[SSC21-WKV-08]

Design and Development of Prelude, Satellite for Seismic Precedence Detection and Verification Using VLF Radio Waves for Navigation Obtained in Orbit

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ABSTRACT

In this study, we analyzed the ionospheric anomaly in the D region, which precedes the occurrence of earthquakes, by focusing on the VLF radio wave for navigation, which is used for military communication, among the observation data of the earth observation satellite DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions). We analyzed the ionospheric anomaly in the D region that occurs prior to an earthquake. Next, based on the results, we propose the design of a 6U nano-satellite dedicated to the detection of earthquake precursory phenomena using navigational VLF radio waves: Prelude (Precursory electric field observation CubeSat demonstrator). The design of Prelude (Precursory electric field observation CubeSat demonstrator) is proposed.

In a previous study, the authors of *Němec*, Kamogawa et al. attributed this decrease in intensity to an increase in electron density in the D region. Kamogawa et al. attributed this decrease to an increase in electron density in the D region. Based on these results, our proposed satellite mission will be to observe ionospheric anomalies in the D-region that precede earthquakes for the purpose of short-term earthquake prediction in the future.

Němec et al. and Kamogawa et al. have studied the variation of electron density in the D region by analyzing the radio waves generated by lightning. However, the accuracy of this method is limited for the following three reasons: 1) the frequency of lightning is different depending on the season, 2) the frequency range of lightning is wider than that of thunderstorms, and 3) there are dispersion characteristics of radio waves due to ionospheric plasma. Therefore, in this study, we focused on the variation of electron density in the D region by focusing on the VLF charged wave for navigation, which has a constant frequency, continuous transmission, and temporal and spatial continuity. As a case study analysis, we confirmed the validity of the analysis of navigational VLF waves by focusing on the earthquake in southern Sumatra.

The results show that the navigational VLF signal intensity decreases significantly before the earthquake compared to the trajectories in the comparison counties. This suggests that the effects of ionospheric fluctuations shown by *Němec* In addition, we found that the VLF radio wave strength of Prelude was significantly reduced before the earthquake. Furthermore, this study showed the effectiveness of navigational VLF radio waves as a new analysis target for Prelude's mission analysis. Therefore, we considered that there is a room to introduce a flexible system for the design and development of the science mission during the design and development of this satellite by using Systems Modeling.

BACKGROUND

We are currently workingona6U earth science satellite Cube Sat, Prelude (Precursory electric field observation CubeSat demonstrator). This satellite is designed to observe the VLF wave intensity decrease prior to earthquakes in the ionosphere, which has been statistically superior to the DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) satellite launched by the French Space Research Center (CNES). It is a nano-satellite, Prelude (Precursory electric field observation CubeSat demonstrator), which specializes in elucidating the physical mechanism of VLF wave intensity reduction prior to earthquakes in the ionosphere.

Fig. 1 shows the outline drawing of the satellite. Fig. 2 shows an overview of the mission design. The electrodes at the end of the two booms shown in Fig. 1 will acquire electric field data in the ionosphere and observe the decrease in the electric field strength of the VLF charged wave, which may be a leading phenomenon. In addition, the GNSS receiver mounted inside the satellite will be used to acquire TEC (Total Electron Content) to observe the state of electron density around the F region of the ionosphere.

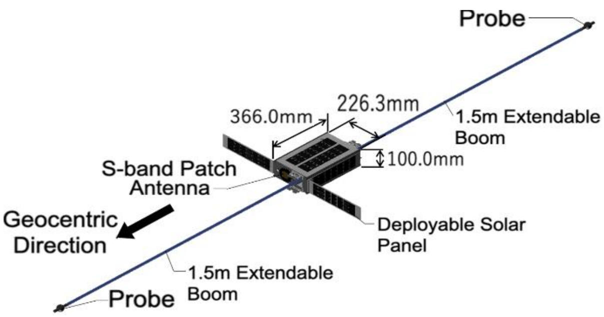

Fig. 1: Prelude (Precursory electric field observation CubeSat demonstrator)

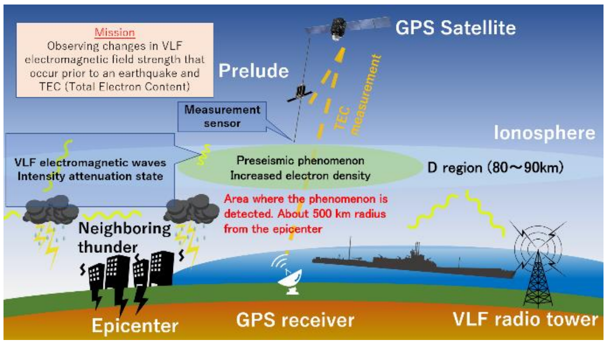

Fig. 2: Misson Overview

As shown in Fig. 2, the Prelude satellite will perform the following missions within a 500 km radius around the epicenter.

① Observe fluctuations in the VLF electric field strength that precede earthquakes.

(2) Observation of TEC changes that precede an earthquake

In addition, we are considering the following three goals for this satellite to be achieved in the future.

A. Statistical evaluation and detection of seismic precursors

(i) Measure and statistically evaluate the VLF band radio waves that can be used to determine whether or not there is an anomaly before an earthquake.

(ii) Using the acquired data, determine the leading phenomena on the trajectory using machine learning technology, and downlink the warning information.

B. Development of an on-orbit experimental platform: CubeSat will facilitate future research on seismic precursors, disasters such as tsunamis, and space weather.

(i) To build an on-orbit platform for researchers and engineers in universities and companies.

(ii) By expressing not only the satellite itself, but also the satellite design information in a system design language, we aim to achieve global probabilistic earthquake prediction by using 12 satellites of the same type to cover the entire globe at all times and by collaborating with ground observations.

C. Dissemination of satellite observation technology: In order to publicize the observation of seismic precursors using nano-satellites, on-orbit observation data (data, camera images, etc.) will be released and publicized on the web page.

We are planning to contribute to society by reducing human suffering through earthquake prediction and warning, with a view to announcing the usefulness of satellites. In this study, we will focus on VLF radio waves for ships in order to "measure and statistically evaluate VLF band radio waves that can be used to judge whether or not there is an anomaly before an earthquake", and show the usefulness of the analysis. In addition, we will design a mission to acquire the VLF radio waves for navigation in orbit.

PREVIOUS RESEARCH

DEMETER, the original instrument of the Prelude project, was launched on June 29, 2004 for the purpose of seismo-electromagnetic observation and observation of the Earth's electromagnetic environment, and operated for about six years until the end of 2010. During this period, about 9,000 earthquakes of magnitude 4.8 or greater occurred globally, which are subject to analysis. *Němec* et al. statistically analyzed the relationship between earthquakes and electromagnetic wave intensity near the satellite orbit using the observation data of the early stage of DEMETER operation (2.5 years). As a result, they reported that within 4 hours before the occurrence of an earthquake of magnitude 4.8 or greater, the nighttime VLF band intensity decreases by more than 3σ (equivalent to about 4-6 dB) around the frequency of 1.7 kHz (Fig. 3)[1]. Six parameters were used as analytical conditions for this phenomenon. By dividing the parameters into time (around 22:30 local time), magnetic latitude (2 [deg]), magnetic longitude (10 [deg]), frequency (10 kHz), and geomagnetic state (quiet; 0 to +1, moderate; +1 to +2, and active; +2 to +2), we found that the seismic frontal change occurs when the epicenter is generally within 3 degrees of the satellite nadir. In addition, we found that the frequency bands of the seismicity decrease significantly. In addition, the frequency band around 1.7 kHz, which is the frequency band that decreases significantly, coincides with the first-order cutoff frequency of the Earth-ionosphere waveguide mode electromagnetic wave propagation at night. It was speculated that this phenomenon may occur when the ionospheric altitude drops and the cutoff frequency changes before an earthquake.

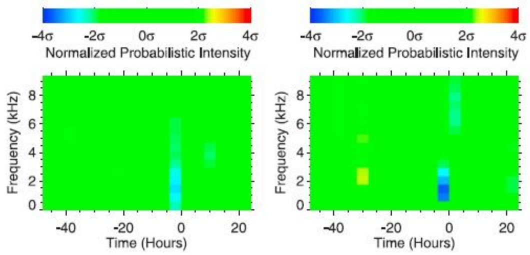

Fig. 3: Decrease in nighttime VLF band electromagnetic wave intensity

Kamogawa et al. hypothesized that the reduced VLF-band electromagnetic waves were not caused by ELF/VLF hiss from the magnetosphere, which is difficult to observe at night, but by the attenuation of electromagnetic waves originating from earth lightning as they propagated through the ionosphere D, E, and F regions. Using on-orbit data from the DEMETER satellite, we attempted to investigate the state of the ionosphere by using Heusler waves, one of the propagation modes of VLF-band electromagnetic waves originating from earth lightning, as a remote sensing tool near the epicenter. In the ionosphere, electromagnetic waves propagating as Heusler modes lose energy due to collisions between electrons and particles, i.e., absorption of radio waves is caused. In the D and E regions, Heusler waves are mainly absorbed by electron-neutral atmosphere collisions, while in the F region, so-called Coulomb collisions, or electron-ion collisions, dominate [3]. Therefore, the amount of absorption can be estimated by the electron density and temperature in the ionosphere of the propagation path, the density of the neutral atmosphere, and the direction and size of the earth's magnetic field lines. The absorption of electromagnetic waves generated by lightning near the epicenter that enter the ionosphere as a Heusler mode is estimated by the following equation (1), and the difference in the absorption compared to the case where the electromagnetic wave is not related to the earthquake is investigated.

$$A = \int_{h_0}^{h_1} \alpha dh \quad , \alpha = \chi \frac{2\pi f}{c} \qquad (1)$$

A is the amount of absorption from altitude h0 to h1, α is the absorption coefficient, and χ is a parameter that determines the refractive index related to absorption. Based on the difference in absorption, we estimated the increase of ionospheric electron density in the region. As a result, it was found that the electron density increased by 20-30% in the D region of the ionosphere when the absorption of electromagnetic waves was 6 dB, as shown in Fig. 4 [4]. However, since the study by Kamogawa et al. was a case study analysis, no statistical correlation was shown as a seismic precedence phenomenon. Therefore, on-orbit data for further statistical analysis is required to elucidate the mechanism of the electron density increase in the D region of the ionosphere.

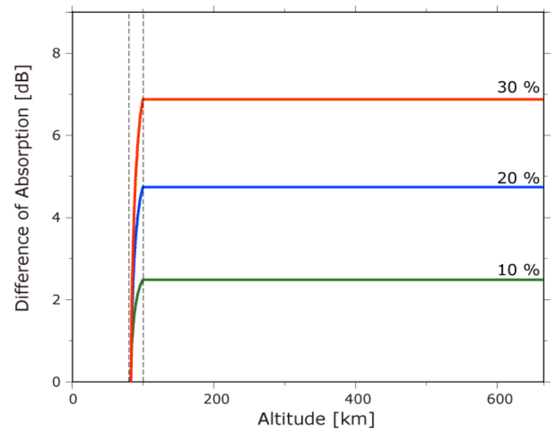

Fig. 4: Difference in the amount of absorption of electromagnetic wave intensity due to the increase in electron density in the ionosphere

However, in the midst of these studies, there are opposing opinions that the variation in the strength of the earth's electric field and the increase in electron density may be caused by other factors. One of the objections is that the magnetosphere was disturbed by space influence and the electric field was also disturbed. Fig. 5 shows the state of the Earth's magnetic field at the time of the DEMETER observation (F10.7). This graph shows that the state of the magnetosphere is stable during the DEMETER observations, so the criticism that it is due to space influence has been resolved. However, the fact that the electromagnetic waves we have been analyzing so far are derived from lightning has led to questions such as, "Isn't lightning itself affecting the electric field? and "Isn't the electron density increasing due to the lightning? There is still no clear answer to these concerns.

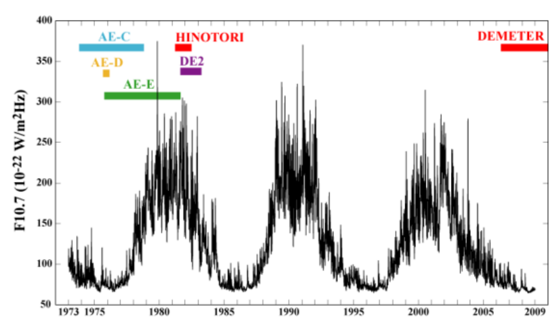

Fig. 5: F10.7 variation & mission periods of satellite

USEFULNESS OF VLF RADIO ANALYSIS FOR NAVIGATION

In this study, we focus on VLF radio waves for navigation, which are used for communication with submarines. In the previous section, we discussed the possibility that lightning itself may affect the electric field, since the electromagnetic waves we have analyzed so far are derived from lightning. Since the electromagnetic waves analyzed so far are derived from lightning, criticisms such as "Isn't lightning itself affecting the electric field? In this study, we have considered such criticisms. In this study, we focus on artificial radio waves emitted from the ground in order to eliminate such possibilities. The advantage of navigational VLF is that it has a specific source and a specific frequency, as shown in Fig. 6. The advantage of VLF radio waves for navigation is that they have a specific source and a specific frequency, as shown in Fig. 6, which makes it possible to clearly identify the target of analysis. In addition, artificial radio waves have a particularly high transmission power and are close to constant, making it easier to visualize the decrease in intensity.

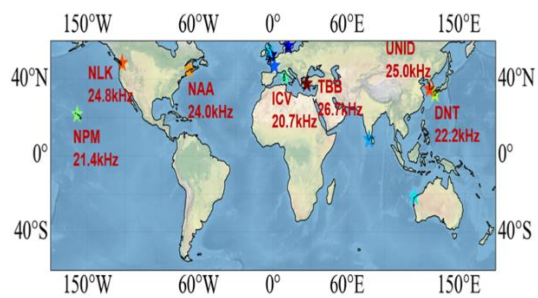

Fig. 6: VLF radio transmission stations around the world .

ANALYSIS DATABASE

In this study, we analyze the data of earthquakes with epicenter depths of 40 km or less and magnitudes of 4.8 or greater that occurred between 2004 and 2010 using the DEMETER satellite. Earthquakes that occurred within 30 km of the epicenter within 30 days of the main shock were defined as aftershocks, and the declustering code provided by the Japan Meteorological Agency (JMA) was used to decluster and analyze only the main shock data [4]. In addition, since it has been reported that the larger the earthquake, the larger the anomaly in the ionospheric fluctuations [5], we chose the earthquake with the largest magnitude as the case for analysis. Therefore, in this study, the southern Sumatra earthquake (M 6.8) that occurred at 16:07:00 on 2010-03-05 was selected for analysis.

Reference orbits for comparison of VLF radio waves for navigation

A reference orbit is selected for comparison with the intensity of navigational VLF radio waves in the seismic orbit (hereinafter referred to as the reference orbit). In this paper, the reference orbit for comparison is the orbit that satisfies the following conditions: magnetic latitude within 3 degrees, magnetic longitude within 3 degrees, kp index of geomagnetic state less than 2+, and within ± 15 days. A total of seven orbits were selected for comparison to the seismic orbit of the South Sumatra earthquake. Fig. 7 shows the positional relationship between the seismic orbit and the reference orbit and the epicenter.

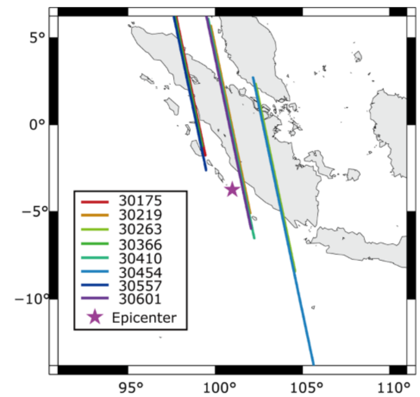

Fig. 7: The positional relationship between the seismic trajectory, the control trajectory, and the epicenter. The numbers in the legend represent track numbers. 30366 is the seismic trajectory.

Navigational VLF radio waves to be analyzed

In this study, we will analyze the changes in the electric field strength of VLF radio waves for navigation. Fig. 8 shows a time series of the electric field strength by frequency of the spectral data obtained by FFT analysis of the electric field data of the DEMETER satellite when it passed through the orbit of 30366, the orbit just before the earthquake.

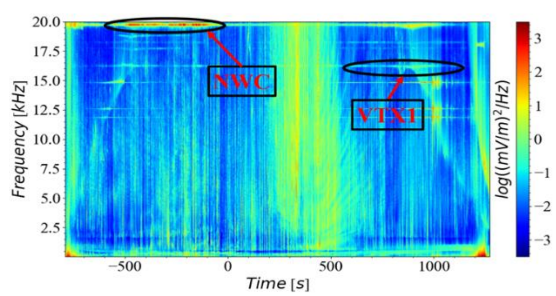

Fig. 8: Spectral time series diagram (Earthquake Orbit)

In this Fig. 8, there is a transmitting station that emits VLF radio waves for navigation near South Sumatra. These stations are NWC (19.8 kHz) in Australia and VTX1 (16.3 kHz) in India. In particular, since the time near the epicenter is 0 [s], we believe that NWC (19.8 kHz) is the most affected by the earthquake front. Therefore, we assume that the NWC (19.8 kHz) is the target of the following analysis.

Analysis process and electric field intensity change

First, the NWC (19.8 kHz) to be analyzed is extracted from Fig. 8. Then, the time series graph of the navigational VLF electric field intensity for orbit number 30366 is shown in Fig. 9.

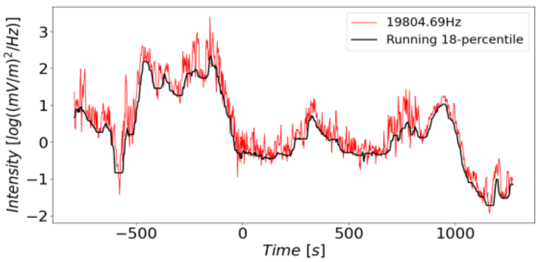

Fig. 9: VLF field strength time series data (Orbit; 30366)

The graph shows a mixture of lightning-derived VLF electric field components (spiky red line) and navigational VLF electric field components (black line) as the main components. In this case, the spike-shaped lightning component in the graph is not necessary to measure the change in the electric field strength for navigation. Therefore, we use a process called moving percentile (see Appendix). When the data are sorted in ascending order, the p percentile (0≤p≤100) is the value that is in the p% of the total, counting from the smallest. When P is a decimal number, the integer part of P is denoted by ρ and the decimal part by r. When the n data are sorted in decreasing order, the ρ and ρ + 1 data are denoted by Kρ and Kρ+1, respectively.

$$P = (n + 1)p/100 \quad (2)$$

$$Z = K\rho + r(K\rho + 1 - K\rho) \quad (3)$$

In this study, the moving percentile value was set to 18% to eliminate spikes. In this study, the spikes were removed by setting this moving percentile value to 18%. This process was then applied to a total of eight orbits, including the comparison reference orbit as shown in Fig. 9.

Analysis results of VLF band radio wave strength for navigation during an earthquake

Of the eight orbits for which the variation of the navig ation radio wave has been obtained, the averages of the electric field strength of the seven orbits for comparison reference are newly created as representative values. Th e variation of the eight orbits and the average of the sev en orbits are superimposed as shown in Fig. 10.

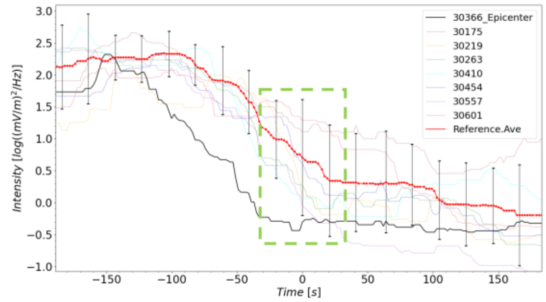

Fig. 10: Fluctuation of VLF radio waves (19.8 kHz) for 8 orbits and the average of the 7 reference tracks

The closest time to the earthquake location in Fig. 10 is 0 s. In this study, the error bars of the mean line in the trajectories to be compared were created, except for trajectory 30366, which is the closest trajectory to the earthquake. This error bar is used to judge the range up to 3σ (99.9%) as no anomaly. Figure 10 shows that around -35[s] to 35[s], only the orbit closest to the epicenter showed a decrease in radio wave intensity that was outside the 3σ range near the epicenter. Therefore, the statistical results of $N\check{e}mec$ Therefore, it is possible to detect anomalies by analyzing VLF radio waves for navigation in this study. As a quantitative evaluation, the electric field strength of the seismic trajectory was calculated as I_E As a quantitative evaluation, the electric field strength of the seismic trajectory was calculated as I_R The average electric field strength of the reference is $\bar{I}_R$ The average electric field strength of the reference is The amount of decrease in the electric field strength of the seismic trajectory ΔI is

$$\Delta I = I_R - I_E \quad (4)$$

$$\Delta I = \bar{I}_R - I_E \quad (5)$$

Equation (4) shows how the time series changes. In equation (4), the difference between the electric field strength at 19.8 kHz (NWC) of each comparison reference and the seismic orbit shows how the time series is changing. Using equation (5), we can see how much the radio intensity of the closest orbit to the earthquake has decreased when compared to the orbit with no anomaly, by taking the difference from the comparison value. Therefore, using Equation (4) and Equation (5), the difference of the electric field strength in the closest orbit at the time of the earthquake from the comparison reference orbit and the average line is shown in Table 1.

Table 1: Electric field strength reduction amount of the VLF (NWC: 19.8 kHz) radio waves (Earthquake Orbit)

Orbit Number	Universal time nearest the epicenter	Day of Year	I	ΔI
30366	2010/3/5 15:07:47.729	64	-0.2662	
30175	2010/2/20 15:08:17.707	51	1.1288	1.3950
30219	2010/2/23 15:00:14.645	54	0.2763	0.5425
30263	2010/2/26 14:52:48.677	57	0.6250	0.8912
30410	2010/3/8 15:00:17.179	67	0.0147	0.2809
30454	2010/3/11 14:52:49.38	70	0.5379	0.8041
30557	2010/3/18 15:07:43.330	77	0.0438	0.3100
30601	2010/3/21 15:00:17.876	80	1.2837	1.5499
Reference Average			0.8963	1.1625

It can be seen that the average line of the comparison object is 1.1625 larger than the electric field strength of the seismic orbit. The difference with the other comparison orbits also quantitatively shows that the electric field strength of the seismic orbit is lower. These results indicate that navigational VLF signals may be affected by the ionospheric anomaly that occurs before an earthquake. In addition, it was found that the intensity of the navigational VLF radio wave was affected by the ionospheric anomaly, and the electric field intensity decreased by about 1.1625[ ].log$[(mV/m)^2/Hz]$ In addition, it was found that the strength of the navigational VLF radio waves was affected by ionospheric fluctuations, and the electric field strength decreased by about 1.1625 $[\log[(mV/m)^2/Hz]]$.

NEW MISSION ANALYSIS FOR PRELUDE

The results of our analysis suggest that it is worthwhile to analyze navigational radio waves. Next, we show that Prelude can analyze both navigational VLF and lightning electromagnetic data.

Prelude mission data

The Prelude mission data consists of four main components. Figure 11 shows the structure of the Prelude mission data, where the survey mode is the analysis of the data recorded 4 hours before the nighttime earthquake. The frequency resolution of the spectrum is 1024 points, and the time resolution is 1 Hz. Burst Mode is the raw data. Burst Mode is raw data, which is on-orbit data for one orbit per day for earthquakes of magnitude 4.8 or greater within 5° latitude and longitude of the earthquake site. The timing of this observation is always during the night. (Survey Mode and Burst Mode are collectively referred to as EFP (Electric field probe). GTO (GNSS TEC observation) obtains TEC (Total electron content) data in the D region from GNSS satellites, and EDP (Electron density and temperature probe) observes electron density and electron temperature around the satellite. HK (House keeping) is the data obtained by monitoring the health of the satellite. These data are assumed to be downlinked at a data rate of 1 Mbps. If the downlink volume is 70 Mbytes, the downlink time is 560[s]. When the satellite altitude is 600[km], the maximum communication time is 562.6[s]. However, since it is usually sufficient to downlink only the necessary data, the communication time is less than 560[s]. Therefore, we believe that it is possible to operate a satellite in a low orbit.

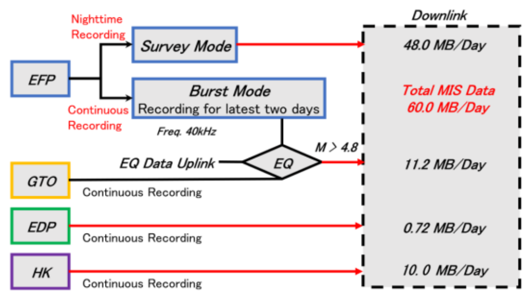

Fig. 11: In traditional Observation flow and Amount of mission data of the Prelude mission design

Proposal for Mission Design

The conventional design of Prelude assumes the analysis of electromagnetic data of lightning. As shown in Figure 11, the analysis data is 48.0 [Mbyte/day]. The frequency range at this time is 20 kHz. The analysis data has a frequency resolution of 1024 (one point; 19.53 Hz). The electromagnetic waves of lightning range from a few Hz to several tens of kHz. Therefore, when analyzing the data, the raw data is subjected to FFT analysis and the 20 kHz portion is processed. On the other hand, the frequency bandwidth of the VLF radio wave for navigation is 100 Hz. The analysis of the VLF radio wave for navigation is simply a matter of extracting the specified frequency from the lightning analysis results. Therefore, we believe that it does not affect the maximum amount of mission data. Therefore, this research can be incorporated into the design of the Prelude mission as a new analysis target.

CONCLUSION

In this study, we showed that the intensity of the navigational VLF radio wave decreased by more than 3σ in the closest orbit before the earthquake. Therefore, we thought that the changes in the ionosphere that are expected to occur before an earthquake could be captured by navigational radio waves. In addition, since the VLF radio wave does not affect the amount of mission data, we thought that it could be incorporated into the analysis.

Acknowledgements

This study was funded by Earthquake Res., Inst., the University of Tokyo, Joint Research program 2020-KOBO09. This study is also supported by WNI foundation.

Future Issues

In the space environment, it is necessary to design with the real environment in mind because repairs are not possible. Therefore, it is necessary to model the mission considering not only the mission data but also the actual operation in the future development.

This study is a temporary example analysis. Therefore, it is necessary to confirm statistically that the intensity of VLF radio waves for navigation is reduced by earthquakes. Then, it is necessary to derive the anomaly, detection rate, and earthquake occurrence rate of the VLF radio wave for navigation. Finally, since we are aiming at a new earthquake prediction and warning system by using satellite swarms, there is room to consider how to transmit prediction and warning messages and how to reduce earthquake damage.

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