Exploring the difficulties in forecasting earthquake location with inhomogeneous ionospheric perturbations

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Research Article

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Exploring the difficulties in forecasting earthquake location with inhomogeneous ionospheric perturbations

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Abstract

Earlier studies have recorded seismic effects in sub-ionospheric Very Low Frequency (VLF) signal, predominantly examining a single VLF propagation path associated with a specific earthquake. This research expands on these findings by taking a more advanced setup. Using Japan’s VLF network with eight stations nationwide and a single transmitter signal from JJI (22.2 kHz), our study examines four earthquakes, each with a magnitude over 6, happening near VLF network locations. Chosen earthquakes are Iwaki on July 11, 2014, Aomori prefecture on August 10, 2014, Ogasawara on May 30, 2015, and Makurazaki on November 13, 2015. Three are shallow and close to land, but deliberately included are one deep oceanic quake (Ogasawara) at 664 km depth and one occurring under pre-geomagnetic storm conditions six days before (Makurazaki). We examine nighttime VLF signal distortion during the earthquake events and investigate the presence of atmospheric gravity waves (AGW). This study supports the notion
that deep oceanic earthquakes can perturb the ionosphere at considerable distances from their epicenter. Furthermore, we investigate the simultaneous ionospheric impact due to geomagnetic storms and the earthquake. Through the examination of seismic effects preceding the storm occurrence, we find the likelihood of seismogenic effects that are not contaminated by other factors. The response of the initial seismogenic perturbation varies at different distances from the epicenter. Surprisingly, nearby receivers do not experience early disturbances. This indicates how challenging it is to forecast the location of earthquake.

Keywords: Very Low Frequency (VLF) signal Network, Earthquake precursors, Earthquake location forecasting, Deep Earthquake, Atmospheric Gravity Waves (AGW), Ionospheric perturbation, LAIC, geomagnetic storm, Inhomogeneity of pre-seismic anomalies

1 Introduction

The Earth’s atmosphere, particularly its ionospheric region, is highly susceptible to both terrestrial and extraterrestrial events. Ground-based radio signal monitoring systems utilize the atmosphere as a detection tool to study the impact of these events. The ionosphere, acting as a reflector for radio signals at various heights depending on their frequencies, facilitates long-distance communication through the Earth-Ionosphere-WaveGuide (EIWG). In the daytime, Very Low Frequency (VLF/3-30 kHz) signals reflect from the D-region of the ionosphere, while at night, they lower the E region. Any unusual disturbances in the lower ionosphere can be observed through changes in VLF signal characteristics. Sudden modifications in the signal are attributed to alterations in signal reflection height and attenuation, thereby influencing the signal modal shift within the modified EIWG. Both terrestrial events (earthquakes, volcanic eruptions, typhoons, lightning) and extraterrestrial events (solar flares, geomagnetic storms, solar eclipses) are responsible for perturbations in the lower ionosphere and disturbances in VLF signals during both day and night. The potential interactions between the ionosphere and seismic
activities, considered lithospheric phenomena, are explored through hypothe-
ses proposed by researchers such as Hayakawa and Molchanov (2002), Freund,
(2011), and Pulinets and Ouzounov (2011). The seismogenic process in the
lithosphere can couple with the atmosphere through three proposed channels:
Thermal, Electromagnetic, and Acoustic. While thermal signatures remain
undetectable by VLF/LF radio sounding methods, perturbations through the
acoustic and electromagnetic channels can be investigated using the VLF/LF
(LF, Low Frequency 30-300 kHz) method. In the electromagnetic realm,
earthquakes exhibiting cracks can generate electrical charges through pro-
cesses like triboelectricity and piezoelectricity. These charged particles become
a significant source of ionospheric perturbations. Other contributors include
the emission of Radon from faults and the release of electromagnetic waves in
the Extream Low Frequency (ELF/3-30 Hz), Ultra Low Frequency (ULF/300
Hz-3kHz), and VLF ranges. Atmospheric gravity waves (AGW) play a pivotal
role in the acoustic channel’s perturbation, originating as mechanical periodic
thrust from the Earth’s crust due to earthquake shocks. As these AGWs travel
through the lower ionosphere, they induce oscillatory changes in ion density.

Anomalous patterns in sub-ionospheric VLF radio signal propagation have
been documented in various previous research studies during earthquake
events. These studies, including those by Gokhberg et al. (1989), Gufeld et al.
(1992), Molchanov and Hayakawa (1998), Clilverd et al. (1999), Rodger and
Cliverd (1999), Hayakawa et al. (1996a,b, 2000), Chakrabarti et al. (2005),
and Molchanov and Hayakawa (2006), have reported a noticeable shift in the
terminator times of two signal minima amplitude deviations that typically
occur during sunrise and sunset. This shift is observed towards the nighttime
segment of the signal, leading to abrupt changes in signal day length and
night length. The time required to reach the minimum deviation terminator point during sunrise, known as D layer preparation time, and the time taken to recover signal strength from the sunset minima point, referred to as D layer disappearance time, exhibit anomalous temporal changes before earthquakes, as noted in studies by Chakrabarti et al. (2007, 2010). Additionally, the nighttime segment of the signal displays disturbances during these events, as highlighted by Rozhnoi et al. (2004), Maekawa and Hayakawa (2006), Hayakawa et al. (2010), Kasahara et al. (2010), Ray et al. (2011, 2012), and Sasmal et al. (2010). Numerous past studies, employing both VLF, LF sounding methods (e.g., Molchanov and Hayakawa (2001), Miyaki et al. (2002), Rozhnoi et al. (2004, 2007), Korepanov et al. (2009), Chakraborty et al. (2018)) and satellite observations (e.g., Yang et al. (2009)), have identified AGWs during these events. The severity of signal disturbance from typical patterns significantly depends on the characteristics of the signal path, distance from the seismic epicenter and preparation zone, as well as the magnitude and depth of the earthquake.

Multiple signal propagation paths are used to construct a typical VLF signal network. The strategic advantage of employing such a well-distributed signal network lies in its ability to cover extensive geographical regions, enabling the monitoring of a greater number of seismic events. In this study, we utilize the VLF network situated in Japan, a region highly susceptible to earthquakes globally. So we had a sufficient number of earthquakes of magnitude over 6 in the vicinity of the VLF network to support our research. The VLF network we used in this study is composed of eight signal-receiving stations from the north, NSB (Nakashibetsu), STU (Suttsu), AKT (Akita), KTU (Katsuura) in Chiba prefecture, KMK (Kamakura) in Kanagawa prefecture, IMZ (Imizu) in
Toyama prefecture, TYH (Toyohashi) in Aichi prefecture, and ANA (Anan) in Tokushima prefecture. All these receiving stations operate with a uniform receiving system featuring a conductive rod antenna. Both signal amplitude and phase data are recorded through MSK (minimum shift keying) and ASK (amplitude shift keying) modules, encompassing a frequency bandwidth of 10–40 kHz and a sampling rate of 1 second. Each day records a total of 86400 data points over 24 hours. The history and necessary details of this VLF network can be found in the publications of Hayakawa et al. (2018); Hayakawa (2019). Given the potential anisotropic nature of perturbations, observing a single signal path might not reveal significant anomalies, potentially leading to erroneous conclusions. To enhance accuracy, it becomes imperative to augment the number of VLF/LF monitoring receiving stations. This study strives to achieve that heightened level of precision, especially under different seismic conditions, rendering it a crucial endeavor. Hayakawa and his scientific team demonstrate how their VLF-LF network can be utilized to detect pre-earthquake signatures happening around the Japanese island in their publication 2018 Hayakawa et al. (2018). They applied the nighttime fluctuation method over many earthquakes in 2014 with different magnitudes and locations with this network data to identify the pre-earthquake signature and demonstrate the result for a major inland Nagano ken Hokubu earthquake of magnitude 6.7 happened on 22 November 2014 with 4 receiving station data (JJY-IMZ, JJY-TYH, JJI-AKT, JJI-STU) and they found strong precursors before 10 days from this earthquake event. The 2016 Kumamoto earthquake was also studied by this 8-receiver network (Asano and Hayakawa (2018)) and they obtain multiple signal paths Spatio-temporal evolution of ionospheric perturbation. We have done the multi-path study with four different earthquakes which is some extent of the previous work. The details of the
four earthquakes are given in the next section. We gave maximum attention to the conventional nighttime fluctuation method to establish the seismic correlation. We also analyzed the nighttime signals via wavelet power spectrum (WPS) to identify the possible presence of wave-like structures (trace of AGW) during all these four earthquakes.

Existing research indicates that earthquake with a magnitude surpassing 5.5 are more effectively discerned through VLF sounding techniques (Hayakawa et al. (2010); Sasmal et al. (2010)). Consequently, we deliberately selected earthquakes of higher magnitude to investigate seismic anomalies comprehensively. Our focus extends to exploring the dependence of seismic phenomena across multiple VLF signal paths and delving into the behavior of very deep earthquakes, among other perspectives. To streamline our investigation, we established a criterion that prioritizes other conditions. Earlier studies also have suggested that shallow earthquakes (depth > 40 km) exhibit a higher probability of presenting pre-seismic evidence through VLF signals compared to their deep counterparts of the same magnitude (Chakrabarti et al. (2010)). However, a study in the vicinity of Japan has identified pre-seismic effects associated with deep earthquakes (Yamaguchi and Hayakawa (2015)). Leveraging this opportunity, we aim to scrutinize a deeper earthquake in the region through multiple VLF propagation paths. Specifically, we direct our attention to the oceanic Ogasawara EQe, which strikes a depth of 664 km, in this study.

The extra-terrestrial phenomena such as geomagnetic storms caused by solar coronal mass ejection can create a contaminating pre-seismic influence through both electromagnetic and acoustic channels (generation of AGWs) (Biswas et al. (2020)). For a more advanced study, we chose one pre-geomagnetic storm
earthquake Makurazaki that happened on 13\textsuperscript{th} November 2015 and a moderate geomagnetic storm (Dst – 100 nT) began 6 days prior to the event. If the anomalies are observed before six days or storm day they cannot be treated as contaminating effects because geomagnetic storms only perturbed the signal on or after the storm event. The other three events are considered in pre-quiet geomagnetic conditions.

2 Details of the four earthquake and geomagnetic activities around these events:

**Iwaki earthquake.**: This earthquake hits at oceanic area 131 km east of Iwaki city on 11\textsuperscript{th} July 2014, 19:22 UTC. The epicenter is located at the geographical coordinate 37.00520\degree N, 142.45250\degree E with magnitude 6.5 (All information collected from the Japan Meteorological Agency website), and hypocentral depth was 10 km. To pay attention maximum toward seismo-ionospheric perturbation it is important to check the geomagnetic activities before the event. The geomagnetic activity was significantly quiet until about 15 days before this event, as evidenced by Dst, $K_p$ and $a_p$ indices in Figure 1.
Fig. 1: From the top panel Dst, $K_p$ and $a_p$ indices activity has been shown around $\pm 15$ days from the Iwaki earthquake day. '0' of x axis is the earthquake day (11/07/2014 in UTC).

Aomori prefecture earthquake.: This earthquake struck at 78 km east of Mutsu city, Japan on 10\textsuperscript{th} August 2014, 03:43 UTC. The magnitude was 6.1 and the hypocenter depth of 51 km. The epicenter is located at the geographical coordinate 41.17\degree N, 142.19\degree E. This location is close to the NSB, AKT, and STU VLF receiving stations. The geomagnetic activity during the $\pm 15$ days from the event is shown in Figure 2. We can observe the quiet geomagnetic condition here.

Ogasawara earthquake.: This powerful earthquake occurred on 30\textsuperscript{th} May 2015, 11:23 UTC at sea from west of Japan’s remote Ogasawara (Bonin) island. This activity was one of the deepest hypocentral seismic events with a depth of 682 km and a magnitude of 7.9. The geographical location of the epicenter was 27.8386\degree N and 140.4931\degree E. Previously it was estimated that the ionospheric perturbations generally triggered near around above the earthquake epicenter and its preparation zone hence no abnormal change in a far way of VLF signal expected. But in 2014 H. Yamaguchi and M. Hayakawa (H.
Yamaguchi and M. Hayakawa, 2014) presented evidence of significant abrupt change in VLF/LF (Low Frequency) signal for far and deep (300-400 km) oceanic earthquake. As we mentioned before that we want to check these circumstances again by considering this earthquake in our list with a little more distance and depth. We found pre-geomagnetic activity was quite enough (Figure 3).

Makurazaki earthquake: On 13th November 2015, 20:51 UTC this earthquake struck off the southwest coast of Japan 160 km from Makurazaki town. The magnitude and depth were 6.7 and 12 km. Epicenter located at geographical coordinate 31.0009° N, 128.8729° E. This location is close to our signal Transmitter JJI. A moderate type (G2) the geomagnetic storm began on 7th November 6 days before the earthquake. with Dst index reached below -100 nT and $a_p$ touched 80 which saturated the next day (Figure 4), Also several minor geomagnetic storms (G1) indicated from 9 to 11th November.
Fig. 3: From the top panel Dst, $K_p$ and $a_p$ indices activity has been shown around $\pm$ 15 days from the Ogasawara earthquake day. ‘0’ of x axis is the earthquake day (30/05/2015 in UTC).

Fig. 4: From the top panel Dst, $K_p$ and $a_p$ indices activity has been shown around $\pm$ 15 days from the Makurazaki earthquake day. ‘0’ of x axis is the earthquake day (13/11/2015 in UTC).

In figure 5, we illustrate the locations of four earthquake epicenters with their preparation zone circle (Dobrovolsky et al. (1979)), the working VLF network consists of eight VLF receiving stations (yellow triangle) connecting by the VLF signal path from the JJI transmitter (sky blue diamond). The details
### Table 1: Details of earthquakes and distance between their epicenter and 8 VLF receivers.

<table>
<thead>
<tr>
<th>Earthquake Name and Location</th>
<th>Information</th>
<th>Epicentre distance from receiver (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iwaki</td>
<td>Date:11/07/2014, Time:19:22 UTC, M=6.7, d=20 km</td>
<td>AKT 787, ANA 480, IMZ 322, KMK 282, KTU 756.8, NSB 670, STU 523, TYH 400</td>
</tr>
<tr>
<td>Aomori pre.</td>
<td>Date:10/08/2014, Time:03:43 UTC, M=6.1, d=51 km</td>
<td>AKT 214, ANA 1047, IMZ 658, KMK 691.6, KTU 689, NSB 349, STU 243, TYH 830</td>
</tr>
<tr>
<td>Ogasawara</td>
<td>Date:30/05/2015, Time:11:23 UTC, M=7.9, d=682 km</td>
<td>AKT 1360, ANA 872, IMZ 1042, KMK 832, KTU 810, NSB 1788, STU 1659, TYH 820</td>
</tr>
<tr>
<td>Makurazaki</td>
<td>Date:13/11/2015, Time:20:51 UTC, M=6.7, d=12 km</td>
<td>AKT 1411, ANA 629, IMZ 992, KMK 1103, KMK 1161, NSB 1987, STU 1651, TYH 896</td>
</tr>
</tbody>
</table>

Fig. 5: Map view of the locations of 4 earthquake epicenters and their preparation zone (light green, pink, blue, and light yellow star), VLF transmitter JJI (sky blue diamond,) and 8 VLF receivers (yellow triangle). The orange lines are the great circle VLF signal paths and the white lines are the tectonic plate boundaries.
3 Methodology:

Using the data from all eight receiving stations for these four events, we estimate the nighttime trend. The total number of days for the observation is 31, such as the 15 days before and after each individual event. We select a total of 6 hours and 30 minutes of nighttime data (JST 21:00:00 – 27:30:00). Total nighttime duration is taken from a single recorded data file and 27h. 30 min. means 03:30 AM of the next JST date (VLF data recorded for 24 hours with a single second frame in UTC which contain two JST working date in a single data file). To evaluate a single night’s trend, we first measure the average nighttime amplitude over the total 31 nights, then calculate the total amplitude deviation from the 31 nights’ average value. This total deviation is estimated per unit of seconds or period which is called the trend. The more the signal shifts from the average value more likely the value of the trend for a single night and this is the way to observe the signal’s abnormality. The formula for the trend is shown below.

\[
Trend = \frac{\int_{t=N_b}^{t=N_e} (amplitude(t) - average\ amplitude\ (t)) \ dt}{N_e - N_b} \tag{1}
\]

Here, the \(N_b\) and \(N_e\) is the beginning and end times of the nighttime data in seconds. To normalize the Trends, we divide each value with standard deviation (\(\sigma\)) of a total of 31 numbers of trends. The VLF signal abnormality due to seismic effect identification is done by the trend which reached +−2\(\sigma\) level. The next segment of our analysis is proceed by doing the mother Morlet wavelet power spectrum with implies the 95% of significance level and frequency parameter of 6 (Torrence and Compo, 1998). In order to remove the large periodicities that are not related to AGWs, we first subtracted the individual raw minute scale data from their 10 minutes running mean value data before computing the final wavelet for each individual night of data. We
also have drawn the cone of influence line (COI) in WPS, values outside this COI region are not considered valid values. We found no significant pre-seismic perturbation earlier than 15 days from all the events in both of the channels and we represented our results within the band of 15 days before the event.

4 Results

We are now presenting our results after applying these two VLF methods over 4 individual earthquakes. Let us first demonstrate the results obtained from VLF nighttime fluctuations around 4 earthquakes one by one.

From figure 6, we can see substantial negative trends below the -2σ level from the AKT data before 6 days, from the IMZ before 14 days, from the KMK before 4th, 6th and 11th days, form the NSB before 10th and 14th days and before four days from the STU station data. From the ANA station, we get a negative -2σ trend only after three days from the event. For the KTU station, unfortunately, no data is available before 6th, 10th and 14th days, and these days show specific abnormality in other receiving stations. In the TYH station data, although there are no -2σ fluctuations but before ten days the trend almost decreases near -2σ level. This decrement may be due to seismic effects but in less amount. Here, we can observe the pre-seismic fluctuations before the Iwaki earthquake on some common days, such as before four, six, and 10-14 days.

In the case of Aomori earthquake (Figure 7), we observe a decrement in corresponding signal strength (trend) below -2σ level prior the event of six days in the AKT, before one and 11th days in the ANA station, below -3σ level in the STU before four days and again below -2σ level before 11 days in the TYH
Fig. 6: The plots begin from top to bottom indicating the Normalized nighttime trends for following VLF paths of (a) JJI-AKT, (b) JJI-ANA, (c) JJI-IMZ, (d) JJI-KMK, (e) JJI-KTU, (f) JJI-NSB, (g) JJI-STU and (h) JJI-TYH. The receiver’s name was shown at top of each plot. The ‘0’ x-axis is the Iwaki earthquake day (11/07/2014). The horizontal grids indicate the normalized levels. The empty bars are the date on which no data are available and perturbation days are highlighted in red color.

station. Interestingly like the case of the STU same as before four days before the event, we observed the abnormal augmentation in signal amplitude above $+2\sigma$ level in the IMZ and above $+3\sigma$ level in the NSB station data. The KTU station data show no observable aberrant changes, however the KMK a negative trend of below $-2\sigma$ level can be seen on the next day of the earthquake.

The results for another illustration of a very deep and far oceanic Ogasawara earthquake (Figure 8) exhibit VLF precursors in this study and make promising evidence toward the possibility of the ionospheric perturbation far from
Fig. 7: Same as figure 6 for the Aomori pre. earthquake. The empty bars are the date on which no data are available.

a very deep oceanic earthquake. We notice a positive $+2\sigma$ shift (amplitude enhancement) in the AKT signal before eight days then depletion in signal amplitude (trend) below $-2\sigma$ level in the ANA before eight and ten days, below $-3\sigma$ level of reduction in the KMK signal amplitude before fifteen days, similar to the AKT same positive $2\sigma$ fluctuation is also found before eight days in the KTU with a $-2\sigma$ trend just before the event day and below $-2\sigma$ trend before six days in the STU and eight days in the TYH station are noted. Where the IMZ and the NSB are unable to give any precursory effect. Although a high geomagnetic activity is present after nine days from the event, we find some post-effects before this high geomagnetic activity like the positive shift of trend up to $2\sigma$ level after three days in both the AKT and IMZ data and decrement below $-2\sigma$ level after five days in the NSB signal. It is experienced
from the above results, the ionospheric anomalies are mainly recorded before six to ten days from the Ogasawara earthquake via multiple signal paths observation where the KTU showed another late response only before one day and one very early response before fifteen days in the KMK signal.

Before discussing the Makurazaki results (Figure 9), it is important to recall that a geomagnetic storm (G2) occurred six days before the event and persisted five days prior to the incident (Figure 4). Figure 9 shows that the AKT signal experiences two consecutive positive amplitude improvements up to $+2\sigma$ level before one and two days, whereas the IMZ signal experiences a negative $-2\sigma$ trend before one day. In the case of KMK and NSB signal Trend touches the positive $2\sigma$ level before 10 days (KMK) and eight days (NSB)
Fig. 9: Same as figure 6 for the Makurazaki earthquake and -6 to -5 are the geomagnetic storm condition. The horizontal grids indicate the normalized levels. The empty bars are the date on which no data are available.

from the earthquake, which are the unaffected time zone from the geomagnetic activity (as this abnormality occurred before the storm event which began before 6 days and non-affected anomalies days highlights by red color in figure 9). At last, the TYH signal shows the below $-2\sigma$ level depletion prior to four days from the seismic event. The perturbation days after the storm day are indicated by orange color in figure 9. Whereas the ANA, KTU, and STU signals remain silent. In the part devoted to conclusions, these findings will be addressed in detail.
(a) AKT

(b) ANA

(c) IMZ

(d) KMK
(e) KTU

(f) NSB

(g) STU
After looking into the electromagnetic channel now, we are going to the acoustic mode of perturbation by presenting the result obtained from WPS. Figure 10, represents the WPS analysis results of 8 different signal paths since 15 days from the Iwaki earthquake. In the AKT station’s data, we observe the presence of periodic structures for several days. We observe periodic structures around 32 to 50 minutes before three days (08/07/2014), 30 to 60 minutes, and around 90 to 100 minutes before 5 days (06/07/2014), and both around 50 minutes of periodicity found before 13th and 15th days. Periodic structures are found before five days in the ANA data around 32 and 64 minutes. The thing that needs to be noted is that the effective perturbation times through the electromagnetic channels are not the same at all with acoustic. We find no significant pre-seismic anomalies via the nighttime fluctuation method in ANA data but observe the effect of the acoustic channel. So, in a single propagation path, sensitivity is looking different for distinct channels, which is pretty intriguing. These two channels seem not to work simultaneously. The fact will be discussed later in detail. From the IMZ signal, we observed periodicity around 60 minutes on event day (11/07/2014), periodicity around
50-64 minutes before eight days, and periodicity around 45-55 minutes 15 days from the event. From the KMK signal, periodic structures are only recognized before five days, with periodicities peaking at 64 minutes and exhibiting all periodicities below that to 32 minutes. The sole day of periodic signature is observed for the KTU signal has periodicities between 32 to 64 minutes which are before five days. The days with no data are indicated by the blank areas in the WPS of the KTU. The NSB stations capture the lower periodicities during this event like periodicities around 45 minutes on the earthquake day whereas periodicities around 40 minutes are observed before 4, 6, 11, and 13 days. The periodic activity on event days (periodicities of 32-60 minutes), before four days (periodicities of 64 minutes), before 6 days (periodicities of 64 minutes), and before 10 days (focusing periodicities on 64 minutes and higher around 128 minutes not considerable) are found in STU data. TYH shows no AGW activities.
(a) AKT

(b) ANA

(c) IMZ

(d) KMK
Fig. 11: Same as figure 10 for Aomori earthquake.
AGW activities are also highlighted in the WPS diagram of Aomori-pre. (Figure 11). The low magnitude of the periodic structure is found before 2 days (around 40 minutes) and a good amount of activities happened before 6 days (periodicities around 40-60 minutes) in the AKT signal. In the ANA, we observe activities early two days (around 64 and 40 minutes) and before 15 days (around 32 and 64 minutes) from the event. The IMZ data shows AGWs on many days with different levels of amount. Low instance AGW activities are recorded on event day (around 40 minutes), before 2 days (between 32-40 minutes), three days (around 60 minutes), and 12 days (around 80 minutes).

High-magnitude of activities are recorded before ten days (around 64 minutes), 14 days (periodicity 90-100 minutes), and 15 days (50 minutes) from the seismic event. Only a single day of AGW activity is observed in the KMK signal before three days (around 40 minutes). In the KTU data, AGW activities are observed before 12 days (between periodicities of 32-60 minutes) and 14 days (around 35 minutes) from the event. About 40 minutes of periodicity detect before two and three days in the NSB data. The STU data indicate the AGW activities before four days with periodicity around 80 minutes and 40 minutes, whereas before ten days most of the high-power activity remain outside of the COI region and a small portion of it remain inside of COI about periodicity from 35 to 80 minutes. In the TYH data, high periodic activity before 2 days (around 70 and 32 minutes) and medium activities before 11 days (around 50 minutes) are observed.
(a) AKT

(b) ANA

(c) IMZ

(d) KMK
Fig. 12: Same as figure 10 for Ogasawara earthquake.
During the following case study, we have evidence that the AGW can travel long distances or can be generated at long distances from the deep oceanic earthquakes epicenter. From the WPS results of figure 12, we observe the trace of periodic structure around the periodicity of 40 minutes before 6 days in the AKT station, activity presents before two days (periodicities around 32 minutes), ten days (periodicities around 40 minutes) and 15 days (periodicities between 50 to 64 minutes) from the event in the ANA data. Periodic structures in the IMZ that last between 40 and 60 minutes are only detected before eight days. For both the KMK and KTU data, we assert that there are no AGW effects. In the NSB data AGW activities are present before two days (periodicities of 64 minutes), three days (around 64 minutes), and 9 days (around 45 minutes) from the event. The STU data shows AGW activities before six days (periodicities from 45-60 minutes) and 14 days (maximum periodicity around 64 minutes). Only before ten days, the TYH data shows AGW activities with maximum periodicities of around 40 minutes. So, here are lots of AGW activities observed before the deep and distanced Ogasawara earthquake.
Fig. 13: Same as figure 10 for Makurazaki earthquake.
As we mentioned earlier that some past studies evidenced that the AGW can also be a resulting factor due to geomagnetic storms as well the seismic events. When we observed AGW activity after the storm event it cannot say specifically which event is responsible for this or a combined process and this is a contradictory situation. The AGW activities before the storm event may consider a pre-seismic phenomenon. Let us now check the WPS result for the Makurazaki case (Figure 13) and discuss what we got from it. First in the AKT signal only before 11 days, periodic structures around 40 minutes are found which is before the storm activity. In the ANA signal AGW with a periodicity of around 32 minutes is observed before 3 days (contaminating) and before 9 days (periodicities of 40 minutes). High activity AGW with a low periodicity of 40 to 45 minutes before eight days and a periodicity of 50 minutes before 15 days are identified, both occurring before the storm day in the IMZ signal. The KMK data shows AGW activities before three days (around 48 minutes), eight days (32 minutes and 50 minutes), and 11 days (around 40 minutes) from the seismic event. The KTU data shows an evolution of AGW between five to seven days prior to the event. Before seven days which is the previous night of the storm, the signal shows periodicities around 50 to 60 minutes. On the next night, which is the geomagnetic active night the periodicities reach a higher value of around 100 minutes, and again on the next day (before 5 days), the periodicities evolved to around 48 minutes. So, we can observe a sudden evolution in periodicity at storm night. Besides that, activity is also present before 13 and 15 days (not contaminating) in the KTU. By looking into the NSB signal’s WPS, we can see AGW activities before four days (periodicity of 80 minutes), five days (periodicity of 64 minutes), eight days (around 60 to 70 minutes), nine days (around 40 minutes) and 10 days (around 32 minutes). In the STU signal, the AGW activities observables
are before six days (periodicities between 32 to 48 minutes), relatively fewer signatures before five and nine days (at the COI corner after one and half hours around periodicities of 40 minutes), and before 13 days (around 64 minutes). In the TYH data, we can see the AGW activities before three days (periodicities from 32 to 48 minutes), high activity before four days with almost coverage of all ranges of periodicities except around 70 minutes, and before 10 days with periodicities of 64 minutes from the earthquake night. We can observe both contaminating AGWs and seismogenic AGWs from most of the receiver data. We have summarized the results in a Tabular form below (Table 2 and 3).

5 Discussion

We detect pre-seismic anomalies through both electromagnetic and acoustic channels of LAIC for the Iwaki, Aomori, and Ogasawara earthquakes. In contrast, the Makurazaki event exhibits less prominent electromagnetic signatures but significant impact through the acoustic channel. Aomori and Iwaki, occurring 462 km apart on the same tectonic plate with magnitudes of 6.1 and 6.7, respectively, display dissimilar seismogenic impressions in terms of perturbation timing and intensities due to significant differences in the coverage of the preparation zone (see Figure 5). The response of the first seismogenic perturbation varies with distance from the epicenter for individual earthquake events— Iwaki, Aomori, Ogasawara, and Makurazaki. The receivers, located at different distances from each epicenter, facilitate this study. Figure 14 illustrates this variation observed from the electromagnetic channel for three events, excluding the Makurazaki event due to minimal electromagnetic effects before the geomagnetic storm. Observations reveal that nearby VLF receivers do not consistently experience the first disturbance compared to more distant receivers, deviating from general expectations. For the event of
<table>
<thead>
<tr>
<th>station</th>
<th>AKT</th>
<th>ANA</th>
<th>IMZ</th>
<th>KMK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Iwaki Earthquake</strong>: 11/07/2014, 19:22 UTC, M=6.7, d=20 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend before and $\sigma$ level</td>
<td>6 days $&lt;-2$</td>
<td>No</td>
<td>14 days $&lt;-2$</td>
<td>4, 6, 11 day $&lt;-2$, $-2.5$, $=-2.5$</td>
</tr>
<tr>
<td>AGW before</td>
<td>3, 5, 13, 15 days</td>
<td>5 day</td>
<td>0, 8, 15 day</td>
<td>5 day</td>
</tr>
<tr>
<td><strong>Aomori pre. Earthquake</strong>: 10/08/2014, 03:43 UTC, M=6.1, d=51 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend before and $\sigma$ level</td>
<td>6 day $&lt;-2$</td>
<td>1, 11 day $&lt;-2$, $-2.5$</td>
<td>4 day $&gt;+2$</td>
<td>No</td>
</tr>
<tr>
<td>AGW before</td>
<td>2, 6 day</td>
<td>2, 15 day</td>
<td>2, 3, 10, 12, 14, 15 day</td>
<td>3 day</td>
</tr>
<tr>
<td><strong>Ogasawara Earthquake</strong>: 30/05/2015, 11:23 UTC, M=7.9, d=682 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend before and $\sigma$ level</td>
<td>8 days $&gt;2$</td>
<td>8, 10 day $&lt;-2.5$, $-2$</td>
<td>No</td>
<td>15 day $&lt;-3$</td>
</tr>
<tr>
<td>AGW before</td>
<td>6 day</td>
<td>2, 10, 15 day</td>
<td>8 day</td>
<td>No</td>
</tr>
<tr>
<td><strong>Makurazaki Earthquake</strong>: 13/11/2015, 20:51 UTC, M=6.7, d=12 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend before and $\sigma$ level</td>
<td>1,2 days $&gt;2$</td>
<td>No</td>
<td>1 days $&lt;-2$</td>
<td>No</td>
</tr>
<tr>
<td>AGW before</td>
<td>11 day</td>
<td>3, 9 day</td>
<td>8, 15 day</td>
<td>3, 8, 11 day</td>
</tr>
</tbody>
</table>

Table 2: Nighttime fluctuation and Wavelet results in tabular form for 4 earthquakes for four VLF receiving stations AKT, ANA, IMZ, and KMK. Only pre-effects are highlighted here.
<table>
<thead>
<tr>
<th>station</th>
<th>KTU</th>
<th>NSB</th>
<th>STU</th>
<th>THY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Iwaki Earthquake</strong>: 11/07/2014, 19:22 UTC, M=6.7, d=20 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend before and $\sigma$ level</td>
<td>No</td>
<td>10, 14 day $&lt; -2$</td>
<td>4 day $&lt; -2$</td>
<td>No</td>
</tr>
<tr>
<td>AGW before</td>
<td>5, 8, 10 day</td>
<td>4, 6, 11, 13 day</td>
<td>0, 4, 6, 10 day</td>
<td>No</td>
</tr>
<tr>
<td><strong>Aomori pre. Earthquake</strong>: 10/08/2014, 03:43 UTC, M=6.1, d=51 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend before and $\sigma$ level</td>
<td>No</td>
<td>4 day $&gt; 3$</td>
<td>4 day $&lt; -3$</td>
<td>11 day $&lt; -2$</td>
</tr>
<tr>
<td>AGW before</td>
<td>12, 14 day</td>
<td>2, 3 day</td>
<td>4, 10 day</td>
<td>2, 11 day</td>
</tr>
<tr>
<td><strong>Ogasawara Earthquake</strong>: 30/05/2015, 11:23 UTC, M=7.9, d=682 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend before and $\sigma$ level</td>
<td>1, 8 day $&lt; -2$, $&gt; 2$</td>
<td>No</td>
<td>6 day $&lt; -2.5$</td>
<td>8 day $&lt; -2.5$</td>
</tr>
<tr>
<td>AGW before</td>
<td>No</td>
<td>2, 3, 9 day</td>
<td>3, 14 day</td>
<td>10 day</td>
</tr>
<tr>
<td><strong>Makurazaki Earthquake</strong>: 13/11/2015, 20:51 UTC, M=6.7, d=12 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend before and $\sigma$ level</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>4 day $&lt; -2.5$</td>
</tr>
<tr>
<td>AGW before</td>
<td>5 to 7 day</td>
<td>4, 5, 8, 9, 10 day</td>
<td>6, 14 day</td>
<td>3, 4, 10 day</td>
</tr>
</tbody>
</table>

**Table 3**: Same as table 2 for other four stations KTU, NSB, STU, and TYH.
Iwaki (top panel of figure 14), the first perturbation strike at 480 (IMZ) and 756.8 (NSB) km away (table 1) from the epicenter before 14 days. The second farthest station, the NSB, experiences the possible earliest seismogenic effects, whereas the most nearby station, the KTU, which is 282 km away, does not. In the case of Aomori earthquake (middle panel of figure 14), the first effect is noticed before 11 days at 691.6 km (KMK) and 1047 km (ANA) away from the epicenter. Other receivers are situated nearer than these two station. The nearest receiver, located at 214 km (AKT) away, showed anomalies after 5 days (6 days before the event) from the first disturbance, whereas the farthest station, the ANA suffered the earliest signature. The STU, NSB, and IMZ, located 243, 349, and 658 km away, experienced pre-seismic anomalies on the same day before the event, despite being significantly separated from each other. Two of the nearest receivers of the Ogasawara earthquake epicenter are KTU and TYH, situated at 810 and 820 km far, respectively. These two closely located receivers show perturbation on the same day before 8 days from the main shock. But, the very first perturbation occurred early, 15 days before the event at 832 km away (KMK). The interesting fact is that the TYH and KMK are only separated by 12 km, whereas the KTU and TYH are separated by 10 km. This means that although the KTU and TYH experienced a disruption on the same day, the effects on the KMK before 15 days had no discernible impact from 12 km away. The far most receiver, the NSB locate at 1788 km away, suffer no disturbance, but the STU station signal faces the impact before six days which is 1659 km away.
**Fig. 14:** Variation of first perturbation day with distance from the epicenter from the electromagnetic channel. The top panel is for Iwaki earthquake, the middle panel is for Aomori earthquake, and bottom panel for Ogasawara earthquake.

**Fig. 15:** Same as figure 14 but from acoustic channel. The new bottom panel is the variation for Makurazaki earthquake.
Analysis of distance to first perturbation variation is also conducted for the acoustic channel which is represented by figure 15. Due to the numerous pre-seismic AGW activities that occurred prior to the storm event, we include Makurazaki earthquake in this observation (bottom panel of figure 15). The top panel of figure 15 indicates that the first pre-seismic perturbation during Iwaki earthquake occurs 15 days at 400 km (AKT) and 480 km (IMZ) away from the earthquake epicenter. The same station IMZ also shows the first electromagnetic perturbation before 14 days. This region of the IMZ may be possible first sensitive seismogenic preparation region via both channels. The closest station, the KTU, located 282 km away, experiences AGW perturbation but no electromagnetic effect. In the case of Aomori earthquake, the first perturbation is observed prior to 15 days at the far most station the ANA 1047 km away, and the mid-distant station IMZ (658 km away). The stations KTU (689 km from the epicenter) and KMK (691.6 km from the epicenter) are only 2.6 km apart, but they both showed the effect of pre-seismic AGW on different days. The AGW activities are highlighted in the KMK and KTU signals before 6 and 12, 14 days (table 2, 3) respectively. Another hand, these two stations remained silent by the electromagnetic channel. In the aspect of perturbing distance resolution, only the difference of 2.6 km there is changed the scenario for the same effect. For Ogasawara earthquake, the ANA and STU station’s signal suffered the earliest disturbance prior to 15 and 14 days and they are located at the distance of 872 and 1659 km from the epicenter. Here, the two nearest receivers KMK and KTU faced no AGW effect during this event. We also can see that The AGW excitation reaches early at the distance of 1659 km far from the epicenter during this deep most earthquake preparation activities. Before 15 days, the first possible seismogenic AGW effect caused by the Makurazaki event is encountered at a distance of 992 km
(IMZ) and before 14 days at a distance of 1651 km (STU station). In terms of the epicenter, the nearest and farthest receivers are 629 (ANA) and 1987 (NSB) km away, respectively. Aside from that variation, we also can see the presence of AGW anomalies before the geomagnetic storm which was not seen in the case of Imphal earthquake by (Biswas et al., 2020). Those signatures could not be possible for the storm event, despite the fact that no significant meteorological events or volcanic activity (https://volcano.si.edu/ and https://www.data.jma.go.jp) occurred in this region during this time. We can say that anomalies before the six days are possibly seismogenic. As a result, even if there were geomagnetic disturbances before the earthquake, we may be able to obtain a non-contaminating situation using the radio technique only if the earthquake preparation shows its existence likely before the storm.

The Observational investigation of distance to initial disturbance via both channels shows that the concept such as the source of perturbation beginning at the epicenter and diverging with decreasing intensity is difficult to establish. In most cases, the nearest receivers are delayed to experience but far more stations even the farthest experience first. The inhomogeneity at the Ionospheric perturbation with the geographical distance may be one of the reasons for this. Our recent study Biswas et al. (2022) also reported the spatial inhomogeneity of electron density perturbation during Samos earthquake, where the different regions of the lower ionosphere exited differently even at the same location but at a different time on a single day. In this study, two separate and independent channels of perturbation rise to the same dignity.
6 Conclusion

We employ VLF radio-sounding techniques to identify pre-seismic signatures in the nighttime lower ionosphere associated with four earthquake activities. The study successfully discerns potential pre-seismic indications for all these events through both electromagnetic and acoustic mechanisms. Notably, this investigation validates expectations of distinct signal routes being perturbed with varying intensities and timing. In contrast to relying on a single or a few propagation paths, our approach utilizes eight different receivers situated in diverse locations relative to the earthquake epicenter. The advantage of employing a multipath probe lies in the potential to detect the earliest indications of earthquake preparation. Interestingly, we observe certain receivers, such as ANA and KTU via the electromagnetic channel, and TYH via the acoustic channel, remaining silent before the event during the Iwaki event (refer to Table 3). This observation underscores the importance of employing multiple paths, as relying solely on specific paths might lead to inconclusive results, while a broader approach enhances the accuracy of conclusions. Building upon the work of Yamaguchi and Hayakawa (2015), who observed pre-seismic signatures solely through the electromagnetic channel for two deep earthquakes in the Torishima area, we extend the study to a more profound event—the Ogasawara earthquake (682 km deep). This event, 237 km deeper than the previous Torishima study, reinforces the conclusion that radio techniques are adept at identifying very deep activity. Our findings reveal significant lower-ionospheric disturbance through both the electromagnetic and acoustic channels. Remarkably, the perturbation extends beyond 1600 km from the epicenter during the Ogasawara event (refer to Table 14 and 15). The study conducted during the Maku-razaki earthquake illustrates how pre-seismogenic evidence can be observed
in the presence of pre-geomagnetic activity or under non-contaminated conditions. Referencing the work of Biswas et al. (2022, 2023a), who demonstrated the special and altitudinal inhomogeneity of seismogenic perturbation during the 2020 Samos earthquake and 2016 Fukushima earthquake respectively, our study similarly identifies inhomogeneity through both channels, as discussed in the dedicated section. The variation in distance to perturbation reaffirms that the ionosphere in the nearby geographical region surrounding the epicenter is not perturbed isometrically in terms of both time and intensity. This study underscores the challenging nature of determining the location of an approaching seismic event due to the scattered and unpredictable inhomogeneity phenomenon resulting from the preparation mechanism. To forecast the location, we need to find alternative possible technique.

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References


Article Title


