Report of the National Research Institute for Earth Science and Disaster Prevention, No. 61 ; March, 2001

Spatio-Temporal Relationship between Anomalous ELF/VLF Band Signals and Earthquakes

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Abstract

We investigated the temporal and spatial relationship between earthquakes and pulse-like signals in the ELF/VLF ranges (1-10kHz) (VPS) in order to understand the intrinsic relationship between these phenomena and earthquakes as well as to understand the mechanisms producing them. Use are made of a number of VPSs and VPS source location data from October 1995 to December 1997 obtained by an observation network consisting of five sites. Analyses were conducted over ten-day periods in which moderate earthquakes occurred. It has been confirmed, in agreement with previous reports, that the VPS radiation precedes almost all earthquakes, and that the VPSs of sufficient amplitude to be simultaneously observed at more than four sites are scarcely emitted from the epicentral region, but a few hundred kilometers distant from the epicenter

We think that the VPSs are emitted in the lower atmosphere through an electromagnetic instability process. There are indications that small-amplitude VPSs occur in the vicinity of the epicenter during the preparatory stages of shallow earthquake occurrence.

Key words : Earthquake precursor, Electromagnetic field, ELF/VLF, Pulse number, Source location

1. Introduction

After it was suggested that electromagnetic radiation is a short-term or an imminent-term precursor to an earthquake (Ulomov and Mavashev, 1967 ; Zubkov and Migunov, 1975), electric, magnetic, and electromagnetic anomalies have been investigated covering wide frequency ranges (e.g. Rikitake, 1976 ; Gokhberg *et al.*, 1988 ; Parrot and Johnston, 1989 ; Popov *et al.*, 1989 ; Park *et al.*, 1993 ; Parrot *et al.*, 1993 ; Hayakawa and Fujinawa, 1994). Of these, the electromagnetic signals in the low frequency (LF), extremely low frequency (ELF), and very low frequency (VLF) bands have been suggested to be more significantly related to processes preceding earthquakes (Gokhberg *et al.*, 1982 ; Ralchovski and Christokov, 1985 ; Sobolev and Husamiddinov, 1985 ; Parrot *et al.*, 1985 ; Oike and Ogawa, 1986 ; Parrot and Mogilevsky, 1989 ; Fujinawa and Takahashi, 1990). However, we lack a thorough evaluation on the basis of well-organized guidelines such as those recommended by the IASPEI subcommittee (Wyss, 1991 ; Wyss and Booth, 1997). Such kind of evaluation for each candidate of precursors is also essential to answer the question whether earthquake prediction is indeed possible (e.g. Geller, 1991 ; Hamada, 1991).

Pulse-like signals in the ELF and VLF bands (1-10 kHz) (hereinafter VPSs) have been reported to precede many larger earthquakes than moderate ones.

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And the number of these signals per unit time has been shown to be substantially uncontaminated by environmental electromagnetic noises (e.g. Gokhberg *et al.*, 1982, Ralchovski and Christokov, 1985 ; Sobolev and Husamiddinov, 1985 ; Oike and Yamada, 1994 ; Fujinawa *et al.*, 1997). In addition, the parameter has a kind of usability in the point of a high degree of similarity on a regional scale (Fujinawa *et al.*, 1997 ; Fujinawa and Takahashi, 1998). It is quite different from other types of parameter such as intensity of electromagnetic radiation (Gokhberg *et al.*, 1982 ; Fujinawa and Takahashi, 1990). For instance, intensity of near dc component has been shown to have strong locality of the sensitivity (e.g. Varotsos and Alexopoulos, 1984 ; Yoshino, 1991).

To further clarify the relationship between these signals and earthquakes, and to investigate the mechanism by which the signals are produced, we need knowledge of their source regions with regard to earthquake rupture areas (Yoshino, 1991 ; Hayakawa *et al.*, 1993 ; Takahashi and Fujinawa, 1993 ; Parrot *et al.*, 1993). In the present report we limited our interest to the problems whether the VPSs emit in earthquake preparatory processes synchronously in terms of time and location. We need to discriminate the VPSs from signals due to the lightning discharge process (Yamada and Oike, 1996 ; Enomoto *et al.*, 1997a) and from urban noises (Yoshino and Tomizawa, 1990). Once we obtain the knowledge regarding the signal location we would be able to build more confident models of generation mechanisms (Parrot *et al.*, 1993).

Yoshino (1991) located the source of anomalous emissions in the LF band (81-82 kHz) by using a direction-finding technique at multiple sites. Recent developments in accurate clock synchronization using the GPS now enable us to adopt a different approach utilizing arrival times of the VPS at multiple observation sites. The new approach to determining the location of the VPS source has been in use in central Japan since October 1995 (Fujinawa *et al.*, 1997). The preliminary report showed that the VPSs might not originate around the epicenter.

Here we present the results of a statistical evaluation addressing the question whether the VPSs originate in the epicentral region, or whether the number of VPSs increases imminently before major earthquakes. The evaluation is based on a nearly uniform dataset generated during approximately two years by an observation network. It should be noted, however, that this semi-quantitative study relys on a subjective choice of criteria to discriminate the anomalous state from the normal state. The sampling way of earthquakes to correlate anomalous phenomena is also subjective. A confidential evaluation for the particular phenomenon should use the criteria chosen objectively. It is because of the necessity of inter-group cooperative efforts to cover many dimensions of parameter space (Bise and Rauscher, 1994). Although the work described in the present report does not satisfy these conditions, it could provide a useful basis for a more thorough investigation for the VPSs as an earthquake precursor.

2. Observation

The observation methods are briefly explained here focusing on the instruments and data analysis (for more detail see Fujinawa *et al.*, 1997). Multiple components of electromagnetic field observations have been conducted since October 1995 at four observation sites—Hasaki (HAS), Chikura (CKR), Koufu (KOF) and Sagara (SAG)—in central Japan (Fig. 1). The largest distance between observation sites in the network was approximately 250km. In October 1996 another site, Nagaoka (NAG), was added to the north of the original network to locate the source point more accurately and to detect the VPSs within a larger region. Three components of subsurface electric field strength were measured : two horizontal components using two mutually perpendicular pairs of 8-m-long dipoles 10 to 50m apart, and the vertical

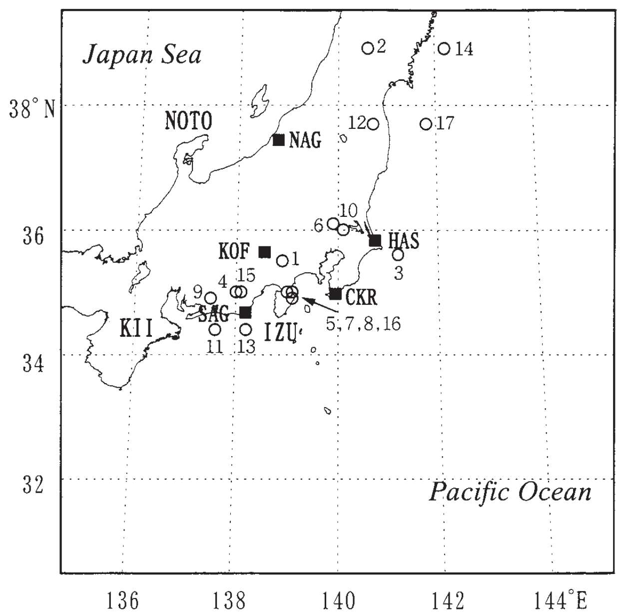

Fig. 1 Locations of electromagnetic field observation sites in the central part of Japan (■). Circles (○) show epicenters of earthquakes used in this stady.

using the casing pipe antennas with lengths from about 150m to 800m (Fujinawa and Takahashi, 1990). Three components of the magnetic field were also measured (except at KOF) using induction magnetometers (Fig. 2).

The VPS signals were recorded selectively using a trigger-recording device monitoring the strength of the vertical electric field. The threshold level was chosen after an experimental observation of approximately one month so as not to record local noises. The different lengths of the boreholes resulted in different sensitivities at different sites. The noise level is dependent on the electromagnetic condition of the observation sites with the result that there are slight differences in the amplification gain at individual sites. Data were sampled at 50 kHz for the sake of recording waveforms of ELF/VLF signals.

The arrival times of each VPSs at more than four observation sites were used to determine the source coordinates in the three-dimensional space and the origin time using the same procedure as the earthquake hypocentral parameter determination (e.g. Aki and Richards, 1980). Considering the transmitting time of the radio waves for distances comparable with the typical dimensions of the observation network and the frequency band of VPSs, it was necessary for time measurements to have an accuracy exceeding several microseconds. All the clocks at the observation sites were synchronized using GPS time signals, and the overall time recording accuracy was better than $\pm 5\mu s$. It is expected that more accurate source parameter values can be obtained if we have more observation sites.

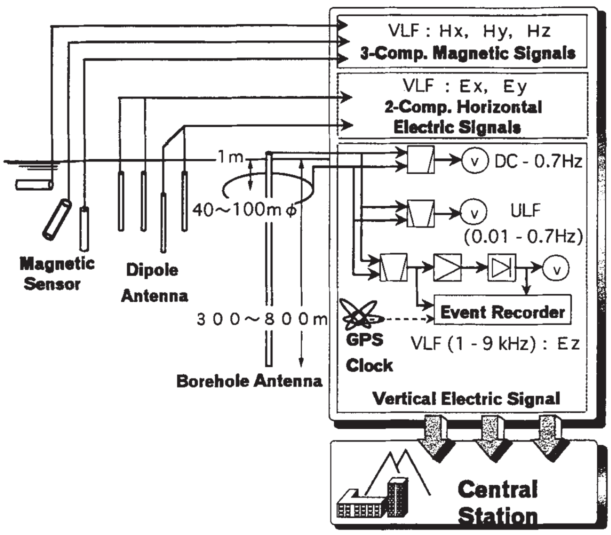

Fig. 2 Schematic diagram of multiple-component measuring equipment used to locate the source point of VPSs. The electric field was measured using a pair of horizontal dipoles that is 8m long in length at a distance of 20-50m apart and using a vertical monopole that is 600-800m long and is surrounded by a circle of wire (with a radius 10-20m) buried at the depth of approximately 1m. The magnetic field was measured by three mutually perpendicular induction -type magnetometers (BF-6, EMI). Recorded data were transmitted to a central station once every night.

For the 30 steps of the prescribed maximum amplitude, the number of VPSs was counted every ten minutes at each site. This enabled us to obtain the amplitude spectrum of a number of the VPSs.

Originally we suspected that many VPSs would be observed in the network and that we could therefore locate the source region by using the correlation time lag of the time sequences at a pair of observation sites (Takahashi and Fujinawa, 1993). As in VLBI measurement, the correlation time lag data would provide the average source bearings. Preliminary experiments, however, revealed that the number of VPSs with an amplitude of sufficient magnitude to be observed at all the sites was very small (Fig. 3). As a result, the correlation time lag was determined almost by environmental background noises and did not provide meaningful information regarding the VPS propagation direction.

On the other hand, it is generally easy to identify each signal at different sites by using a time window corresponding to the time required for the VPSs to propagate at the velocity of free-space electromag-

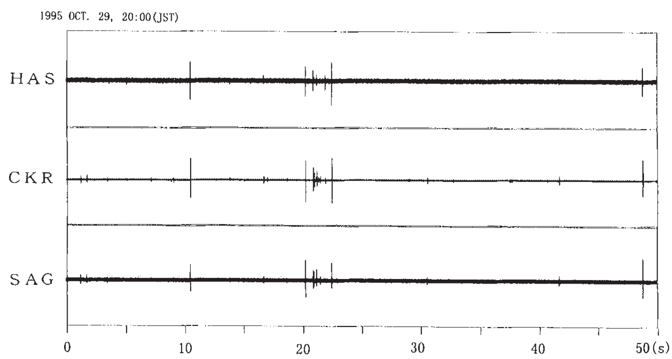

Fig. 3 An example of continuous records of the ELF/VLF band signals in the vertical electric field for 50 sec. at three sites. Because there are many signals well above the background noise level, the correlation time lag between any pair of time series could not provide meaningful information as to the phase difference of the arriving signals of the prominent amplitude.

netic waves, the longest distance between any two sites in the network (Fujinawa *et al.*, 1997). This easiness of identification was mainly due to the accuracy of the GPS clock as well as to the larger recurrence time of VPSs compared to the time interval of 70 ms for one sample data acquisition. Generally speaking, the waveforms of VPSs observed simultaneously at different sites display a greater similarity than the waveforms of seismic waves. It is because that the VPSs propagate in a more homogeneous medium than the crust through which seismic waves propagate.

Determination of source location

A comparison of the six electromagnetic field components in Fig. 4 shows that there are no essential differences in S/N among six components, at least to read arrival times of VPSs, though a little bit better for the vertical electric field component. But effectiveness of each electromagnetic component for detecting anomalies seems to depend on the frequency and the geophysical regime. For instance, the ULF

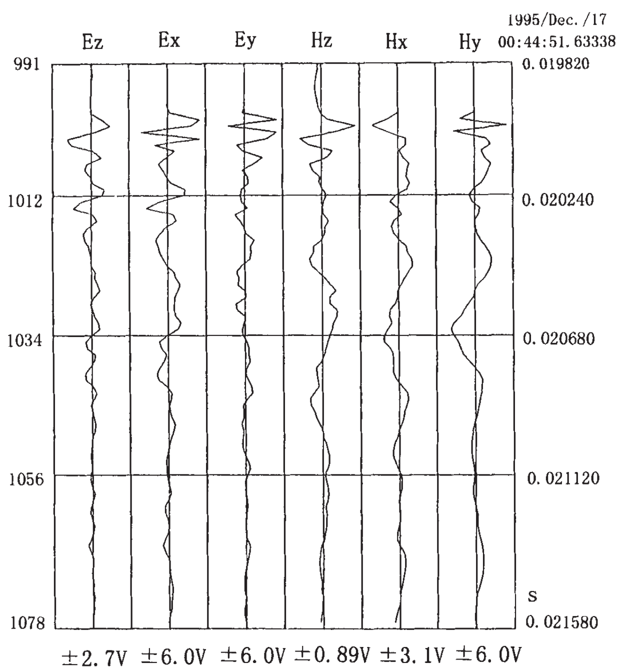

Fig. 4 The example of VPS waveforms of three components of the electric fields (Ez, Ex, Ey) and of three components of the magnetic fields. The horizontal scales are normalized so that the maximum amplitudes can be all virtually identical. There are no essential differences in reading arrival time and in the S/N at least for the ELF/VLF band, although generally the S/N for the vertical electric field measured by the borehole antenna is a little better.

ranges of the vertical electric field are higher in the S/N in comparison with the horizontal electric field data for geological events related to magma activity (Fujinawa *et al.*, 1992 ; Park *et al.*, 1993 ; Fujinawa and Takahashi 1996). In the present analysis we used only the vertical electric field data except in cases where the arrival direction was calculated on the basis of the direction finding method.

A standard time table requires knowledge of the propagation path in the three propagation media related to the present problem : underground Earth, the atmospheric layer, and the ionosphere (e.g. Wait, 1967). The small value of the skin depth of order 100m for the ELF/VLF band under the typical geo-resistivity value in and around the network excludes the possibility of underground propagation unless we take into account any particular of conductivity heterogeneity such as an underground waveguide or conductive path (e.g. Yoshino, 1991 ; Varotsos *et al.*, 1998).

The VLF waves propagate in the air as direct waves, surface waves, sky waves reflected from the ionosphere, and as guided waves between the ionosphere and the conductive ground surface (Wait, 1967). We can infer from previous experimental and theoretical results on the VLF wave propagation and from our somewhat intuitive analysis of waveforms that we need to consider only the direct path propagation mode only for events emitted within a distance of several hundred kilometers around the network (Fujinawa *et al.*, 1997). And it is noted that the propagation velocity of the wave-guide mode between the earth's surface and the ionospheric reflection layer is only a few percent smaller than that of the direct mode. Assuming only the direct path is the simplest to determine the source location parameter. More accurate or extended analysis should use a full wave analysis (e.g. Cooray and Orville, 1990 ; Nagano *et al.*, 1993).

Smaller events were sometimes recorded before or after the main events triggering the recorder. These subsidiary events were analyzed with regard to the difference between their arrival time and that of the main event. They were found not to be different phases of the main event but independent events, which were probably induced in the vicinity of the source of the main event (Fujinawa *et al.*, 1997). So those subusidary events are discarded in the source location.

The source position (x_0, y_0, z_0) in a rectangular Cartesian coordinate system with the x axis oriented east-west, the y axis oriented north-south, and the z

axis oriented vertically and the origin time t_0 were obtained by solving nonlinear governing equations,

$$(x_i-x_0)^2+(y_i-y_0)^2+(z_i-z_0)^2=c^2(t_i-t_0)^2, \quad i=1,2,3, \quad \cdots\cdots\cdots\cdots(1)$$

using the arrival time data t_i at i-th observation site with coordinates (x_i, y_i, z_i). The area covered with the network in the present work is small enough for the curvature of the Earth to be neglected in the parameter determination procedure. The propagation velocity c was taken to be that of electromagnetic waves in the air.

The solution was obtained through an iterative procedure using several subsidiary means, such as reducing the correction term in the iteration in order to obtain a stable solution because of the marginal amount of data available for solving the inversion problem. The dependence of the solution on the initial spatial coordinate values in the inversion was checked by selecting the solution with the smallest difference between the observational arrival time data and the model data (hereafter denoted O-C).

The initial phases of events were generally sharp for arrival times to be read with an accuracy of some 20μs corresponding to the smallest unit of the 50kHz data sampling rate. The evaluation of the accuracy of parameter determination with and without taking into account the quality of the data resulted in source point location differences of less than a few tens of kilometers. The quality of the arrival time readings was occasionally poor when the event was remote or when the signal was small and noisy. In those cases the parameters were determined to an accuracy of several tens of kilometers.

Moreover, the similarity of both the waveforms (**Fig. 5**) and the amplification gains at different sites enabled us to use the trigger times t_i* instead of the arrival time t_i. The accuracy of location determination is of a few tens of kilometers when the VPS source was not distant from the network. Therefore we used triggered times t_i* in this report except where otherwise noted. We did this for a practical reason: to reduce manual reading time because so many VPSs were observed. It is enough for testing the hypothesis that the VPSs are emitted from the epicentral region. The several adopted approximations are not expected to affect the conclusion.

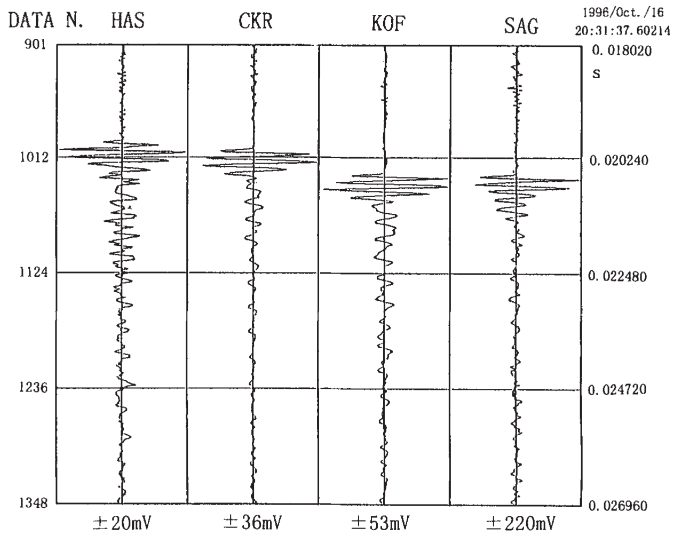

Fig. 5 Waveform records of the vertical electric field identified as same event at four sites. Horizontal scales are for input electric field strength prior to the amplification. It is indicated that the waveforms are very similar. We were therefore able to use the time of triggering to calculate source parameters instead of the arrival time, which is time-consuming to read when there are conspicuous background noises.

Assessment of the algorithm

Two methods were used to check the algorithm of determining the source location. One was comparing the location with the lightning locating data and the other was comparing the location with the results obtained by the direction-finding method.

The first method relying on the lightning locating data is not expected to provide definite results, however, because it gives rise many kinds of emissions including the lightning discharge process of the VPSs and the return stroke. We found that the VPSs are not the return stroke themselves on the basis of occurrence time of those phenomena. Both the occurrence time of the return stroke and the VPS origin time were estimated using the GPS clocks, and accordingly the accuracy of those occurrence times should be at worst several tens of microseconds.

But, the VPS sources were found frequently located in the region of active lightning processes. The source points of such VPSs were suggested to be coincident with the locations of return strokes within several kilometers indicating that the source location algorithm works well.

The second approach is comparing the source location through the present algorithm with those through the direction-finding method. The direction-finding method is based on the goniometric technique using two horizontal components of the magnetic field (e.g. Yoshino, 1991; Zhang *et al.*, 1994). The electromagnetic field induced by a vertical electric current dipole in the air is known to be approximately described by assuming that the Earth's surface is a perfect conductor when we think only of the direct wave mode. In a spherical coordinate system (r, θ, ϕ) with the z axis ($\theta=0$) directed upwards, the Hertz vector due to the vertical current micro-dipole of length ds carrying current I fluctuating with radian frequency ω has only the vertical component. Furthermore, the horizontal magnetic field vector H_ϕ at any observation point is in the plane perpendicular to the dipole and is perpendicular to the source direction vector,

$$H_\phi=\frac{iI\mathrm{d}s}{2\lambda r}\left(1+\frac{1}{ikr}\right)\sin\theta e^{-ikr}, \qquad (2)$$

where r is the distance between the current dipole and observation point, λ is the wavelength, $k=\omega\sqrt{\mu\epsilon}$, ϵ dielectric constant and μ permeability. The first term in parentheses of the right hand side of (2) corresponds to the radiation term, and the second to the induction term. Thus the directional property of the magnetic field with regard to the direction of the source does not depend on the distance from the source.

The vector diagram of the horizontal magnetic field $\boldsymbol{H}_h$ (H_x, H_y) as illustrated in Fig. 6a, the polarization diagram is shown to be approximately linear. Here the vectors are shown so as to be perpendicular to the horizontal magnetic field $\boldsymbol{H}_h$ for the part of the initial phase providing us with a bearing direction of received signals.

In contrast, polarization diagrams for the combination including the vertical magnetic component H_z, were rarely found to be linear. Further, the polarization diagrams for combination of the vertical electric component E_z and any of the horizontal magnetic components were generally linear. It provides useful data for understanding the characteristics of the borehole antenna (Nakayama and Fujinawa, 1994 ; Fujinawa and Takahashi, 1994 ; Sakanaka *et al.*, 1995 ; Fujinawa *et al.*, 1995). A combination including the horizontal electric field E_x or E_y on the other hand generally resulted in a complex diagram far from linear configuration. This might be attributed to the electric field distortion due to conductivity and inhomogeneity around observation sites, such as that induced by galvanic distortions (e.g. Kaufman and Keller, 1981).

The initial phases of the VPSs were not always similar for different electromagnetic field compo-

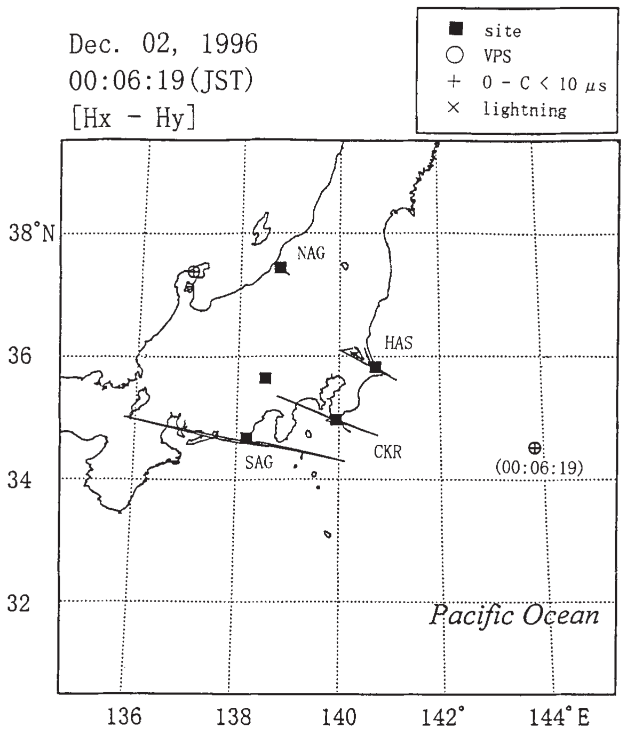

Fig. 6a A comparison between the VPS source location determined by the direction-finding method based on the polarization diagram and determined by the arrival-time method (⊕) when the event at 00^h 06^m 19^s is outside the network of observation sites.

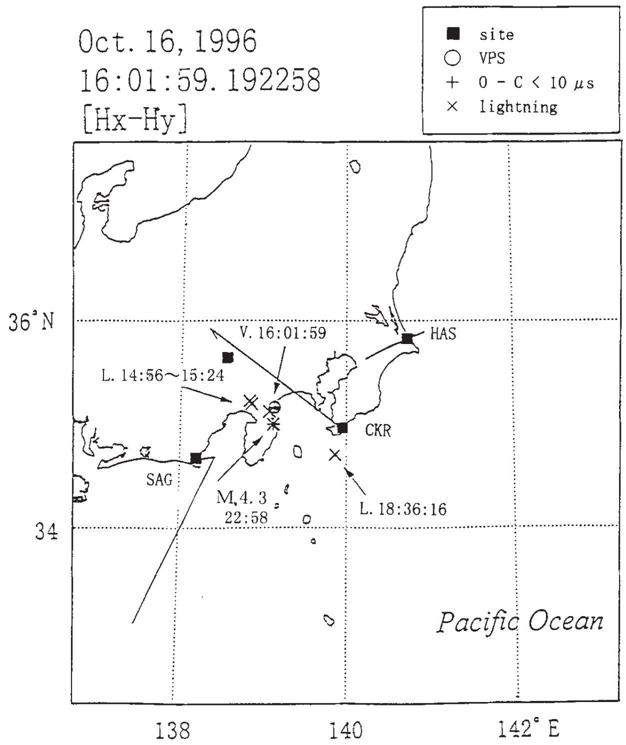

Fig. 6b Same as Fig. 6a except that at the tigger time of 16^{h}01^{m}59. 192258^s, 16 Oct. 1996. The event is within the network of the observation sites. (×) lightning discharge, (∗) earthquake epicenter, (○) VPS source location.

nents. There were some events with different numbers of dominant peaks or different dominant frequencies. The linear polarity of the horizontal magnetic components, however, could be observed for almost all events if we limited the portion of the waveform excluding those parts with lower degrees of similarity.

As can be seen in Fig. 6a and 6b, the direction-finding methods provide generally consistent source locations. Fig. 6a concerns the case of a VPS source a little outside the network, and Fig. 6b the case inside the network. In both figures the source location determined using the arrival time data is shown by a circle (○) (a cross in the circle '⊕' indicates that O-C is less than $10\mu s$). Horizontal magnetic field polarization diagrams for four (Fig. 6a) or three sites (Fig. 6b) have been drawn. The polarization diagrams at all sites are seen to be very similar linear type possibly because of the considerable dissipation of the induction term in Eq. 2.

The comparison of the two methods for source locations reveals satisfactory agreement, although the difference between the estimates is larger for the source outside the network (Fig. 6a), just as that the hypocentral parameter determination error is larger for earthquakes outside the observation network (e.g. Aki and Richards, 1980). For VPS events inside the network, the estimates agree to within a few tens of kilometers (Fig. 6b). We therefore think that the source point determination algorithm using the VPS arrival time is sufficiently accurate for our ultimate purpose to determine the VPSs originating from the epicentral region of major earthquakes that have rupture dimensions of several tens of kilometers. Further, the generally linear polarization of the horizontal magnetic field vectors suggests that the VPSs are largely due to vertical dipoles.

The goniometric direction-finding method is based on the assumption that the incident wave is linearly polarized and monochromatic. Failure of assumptions sometimes results in errors in the determination of the arrival bearings (Hayakawa *et al.*, 1993). The discrepancy between the arrival-time result and the direction-finding result could therefore be due to the these situations. It is to be noted that a more refined direction-finding method requiring fewer assumptions was proposed by Okada *et al.* (1977) for determining the locations of the whistler sources.

Because lightning discharges generally accompany the VPSs (Yamada and Oike, 1996 ; Enomoto *et al.*, 1997a), we used data from lightning discharge monitoring services (Franklin Japan Co., Ltd., and Weather News Co. Ltd.) and data from JMA using SAFIR (Kawasaki *et al.*, 1994) in this investigation. And, the geomagnetic activity index data reported by Hiraiso Solar Terrestrial Research Center (Communications Research Laboratory : (CRL) was also used to examine the possibility that the VPS activity is induced by geomagnetic storms.

3. Results

We analyzed the source location data of the VPSs recorded around the occurrence time of earthquakes. We treated earthquakes with a magnitude of larger than 5.0, and with a hypocentral depth of less than 100 km, in and around the network (Fig. 1). Data associated with earthquakes with a magnitude of less than 5.0 and larger than 4.0 occurring just inside the observation network were also used. There are no definite reasons, however, for limiting to larger earthquakes to investigate the relationship between earthquakes and VPSs (Sumitomo, private communication). Smaller earthquakes may also induce prominent emissions. The primary mechanisms of the induced electromagnetic phenomena is the micro-cracking in the future rupture region.

Moreover, we do not intend to treat other prediction-related probabilities, for instance, the possibility concerning the frequency of VPSs occurrence without following the earthquakes. These situations are not taken into account because the primary goal of the present analysis is limited to ascertaining whether or not there is VPSs emission from the vicinity of imminent earthquakes.

The earthquakes included in the chosen parameter windows are listed in Table 1. There are 12 moderate earthquakes, with magnitudes exceeding 5.0 in or around the observation network ; (○ in the rightmost column), and 5 smaller earthquakes with magnitudes of less than 5.0 inside the network (△). The data in this table is from the seismic catalogue of the Japan Meteorological Agency (JMA). Two major earthquakes occurred successively on the 3rd and 4th March 1996 (Nos. 7 and 8), and two more on the 11th October (Nos. 13 and 14). Each of these pairs of earthquakes are regarded as one event in the correlation analysis, because the 10-day time window we used is longer than the time difference between these successive earthquakes.

The 10-day time window was chosen by referencing the VPS number distribution around the time of earthquake occurrence (Oike and Yamada, 1994). The distribution has one prominent peak approximately two days before the earthquakes. To perform a

No.	TIME	PLACE	LAT.	LON.	DEP.	MAG.	COM.
	1995 Oct.∼						
1	1996 Mar. 6 23:35	Yamanashi-ken-tobu	35°28′	138°57′	20km	5.8	○
2	1996 Aug. 11 03:12	Akita-ken-nairikunanbu	38°55′	140°38′	7	5.9	○
3	1996 Sep. 11 11:37	Chiba-ken-tohooki	35°38′	141°12′	53	6.2	○
4	1996 Oct. 5 09:51	Shizuoka-ken-seibu	35°03′	138°02′	26	4.4	△
5	1996 Oct. 16 22:58	Izu-hanto-tohooki	34°59′	139°07′	5	4.1	△
6	1996 Dec. 21 10:28	Ibaraki-ken-nanbu	36°06′	139°52′	53	5.4	○
7	1997 Mar. 3 23:09	Izu-hanto-tohooki	34°58′	139°10′	3	5.0	○
8	1997 Mar. 4 12:51	Izu-hanto-tokooki	34°57′	139°10′	2	5.7	○
9	1997 Mar. 16 14:51	Aichi-ken-nanbu	34°56′	137°32′	39	5.8	○
10	1997 Mar. 23 14:58	Ibaraki-ken-nanbu	35°58′	140°06′	72	5.0	○
11	1997 May 24 02:50	Ensyunada	34°30′	137°30′	23	5.9	○
12	1997 Sep. 29 23:46	Choshi	37°42′	140°42′	60	4.5	△
13	1997 Oct. 11 14:41	Ensyunada	34°40′	138°02′	30	5.0	○
14	1997 Oct. 11 18:45	Miyagi-ken-oki	38°54′	142°12′	50	5.3	○
15	1997 Oct. 21 19:55	Shizuoka-ken-seibu	35°01′	138°02′	30	4.4	△
16	1997 Nov. 1 20:37	Kanagawa-ken-seibu	35°02′	139°01′	10	4.0	△
17	1997 Dec. 7 13:30	Fukushima-ken-oki	37°07′	140°08′	80	5.7	○
	∼1997 Dec.						

Table. 1 Focal parameters of earthquakes that occurred around the VPS observation network indicated in Fig. 1 and that are treated in the present work. All had a focal depth of less than 100km. Those with a magnitude of larger than 5.0 are marked with a ○, and those with a magnitude of less than 5.0 are marked with a △.

stricter test, the choice of the free parameters should be carried out more systematically and should be based on the data set that is independent of the data sample to be evaluated (Fujinawa, 1991 ; Wyss, 1991). In this respect the present work should be regarded as a preliminary experiment waiting for a more rigorous test.

Earlier analysis of the VPS source location at the time of a major earthquake on 3 March 1996 suggested that the emissions were induced not in the epicentral region but in the region that was a few degrees of longitude and latitude distant (Fujinawa *et al.*, 1997). We are going to investigate VPS sources for all moderate shallow earthquakes which occurred in the central part of Japan during the two years' test period. At first we will show three typical cases of the VPS source location with regards to the earthquake epicenter.

(1) *Remote emissions*

Shortly after this experimental observation network was set up, a major shallow earthquake (with a magnitude of 5.8) occurred within the network ; and this case was analyzed in detail in the past (Fujinawa *et al.*, 1997). Changes in the number of VPSs were found, in agreement with previous studies (e.g. Ralchovski and Christokov, 1985 ; Oike and Ogawa, 1986 ; Yamada and Oike, 1996 ; Fujinawa and Takahashi, 1998) to be well correlated with the earthquake occurrence. However, the VPSs that increased in number prominently on the day preceding the earthquake (5 March 1996) were found to originate over the ocean some 300km distant from the epicenter. This was a disappointing result, contradicting original expectations that the source location data would provide useful information concerning the location of imminent earthquakes (Yoshino *et al.*, 1985; Takahashi and Fujinawa, 1993; Hayakawa *et al.*, 1993). It is conjectured that VPS emissions may be produced by electromagnetic processes in the Earth's atmosphere possibly due to some triggering effects under the condition of critical state in terms of electic discharges. The generation mechanism is to be discussed in more detail later.

As another example of increase in the number of the VPSs preceding earthquakes and of the VPS source region at a distance of several hundred kilometers from the epicenter, in Fig. 7 we show changes in the number of the VPSs and in Fig. 8, the VPS source distribution.

The number of the VPSs per hour for four observation sites (HAS, CKR, KOF, and SAG) is shown in Fig. 7 together with the simultaneously recorded events, which are identified as the same events (Syncro.) on the basis of the time window already described. When this data was gathered, the NAG site was not yet available. The number of lightning return-strokes per hour is shown at the bottom of the figure (Fig. 7f; data from Franklin Japan Co., Ltd.). The data shown covers the period from 5 to 15 September 1996. The VPS number increases around the earthquake, although this increase is a little unclear owing to the considerable fluctuations at each site and slight changes of the VPSs number in the time period shown. At Kofu (c), for example, there are many large abrupt short period changes. These can largely be attributed to the daily and weekly changes in civil activity because that the observation site is just inside the town. The apparent saturation of the number at HAS on 10 September, a day before the occurrence of the earthquake with a magnitude of 6.2, is probably due to very large number of data overflowing storage capacity of the recording device. It is certain that the number of the VPSs at HAS was much larger than that shown in Fig. 7. Taking this situation into consideration, we can infer that the trend of increas-

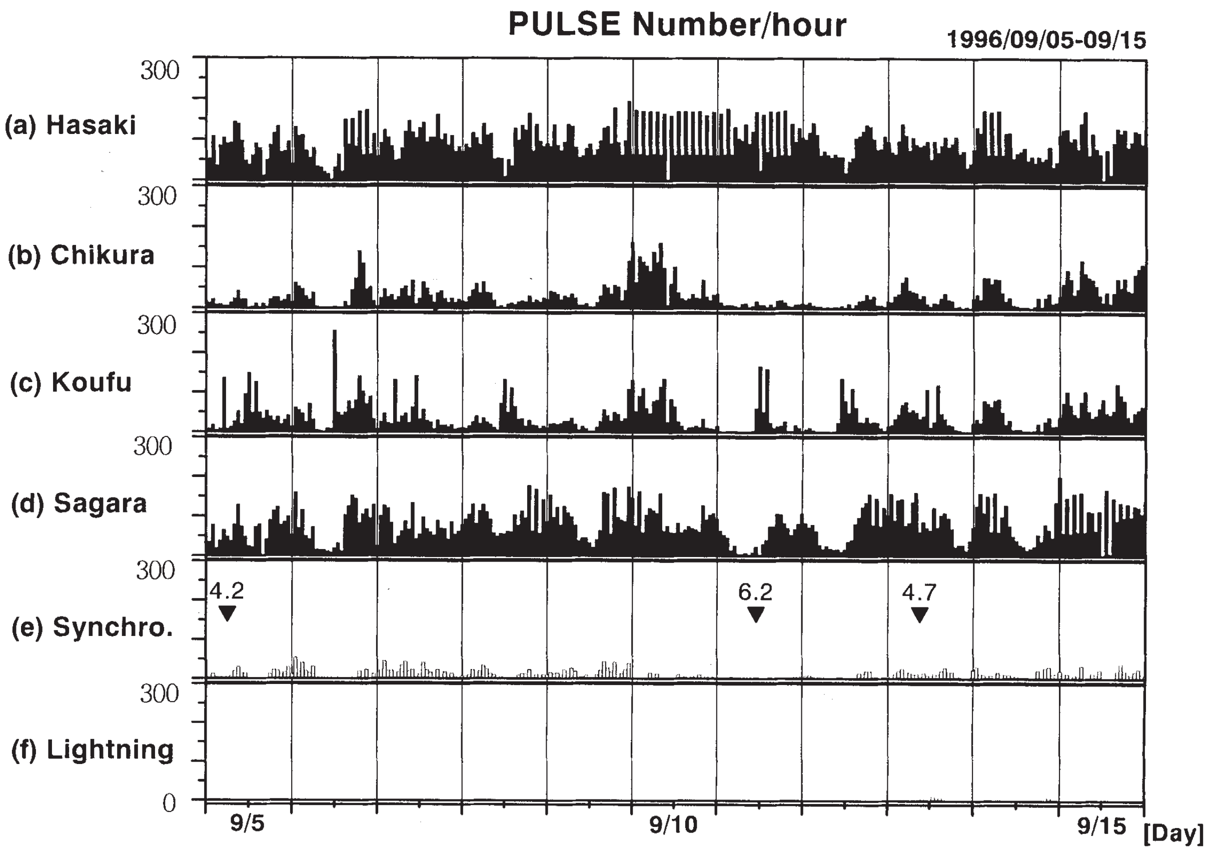

Fig. 7 The number of VPSs at four sites with amplitudes six times as large as the threshold level before and after the major earthquake (magnitude 6.2) on 11 September 1996 occurred off one of the sites, HAS. SYNCHRO. means the numbers of events observed at all the sites and identified as the same signal on the basis of a time window criterion. The number of return strokes observed by the lightning monitoring network covering Honshu is shown in the lowest panel (Lightning).

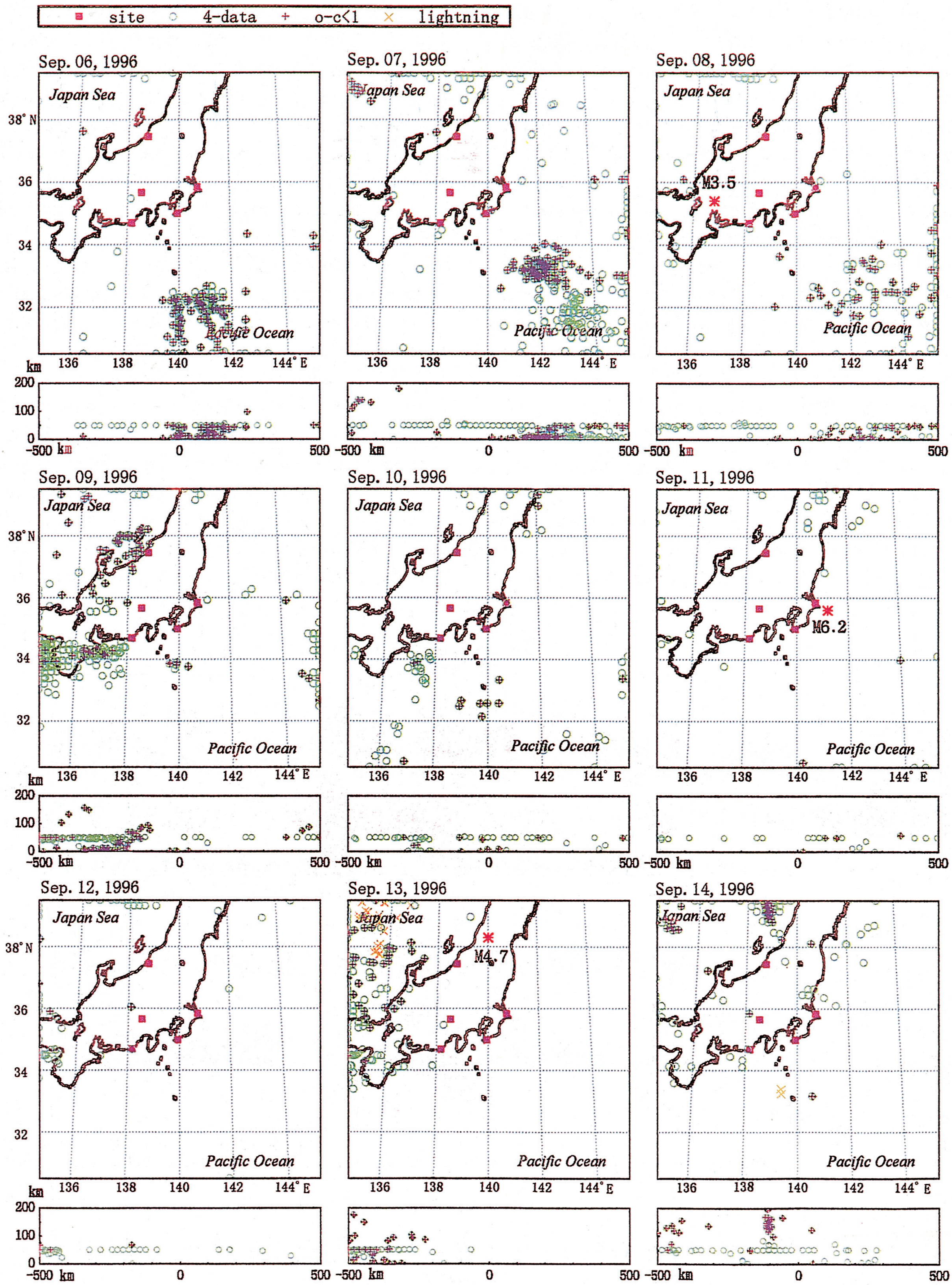

Fig. 8 VPS source point projections (○ : a "+" added in the circle denotes a better determination, one with O-C less than 10 μs) in the horizontal plane (upper sheet) and in the east-west vertical plane (lower sheet) for 9 days. The period includes the day of a major earthquake with a magnitude of 6.2 on 11 September 1996 that occurred off HAS (No. 5 in Table 1). The source locations were determined using the arrival times of VPSs at four sites.

ing VPSs number at HAS on 10 September, is nearly the same as that at the other three sites. The increased number of the VPSs can be seen more clearly from the changes in the number of simultaneously observed events (Fig. 7e) at four sites from 4 to 9 September, preceding this earthquake. The number is the smallest on the day of the earthquake. We can also see an increase in the number of the VPSs after the earthquake, through 12 September to 18.

These features are in general agreement with the average changes in the number of the VPSs around the time of moderate-scale earthquakes reported by Oike and Yamada (1994), who analyzed approximately ten years worth of data gathered at one site.

The increased number of the VPSs was not accompanied by conspicuous lightning discharges, as is seen from the bottom panel of Fig. 7(f). There were essentially no lightning return strokes on the days when the number of the VPSs increased. But, we can see a small number of return strokes on 13 September, and a very large number on 17 September, when the number of the VPSs increased after the earthquake. The increased signals from 5 September to 7 were independently recognized as anomalous through several steps of assessment using data at multiple electric field observation sites, lightning data and thundercloud data (Enomoto *et al.*, 1997a). Geomagnetic activity was very calm, with ΣKp indexes of 9 and 7 on the ninth and the tenth, suggesting that the marked increases in the VPSs number were not caused by changes in solar activity.

Source points are projected on the horizontal (upper part) and EW-directed vertical plane (lower part) for nine days including the day of occurrence of a major earthquake with a magnitude of 6.2 (No. 3 in Table 1). The earthquake with a magnitude of 6.2 on 11 September 1996 occurred off Hasaki, near one of the observation sites in the present network. The hypocenter of this earthquake is indicated by a '*' in Fig. 8. For practical reasons, the arrival times used to determine the VPS source parameters are those of the trigger time. Each panel corresponds to one day. The distribution of events with O-C larger than 10μsec corresponds to the network configuration. Accuracy with which the horizontal source position is determined is of the order of 10km for events within the network, but worsens for events outside the network (Fujinawa *et al.*, 1997). A concentrated location at the altitude of 50km seen in Fig. 8 is largely artificial on behalf of the selected value of initial altitude to $z=50$km in the inversion procedure. It is known that the accuracy of vertical coordinates determination in seismology is a few times less than that of the horizontal coordinates (e.g. Aki and Richards, 1980). The altitude of the VPSs is to be touched upon in more detail later in the discussion of generation mechanism.

The VPS source points corresponding to the prominent increase in the number of the VPSs before earthquakes, from 6 September to 8, are seen to drop in a south region or some 300km southwestward from the epicenter of the earthquake that occurred on 11 September. But, those on 9 September are predominantly in the westward direction around the Kii peninsula (around 34°N, 135°E), and minorly in the northward direction near the NAG site. We note that, there are no prominent lightning discharges ($\times$ in the figure) on the days preceding the earthquake. The return strokes of lightning discharges can be seen in the northwestern part of the region on 13 September. Part of the increased number of the VPSs on 13 September is thought to be associated with the lightning activity off the Noto peninsula (around N39°, E135°) since there is a considerable overlapping between VPS sources and lightning discharges sources.

Source location data shows that the VPSs are not emitted directly from the epicentral area. This case is another example providing evidence to support the "induced emission" hypothesis rather than the "direct emission from the epicentral region" hypothesis (Fujinawa *et al.*, 1977); this point will be discussed in more detail later. It is certain that there are no clustered VPSs near the epicenter, but we can see one VPS located very near the epicenter every day from 7 to 9 September. This point will also be discussed in detail later with regards to the possibility that some of VPSs are emitted directly from the epicenter.

(2) *Coincident Case*

Here we present a case in which there is a very close spatial and temporal relationship between the VPSs and the seismic swarm activity, which occurred east off the Izu peninsula on 16 October 1996 (No. 5 in Table 1). The case demonstrates the possibility that conspicuous radio waves could emit directly from the epicenter region. Panels a, b, and c in Fig. 9 show the changes in the number of the VPSs with amplitudes six times as large as the chosen threshold values. The values are selected by considering background noise level at each site. The seismic swarm occurred, from about 21 : 00 (JST) on 15 October 1996 off the east coast of the Izu peninsula (Fig. 2), as one of the seismic events that occur almost periodically in this region. This activity has long been providing a good natural laboratory for studying geophysical phenomena associated with the occurrence of earthquakes (e.g. Okada and Yamamoto, 1991 ; Japan Meteorological Agency, 1990). Besides the reports of prominent ground tilts and volumetric strain changes apparently related to these seismic swarms (Shimada *et al.*, 1990 ; Okada and Yamamoto, 1991), there are also several reports of prominent electromagnetic phenomena correlated with the activity (Fujinawa and Takahashi, 1990, 1996 ; Hata and Yabashi, 1994 ; Sasai *et al.*, 1998 ; Honkura *et al.*, 1998 ; Matsumoto *et al.*, 1996). The ground crustal movements were observed by GPS (Shimada *et al.*, 1990 ; Fujinawa *et al.*, 1991), ground tilt meter (Okada and Yamamoto, 1991), and volmetric strain meter (Japan Meteorological Agency, 1990).

From Fig. 9 the number of the VPSs is seen to have evolved in good temporal correlation with the seismic swarm activity. The Panel e in Fig. 9 shows the number of the VPSs observed simultaneously at the four sites. It is suggested that many of the signals detected at the individual site have large amplitude to be detected by the whole network rather than small one only to be detected at selected sites. Panel f shows the number of lightning return strokes reported by a commercial lightning monitoring service. The lightning activity, though of considerable scale on 15 October, and smaller on 16 October, mimics the changes in the VPS number and the seismic activity. It provides another example of the close relationship between three phenomena : earthquakes, VPSs, and lightning discharges (Oike and Ogawa, 1986 ; Oike and Yamada, 1994 ; Enomoto *et al.*, 1997a).

Fig. 10 shows the source points of the VPSs observed on each day of an 9-day interval including 16 October 1996, when a moderate earthquake with a magnitude of 4.3 occurred. we checked source distribution for whole 11 days for the hypothens test. From the source data for the 14, 15 and 18 October we can see that the increased numbers of the VPSs on those days are related to the lightning activity off the Noto peninsula in the Japan Sea (Fig. 1), since there is conspicuous overlapping of VPS sources and lightning return strokes. Those VPSs could be thought to be irrelevant to the earthquake. There are, however, no return strokes reported for 13 October, despite scat-

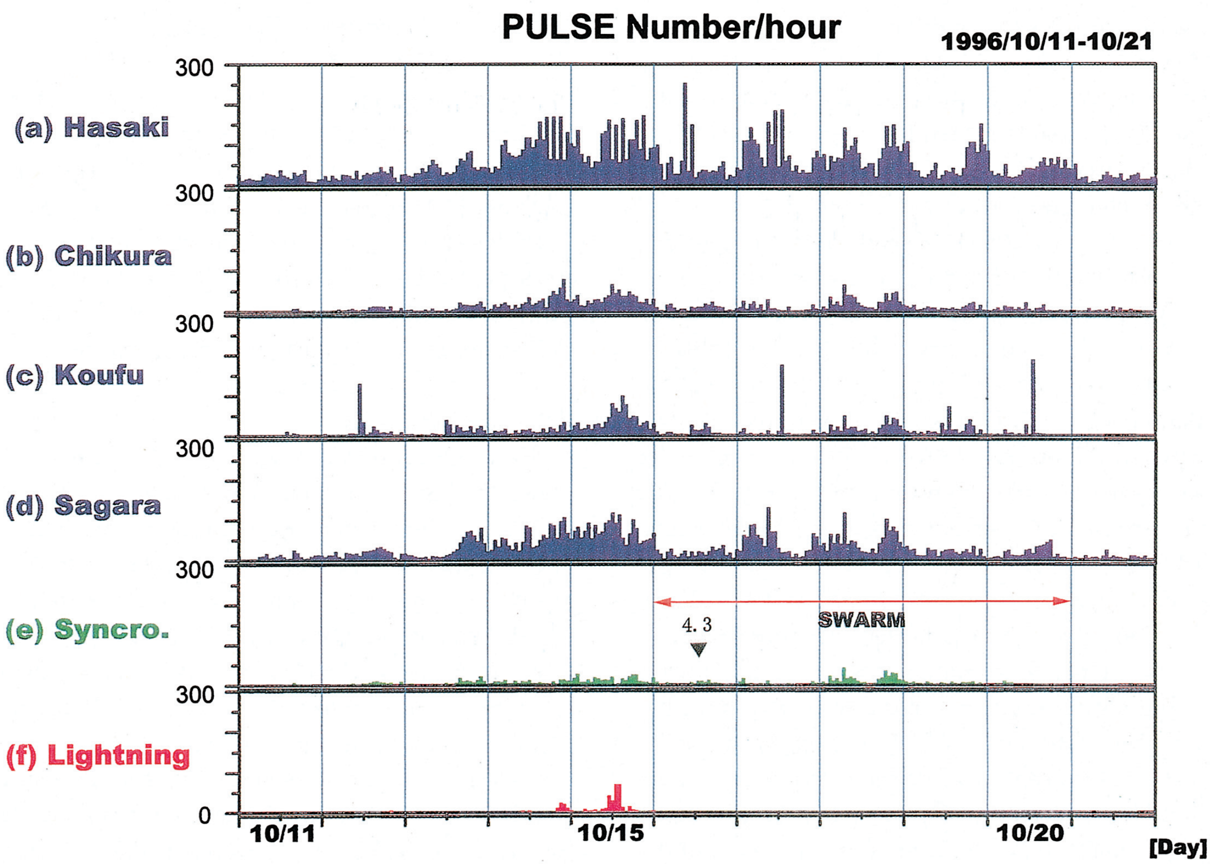

Fig. 9 Same as Fig. 7 except for the time of the earthquake : 16 October 1996. The event is one of the almost periodical seismic swarm activity which occurred from 1976 off the east coast of the Izu peninsula.

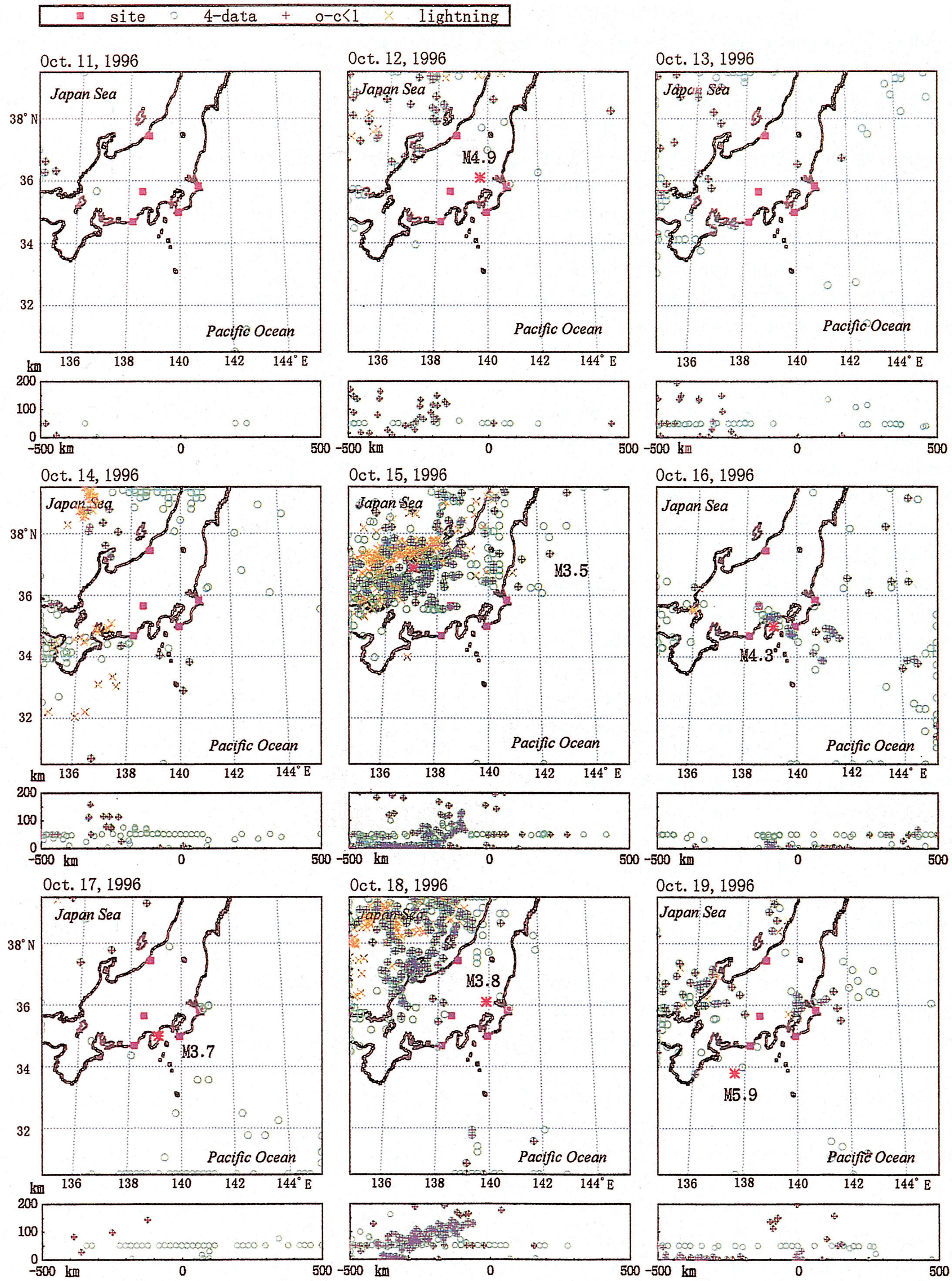

Fig. 10 VPS source location projections for nine days including the 16 October 1996 earthquake at the time of the seismic swarm (epicenter is indicated in Figure by '∗') off the east coast of the Izu peninsula. The upper part of each portion is the horizontal plane, and the lower part is the east-west vertical plane. Note the conspicuously concentrated distribution of the VPSs around the seismic swarm activity on 16 October 1996. There were a small number of lightning discharges (×) around the seismic swarm region, which can be seen in Fig. 11.

tered VPSs were observed. The VPSs might result from minor atmospheric electric discharges in rain clouds. But the strength of discharges were too small to be identified as return strokes. It is clearly seen that there is a concentration of the VPS sources around the region of the seismic activity ('*' in **Fig. 10**, with several sparse sources that are distant from the network on 16 October. The concentration of the VPSs around the epicenter is quite exceptional, occurring only once in 17 cases treated. It is noted that it was only on 16 October that we had the VPS source concentration around the epicenter in a time period of several days of appreciable increases in the number of the VPSs in the middle of October (**Fig. 9**).

Near the time of the concentrated VPS emissions, a small amount of lightning activity (× in **Fig. 10**) was discernible around the epicenter but a little to the south-east. This is seen more clearly in **Fig. 11**, which is an enlargement of **Fig. 10** around the epicenter. The Japan Meteorological Agency reported that there was a spot of radar echo near the two concentrated VPS sources in **Fig. 11**, suggesting that there were considerably strong rain clouds in that area. Accordingly, the VPSs were located near the epicenter ('*' in **Fig. 11** could to be related to the atmospheric electric discharge processes. However, such a peculiar concentration had never seen in the whole source location distribution during total experimental period when there could probably be enough cases of similar meteorological conditions. Therefore we think that the VPS emissions on this day were induced in association with the seismic swarm.

In more than two years of data records evaluated in the present study, this was the only one case in which the source regions of the VPSs, were so closely correlated with earthquake occurrence in time and coincided with the epicentral region of the earthquakes. It is in agreement with results by Yoshino *et al.* (1985) that, with regard to the anomalous LF band signal, the source location inferred using the direction-finding technique very rarely coincided with the epicenter. Therefore we could imagine that the concentrated VPSs are induced in the process of electric discharges including return stokes ; which were triggered by the Earth's surface changes even if the VPSs are not the direct consequence of the subsurface electric field modification.

As is well known in seismology, the altitude could not be determined as accurately as the horizontal position. Nonetheless we can expect that the altitude data of the present accuracy to provide a clue at least as to whether the source region is in the atmosphere or the ionosphere. The constraint is useful in investigating the generation mechanism of the VPSs. The source region of concentrated events from 12 : 00 to around 13 : 00 on 16 October were located near the epicenter. For these events, the altitude z is more accurately estimated because that they were inside the network.

The average altitude of the group events is

$$z = 22\text{km} \pm 18\text{ km}, \tag{3}$$

The frequency distribution of altitudes of the VPSs shows a large peak near the ground (z=0-10km), and a small peak in the mesosphere (at around z=40km). These solutions were obtained by starting the iterative procedure with z_0=50km. Starting the inversion procedure either from the ground's surface (z_0=0) or from smaller altitude z_0=25km resulted in fewer sources at altitudes above 25km than the case z_0= 50km. The altitude values determined through the inversion depend somehow on the initial altitude. However, it is highly probable that most VPS sources are in the troposphere, some are in the mesosphere, but there are hardly any in the ionosphere.

The present case showed that the source of the VPSs can be very near the epicenter and its altitude is in the lower atmosphere near the ground's surface. Accordingly, we can consider three possible mechanisms which generated the VPSs : first, emissions directly from the epicentral region ; second, emissions triggered in the troposphere under a critical condition of lightning activity ; third, the simultaneous occurrence of both of these mechanisms. Direct emission is the simplest answer, since the swarm activity sites and VPS wave source regions virtually coincide. The generation mechanism will be treated in more detail later.

(3) *Case without radiation*

The seismic swarms east of the Izu peninsula have been providing valuable data about various kinds of precursory phenomena (Ida and Mizoue, 1991), including electromagnetic field changes (e.g. Fujinawa and Takahashi, 1990, 1996 ; Hata and Yabashi, 1994 ; Sasai *et al.*, 1998 ; Honkura *et al.*, 1998).

Fig. 12 shows the VPS source distribution from 27 February through 7 March 1997, during which period there was another earthquake swarm off the east coast of the Izu Peninsula accompanied by the largest earthquake with a magnitude of 5.6 (No. 7 in **Table 1**). From the source data plotted in **Fig. 12** we see that there were almost none of the VPSs around the epicenter. It shows that few number of the VPSs were

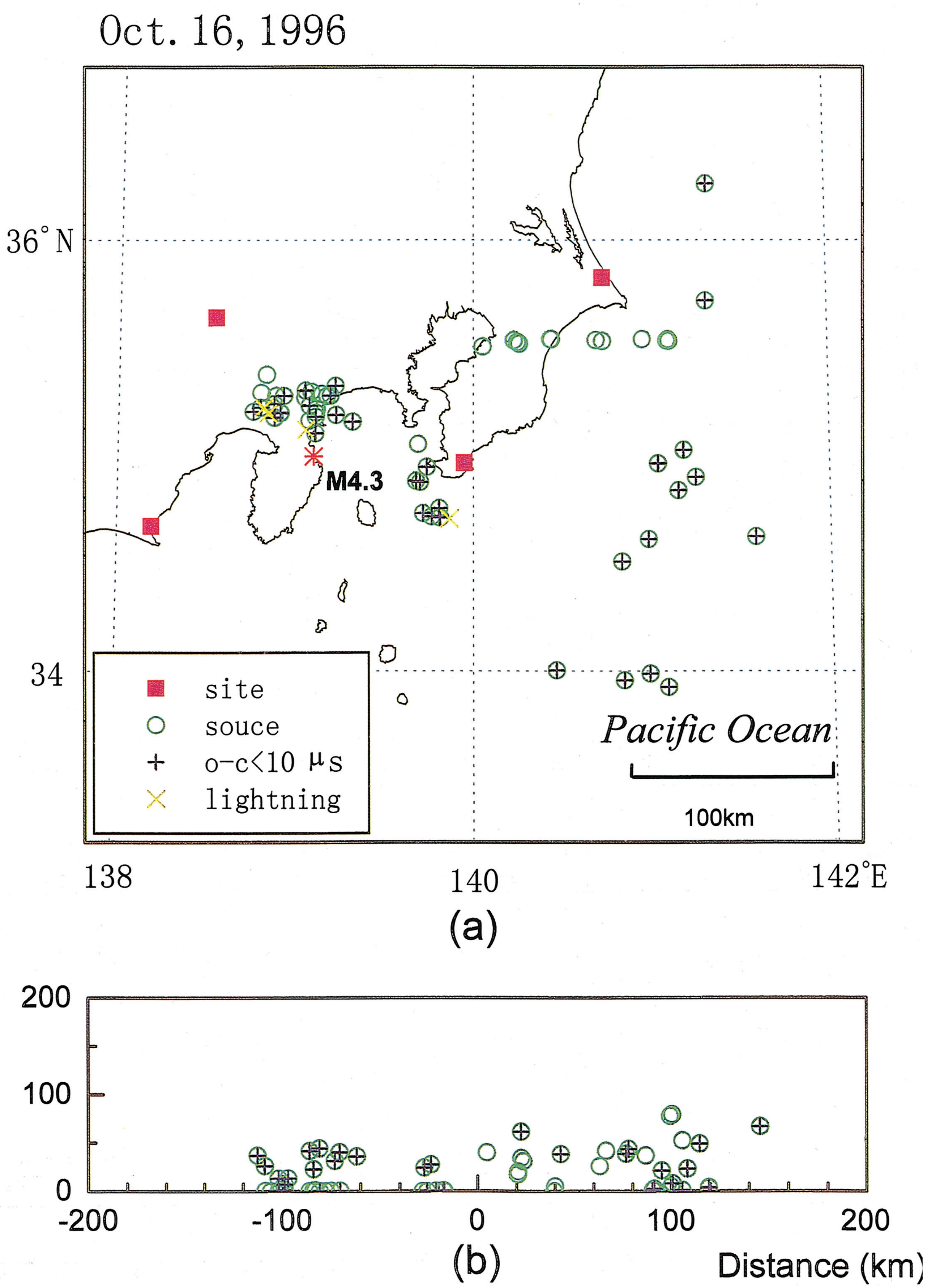

Fig. 11 An enlargement of the October 16, portion of Fig. 10 for the region near the seismic swarm east of the Izu peninsula.

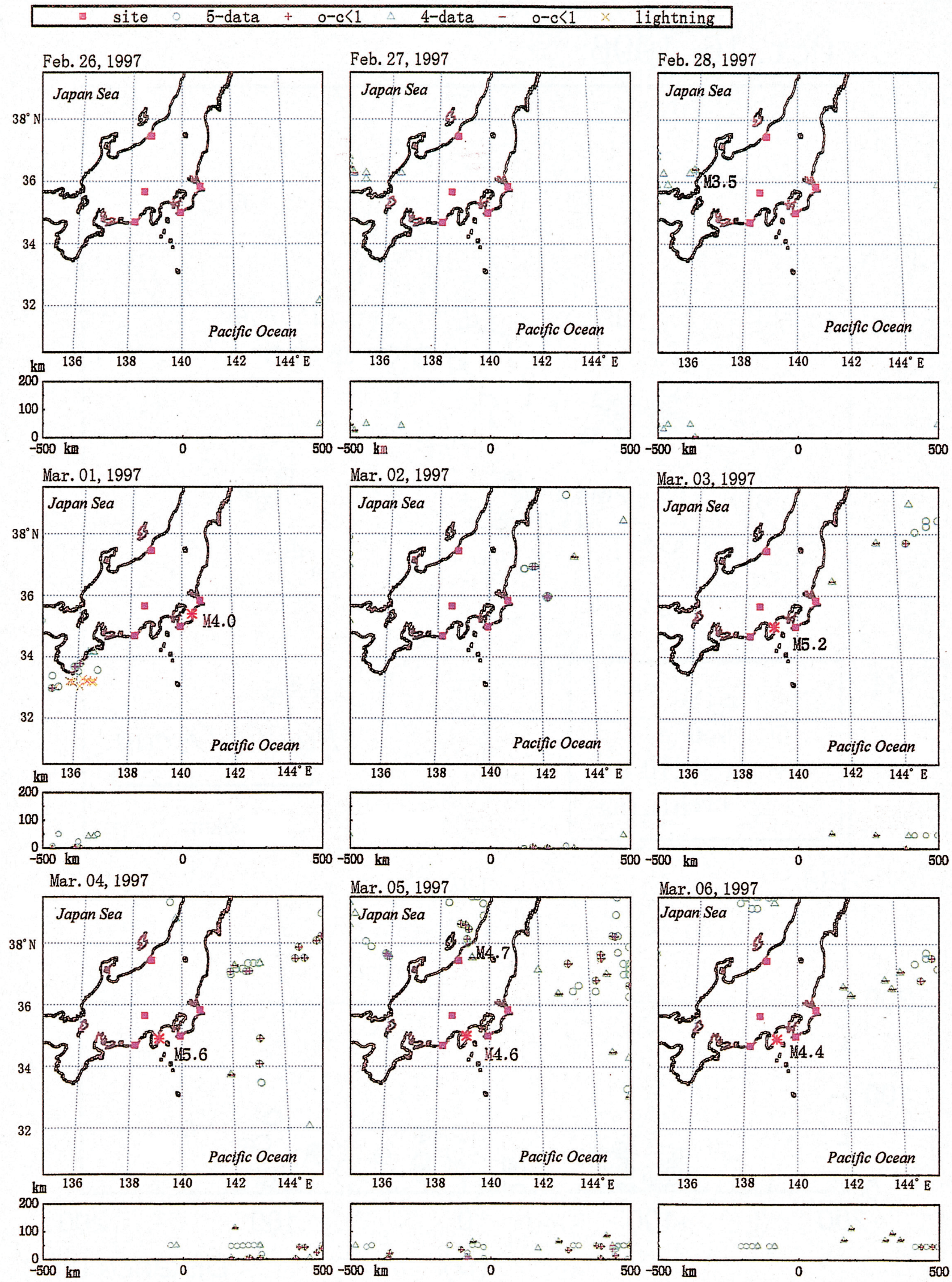

Fig. 12 VPS source point projections for 9 days around the day of seismic swarm east off the Izu peninsula with major earthquakes with magnitudes of 5.7 and 5.8 on 3-4 March 1997. In this case there were neither VPSs around the epicentral region nor any indication of the VPS number increase.

observed simultaneously at four sites to enable us to obtain the source location. They were scattered in the western region on 28 February, and off the Kii peninsula on 1 March. In fact, there is even no prominent increase in the VPS number in the time period chosen from 21 February to 8 March prior to the earthquake (Fig. 13), which contradicts the empirical relationship. In all the earthquake samples treated here, this is another type of exception in which an increased number of the VPSs did not precede major earthquakes. We can interpret this result in two ways: the chosen time window is not large enough, or no electromagnetic phenomenon occurred. In fact the evolution in the number of the VPSs shows considerable variability (Oike and Yamada, 1994). We have not sufficient data to answer this question; the point remains to be investigated in more detail in the future.

(4) *Statistical Evaluation*

Table 2 summarizes the results of statistical evaluation on the number of the VPSs and the locations of the sources of the VPSs in relation with moderate earthquake occurrence. In the first large column (Pn) of Table 2 the results concerning the number of the VPSs are listed. The circles (○) denote the case that the VPSs increase, triangles (△) denote ambiguous cases, and crosses (×) denote cases that the VPSs do not increase. It can be seen that the only exceptions to the rule is the time of seismic swarm off the east of the Izu Peninsula on 4 March (case Nos. 7 and 8). The probability of increase in the number of the VPSs prior to an earthquake amounts to approximately 95%, in agreement with previous reports (Oike and Ogawa, 1986; Fujinawa and Takahashi, 1998). It should be noted, however, that we did not use the objective criterion for judging the occurrence of increase, but checked qualitatively whether there was apparent increase continuing for more than a few days prior to the earthquake. Geomagnetic activity parameter (ΣKp) is used to check whether the VPSs observed are of the plasmaspheric hiss (Hayakawa and Sazhin, 1992) or another type of natural emission at low latitudes. That is because, it is known that the VPSs are induced by geomagnetic activity (Ondoh *et al.*, 1982). We define the largest value of ΣKp in one week period preceding the earthquake occurrence as ΣKp (max). The ΣKp is the sum of eight Kp-index values on each day. The values of ΣKp (max) on Nos. 3, 7, 8, 13, and 14 exceed 30, indicating that those cases could be influenced by geomagnetic activity during one week preceding these earthquake occurrences. On the other hand, it is seen that the values of ΣKp

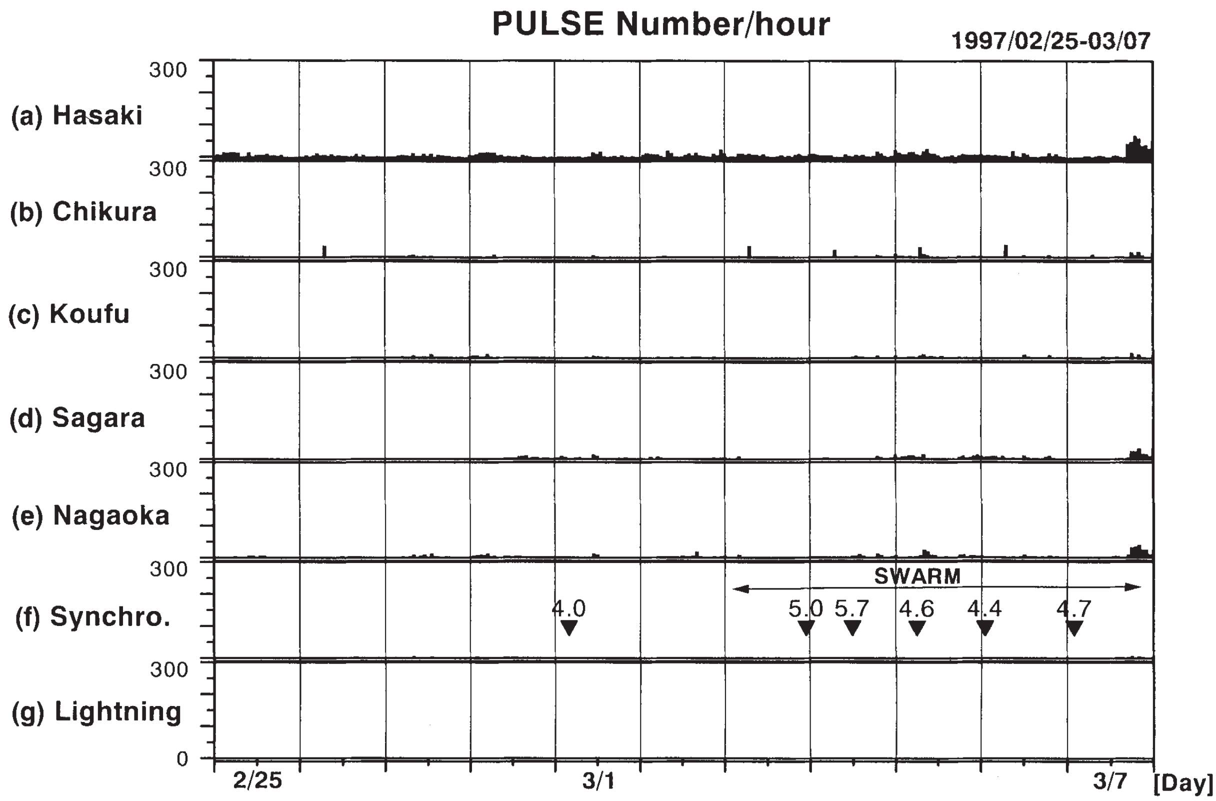

Fig. 13 Same as Fig. 7 except for the time period, which here includes the earthquake on March 4 1997. There is no apparent increase at any site contrary to other cases.

No.	Pn (triggered SRS)			Σ Kp (max)	S (source)	
	global	L	singular	maximum sum of eight Kp values	cluster to epicenter	isolated near epicenter
1	○	○	×	18	×	×
2	–	–	–	14	–	–
3	○	×	○	32	×	○
4	○	○	×	24	×	○
5	○	○	△	25	○	×
6	○	×	○	22	△	△
7	×	×	×	34	×	×
8	×	×	×	34	×	×
9	○	×	○	22	×	○
10	○	–	○	16	×	×
11	○	○	○	17	×	○
12	○	○	×	22	△	○
13	○	×	○	30	×	△
14	○	×	△	30	△	×
15	○	○	○	12	×	○
16	○	○	×	25	×	×
17	○	○	△	16	△	△

Table. 2 Results of the data analysis testing the hypotheses that the number of the VPSs observed during the 6 days prior to an earthquake occurrence increases or not in the left large column : (Pn), and source location of the VPSs around the epicentral region (in the right large column : S). The symbol ○ denoting agreement with the hypothesis, × a contradiction of the hypothesis, and △ unclear cases. In the Pn column "global", "L", and "singular" denote apparent increases of the VPS number continuing for a few days above the normal state at all sites, lightning activity, and singular increase at the nearest site to the epicenter, respectively. In the S (ource) column "clustering", and "isolated" denote a large number of dropping of the VPS sources around the epicenter within several tens kms, and for several sources, respectively. Case No. 2 had insufficient data.

(max) on Nos. 1, 2, 6, 9, 10, 11, 12, 15, and 17 are smaller than 24. Therefore, we could say that increases in the VPSs for almost all cases are not related to geomagnetic activity.

The second sub-column of the column "Pn" concerns the appearance of lightning discharges (L) reported by a service company (Franklin Japan Co., Ltd.). The criterion for the presence of lightning was also qualitative as in the case of the VPSs increase.

The probability of considerable lightning activity accompanied by major earthquakes amounts to approximately 60%, generally in agreement with previous statistical evaluations (Oike and Yamada, 1994 ; Enomoto *et al.*, 1997a). There were a few cases of appreciable VPSs emission that was not accompanied by lightning discharges, as in previous report (Fujinawa *et al.*, 1997). It is possible, however, that there were intense rain clouds on the days during which return-strokes did not occur but there were small atmospheric discharges with electric field strengths of the order of milivolts per centimeter. The latter were not identified as return strokes with electric field strengths of the order of volts per meter. The possibility might be inferred from the intense radar echo data (Enomoto *et al.*, 1997a), but here we did not use the meteorological data to confirm this point.

The second large column (S) of Table 2 lists the result of the analysis to check the presence of the clustered VPS sources around the earthquake epicentral region. Here, the clustered sources mean that a sufficient number of the VPSs locate in the small region, such as those observed on 16 October 1996 (Fig. 8). The criterion for clustering the VPSs is rather subjective as in the cases of other VPS number and lightning activity phenomena. The results listed in Table 2 indicate that there was only one case in which the VPS sources were around the epicentral region, and there are four cases in which this might have been the case. The prominently increased VPSs before earthquakes were mostly located not just around the epicenter, but at a slight distance from the rupture region.

Therefore we should reject the hypothesis that the VPSs emit directly from the epicentral region of major earthquakes. It is stressed, however, that the result concerns cases under the constraints of the present experiment for the VPSs with amplitude that is sufficiently large to be observed at all the sites separated by approximately 250km. The VPSs whose numbers increased prominently before earthquakes are distributed virtually within a latitudinal interval of several degrees and a few degrees of longitudinal. This is in agreement with results of satellite data analysis (Larkina *et al.*, 1988 ; Parrot and Mogilevsky, 1989 ; Molchanov *et al.*, 1993 ; Serebryakova *et al.*, 1992). We have no evidence, however, to prove that the anomalous electromagnetic field changes observed on satellites are the same as the VPSs of present interest.

On the other hand, it should be noted that Henderson *et al.* (1993) could not detect clearly distinguishable ELF/VLF signals associated with earthquakes using same kind of satellite observations in the frequency range from 4 Hz to 512 kHz. The discrepancy have not been resolved, although an attempt was made to explain the opposite observational result as the contamination of the electric field by natural electrostatic noises by Parrot (1994). We need simultaneous measurements on satellite and on land to investigate the problem.

4. Discussion

In point of fact, even after obtaining VPS location data we are still not in the position to discriminate the VPSs induced by atmospheric electric processes from those induced by geoelectric effects in the earthquake preparatory processes. We need another data for this purpose. The VPS location data are useful in cases where the VPS sourses are located in regions where the return strokes of lightning discharges are not found (e.g. Fujinawa *et al.*, 1997), or in cases that radar echo data are additionally available (Enomoto *et al.*, 1997a). In using the lightning discharge location data, the range of the lightning monitoring system should be taken into account. The empirical relationship between the number of flashes and the number of associated LF noises was proposed by Yamada and Oike (1996) to differentiate two types of the VPSs.

Strictly speaking we may need to consider all the atmospheric electric discharge processes resulting in return strokes and inter-cloud discharge as well as those subsidiary discharges such as stepped leader, dart leader, the M-component, and the K-process (e.g. Uman, 1987). The large-scale discharges of return strokes and inter-cloud discharges may be differentiated on the basis of their radiation strength. But it will only become possible to differentiate the small-scale discharges of stepped leader, M-component, and K-processes after more thorough knowledge of those characteristics is obtained using instruments specially designed for the purpose.

This study has showed that the number of the VPSs generally increases before major shallow earthquakes in agreement with a short-term statistics of our observation (Fujinawa and Takahashi, 1998) and with the longer-term statistics of Oike and Yamada (1994). Lightning discharge activity is also frequently associated with earthquakes and with increases in the number of the VPSs (Oike and Yamada, 1994 ; Enomoto *et al.*, 1997a ; Fujinawa and Takahashi, 1998). We showed that the sources of the VPSs that precede earthquakes rarely drop on the epicentral region. Therefore the VPSs provide useful information for predicting the occurrence time of earthquakes, but is not practically useful for forecasting the location of imminent earthquakes.

Two typical groups of generation mechanisms of VLF waves have been proposed (e.g. Park *et al.*, 1993 ; Parrot *et al.*, 1993) : direct emission from the earthquake epicentral region (Nitsan, 1977 ; Warwick *et al.*, 1982 ; Martelli and Cerroni, 1985 ; Ogawa *et al.*, 1985 ; Oike and Ogawa, 1986 ; Gokhberg *et al.*, 1987 ; Cress *et al.*, 1987 ; Parrot and Mogilevsky, 1989 ; Yamada and Oike, 1996), and indirect emission through redistribution of electric charges in the Earth's atmosphere, including the magnetosphere, the ionosphere, and the troposphere (Pierce, 1976 ; Lockner *et al.*, 1983 ; Gokhberg *et al.*, 1984 ; Popov *et al.*, 1989 ; Fujinawa *et al.*, 1997).

Changes of electromagnetic field in the earthquake rupture region are thought to be induced by the movement and the compression of small rock fragments (Parrot and Mogilevsky, 1989). They are microfracturing which produces electric charges through piezoelectric phenomena (Finkelstein *et al.*, 1973 ; Yoshida *et al.*, 1997), triboelectric phenomena (Parkhomenko and Balbatchyan, 1981 ; Enomoto and Hashimoto, 1990), ion generation (Freund *et al.*, 1994), charge separation at dielectric grains of the crust (Vorobijev, 1970), and electrokinetic effects due to water movement (e.g. Ishido and Mizutani, 1981 ; Yoshida *et al.*, 1998). There is not yet definite field experiment to demonstrate which mechanisms are dominant. Those electromagnetic field changes in depth are considered to induce electromagnetic field changes at the Earth's surface and electromagnetic emission. Yoshino (1991) proposed an efficient antenna structure around the conductive anomaly of faults.

It is proposed that indirect emissions in "higher" frequency bands, such as the VLF band, are induced by atmospheric electric field changes in the particular region of critical state, which are induced by electical changes in the Earth's surface. All atmospheric layers including the ionosphere, the magnetosphere and the lower atmosphere are involved. The mechanisms by which the electromagnetic field changes of the Earth' s surface are transferred to the emission location are also unclear. Several mechanisms have been proposed, such as activation through enumerated aerosol and/or gas (Popov *et al.*, 1989 ; Hayakawa *et al.*, 1996) and acoustic or ULF electromagnetic wave propagation (Molchanov and Hayakawa, 1998). We do not, however, think that the acoustic wave mechanism (Gokhberg *et al.*, 1988) is plausible because foreshocks are usually small.

Here we propose possible mechanism based on the present observational results. In almost all cases, the VPS location is situated at a considerable distance from the epicenter, leading us to adopt the induced emission mechanism in the atmosphere. From this standpoint, both VPS radiation and lightning discharges can be interpreted as phenomena of unstable atmospheric electric processes as induced in the troposphere. The minor electric process concerning the VPS radiation in the troposphere may differ from any of the major processes such as inter-cloud discharges and return strokes. For example, the phenomena may be air discharges caused by the intrusion of aerosol or radioactive gas emissions such as radon (Tzerfas, 1971 ; Kondo, 1968 ; Tribusch, 1978 ; Pierce, 1976) or through electrostatic field changes in and around the rupture zone in the earthquake preparatory processes (Molchanov *et al.*, 1998).

It is suggested that there are cases in which electromagnetic intensity increases prominently before earthquakes without any indication of meteorological origin (Emonoto *et al.*, 1997a). Those increases might be related to "bolts in the blue sky" (Uman, 1987). The phonomena provide evidence that not all the anomalous electromagnetic phenomena are induced as genuine meteorological processes.

The variety of spatial relations between the source region and the epicenter can be explained by differences in geophysical situations (Parrot *et al.*, 1993). They relate to the degree of criticality concerning atmospheric electric discharges leading to the lightning discharge. Regions of the near critical condition in the atmosphere could be triggered to electric discharges by aerosols or enumerated radon emissions from the seismic source under favourable conditions. In the case of very clear weather and very stable condition the triggering substances could not encounter the region of the critical condition and would travel up to the ionosphere without inducing radiation in the troposphere or the mesosphere.

We would like to remind that thunderstorms can be induced by energetic cosmic rays when the electric charge distribution in the atmosphere is in a critical condition (Herman and Goldberg, 1978 ; Milkis, 1986). The mechanism concerns the phenomenon of the atmospheric electricity in which a small deviation induces more energetic processes (Popov *et al.*, 1989). The atmospheric electricity depends on local geological structures such as modulating thunderstorm activity (Saraev *et al.*, 1974), supporting the triggering effect hypothesis. For instance, electromagnetic phenomena observed by various groups at the time of the Hyogo-ken-nanbu Earthquake with a magnitude of 7.2 on 17 January 1995 (Enomoto *et al.*, 1997b) can be interpreted using this scenario ; coseismic light (e.g. Enomoto and Zheng, 1997), anomalous emissions in 22.2 MHz (Maeda, 1996), in 558 kHz (Yoshino, 1997), and ELF/VLF bands (Yamada and Oike, 1996 ; Fujinawa and Takahashi, 1995).

Here, however, we lack the deterministic data to establish which of these mechanisms was at work. A mixture of generation mechanisms is also plausible, as is suggested by the different time evolutions of the small-amplitude VPSs and that of large-amplitude at the time of the great Kuril earthquake on 4 October 1995 (Fujinawa and Takahashi, 1998). In any event, further experiment is needed to know the mechanism responsible for the VPSs that are closely related to major shallow earthquakes.

Although most VPSs are found to originate in the lower atmosphere, another type of the VPSs might be induced by electron density changes in the ionosphere (Gokhberg *et al.*, 1982 ; Rachovski and Christokov, 1985 ; Parrot *et al.*, 1985 ; Popov *et al.*, 1989 ; Fujinawa *et al.*, 1997). There is a reasonable body of evidence indicating that electron density alters the ionospheric critical frequencies f_0E_s and f_0F (Parrot *et al.*, 1985 ; Parrot and Mogilevsky, 1989), and the phase change of the Omega signal in the frequency range from 10 to 15 kHz (Gokhberg *et al.*, 1985, 1987, 1989 ; Tate and Daily 1989 ; Morgounov *et al.*, 1994 ; Molchanov *et al.*, 1998). Moreover, it is noteworthy that the ionosphere is modulated 1 to 5 days prior to an earthquake (Gokhberg *et al.*, 1989) with the time interval being comparable to that during which the the number of the VPSs increases. In this respect, the VPS emissions observed by satellites could not be generated in the ionospheric or the magnetospheric atmosphere, but they may be induced in the lower atmosphere especially at the time when there are no significant changes in the ionospheric condition (Parrot and Mogilevsky, 1989).

It was shown here that the VPSs did not cluster around the earthquake epicenter. A more detailed inspection of the data suggests that the number of the VPSs increases to a slightly greater extent prior to an earthquake at the site near the epicenter than at more remote sites. Recall, for example, that so many VPSs were observed at the nearest site on 11 September 1996 where the data storage overflowed (Fig. 7). The result of a qualitative inspection for this kind of singular increase at the nearest site is listed in the column labeled "singular" in Table 2. Circles indicate the presence of such kind of increase, crosses indicate the absence of such local increase, and triangles indicate ambiguous cases. There are localized increases in 7 cases out of 15 earthquakes. A more detailed qualtitative analysis is desirable to test the hypothesis more rigorously. At the same time an observation network more suitable for identifying the feature should be developed.

As to the VPS source location, it is suggested that there are several isolated VPSs. Those VPSs were generally located very close to the epicenter of earthquakes, although most of the VPS sources were located at a considerable distance from the epicenter. Fig. 8 illustrates the case at the time of the September 11 earthquake off Ibaraki prefecture, which occurred just near the Hasaki site. There were such isolated VPSs near the epicenter two and three days before the earthquake occurred. It is not, however, easy to identify the isolated VPS sources without prior knowledge of the location of the target earthquake. Nevertheless, their presence or absence are shown for each of the cases in Table 2 : the circle means they were rather easy to identify, the cross means there were no such sources, and the triangle means that there may have been such sources. We see that there are a fair number of cases in which there were isolated VPS sources near the earthquake epicenter. It is noteworthy that there is a good correlation between the features of singular increases in the number of the VPSs and the presence of isolated VPS sources around the epicenter : isolated VPSs and singular increases in the number of the VPSs frequently occurred concurrently. There may be smaller-amplitude VPSs emitted from the epicentral region of a future earthquake. The suggestion is in agreement with the report of increase in radio wave noise increase near the fault that caused the disastrous Kobe earthquake on 17 January 1995 (Yoshino, 1997). It is coincident with several cases of bearing direction to the earthquake epicenter (Baba *et al.*, 1998), and the general coincidence of the horizontal bearing of the anomalous burst-like emission of 82kHz to the active craters at the time of the volcanic eruption at Mt. Mihara in November 1986 (Yoshino and Tomizawa, 1990).

Laboratory experiments provide evidence of electromagnetic emissions in the preparatory processes of main rupture of rock samples (Nitsan, 1977 ; Yamada *et al.*, 1989 ; Warwick *et al.*, 1982 ; Martelli and Cerroni, 1985 ; Ogawa *et al.*, 1985 ; Cress *et al.*, 1987) supporting direct emission hypothesis. It is particularly noteworthy that the dominant frequency of the energy spectrum of the radiation is 1.5 kHz (Cress *et al.* 1987) being nearly the same frequency band as that of the VPSs of our observation. Direct but small VPS emissions from the epicentral region seems to be real.

The generation of the electromagnetic radiation has been assumed to be induced by boundary charge phenomenon (Yamada *et al.*, 1989), and fracto-emissions (Martelli and Cerroni, 1985 ; Enomoto and Hashimoto, 1990 ; 1994), on the basis of laboratory experiments. However, we lack supporting data in the field at present.

Propagation of the ELF/VLF signals from the deep ground to the surface is unlikely because of the large spatial attenuation factor :

$$\alpha=(\pi f\mu\sigma)^{1/2}, \qquad (4)$$

where f is frequency, μ is magnetic permeability and σ electric conductivity. We need to identify some efficient energy transfer mechanism for the ELF/VLF signals (or signal propagation) under the ground, such as electrostatic induction or electromagnetic induction through a series of electrically heterogeneous layers (Enomoto, 1996), ULF waves (Parrot *et al.*, 1993) or through highly mobile charge carrier propagation (Freund *et al.*, 1994). In this respect, Kondo (1968)'s report that the atmospheric electric field decreased at the time of an earthquake deserves notice. The electic conduit for peculiar propagation is thought to be a pre-existing fault (Sumitomo, 1994 ; Yoshino, 1991 ; Dea *et al.*, 1994 ; Varotsos *et al.*, 1998). Heating at the fault under the increased compressional stress (Lockner *et al.*, 1983) is proposed to result in a large increase of the conductivity and a consequent appreciable decrease of the attenuation factor α. However, we need more experimental evidence to assess these hypotheses (Varotsos *et al.*, 1998).

5. Conclusion

Temporal and spatial data were used to test the hypothesis that the number of the ELF/VLF band pulse-like signals (VPSs) increases before major earthquakes and also to check whether these signals are emitted from the epicentral region of an imminent earthquake. We used data during a period of some two years obtained by using observation networks consisting of four or five sites in the central part of Japan spanning approximately 250km. We selected shallow moderate earthquakes that occurred in and around the observation network, with a focal depth of less than 100km and a magnitude of larger than 5.0. Earthquakes with a magnitude of less than 5.0 were also included if they occurred inside the network. The first hypothesis regarding the increase in the number of the VPSs was confirmed with high probability, though there was one exception out of 15 cases. The second hypothesis regarding signal sources in the epicentral region was rejected at least for large enough amplitude VPSs to be observed regionally by most of sites, with the result of slight possibility to forecast the location of future earthquakes better than at a few hundred kilometers distance. It is possible, however, that small-amplitude VPSs are emitted from the epicentral region to be detected near the epicenter.

The anomalous VPS source was not under the ground but in the troposphere. This source location is consistent with the satellite data suggesting that VLF emissions generally do not emanate directly from the Earth's surface near the earthquake rupture. The VLF signal is thought to be caused by nonlinear processes in the lower atmosphere that are induced by triggering effects due to enumerated gases or aerosols.

Acknowledgments

We sincerely thank many people who contributed to this work, particularly Dr. Shigetsugu Uyehara and Prof. Yukio Hagiwara, for their continuous encouragement, and Dr. Motoo Ukawa, who helped with the source point determination algorithm. We thank Dr. Okuyama of Japan Weather Association for his permission to use the data of SAFIR and Dr. Oleg, A. Molhanov, and Prof. M. Hayakawa for their fruitful discussions. We also would like to thank NEC Corporation, Geothermal Energy Research & Developing Co., Ltd. (GERD), Tecs Corporation, and Nippon Steel Welding Products & Engineering Co., Ltd. for their assistances in our observations and in the production of the measuring equipments. Valuable comments on the manuscript by an anonymous reviewer are greatly appreciated.

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(Accepted : December 27, 2000)

ELF/VLF 帯パルス状信号と地震との空間的・時間的関係

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要　旨

ELF/VLF 帯のパルス状電波（VPS）は，単位時間のパルス数をその特性量として選ぶことにより，地震と時間的に密接な関係を有することが明らかになってきた．しかし，この種の電波は落雷時にも増大することが多く，地震との本質的な関係については明確でない点がある．その関係をより明確にするために，VPS の発生源評定測網により観測を行った．それによるデータの解析の結果，以下の結論となった．

1）地震発生の数日前から VPS が増大するというこれまでの報告（例えば，Oike and Yamada, 1994）と同様に，浅発かつマグニチュード M 約 5 以上の大部分の地震の場合に，VPS 数の増大が検出される．
2）VPS は，落雷時にも常に増大する．然し，落雷のないときにも観測され，地震活動に伴う VPS の存在が示唆される．
3）VPS の発生源は，殆ど全ての場合に震央とはかなり離れた位置に決まり，経度方向に数 100 km の幅，緯度方向には少し狭い幅で分布している．これは，人工衛星による観測結果（Parrot and Mogilevsky, 1989）と矛盾しない．
4）地震に伴う電磁界変動の発生のメカニズムについては，幾つかの説が提案されている．大別すると，震源域から直接的に放射されるというものと，誘起された大気中の電磁場の変動によって何らかのトリガー効果が働き顕著な放電現象があるというものである．今回の解析の結果，後者のトリガー効果を介したメカニズムが有力であることが示唆される．
5）1998 年 2 月 21 日に観測点長岡のごく近辺に発生した M 5.0 の地震の際に，長岡において VPS が異常に増大した．このときの VPS は，震央あるいは震源域から直接に放射たものと考えられる．そのようなことは，対象となった地震の約 70％の場合に起こり，震央付近から放射される VPS の存在が示唆される．

キーワード：地震前兆現象，電磁気現象，電波，時空間相関，メカニズム