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On effective ULF frequency ranges for geomagnetic earthquake precursor

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Abstract. This paper reviews several effective ULF frequency ranges of geomagnetic field used by prior studies to detect earthquake precursor. Since the chosen frequency ranges are rather arbitrary across different studies, it is important to determine whether any particular range is more effective than others to predict earthquakes having different characteristics, i.e. magnitude, depth and epicentral distance. It is found that there is no significant correlation between any earthquake parameter with effective ULF frequency ranges. It is also concluded that frequency ranges of 0.02 - 0.04 Hz and 0.06 Hz are more optimal for earthquake prediction purpose.

1. Introduction

Physical destructions and fatalities caused by earthquakes has been urging researchers around the world to study the possibility of predicting the disaster before it happens. Earthquake prediction, according to Hayakawa [1], are classified into three types based on its time scale namely long-term, medium-term and short-term prediction. The last one whose time scale is between a few weeks to a month is considered as the most important and useful to mitigate the disaster. Hayakawa [2] also maintains that non-seismological approach to accomplish reliable earthquake prediction is the most feasible way; one of the promising methods being via geomagnetic field perturbation observation.

Earth geomagnetic field is continuously varied by external and internal sources. External sources include solar-terrestrial and magnetospheric effects while internal sources include seismological lithospheric processes [3]. One of the challenges encountered in achieving practical geomagnetic earthquake prediction is discrimination of weak seismogenic emission which is possibly originated from earthquake epicenter from external sources [4]. Several methods have been proposed

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and applied by prior studies which can be generally classified into ultra-low frequency (ULF) analysis and non-ULF analysis. ULF analysis will be the center element in this paper.

ULF emission, as emphasized by Hayakawa et al. [5] in one of the earliest studies on geomagnetic earthquake prediction, is defined to be between 0.01 - 0.1 Hz. Despite the widely accepted definition of ULF range, the decision of using narrower frequency ranges within the aforementioned range is typically practiced by previous studies. To add the arbitrariness, different frequency ranges were used by different studies, each has successfully predicted past earthquake events. However, the decisions to choose particular frequency range are often made without unambiguous justifications.

In this paper, we review several ULF ranges adopted by previous studies which appeared to be effective in predicting earthquake occurrences. The relationship between each used frequency range with its respective earthquake parameters will be investigated. Ultimately, the aim is to determine either it is case-by-case basis or there is an optimum frequency range. The included past studies will be listed in later section.

2. ULF for earthquake prediction

To achieve reliable earthquake prediction, it is important to identify the characteristics of electromagnetic emission produced during earthquake preparation phase. ULF is proven to be the best candidate due to its properties of having high skin depth and gets less attenuated. This allows for greater penetration into the Earth crust thus increasing the possibility of eventually being detected on the ground [6]. Moreover, ULF is less likely to be contaminated thus clear signal can be identified as probable earthquake precursor. The "official" frequency range of ULF is rather wider, that is anything below 3 Hz [7]. However, frequency below 0.01 Hz is identified to be quasi-DC while measuring instruments exhibit less sensitivity for frequency range of ULF for earthquake prediction purpose [6–14].

Prattes et al. (2008 & 2011) and Li et al. (2011) [12, 14, 15] suggest the use of skin depth effect relationship to predetermine the effective ULF frequency range. The effect is described by the formula as follows:

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}} \tag{1}$$

where δ is the hypocentral depth, μ is the magnetic permeability, ρ is the resistivity and ω is the angular frequency, where $\omega = 2\pi f$. From the relationship, frequency, f is inversely proportional to the square of depth, δ . Therefore, lower frequency ULF emission is expected to have higher chance of being detected from deeper lithospheric region. Moreover, this study hypothesizes that effective ULF frequency range used for earthquake prediction has inverse relationship with earthquake depth. This hypothesis will be empirically tested using results obtained from previous studies as presented in subsequent sections.

3. Studied ULF frequency ranges

This study describes the chosen effective ULF frequency ranges by prior studies and their findings in this section. 18 studies are reviewed which cumulatively present 26 individual earthquake events. To the best of our knowledge, all past studies which adopted similar signal processing methods are included in this paper to avoid biased findings. Table 1 lists included prior studies with several relevant

parameters of studied earthquakes. Note that for studies with multiple earthquakes, each earthquake parameter is arranged in orderly manner. Besides that, it is also important to mention that some studies used single-value frequency while others used a range of frequency.

Table 1. List of prior studies on earthquake prediction with relevant earthquake parameters. Dash	1 (-)
symbol indicates the detail is not stated in the study.	

Prior study	Location (Year)	Magnitude(s)	Depth(s) (km)	Epicentral distance(s) (km)	Frequency range (Hz)
Armansyah & Ahadi (2017) [16]	Papua Island, Indonesia, (2013 – 2014)	4.1, 4.5, 4.0	10, 10, 12	26, 13, 16	0.022
Ahadi et al. (2014) [17]	Sumatra, Indonesia (2012)	5.7, 6.1	-	233, 442	0.022
Febriani et al. (2014) [18]	West Java, Indonesia (2009)	7.5	57	135	0.007 - 0.013
Kanata et al. (2014) [19]	Tohoku, Japan (2011)	9.0	30	301	0.001 - 0.1
Takla et al. (2013) [20]	Tohoku, Japan (2011)	9.0	24	80	0.022 - 0.1
Takla et al. (2012) [21]	Pisco, Peru (2007)	8.0	39	180	0.022 - 0.1
Hirano & Hattori (2011) [22]	Iwate-Miyagi Nairiku, Japan (2008)	7.2	8	47	0.096
Li et al. (2011) [14]	Kashi & Wenan, China (2003 & 2006)	5.9, 5.9, 5.1	15, 15, 15	120, 137, 53	0.05 - 0.15
Prattes et al. (2011) [12]	L'Aquila, Italy (2009)	6.3	10	5	0.01 - 0.015
Dudkin et al. (2010) [23]	Koyna-Warna, India (2006)	4.7, 4.2	3.9, 5.1	25, 40	0.01 - 0.03
Masci et al. (2009) [24]	L'Aquila, Italy (2007)	4.0, 3.9	16, 8	23, 29	0.007 – 0.013
Saroso et al. (2009) [25]	Sumatra, Indonesia (2004 & 2005)	9.0, 8.7	30, 30	620, 439	0.03
Yumoto et al. (2009) [26]	Kushiro, Japan (1999)	6.4	104	61	0.022 - 0.1
Ida et al. (2008) [27]	Kashi, China (2003)	6.1	10	116	0.01
Prattes et al. (2008) [15]	Bovec, Slovenia (2004)	5.5	6	153	0.02 - 0.1
Molchanov et al. (2003) [28]	Kamchatka, Russia (2001)	6.2	-	-	0.01-0.03
Akinaga et al. (2001) [29]	Chi-Chi, Taiwan (1999)	7.6	11	120	0.007 - 0.013
Hayakawa et al. (1996) [5]	Guam Island, USA (1993)	7.1	60	65	0.01 - 0.05

4. Relationships between frequency ranges and earthquake parameters

In this section, the relationships, or lack thereof between effective ULF frequency ranges and earthquake parameters are presented. Figure 1 - 3 illustrate the effective frequency ranges used by previous studies based on the earthquake magnitudes, depths and epicentral distances respectively.



Figure 1. Effective ULF frequency range against earthquake magnitude, plotted using distinct colors to indicate different studies.



Figure 2. Effective ULF frequency range against depth, plotted using distinct colors to indicate different studies.



Figure 3. Effective ULF frequency range against epicentral distance, plotted using distinct colors to indicate different studies.

From figure 1, it is shown that earthquakes with varying magnitudes have been predicted with almost similar rate. This is due to the fact that larger earthquakes which occur less frequently have higher chance to be predicted. Meanwhile, weaker earthquakes which happen more often have lower chance to be predicted [10]. These attributes contribute to the near similar rate of prediction across magnitudes. From figure 2 and 3, plots are skewed more towards the left side, which correspond to shallower depths and shorter epicentral distances respectively. Shallower earthquakes have higher possibility of being predicted due to shorter distance needed for seismogenic emission to travel to the ground. Shorter distance causes less attenuation on the emission thus producing stronger anomalous signal for more effective prediction. Similarly, earthquakes with shorter epicentral distances, i.e. distance between earthquake epicenter and magnetometer station, have higher chance to be predicted [10].

Through eyeball observation, there is no apparent correlation between effective ULF frequency ranges with magnitudes, depths and epicentral distances in figure 1, 2 and 3 respectively. To study the correlation statistically, this study performed linear regression analysis and found negligibly small correlations between effective ULF frequency ranges with all three parameters. R^2 value for each parameter is shown in table 2.

Table 2. R^2 value for earthquake parameters

Parameter	R^2 value
Magnitude	0.0380
Depth	0.0048
Epicentral distance	0.0007

Hence, it is implied that there is no clear correlation between chosen ULF frequency ranges by prior studies with any of earthquake parameter namely magnitude, depth and epicentral distance.

5. Optimum frequency range

In order to determine whether there exists an optimal effective ULF frequency range for predicting earthquake, the percentage of success for each frequency interval, Δf with 0.01 Hz increment, from 0.01 Hz to 0.15 Hz is calculated. For single-value frequencies, the original value is rounded off to the nearest 0.01 and is taken it as it is. For example, 0.022 Hz is categorized into 0.02 Hz interval. Meanwhile, for ranging frequencies, both upper and lower limits are rounded off and all values between the two extremes, for every 0.01 Hz increment are taken. For example, for frequency range of 0.022 – 0.5 Hz, the values included are 0.02, 0.03, 0.04, 0.05 and 0.06 Hz. Next, the percentage of success is calculated by the following formula:

Percentage of success (%) =
$$\frac{\text{Number of successes}}{\text{Total successes}} \times 100\%$$
 (2)

The results are shown in the bar plot in figure 4. $\Delta f = 0.02$ Hz (representing 0.02 – 0.029 Hz range) has the highest percentage of success (39.3%), followed by $\Delta f = 0.03$ and $\Delta f = 0.06$ Hz (representing 0.03 – 0.039 and 0.06 – 0.069 Hz ranges respectively) with almost equal percentage of ~23%. Other frequency ranges especially those having higher values ($\Delta f > 0.06$ Hz) exhibit far lower percentage of successes. Hence, this study suggests that lower frequency ranges, i.e. around 0.02 – 0.03 Hz and 0.06 Hz are optimum ULF frequency ranges for the purpose of earthquake prediction.



Figure 4. Percentage of success against ULF frequency range.

6. Conclusion and recommendation

In this paper, we reviewed several frequency ranges used by prior studies in predicting upcoming earthquakes. The regression analysis and relationship plots reveal no significant correlation between any earthquake parameter with effective ULF frequency ranges. This is contradictory to the hypothesis we stated before where effective ULF frequency has inverse relationship with hypocentral depth. It is determined that frequencies around 0.02 - 0.03 Hz and 0.06 Hz to be optimal for detecting earthquakes, deduced from the percentage of success calculated. To arrive at more definitive conclusion, a study which examines outputs from using multiple frequency ranges in various earthquake events is recommended. The predictions should be evaluated not only in term of successfulness or the presence of precursor, but also the reliability, indicated by the anomaly strength or amplitude to better determine the correlation.

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