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CHANGES OF THE GEOMAGNETIC SIGNALS LINKED TO TOHOKU EARTHQUAKE ON MARCH 11th 2011

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ABSTRACT
The geomagnetic fields in the atmosphere can be affected by phenomena in the Earth, so that changes of geomagnetic intensity might be used as an indicator of earthquake occurrences. Variations of geomagnetic data have been analyzed in association with the Tohoku Earthquake on March 11th 2011. The Geomagnetic data have been derived from Memambetsu (MMB), Kakioka (KAK) and Kanoya (KNY) Observatories, which are INTERMAGNET observatories. The analysis was performed by calculating the power spectral density (psd) of the ULF signal of Z and H components and then polarizations are observed by comparing the psd of Z and of H. The results showed the difference psd of Z and of H between the KAK observatory (the nearest position to the epicenter) with MMB and KNY (at some greater distance from the epicenter) is quite significant, which can be observed over a period of 10 days before the earthquake occurrence. The polarizations of Z/H in KAK indicate a highest change of intensity which occurred at 18 days prior to the earthquake.

Keywords: Earthquake; Geomagnetic; Polarization; psd

1. INTRODUCTION
Earthquakes are one of natural phenomena that always occur suddenly and locally. Tectonic earthquakes are caused by tectonic activity, such as the sudden shifting of tectonic plates with a very large powerful force. This kind of earthquake generates a lot of damage or natural disasters on the Earth, while strong earthquake vibrations are capable of spreading to all parts of the Earth. The theory of plate tectonics explains that the Earth consists of several layers of rocks, while most of the crust layers will drift and float like snow. These layers move slowly; sometimes they are fragmented and collide with others. This is what causes a tectonic earthquake.

To prevent life from dangerous effects and impacts of earthquakes, we need to make such efforts so as to move far away from the earthquake source as rapidly as possible. It requires correct information about when earthquakes will happen or when earthquake can be forecast. Many papers have discussed earthquake predictions, among them are (Hayakawa et al., 1996 and Kawate et al., 1998), which reported the results of the interpretation of ULF magnetic noise during the Guam earthquake on August 8th 1993. An improved polarization analysis method has been applied in (Masci et al., 2009), which was carried out with a 2006–2008 AQU dataset.

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However, they did not find an increase in the polarization ratios before the earthquake occurred as was expected. Nevertheless, a small increase in the polarization ratios was found before the M3.1 earthquake, which occurred only 9 km away from AQU on September 2006. In any case, this ULF anomaly is not well-defined. It is doubtlessly linked with tectonic events. On the other hand, the data indicate a magnetic anomaly in the AQU-CVT total magnetic field differences that occurred two weeks before the respective earthquakes.

Another study improved the application of the polarization method to the ULF data at Kashi station in China (Ida et al., 2008). This study adopted general standardization (or normalization) by estimating the average and standard deviation during the whole period for each component. By using these standardized geomagnetic field quantities, it was found that the polarization levels, as the ratio of vertical magnetic field component to that of horizontal magnetic field component (Z/H at a particular frequency of ~0.01 Hz (10 mHz), exhibit a significant increase before the occurrence of the M6.0 earthquake on September 1st 2003, with its epicenter distance of 120 km. The researchers commented on the lead time for this earthquake since from 1st to the end of August some enhancements were noted in the polarization data. The maximum polarization occurred a few days before the earthquake.

Kanata et al. (2013) applied a differentiation procedure based on moving averages related to three major earthquakes in the region of Japan; which occurred on September 25th 2003 (M8.3), September 5th 2004 (M7.2 and M7.4) and March 11th 2011 (M9.0), respectively. The researchers found a high magnetic spike ranging from three- to one-month prior to the earthquakes' occurrences, which might serve as a precursor for future data analysis. However, the moving average procedure which has been applied to the differentiation values of the total geomagnetic between two observatories indicates average magnitudes without any anomalies. This study aims to analyze anomalous ULF signals evident in the data of geomagnetic variations that are associated with Tohoku Earthquake M9.0 on March 11th 2011, which is the largest earthquake in the history of Japan.

2. METHODOLOGY/ EXPERIMENTAL

2.1. Earthquake and Geomagnetic Data

The Tohoku earthquake with a magnitude of M9.0 occurred on Friday, 11th 2011 at 05:46:24 UTC and has been reviewed by seismologists. The epicenter was located at 38.297°N, 142.372°E, at a depth of 30 km (18.6 miles), in the region near the East coast of Honshu, Japan; 129 km (80 miles) E of Sendai, Honshu, Japan; 177 km (109 miles) E of Yamagata, Honshu, Japan; 177 km (109 miles) ENE of Fukushima, Honshu, Japan; and 373 km (231 miles) NE of Tokyo, Japan (Source: USGS NEIC (http://earthquake.usgs.gov).

Data from three INTERMAGNET observatories in Japan have been used, i.e. Memambetsu (MMB), Kakioka (KAK), and Kanoya (KNY). The geographical positions of the three observatories and their distances to the earthquake epicenter are listed in Table 1, while Figure 1 depicts their locations and the epicenter location of the Tohoku Earthquake case study.

Table 1 The geographical locations of MMB, KAK and KNY observatories

IAGA code	Latitude	Longitude	Distance to EQ (km)	Elevation (m)
MMB	43.91°N	144.19°E	642	42
KAK	36.23°N	140.18°E	301	36
KNY	31.42°N	130.88°E	1295	107

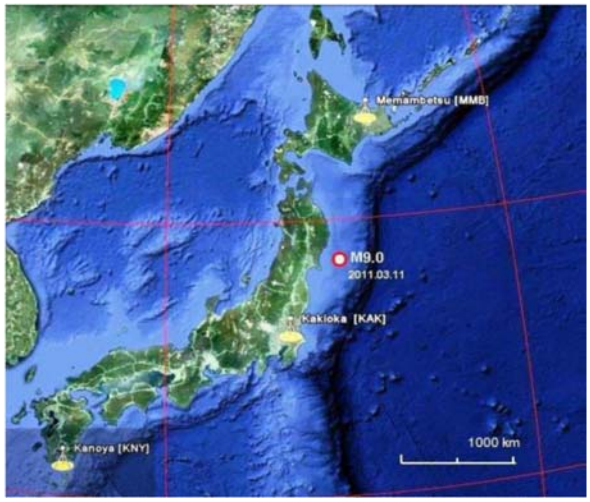

Figure 1 The relative locations MMB, KAK, KNY observatories to the Earthquke (indicated by circles) that occurred on March 11th 2011 (Zubaidah et al., 2013)

To reduce the influence of artificial noise, only one-minute values of the geomagnetic data occurring between 00:00 to 06:00 PM (15:00 to 21:00 UTC) are used. One year's worth of statistical data are collected for the analysis, with six months prior and six months after the earthquake (i.e. October 1st 2010–September 30th 2011 to indicate any fluctuations in the ULF geomagnetic signal.

2.2. Polarization Analysis and Geomagnetic Activity Indices

2.2.1. Polarization analysis

Anomalous ULF signals in the geomagnetic field variation are recognized in electromagnetic studies related to earthquakes. These phenomena are due to the emissions of the Earth's crust at the earthquake source (Dudkin et al., 2010). Previous studies (Hayakawa et al., 1996; Hayakawa et al., 2000; Hayakawa et al., 2007; Molchanov & Hayakawa, 1995; Molchanov et al., 1992) have found signs of anomalous signals emissions before earthquake occurrences, mainly in the ultra low frequency (ULF) band (0.001 to 10 Hz).

In this paper, a case study was conducted by observing anomalous ULF signals in the frequency range from 0.001 to 0.1 Hz, which were associated with the Tohoku earthquake that occurred on March 11th 2011. In this research the Fast Fourier Transform (FFT) method is applied to each component in order to obtain the frequency spectrum. The ULF signals in these frequency ranges are obtained by band pass filtering of the geomagnetic field at frequencies from 0.001 to 0.1 Hz. Furthermore, the signals are processed in the following order:

1. The maximum of ULF signals of $B_Z(f)$ and $B_H(f)$ are selected in the 0.001–0.1 Hz range.
2. The power spectral densities (psd) are calculated for the respective components: $S_Z(f)=\frac{|B_Z(f)|^2}{\Delta f}$ dan $S_H(f)=\frac{|B_H(f)|^2}{\Delta f}$ where Δf is the difference between $f_{up\ cut\text{-}off}$ and $f_{low\ cut\text{-}off}$
3. The next step is to make a comparison of the Z and H components with normalization, according to the following expression $i_n=(S_i(f)-\mu_i)/\sigma_i$, where i represents the

components of Z and H in the frequency domain, $S_i(f)$ are psd of *i* components; μ_i and σ_i are respectively the average value and the standard deviation of the i component over the considered period of time.

4. Finally, the normalized polarization $\frac{Z_n}{H_n}$ data are calculated.

2.2.2. Geomagnetic activity index

To demonstrate the strength of geomagnetic activity that occurs in one day, the Kp index (planetary index) is one of the indices used to express the degree of geomagnetic disturbance which can indicate the occurrence of magnetic storms within the span of a day. This index is calculated as a result of the influence of solar activity and other cosmic activities. The range value indicates a geomagnetic storm if the Kp index ≥ 5; otherwise it is said to be calm. During a one day period a high Kp index can interfere with the magnetic fields recorded at the observatory. The daily Kp index in this study is obtained from the ftp site of *the Deutsches GeoForschungsZentrum* (ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/wdc/), provided by the World Data Center (WDC) University of Kyoto, Japan.

3. RESULTS

Figure 2 shows the original geomagnetic field normalized to the Z and H components of MMB, KAK and KNY observatories during October 1st 2010–September 30th 2011.

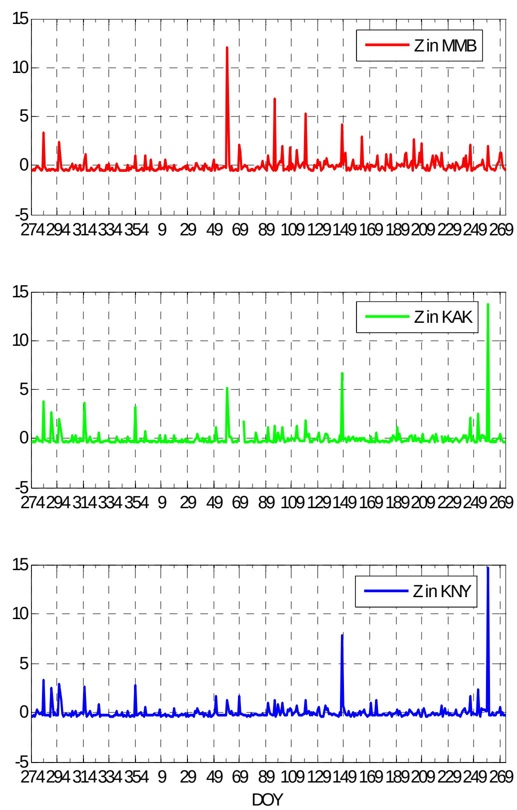

Figure 2 The original geomagnetic fields normalized to the Z and H components of MMB, KAK and KNY observatories during October 1st 2010–September 30th 2011. The left panel is for Z component, the right one is for H component

Figure 3 shows the normalized power spectral density of MMB observatory during October 1st 2010–September 30th 2011. The first panel is for Z components, the second one is for H components, and the third one is for the ratio between Z and H components. Sigma Kp values of corresponding days are depicted in the fourth panel to evaluate the global geomagnetic conditions.

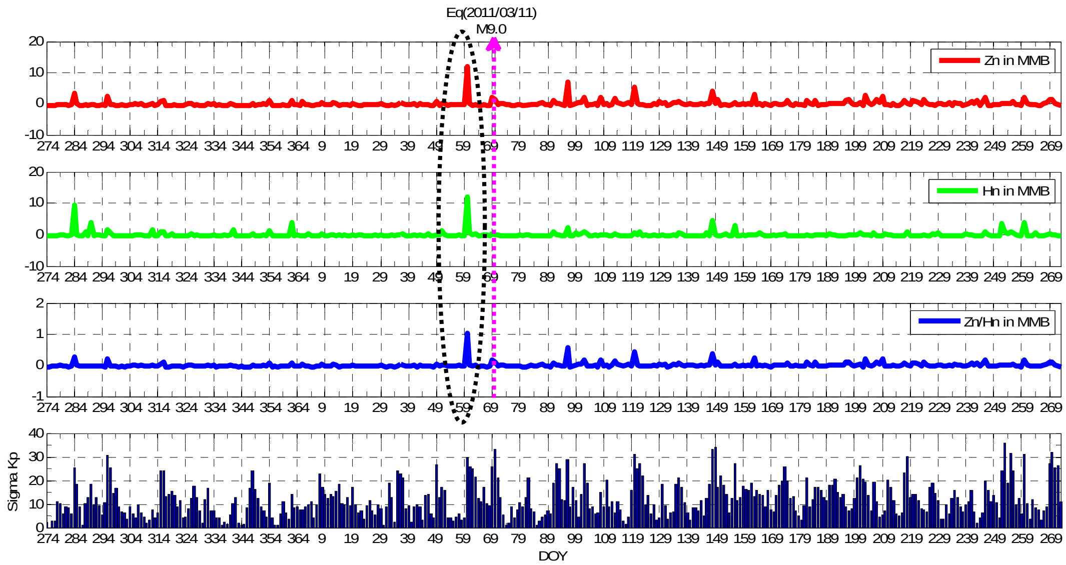

Figure 3 The normalized power spectral densities of MMB observatory from October 1st 2010– September 30th 2011, related to the M9.0 Tohoku Earthquake on March 11th 2011

Figure 4 shows the normalized power spectral density of KAK observatory from October 1st 2010–September 30th 2011. The panels are in the same order as shown in Figure 3.

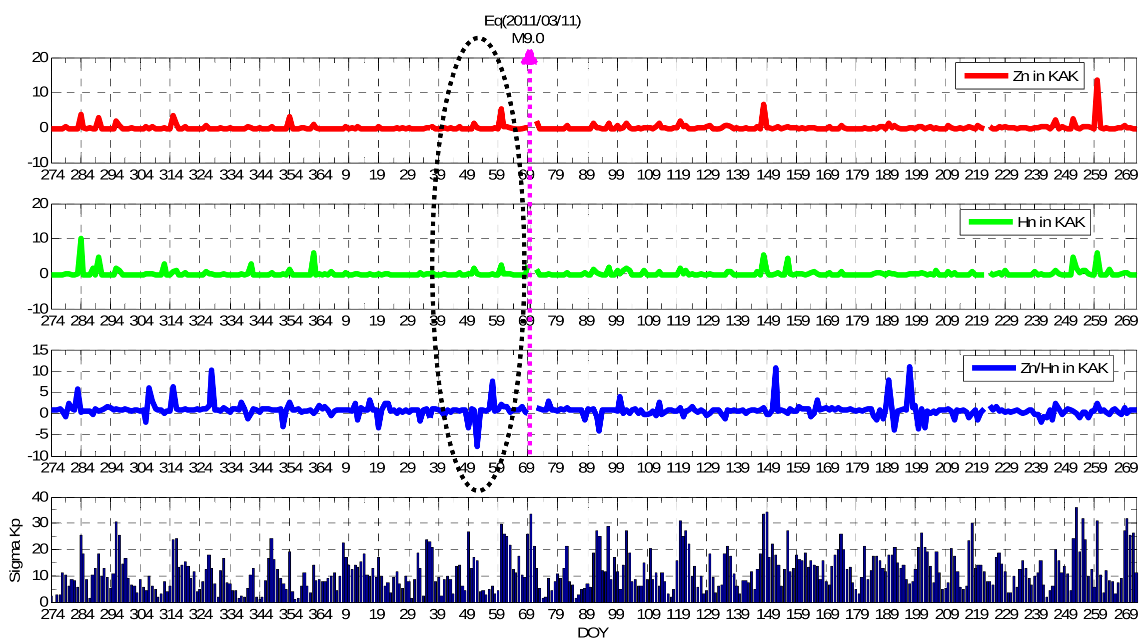

Figure 4 The normalized power spectral densities of KAK observatory from October 1st 2010–September 30th 2011, related to the M9.0 Tohoku Earthquake on March 11th 2011

Figure 5 shows the normalized power spectral density of KNY from October 1st 2010–September 30th 2011. The panels are in the same order as in Figures 3 and 4.

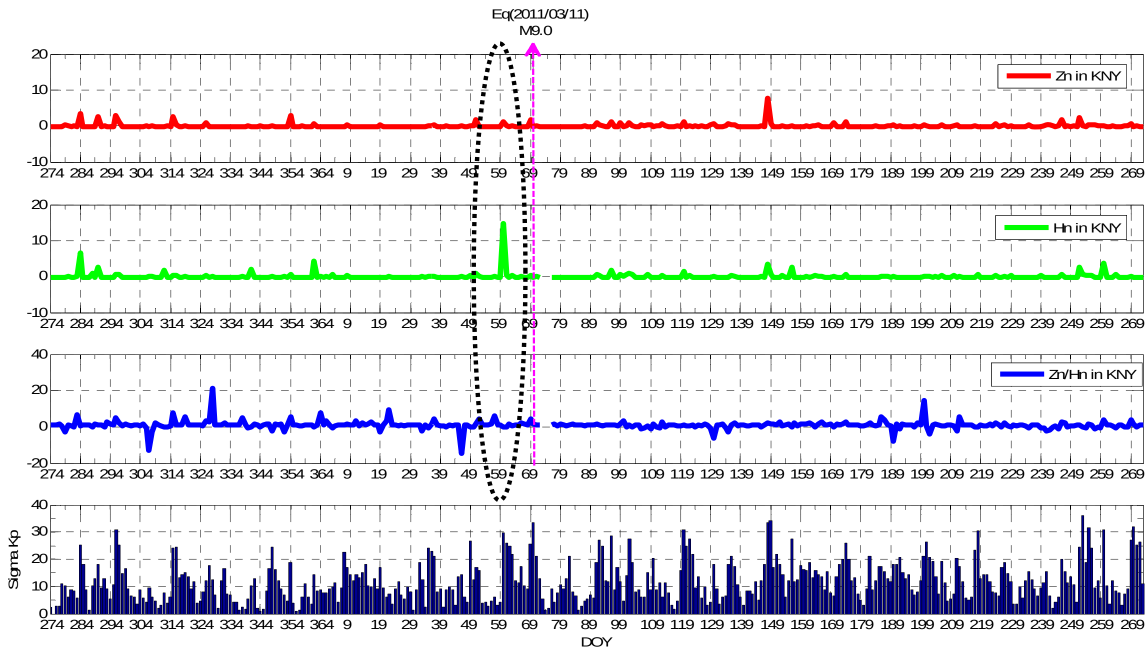

Figure 5 The normalized power spectral densities of KNY observatory from October 1st 2010–September 30th 2011, related to the M9.0 Tohoku Earthquake on March 11th 2011

4. DISCUSSION

As seen on the parts marked with an ellipse in Figure 3, there were anomalous signals clearly existing with their intensity values as calculated in Table 2. The normalized power spectral densities of Z/H increased over a period of 10 days (about two weeks) before the earthquake occurrence (DOY 70) with a ratio of 1.02 and sigma Kp values of 29.7 (mean of Kp index = 3.71), which means that no geomagnetic storms occurred during the anomalous days.

Table 2 Anomalous geomagnetic signals on MMB, KAK, and KNY prior to the Tohoku Earthquake

IAGA code	Normalized psd of Z	Normalized psd of H	Normalized Polarization (Z/H)	Sigma Kp
10 days before earthquake (DOY 60–70)				
MMB	12.04	11.85	1.02	
KAK	5.16	2.54	2.03	29.7
KNY	1.17	14.73	0.08	

As seen on the parts marked with an ellipse in Figure 4, there were anomalous signals clearly existing with their intensity values as calculated in Table 2. In the KAK observatory, 10 days (about two weeks) before the earthquake (DOY 70), it can be shown that the value of Z and H are lower than those of MMB observatory. The value of H is approximately half of Z; therefore, the ratio of Z/H is as high as 2.54, as calculated in Table 2. Moreover, the ratio of Z/H from

DOY 52–57 (during 6 days) indicates very high intensity changes, as high as 15.37, which occurred 18 days (about three weeks) before the earthquake. In this case, the sigma Kp values are less than or equal to 16 (mean of Kp index $\leq$ 2) on those days, which means that no geomagnetic storms occurred during the anomalous days. We are confident that the anomalous signals were local to Honshu, Japan and in close correlation with the earthquake occurrence.

At the KNY observatory indicated in Figure 5, the power spectral densities of Z and H factors at 10 days before the earthquake occurrence shows a very low value of Z component, while the H component is very high, so that the ratio Z/H becomes very small, that is a result of 0.08 and a sigma Kp value that is 29.7 (mean of Kp index = 3.71). This calculation indicates that no geomagnetic storms occurred during the anomalous days as calculated in Table 2.

From the data compiled from all three observatories, the KAK observatory data shows the most obvious indicators prior to the earthquake. This data is indicative of the close proximity to the earthquake epicenter, resulting in the highest recorded intensity of anomalous data (Kanata et al., 2013). Based on these findings, we propose that the precursors can be seen approximately 2 weeks prior to an earthquake. This proposition is in accordance with the research conducted by (Masci et al., 2009; Ismaguilov et al., 2003; Ruhimat et al., 2001). Additionally, it is necessary to conduct observations not only prior to the day of earthquake, but also on the days after the earthquake. Unfortunately, the geomagnetic data are not available in this case, possibility due to power failures at the location of the observatory, which were caused by the earthquake.

5. CONCLUSION

This research found anomalous geomagnetic signals by using normalized polarization of Z/H in the frequency range of 0.001–0.1 Hz as a precursor to the Tohoku earthquake on March 11th 2011. The anomalies can be seen 2–3 weeks prior to the earthquake. One-minute values of INTERMAGNET data can be used in the analysis of ULF range for short-term earthquake predictions.

6. ACKNOWLEDGEMENT

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