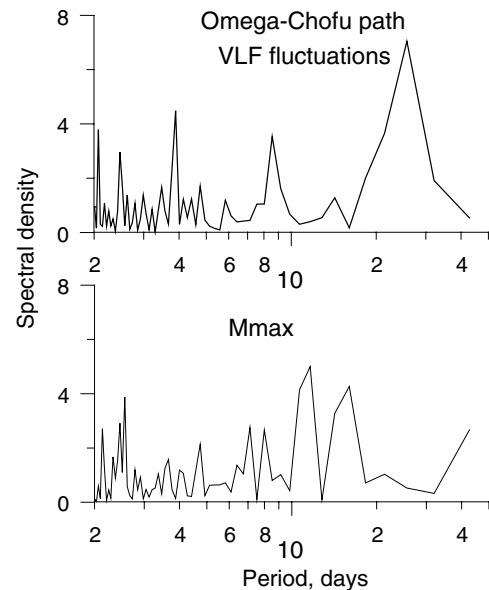


Fig. 14. Spectral contents of variations of dispersion in the Omega amplitude and regional earthquake activity within area of 350 km radius around Tokyo and along the Omega-Chofu propagation path. A peak near 27 days is clearly observed that can be attributed to the tidal or solar rotation period. Pronounced seismic periodicity is seen at ~ 11 and ~ 14 days periods.

signal and variations of daily maximal earthquake magnitude. Corresponding spectra are presented in Fig. 14. A peak near 27 days is clearly observed in the spectrum of day-to-day variations of VLF fluctuations that can be attributed to the solar rotation period. Other peaks at ~ 8 and ~ 4 days have minor amplitude in reference to the principal one in the spectrum. Pronounced periodicity is seen from the spectrum of earthquake magnitude variations at ~ 11 -day and ~ 14 -day periods. It should be noted that previous analysis for the same region (Shvets et al., 2002) has shown that periodical patterns in regional seismicity can appear over an extended time span covering a few years.

6.2. NWC-Chofu VLF propagation path

Shown in Fig. 15 are power spectra of day-to-day dependencies of maximal daily earthquake magnitudes within the 350 km circle area combined with the fifth Fresnel zone of the NWC-Chofu path and of corresponding NWC amplitude fluctuations. We can see that pronounced peaks appear in both spectra at periods of about 13–14 days and near 7-day periods that demonstrate similar spectral content. Also we note that, in contrast to the earthquake magnitude spectrum, a peak in the spectrum of VLF fluctuations at a period close to 27 days is pronounced as in the case of the Omega signal.

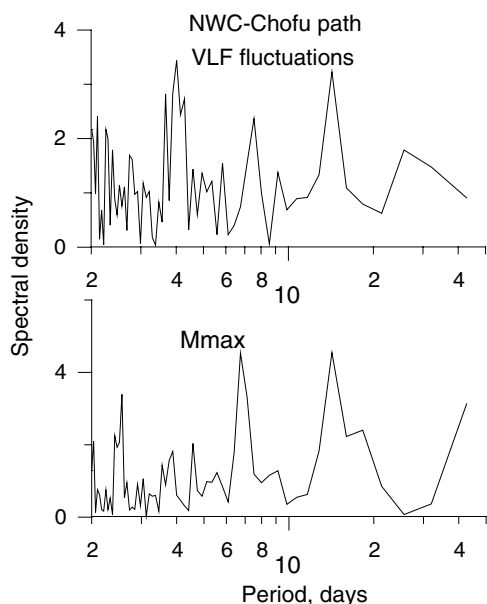


Fig. 15. Power spectra of day-to-day dependencies of dispersion of NWC amplitude fluctuations (upper graph) and maximal daily magnitude of all earthquakes within the fifth Fresnel zone of NWC-Chofu path and area of 350 km radius around Tokyo. In both spectra pronounced peaks appear at periods of about 13–14 days and near four and seven days periods demonstrating similar spectral content. A peak at period close to 27 days in the spectrum of VLF fluctuations can be referred to tidal or solar rotation influence.

7. Discussion and conclusion

The physical mechanisms of seismo-ionospheric influence are poorly understood at present, and possible ways of viewing such interconnections have been discussed in recent monographs by Hayakawa and Fuji-nawa (1994), Hayakawa (1999), and Hayakawa and Molchanov (2002). The first supposes that disturbance of the ionosphere is due to atmospheric electric field drops caused by increases of atmosphere conductivity due to the ionizing influence of radon escaping from a fault zone. Another possibility discussed is that the mechanism involves the influence of seismic or pre-seismic processes on the lower ionosphere through excitation at the earth's surface of acoustic-gravity waves (AGW) and their amplification and dissipation at heights of mesopause (80–90 km) where reflection of VLF radio waves from the lower ionosphere occur during nighttime. Molchanov et al. (2001) and Miyaki et al. (2002) have recently presented some evidence of AGW related to seismic activity. They studied fluctuation spectra in LF signals of 40 kHz in periods of 10 min to a few hours (AGW range) and found good correlation with seismic activity. The results of our study show that precursory VLF anomalies can be observed for earthquakes both under the sea floor and under-land. Underwater release of radon seems to be unrealistic because of its high solubility in the seawater. So, to

explain the effects discussed in this paper, we also lean toward the hypothesis of an acoustic-gravity nature of seismo-ionospheric influence. The finding of wave-like anomalies associated with earthquakes with periods of 1–4 h consistent with the AGW frequency band also supports this hypothesis.

Analysis of earthquakes in a wide area around Tokyo covering a region of complicated tectonic structure has shown periodical behavior in regional seismicity. It was found that periodicities of ~ 7 , ~ 11 , ~ 14 days could be observed in variations of earthquake parameters integrated over large seismically active areas. In this paper we examine a hypothesis on excitation of quasi-periodic oscillations driven by seismic activity by using cross-correlation analysis. It should be noted that at present it is not believed that any periodicities are attributable to sequences of earthquakes (see, e.g., Rikitake, 1976). Thus, further study is required to determine if the periodical behavior of seismic activity found in the present work can be observed in different seismo-active regions and during different time spans.

The seismic periodicity found supposes periodical triggering by some external force or internal mechanism involving the accumulation and release of seismic energy due to possible relative motion of tectonic plates. Because a period of ~ 11 days found for the area around Tokyo cannot be exactly attributed to tidal perturbations, we can then suppose an internal character of the observed seismic periodicity. However, for the area of the Pacific Ocean studied, we observe periodicities at ~ 14 and ~ 7 days which are close to the second and fourth harmonics of the tidal cycle. So, more extended analysis is required to distinguish between internal and external causes of the observed periodicity in seismic activity.

The main results of this work are summarized as follows:

- Analysis of the electric field strength fluctuations in subionospheric VLF signals for relatively short (Omega, Tsushima-Chofu, Tokyo; ~ 1000 km) and long (NWC, Australia-Chofu; ~ 8000 km) propagation paths covering different seismically active areas was performed to look for ionospheric response to seismic activity.
- Spectral analysis of nighttime Omega signal fluctuations revealed wave-like anomalies (oscillations with periods of about 3 h, which correspond to the internal gravity wave frequency band) preceding by 1–3 days or contemporising with moderately strong seismic events of magnitudes 5–6.1 happened in an area that is a combination of a 350 km circle area around Tokyo and the fifth Fresnel zone for the Omega-Tokyo (Tsushima) VLF propagation path.
- Anomalous deviations of nighttime amplitude from current average diurnal runs had been found preceding by two days the largest earthquake with a magni-

tude of 7.1 that occurred under the sea floor near the east coast of Mindanao Island during the observation time in the vicinity of the NWC-Tokyo propagation path.

- Cross-correlation analysis has shown a statistical relationship between Omega signal VLF fluctuations and regional (350 km around Tokyo) seismic activity. The correlation coefficient reaches a maximal value of ~ 0.5 for delays of 2–3 days that correspond to intensification of VLF fluctuations during a pre-seismic period. This type of correlation has not been found in the case of the NWC-Tokyo propagation path.
- Rhythmic behavior in variations of seismic activity integrated over large areas, corresponding to the studied VLF propagation paths has been revealed with periods ~ 7 –14 days. In the NWC-Tokyo propagation path, very close peaks in spectra of daily earthquake magnitude variations and VLF fluctuations are observed with periods of ~ 7 and 14 days. These show similar spectral content. For the region around Tokyo, variations of seismicity show quasi-periodical patterns with periods of ~ 11 days, whereas the closest peak appears at ~ 8 days in the spectra of the Omega fluctuations.
- Spectral analysis of nighttime VLF fluctuations has shown essential periodical components with periods close to 27 days for both studied propagation paths. This periodicity, which is not observed in variations of seismic activity, can apparently be attributed to solar rotation or tidal influence on the properties of the lower ionosphere.

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