MAGDAS project and its application for space weather

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Abstract. We introduce a real-time MAGnetic Data Acquisition System of Circum-pan Pacific Magnetometer Network, i.e. MAGDAS/CPMN for space weather study and application, and its preliminary results. By using this system, we will conduct real-time monitoring and modeling of (1) global 3-dimensional current system, (2) plasma mass density, and (3) penetrating process of polar electric fields into the equatorial ionosphere, in order to understand electromagnetic and plasma environment changes in the geospace during the period of ILWS/CAWSES/IHY.

Index Terms. Space weather, MAGDAS, electromagnetic and plasma environment, geospace.

1. Introduction

One purpose of the Solar Terrestrial Physics (STP) research in the twenty-first century is to support human activities from an aspect of fundamental study. The scientific new aim for the STP society is a creation of new physics; (1) couplings of the complex and composite systems and (2) multi-scale couplings in the Sun-Earth system. The goals for the attainment of the purpose are to construct Network Stations for observations and Modeling Stations for simulation/ empirical modeling. In order to understand the Sun-Earth system and its effects to human lives, the international LWS (Living With a Star) and CAWSES (Climate and Weather of Sun-Earth System) programs started from 2004. The International Heliophysical Year (IHY) program is also planned to start in 2007.

For space weather study on the complexity in the Sun-Earth system, the Space Environment Research Center (SERC), Kyushu University started to construct a new ground-based magnetometer network, in cooperation with about 30 organizations in the world from 2004. The SERC will conduct the MAGDAS (MAGnetic Data Acqusition System) observations at 50 stations in the CPMN (Circum-pan Pacific Magnetometer Network) region, and the FM-CW radar observations along the 210° magnetic meridian (see Fig. 1), in order to understand dynamics of plasmaspheric changes during space storms, responses of magnetosphere-ionosphere-thermosphere to various solar wind changes, and penetration mechanisms of DP2-ULF range disturbances from the solar wind region into the equatorial ionosphere.

On the other hand, electromagnetic phenomena, e.g., ULF, ELF and VLF waves are recognized as useful diagnostic probes of the solar wind-magnetosphere-ionosphere-atmosphere coupled system for space weather studies. These waves convey information about the dynamics and morphology of the coupled system.

In the present paper, at the first we will introduce our real-time data acquisition and analysis system of MAGDAS/CPMN, and preliminary results obtained by this system; (1) monitoring of the global 3-dimensional current system to know the electromagnetic coupling of high-latitude and Sq current systems, and (2) monitoring of the plasma mass density in geo-space to understand plasma environment change during storms. In the second, we will show the FM-CW radar system at L=1.26 to deduce electric field from the ionospheric plasma Doppler velocity. From 24hr monitoring of the ionospheric drift velocity with 10-sec sampling rate by the FM-CW radar observation, (3) we can understand how the polar electric field penetrates into the equatorial ionosphere.

2. MAGDAS/CPMN system

The Circum-pan Pacific Magnetometer Network (CPMN) was constructed by Kyushu University in collaborations with about 30 international organizations along the 210° magnetic meridian and the magnetic equator during the international Solar Terrestrial Energy Program (STEP) period (1990-1997) (see Yumoto and CPMN group, 2001). The 1-sec magnetic field data from the coordinated ground-based network made it possible to (1) study magnetospheric processes by distinguishing between temporal changes and spatial variations in the phenomena, (2) clarify global structures and propagation characteristics of magnetospheric variations from higher to equatorial latitudes, and (3) understand global generation mechanisms of the Solar-Terrestrial phenomena (see Yumoto, 2004, Yumoto and 210° MM group, 1995 and 1996).

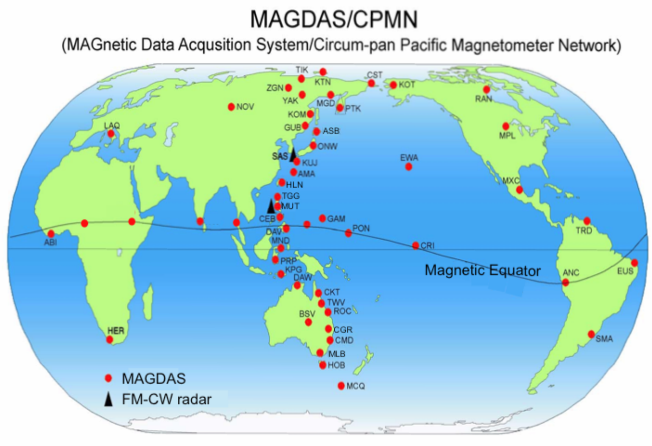

Fig. 1. MAGDAS/CPMN (MAGnetic Data Acquisition System/Circum-pan Pacific Magnetometer Network) system of the SERC, Kyushu University.

For space weather study and application, the Kyushu University group is now re-constructing a new real-time MAGDAS (MAGnetic Data Acquisition System) in the CPMN region, and the FM-CW radar network along the 210° magnetic meridian. New 50 fluxgate-type magneto-meters as shown in Fig. 2 and their data acquisition system from overseas sites to Japan are being deployed by the SERC, Kyushu University from 2005. The new magnetometer system consists of 3-axial ring-core (amorphous metallic alloys) sensors, fluxgate-type magnetometer, data logging/transferring unit, and power unit. Magnetic field digital data ($H+\delta H$, $D+\delta D$, $Z+\delta Z$, $F+\delta F$) are obtained with the sampling rate of 1/16 seconds, and then the averaged data are transferred from the overseas stations to the SERC, Japan in real time. The ambient magnetic field, expressed by horizontal (H), declination (D), and vertical (Z) components, are digitized by using the field-canceling coils for the dynamic range of ±64,000nT/16bit. The magnetic variations (δH, δD, δZ) subtracted from the ambient field components (H, D, Z) are further digitized by a 16-bit A/D converter. Three observation ranges of ±2,000nT, ±1,000 nT, and ± 300 nT can be selected for high, middle, and low-latitude stations, respectively. The total field ($F+\delta F$) is estimated from the $H+\delta H$, $D+\delta D$, and $Z+\delta Z$ components. The resolutions of MAGDAS data are 0.061 nT/LSB, 0.031 nT/LSB, and 0.0091 nT/LSB for ±2,000 nT, ±1,000 nT, and ±300 nT range, respectively. The estimated noise level of the MAGDAS magnetometers is 0.02 nTp-p. The long-term inclinations (I) of the sensor axes can be measured by two tiltmeters with 0.2 arc-sec resolution. The temperature (T) inside the sensor bloc is also measured. The GPS signals are received to adjust the standard time inside the data logger/transfer unit. These data are logging in the Compact Flash Memory Card of 1 GB. The total weight of the MAGDAS magnetometer system is less than 15 kg. The sensitivity, efficiency, capacity, and performance of the MAGDAS systems are tested until the end of March, 2005. After April, 2005, 20 of the new MAGDAS magnetometers were installed at (and/or near) the CPMN stations in 2005.

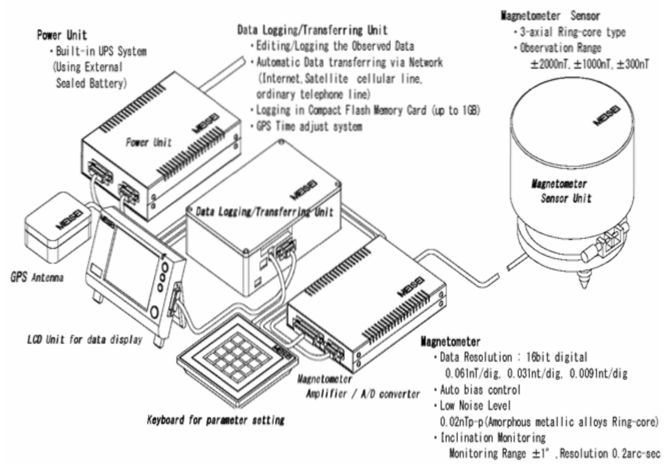

Fig. 2. The component of MAGDAS/CPMN magneto-meter system for real-time data acquisition.

Every day, the data logger at an overseas site generates a file containing averaged 1-sec magnetic data (H, D, Z, F) and a file containing the averaged 1-min magnetic data and inclination and temperature data (I, T) of the magnetometer sensor. The file size of the 1-sec data is less than 1MB. The file size of the 1-min data is less than 50KB. If the communication line at the site does not allow a fast-enough connection, the data logger sends only the 1-min file to the SERC every day; if the connection is fast enough, the data logger sends both the 1-min file and the 1-sec file to the SERC every day. In fact, the data transfer does not have to be on a daily basis: That is, the data-transfer interval can be set to any value between 10 minutes and 1 day, depending on the condition of the following communication lines. The MAGDAS data can be transferred from the overseas stations to the SERC, Japan, by using three possible ways;

A) Special line for INTERNET
If the data logger of MAGDAS at overseas sites can be connected to a special line for INTERNET (via a Switch, HUB, or Router of INTERNET), the data logger uses software called "SSH client" or "FTP client" to automatically establish an INTERNET connection to the SERC, Kyushu University, Japan. Then, the data logger at the sites automatically transfers the MAGDAS magnetometer data to the SERC.

B) Telephone line
If the above A) is impossible but if the data logger of MAGDAS at overseas sites can be connected to a telephone line, the data logger uses it, automatically dials up to a PPP server at the SERC, establishes a connection, and sends the data to the SERC.

C) Satellite telephone line
If the above A) and B) are both impossible, the data logger of MAGDAS at overseas sites uses a satellite-mobile-phone system, automatically dials up to a PPP server at the SERC, establishes a connection, and sends the data to the SERC.

3. Scientific objectives and preliminary results

In order to establish the space weather studies, we have to clarify dynamics of geospace plasma changes during magnetic storms and auroral substorms, the electro-magnetic response of iono-magnetosphere to various solar wind changes, and the penetration and propagation mechanisms of DP2-ULF range disturbances from the solar wind region into the equatorial ionosphere. Figure 3 shows one example of amplitude-time records of 3-component ordinary (upper) and induction-type (bottom) magnetograms observed at the Kujyu station in Oita, Japan, during 24 hrs. The ordinary data (i.e. MAGDAS data (1)) can be used for studies of long-term variations, e.g. magnetic storm, auroral substorms, Sq, etc., while the induction-type data (i.e. MAGDAS data (2)) will be useful for studies of ULF waves, transient and impulsive phenomena. By using these new MAGDAS data, we can conduct a real-time monitoring and modeling of (1) the global 3-dimensional current system and (2) the ambient plasma density for understanding the electromagnetic and plasma environment changes in the geospace.

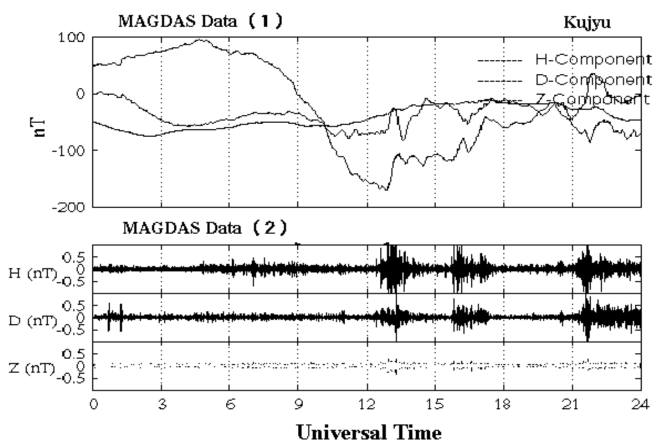

Fig. 3. An example of amplitude-time records of ordinary (upper; MAGDAS data (1)) and induction-type (bottom; MAGDAS data (2)) variations observed at the Kujyu station.

In 2005, MAGDAS magnetometers were installed at 20 stations along the 210° magnetic meridian. After 2005, 30 MAGDAS magnetometers will be installed along the magnetic equator and in Siberia. Figure 4 shows one example of H-component amplitude-time records observed at the MAGDAS stations (ASB, ONW KUJ, AMA in Japan, HLN in Taiwan, MUT, CEB, DAV in Philippines, MND, and PRP in Indonesia, DAW, CGR, CMD, HOB in Australia) during two days of November 10-11, 2005. We can see clear equatorial enhancements near the magnetic equator at DAV, and global nature of si¯, DP-2, and substorm-associated variations.

3.1. Global 3-D current system

The left panel of Figure 5 indicates the ionospheric equivalent current pattern obtained from the CPMN stations along the 210° magnetic meridian during a northern summer. Each ionospheric current vector was estimated by the horizontal magnetic fields observed at each CPMN station at every hour. We will make the ionospheric equivalent current pattern every day using the MAGDAS data (1) as shown in Figs. 3

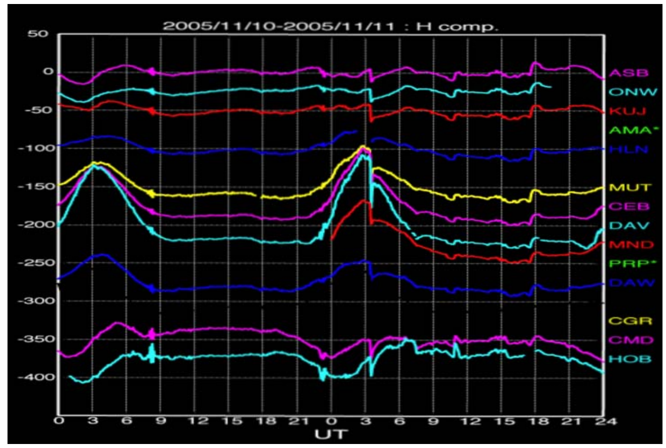

Fig. 4. H-component amplitude-time records observed at the MAGDAS stations (ASB, ONW KUJ, AMA in Japan, HLN in Taiwan, MUT, CEB, DAV in Philippines, MND, and PRP in Indonesia, DAW, CGR, CMD, HOB in Australia) during two days of November 10-11, 2005.

and 4. The right panel of Fig. 5 shows the global 3-dimensional currents and electric potential, with the currents illustrated by ribbons and the potential with + and – (Richmond and Thayer, 2000). At high latitudes the ionospheric currents are joined with **f**ield-**a**ligned **c**urrents (FAC) from the solar wind region into the magnetosphere, and the electro-dynamics is dominated by the influences of solar wind-magnetosphere interaction processes. The total current flows is of the order of 10^7 A. On the other hand, the ionospheric current at middle and low latitudes is generated by the ionospheric wind dynamo, which produces global current vortices on the dayside ionosphere, i.e., counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. The total current flow in each vortex is order of 10^5 A.

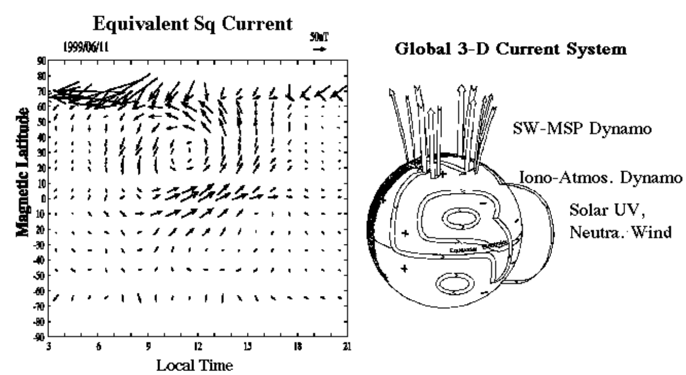

Fig. 5. (Left) The ionospheric equivalent current pattern obtained from the MAGDAS/CPMN data. (Right) Global 3-dimensional current system cased by magneto-spheric field-aligned currents at high latitude and the ionospheric dynamo at middle and low latitudes.

There are strong electric fields at high latitudes, on the order of several tens of millivolts per meter or more depending on the magnetic activity. At middle and low latitudes electric fields are considerably smaller, typically a few millivolts per meter during magnetically quiet periods. During magnetic active periods the part of strong electric fields at high latitude can penetrate into middle and low latitudes, and then the global ionospheric current pattern must be re-organized strongly. In reality the current and electric fields at all latitudes are coupled, although those at high, and middle and low latitudes have been often considered separately. By using the MAGDAS ionospheric current pattern as shown in the left panel of Figure 5, the global electromagnetic coupling processes at all latitudes will be clarified during the ILWS/CAWSES/ IHY period (see Yoshikawa et al., 2003).

Fig. 6(A) shows equivalent ionospheric current patterns obtained from the MAGDAS Data (1) on September 25, 2005 (Kohta et al., 2005). The vertical axis indicates magnetic latitudes of the MAGDAS stations, and the horizontal axis is the local time of the 210^o magnetic meridian stations. The arrows indicate the current vectors obtained from the H and D components, and the color code indicates the negative and positive magnetic Z component. The equatorial electrojet can be seen at the dayside dip equator. There are twin vortices of Sq current, i.e., counter-clockwise and clockwise in the northern and southern hemisphere, respectively. The centers of Sq current patterns are sometime not consistent with the maximum and minimum points of the Z component. Fig. 6(B) is one example of Sq equivalent current pattern obtained by the CPMN data on July 15, 2000, during a disturbed day. The vertical axis indicates geographic latitudes of the CPMN stations, and the horizontal axis is the local time of the 210^o magnetic meridian stations. A clear Sq current vortex, equatorial electrojet, auroral electrojet, and ring current patterns can be identified in the figure. It is newly found a current flowing from the northern hemisphere into the southern hemisphere around 06 hr local time during magnetic storm.

3.2. Plasma mass density

The field line resonance (FLR) oscillations in the Earth's magnetosphere are excited by external source waves, and are so-called as ultra low frequency (ULF) waves (cf. Yumoto, 1988). The amplitude of H-component magnetic variations observed at the ground stations reaches a maximum at the resonant point, and that its phase jumps by 180 degrees across the resonant point (see Yumoto, 1985). The eigen-frequency of FLR oscillations is dependent upon the ambient plasma density and the magnetic field intensity in the region of geospace threaded by the field line, and the length of the line of force as shown in Figure 7. When we observe the eigen-frequency of FLR and assume models for the latitude profiles of the magnetic field and the plasma density (with the equatorial density as a free parameter), we can estimate the plasma mass density in the magnetosphere. Therefore, the FLR oscillations are useful for monitoring temporal and spatial variations in the magnetospheric plasma density. By using ground-based network observations, we can identify the FLR phenomena and measure the fundamental field-line eigen-frequency by applying the dual-station H-power ratio method (Baransky et al., 1985) and the cross-phase method (Baransky et al., 1989, Waters et al., 1991), which have been established to identify the FLR properties.

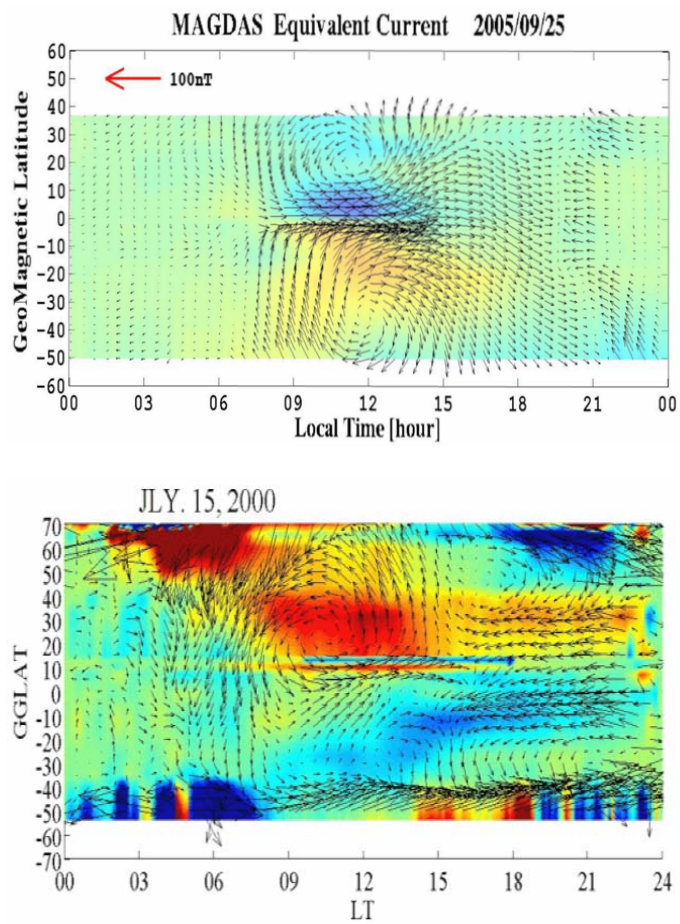

Fig. 6 (A) & (B). MAGDAS Sq current pattern on September 5, 2005 during magnetic quiet day (top), while CPMN Sq current pattern on July 15, 2000 during magnetic disturbed day (bottom) (Kohta et al., 2005).

We will install new MAGDAS magnetometers at several pair stations along the 210° magnetic meridian, and observe magnetic FLR pulsations. Each pair stations are separated in latitude by ~100 km. The MAGDAS data (2) as shown in Fig. 3 will be analyzed by using the two methods, i.e., the amplitude-ratio method and the cross-phase method. As a result, we can identify the FLR events and measure their eigen-frequencies, providing the plasma mass density varying with time.

By using these methods, Takasaki et al. (2006) discussed temporary variations of the plasma mass density during magnetic storm. From ground-based observations at L~1.4 they found a significant decrease in the FLR frequency at during a large magnetic storm as shown in Fig. 8. During 28 - 31 October, 2003, a series of coronal mass ejections hit the magnetosphere and triggered two consecutive large storms. Three ground magnetometers at L = 1.32~1.41 recorded field-line resonances (FLRs) during this interval. The FLR frequencies decreased from 0600 LT on 31 October 2003 during in the main phase of the second storm until 12 LT when the recovery phase of this storm began. After the decrease, the FLR frequencies increased to its value before the storm started at 0600 LT on 31 October in a few hours.

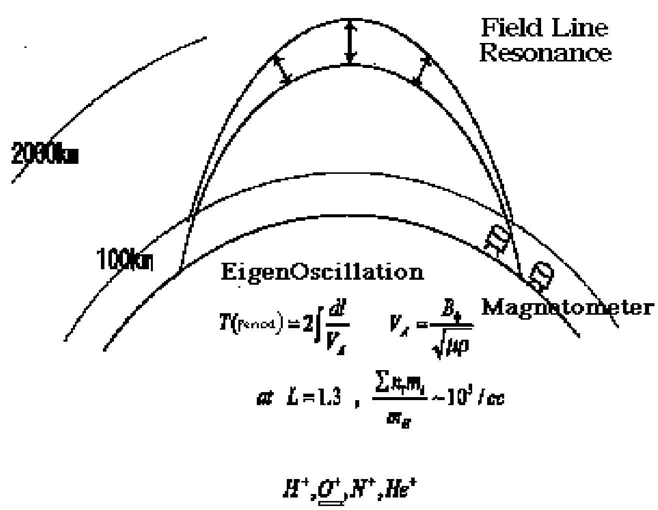

Fig. 7. Plasma mass density ($\rho = \Sigma n_i m_i$) can be estimated from the eigen-frequency (T=2L/V_A) of the field-line resonance (FLR) oscillations identified by using the gradient methods of amplitude-ratio and cross-phase o at dual stations.

The measured decrease in FLR frequency might indicate a relative increase in mass density along the field lines during the magnetic storm. On the other hand, the plasma number density in the ionosphere estimated from TEC values was similar in magnitude taken during quiet time. A possible explanation for the increase in mass density would be an outflow of the heavy ions (e.g., O^+) from the ionosphere to the plasmasphere.

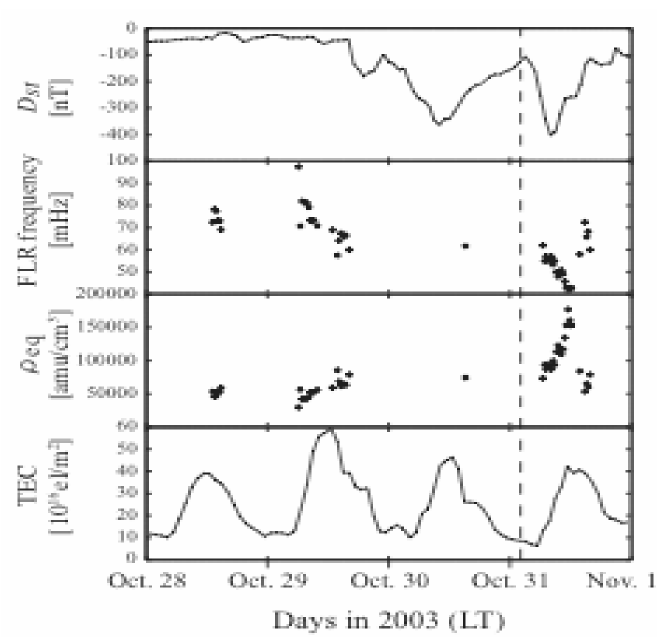

Fig. 8. (From top to bottom) Dst index, FLR frequencies derived from ground observations at L~1.4, ρ_{eq} estimated from data in the second panel, and the total electron content (TEC). The dashed vertical line marks the beginning of the second magnetic storm (Takasaki et al., 2006).

Abe et al. (2006) have applied the dual-station H-component power ratio method, which identifies the field-line eigen-frequency, to eleven-months magnetometer data obtained at two ground stations TIK (L=5.98) and CHD (L=5.55) that belong to the Circum-pan Pacific Magnetometer Network (CPMN). As a result, they have identified two patterns in the frequency dependence of the power ratio (TIK/CHD); one is an increase-then-decrease pattern (named Type 1), and the other is a decrease-then-increase pattern (named Type 2). Type 1 is observed where the Alfvén velocity (V_A) decreases with increasing L, and it has often been reported in literature. In the paper, they mainly studied the Type 2 events which have rarely been reported for the area near L=5.7 (midpoint of TIK and CHD);

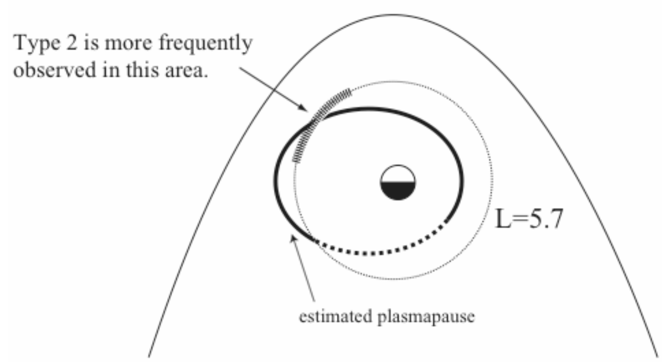

Fig. 9. Schematic picture of the plasmapause location (view from above the north pole). The place where mant Type 2 FLR events were observed is shown by the thick line, and the estimated plasmapause is shown by the black ellipse (Abe et al., 2006).

Type 2 is expected to be observed where V_A drastically increases with increasing L. Their statistical analysis shows that the Type 2 events were observed more frequently in the afternoon sector (especially in 15~18 hr LT) than in the morning sector as shown in Fig. 9. The geomagnetic condition was usually quiet when the Type 2 events were observed. These features are consistent with the interpretation that their Type 2 events were observed at the footpoint of the plasmapause layer, as follows. The plasmapause is the only location around L=5.7 where V_A drastically increases with increasing L, leading to Type 2. L of the plasmapause is smaller than 5.7 at all LT during geomagnetically active times (meaning Type 1 at L=5.7) while it is larger than 5.7 only on the late-afternoon sector during quiet times.

3.3. Ionospheric electric fields

Geomagnetic variations generated by DP2 type current systems coherently appear at the auroral and equatorial latitudes in daytime, and these amplitudes sharply decrease with decrease of latitudes but were enhanced at the dip equator. Equatorial enhancement had been understood as manifestation of Cowling effect for penetration of electric field from polar to the equatorial ionosphere. Furthermore, preliminary reverse impulse (PRI) and main impulse (MI) of geomagnetic sudden commencement (SC) are caused by the

DP2 type current systems, and some type of Pc5 magnetic pulsations are also generated by this current system.

In order to investigate penetration mechanisms of the ionospheric electric fields from the polar to the equatorial ionosphere, we have built a FM-CW radar (HF radar of 2~42 MHz) system at Sasaguri, Fukuoka (geomagnetic latitude θ=23.2°, geomagnetic longitude λ=199.6°) as shown in Fig. 10. The height of dipole antenna is 26 m. HF radio wave of 2~30 MHz is emitted in the vertical direction with 20 W power for ionosonde mode, while radio waves of central frequencies (f_0; 2.5 and 8 MHz) for Doppler mode are emitted during night (09 – 21 UT=18 – 06 LT) and day time, respectively. The speed of sweep frequency and the sampling frequency are 100~1000 kHz/sec and 2000~20,000Hz/sec, respectively. This system can measure the Doppler frequency (Δf) of reflected radio wave from the ionized layer and

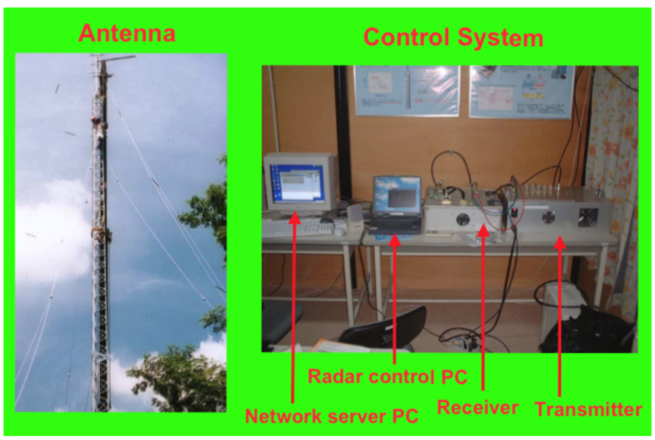

Fig. 10. FM-CW radar system at Sasaguri. 26m dipole antenna (left) and control system including network server, radar control, radio-wave transmitter and receiver (right).

the height of reflection layer with 10-sec sampling rate. From the observed vertical plasma drift velocity ($v = -c\Delta f/2f_0$), we can deduce east-west component of electric field (**E**) in the ionosphere, i.e. $\mathbf{E} = -\mathbf{v} \times \mathbf{B_o}$, where B_o is the ambient magnetic field at Sasaguri.

We have performed correlation analysis between ionospheric Doppler data obtained at the Sasaguri station and geomagnetic variations observed at the CPMN stations, and focus on DP2 type current systems associated with SC and Pc 5, which show equatorial enhancements of magnetic field variations at the dip equator. The ionospheric electric field and its intensity during at the time of SC are estimated as shown in Figure 11. From top to bottom, the number density measured by the ACE satellite in the solar wind region, the H-component magnetic field variations at the CPMN station at Cebu near the magnetic equator, and the Doppler frequency of FM-CW radar at Sasaguri are shown as a function of amplitude-time records during 90 minute on November 4, 2003. The intensity of PI electric field was 0.16mV/m (westward) and MI was 0.54mV/m (eastward) in dayside on November 4, 2003, while MI was 1.01mV/m (westward) in night-side at January 21, 2005, respectively.

At the onset time of SC preceded by PRI on November 4, 2003, the initial change in the ionosphere was observed simultaneous with the geomagnetic initial change in the accuracy of ±6.4s at 0625UT as shown in Figure 11. This result is in agreement with the event at 0519UT on May 9, 2003. Simultaneous observations of the initial changes are not contradictory to the result of the past report, and approve of the instantaneous penetration of the electric fields to the equatorial latitude. At the same time, it proves the quality of the FM-CW radar as an useful tool for detection of ionospheric electric fields.

The electric field variations (period of about 5 min) associated with Pc5 magnetic pulsations were also observed at the low-latitude ionosphere at Sasaguri (geomagnetic latitude θ=23.2°) during the recovery phase of severe magnetic storm on October 30 - 31, 2003 as shown in Figure 12. The top and bottom panel show amplitude-time records

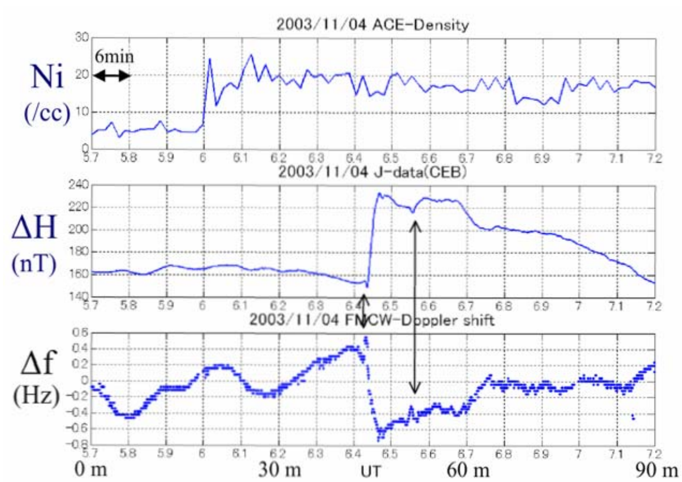

Fig. 11. From top to bottom, the number density measured by the ACE satellite in the solar wind region, the H-component magnetic field variations at the CPMN station at Cebu near magnetic equator, and the Doppler frequency of FM-CW radar at Sasaguri during 90 minute on November 4, 2003.

H-component magnetic field observed at the CPMN station at Yap near the magnetic equator, and the Doppler shifted frequency of HF radio wave measured by FM-CW radar at Sasaguri, respectively, during the period of 00:30-03:30 UT on October 30, 2003. This is the evidence of Pc5 magnetic pulsations produced by DP2-type current system in the low latitude ionosphere. In this case, the phase delay of geomagnetic variations was found to be about 10-40 second to the ionospheric variations. We can not ignore the self-inductance effect of enhanced ionospheric current caused by the Cowling conductivity to understand the phase delay of geomagnetic variations observed at the dip equator in daytime (Shinohara et al., 1997).

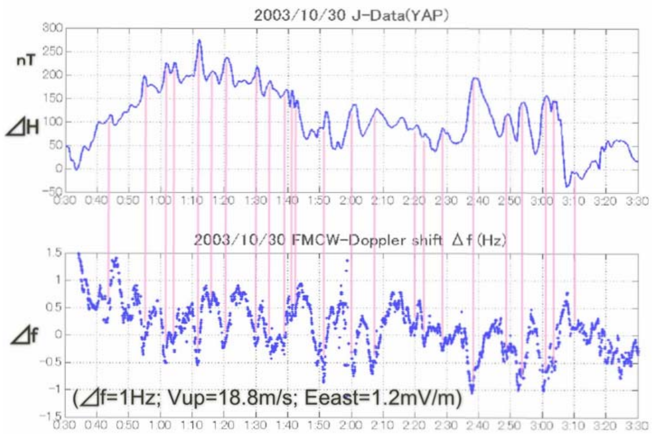

Fig. 12. Amplitude-time records of H-component magnetic field observed at the CPMN station at Yap near the magnetic equator (top), and the Doppler shifted frequency of HF radio wave measured by FM-CW radar at Sasaguri (bottom) during the period of 00:30-03:30 UT on October 30, 2003.

4. Conclusion

Until the end of December, 2005, the SERC, Kyushu University have deployed a new real-time MAGDAS/ CPMN system at 20 stations along the 210° magnetic meridian for space weather study and application. In 2006-07, 30 MAGDAS magnetometers will be installed along the magnetic equator and in the Siberian region. By using the MAGDAS/CPMN system, we will conduct the real-time monitoring and modeling of (1) the global 3-dimensional current system and (2) the plasma mass density variations for understanding electromagnetic and plasma environment changes in the geospace, especially, during the solar flare, coronal mass ejection, magnetic storms, and auroral substorms. Using FM-CW radar chain, we also investigate (3) how solar-wind electric fields and polar electric fields of SC, DP-2, Pc 5 and other disturbances can penetrate into the equatorial ionosphere.

A group of several organizations for geospace environment science in Japan will conduct a coordination of simulation/modeling, ground-based observations and satellite observations to understand couplings of complex, compound Sun-Earth system and generation mechanisms of high energetic particles in the inner magnetosphere during magnetic.

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