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The STEP 210° Magnetic Meridian Network Project

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Imaging the Earth's magnetosphere by using ground-based magnetometer arrays is still one of the major techniques for investigating the dynamical features of solar wind-magnetosphere interactions. The organized ground network data of magnetic fields make it possible (1) to study the magnetospheric processes by distinguishing between temporal changes and spatial variations in the phenomena, (2) to clarify the global latitudinal structures and propagation characteristics of magnetic variations from high to equatorial latitudes along the magnetic meridian (MM), and (3) to understand the global generation mechanism of magnetospheric phenomena. During the international Solar Terrestrial Energy Program (STEP) period of 1990–1997, multinationally coordinated magnetic observations are being conducted along the 190°, 210°, and 250° MMs from high latitudes through middle and low latitudes to the equatorial region, spanning L = 8.50–1.00, in cooperation with 29 organizations in Australia, Indonesia, Japan, Papua New Guinea, Philippines, Russia, Taiwan, and the United States. In this paper, we review the 210° MM Magnetic Observation Project and its initial results.

1. Introduction

A major new international scientific program, the Solar Terrestrial Energy Program (STEP) commenced in 1990 and will continue through 1997. Its purpose is to trace the flow of energy and plasma from the upstream solar wind through the magnetosphere and ionosphere to the biosphere. The ionospheric signatures of the magnetospheric energy transfer process can be recorded on the ground by using appropriate magnetometer networks. Topical Group 2.2 (project leader, S. Kokubun, Solar-Terrestrial Environment Laboratory (STEL), Japan), set up by Working Group 2 for the STEP, is concerned with Coordinated Ground-Based Magnetic Observations for Studies on Response of the Magnetosphere and Magnetosphere-Ionosphere Coupling (COMOSM). Japanese ground-based observation teams proposed a globally coordinated magnetic observation program during the STEP period to study energy and plasma transfer processes and global auroral dynamics (e.g., STEP GBRSC News, August 1991). In order to organize the observations efficiently, working plans were grouped into four categories based on region: polar region, high-latitude conjugate region, middle and low latitudes, and equatorial zone.

During the STEP period, the Department of Earth and Planetary Sciences, Kyushu University (K. Yumoto) and the STEL, Nagoya University (K. Shiokawa, Y. Tanaka), conducts multinationally coordinated magnetic observations along the 190°, 210°, and 250° magnetic meridians (MMs) in cooperation with and/or courtesy of the following institutes and organizations (names of co-investigators and assistants are in parentheses): University of Newcastle (B. J. Fraser, F. W. Menk), Electronics Research Laboratory, DSTO, Salisbury (K. J. W. Lynn, D. M. Sutton), CSIRO Tropical Ecosystems Research Centre (L. K. Corbett, Tony Hertog), Learmonth Solar Observatory and Canberra Observatory of IPS Radio and Space Services (D. G. Cole, J. A. Kennewell, R. Marshall), Weipa North State School (Michael and Chrisella Sbrizzi), Albatross Hotel (Ron Doherty), Birdsville Police Station (J. G. Guan, Owen T. Harms), Dalby Agriculture College (L. R. Harris), Katanning Research Station, Department of Agriculture (D. H. Ryall, T. Bell), and Australian Antarctic Division (R. J. Morris) in Australia; National Institute of Aeronautics and Space (LAPAN) (S. L. Manurung, Obay Sobari, Mamat Ruhimat, Sukmadradjat) in Indonesia; Tohoku University (T. Takahashi, T. Tamura, T. Saito), Tohoku Institute of Technology (M. Seto, Y. Kitamura), Kakioka Magnetic Observatory (S. Tsunomura), Tokai University (T. Sakurai), University of Tokyo (K. Hayashi), and Kyushu University (T.-I. Kitamura, O. Saka, H. Tachihara) in Japan; Paradise New Wewak Hotel (S. Kawabata) and University of Papua New Guinea (D. Yeboah-Amankwah) in Papua New Guinea; Coast & Geodetic Survey Department, National Mapping and Resource Information Authority (Commodore Renato B. Feir, V. C. Dandoy, A. A. Algaba) in the Philippines; Institute of Cosmphysical Research and Radiowaves Propagation (IKIR) (E. F. Vershinin, A. Buzevich, V. Filimonov), Institute of Cosmophysical Research and Aeronomy (IKFIA) (G. F. Krymsky, S. I. Solovyev, N. Molochushkin), and Institute of Physics of the Earth (IFZ) (V. A. Pilipenko, L. Baransky) in Russia; Lunping Observatory, Telecommunication Training Institute (Y.-H. Huang, S.-W. Chen) and Institute of Space Science, National Central University (J. K. Chao, J. Y. Liu) in Taiwan; and U.S. Geological Survey (A. W. Green, D. C. Herzog), Guam Magnetic Observatory (P. Hattori), Pacific Tsunami Warning Center (M. Blackford, W. J. Mass, R. K. Nygard), Koror Observatory of the U.S. National Weather Service (Hirao Kloulchad), and University of Alaska, Fairbanks (S.-I. Akasofu, J. V. Olson, D. Osborne) in the United States.

2. Observations and Data

In July 1990, we installed the first fluxgate magnetometer systems (Yumoto *et al.*, 1992) of the array at Moshiri and Kagoshima in Japan and at Adelaide, Birdsville, and Weipa in Australia. Fluxgate magnetometer data from the Chichijima station were obtained courtesy of the Kakioka Magnetic Observatory. Figure 1 shows these 190°, 210°, and 250° MM stations and their geographic coordinates. The Birdsville site ($L = 1.55$) is near the magnetic conjugate point of Moshiri ($L = 1.59$) in Japan. The Chichijima ($L = 1.14$), Weipa ($L = 1.18$), and Adelaide ($L = 2.11$) sites are near the same meridian as the conjugate point stations. The Kagoshima site ($L = 1.22$) is situated ~2° north of the conjugate point of Darwin ($L = 1.18$) which is ~12° of geomagnetic longitude west of the Weipa station. At Ewa Beach, Hawaii ($L = 1.17$, $\Lambda = 269.36°$), the magnetometer system was installed in January 1991.

In June 1991, fluxgate magnetometer observations were also started at Onagawa, Japan ($L = 1.38$), Wewak, Papua New Guinea ($L = 1.06$), and Guam ($L = 1.01$). We completed installation of magnetometer systems at Dalby ($L = 1.57$), Darwin ($L = 1.18$), and Learmonth ($L = 1.46$) in Australia in summer 1991 and at Biak, Indonesia ($L = 1.05$) in May 1992. We are now extending the 210° MM chain to high northern latitudes in Siberia in cooperation with IKFIA, IKIR, and IFZ of Russian Academy of Science. The magnetometer systems were installed at St. Paratunka ($L = 2.10$), Magadan ($L = 2.83$), Chokurdakh ($L = 5.46$), and Tixie ($L = 5.89$, $\Lambda = 197.06$) in August 1992. Conjugate magnetic observations at Kotzebue, Alaska ($L = 5.40$, $\Lambda = 249.72°$), and Macquarie island, Australia (5.40, 247.84°), started in November 1993 and November 1992, respectively. Magnetic observations at Muntinlupa ($L = 1.00$, $\Lambda = 191.57°$) near the magnetic equator were also started in cooperation with Coast & Geodetic Survey Department, Philippines, in July 1993.

In January 1994, magnetic observations were started at Lunping Observatory ($\Lambda = 189.50°$, $L = 1.06$), Telecommunication Training Institute in cooperation with the Institute of Space Science, National Central University, Taiwan. Installations of the magnetometers at Zyryanka ($L = 3.91$) and Kotel'nyy island ($L = 8.50$) in Siberia were completed by IKFIA in April 1994 and October 1994, respectively. To clarify relationships between auroral electrojets observed at Kotzebue and equatorial electrojets observed near the magnetic equator, a fluxgate magnetometer was installed at Koror ($L = 1.00$) by the Geophysical Institute of the University of Alaska in August 1994.

All-sky television cameras and photometers were also installed at Moshiri, Japan ($L = 1.59$), in October 1991, at Tixie, Russia ($L = 5.89$), in March 1994, and at Canberra, Australia ($L = 2.07$), and Kotzebue, Alaska ($L = 5.40$), in August 1994. The scientific objective of the optical instrumentation is to investigate low- and high-latitude auroras and the relationship between magnetic and optical variations in them. Optical data from Tixie and Kotzebue will be analyzed in conjunction with all-sky television and photometer data from Resolute and Cambridge Bay in the Canadian Arctic.

Table 1 summarizes station names, geographic and geomagnetic coordinates, and L values of proposed observation sites, including established stations, where additional instruments with high time resolutions will be installed during the STEP period. The IGRF-90 model was used to calculate corrected geomagnetic coordinates and L values for a 100-km altitude at each station on January 1, 1993. Months of commencement and abbreviations of institutes and organizations that support or collaborate with the

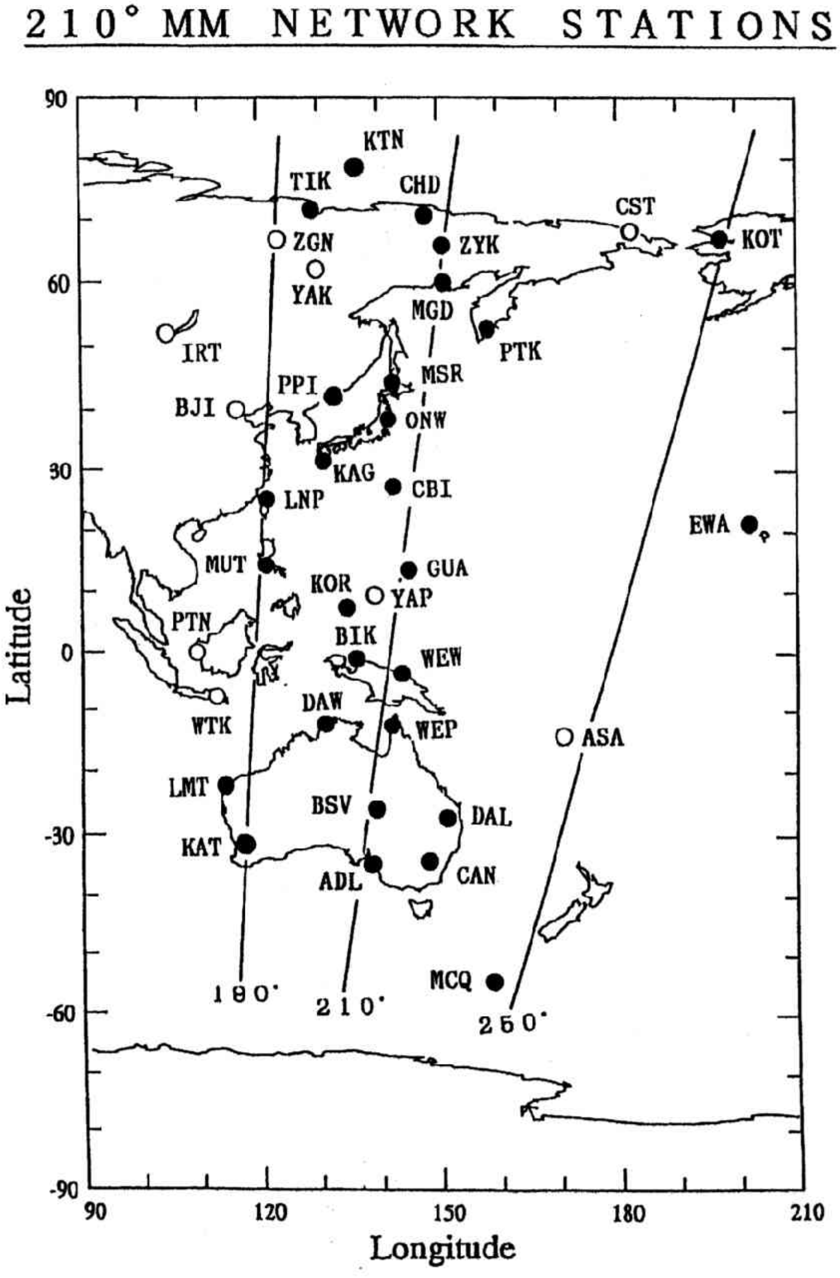

Fig. 1. Map showing geographic coordinates of the 190°, 210°, and 250° magnetic meridian chain stations. See Table 1 for definitions of abbreviation.

(a)

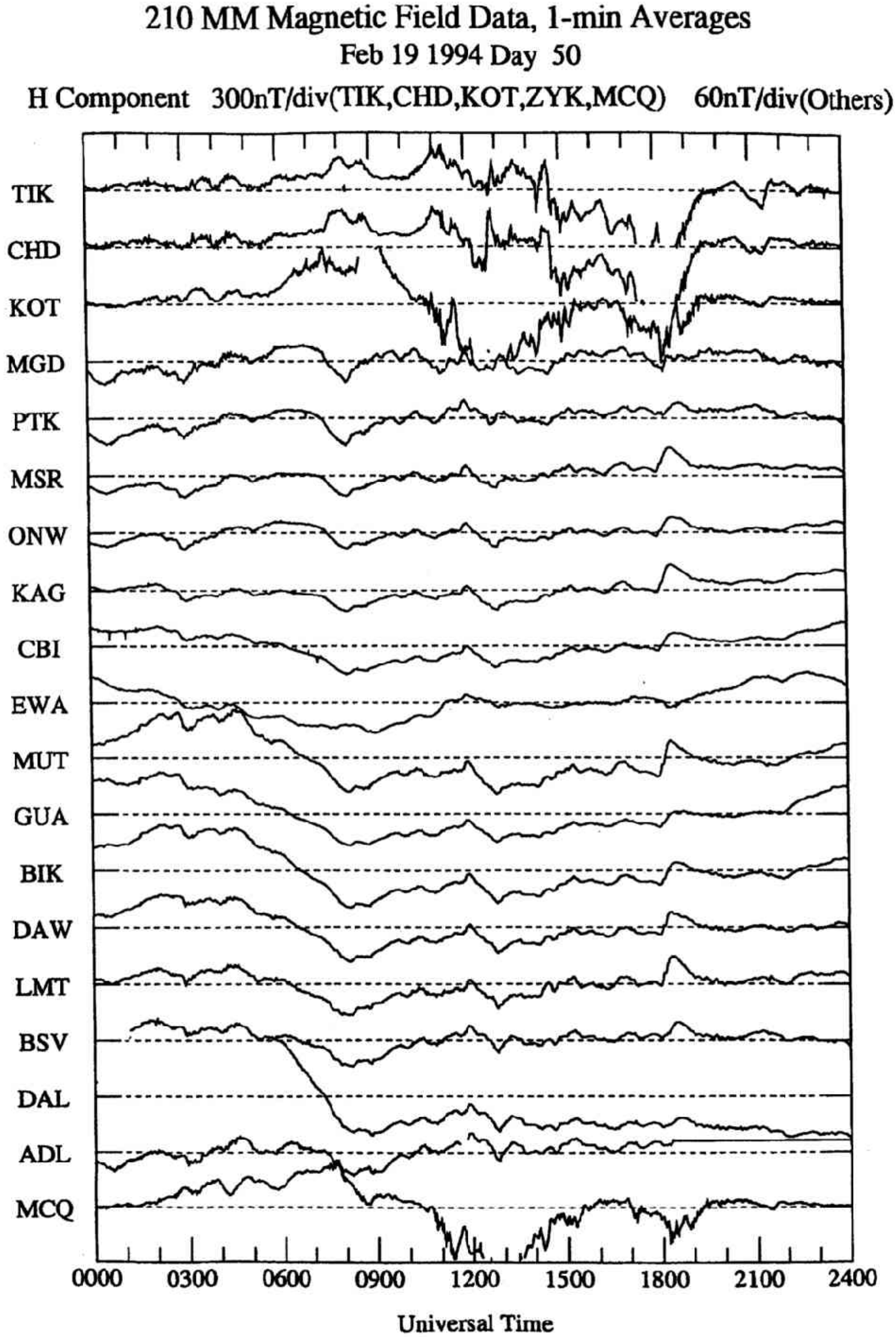

Fig. 2. Amplitude-time records of (a) H- and (b) D-component ordinary magnetic variations observed on February 19, 1994, at the 210° magnetic meridian chain stations of TIK, CHD, KOT, MGD, PTK, MSR, ONW, KAG, CBI, EWA, MUT, and GUA in the Northern Hemisphere, and BIK, DAW, LMT, BSV, DAL, ADL, and MCQ in the Southern Hemisphere. See Table 1 for definitions of abbreviations. The magnetic sensitivity at TIK, CHD, KOT, ZYK, and MCQ and at other stations are 300 and 60 nT/one division, respectively.

(b)

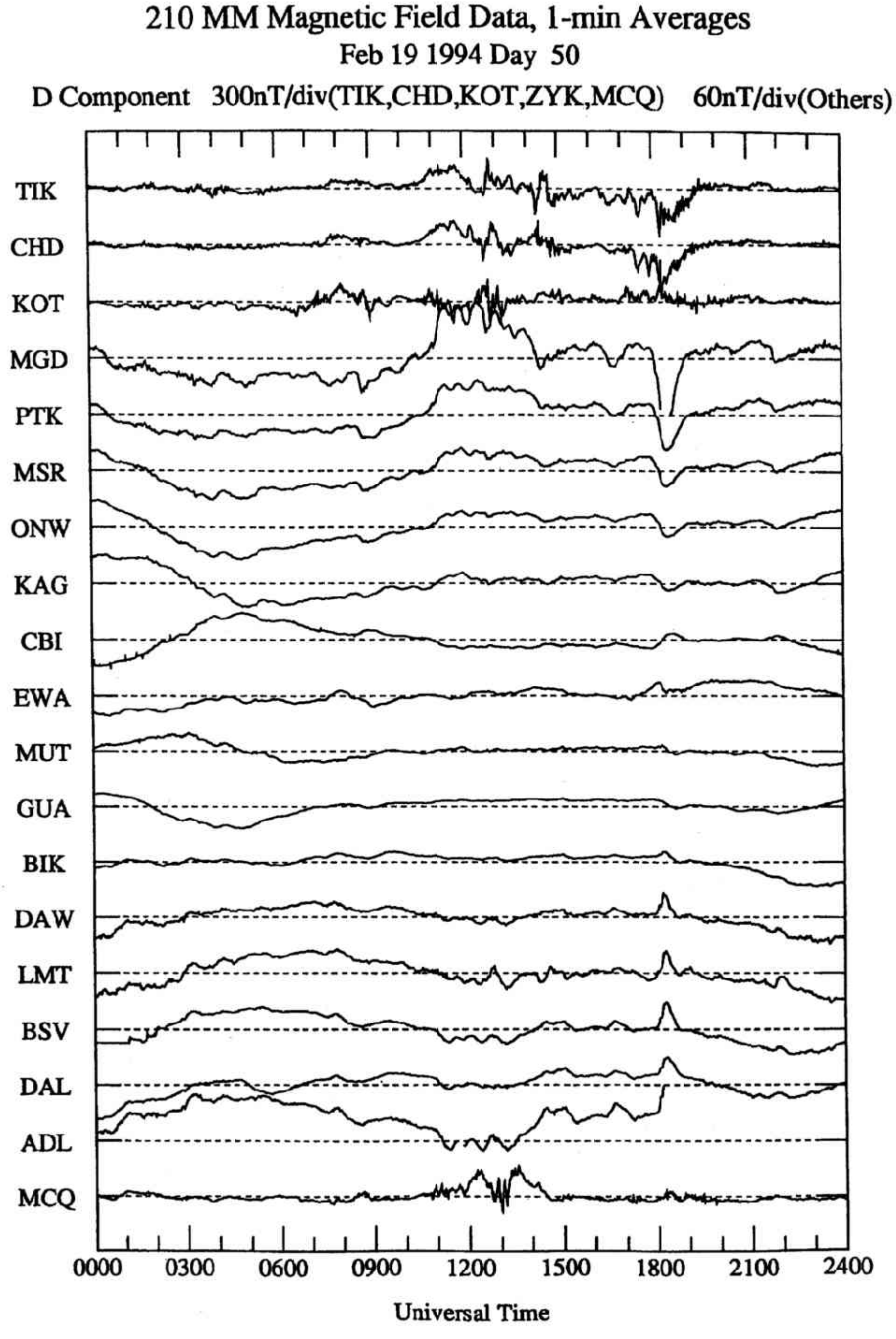

Fig. 2. (continued).

Table 1. Station names, geographic and geomagnetic coordinates, and L values of proposed observation sites.

Station name*	Abbreviation	Geographic coordinates		Geomagnetic** coordinates		L**	Associ. Inst.***	Date of onset
		Lat (deg)	Long (deg)	Lat (deg)	Long (deg)			
Tixie	TIK	71.59	128.78	65.67	196.88	5.89	IKFIA, IFZ	92/8–
Zhigansk	ZGN	66.75	123.26	61.01	193.82	4.25	IKFIA	95/–
Yakutsk	YAK	62.02	129.72	56.08	200.51	3.21	IKFIA	
Irkutsk	IRT	52.17	104.45	47.13	177.01	2.16	ISTP	
Popov Island	PPI	42.98	131.73	36.62	203.63	1.55	POI	95/–
Beijing	BJI	40.06	116.18	34.37	188.40	1.47	IGCAS	
Lunping	LNP	25.00	121.17	13.80	189.50	1.06	NCU, LNP	94/1–
Muntinlupa	MUT	14.37	121.02	3.58	191.57	1.00	CGSD	93/7–
Pontianak	PTN	−0.05	109.25	−11.37	180.49	1.04	LAPAN	
Watukosek	WTK	−7.56	112.63	−18.52	183.85	1.11	LAPAN	
Learmonth	LMT	−22.22	114.10	−34.15	185.02	1.46	IPS, UNC	91/8–
Katanning	KAT	−33.68	117.62	−46.63	188.24	2.12	KRS, UNC	95/8–

210° MM magnetic observation team are also given in Table 1.

Magnetic variation data (ΔH, ΔD, ΔZ, dH/dt, dD/dt, dZ/dt) from all stations except Chichijima were obtained with ring-core fluxgate magnetometers with identical logging systems (DCR-3, KOSMO Ltd.) and time signal generators, as shown in detail by Yumoto *et al.* (1992). The resolutions of ordinary analog outputs V_0 (ΔH, ΔD, ΔZ) in the 0- to 2.5-Hz frequency range are ±300, ±1000, and ±2000 nT/±10 V for low-, middle-, and high-latitude stations, respectively. The time-derivative components (V_{TD}; dH/dt, dD/dt, dZ/dt) were obtained by putting an analog circuit at the output terminals of the ordinary components (V_0). V_{TD} outputs in the frequency range of 0.0–0.1 Hz exhibit essentially the same frequency response as an induction magnetometer. The noise level of the magnetometer system is lower than 0.1 nT rms(root mean square) equivalent. The six magnetic signals (ΔH, ΔD, ΔZ, dH/dt, dD/dt, dZ/dt) and time pulses (1 min, 1 h, 24 h) are registered on a digital cassette tape by means of a digital data logger with a sampling rate of 1 s and 16-bit resolutions of 0.012, 0.039, and 0.078 nT/LSB(Least Significant Bit) at low-, middle-, and high-latitude stations, respectively. Each cassette tape holds 21 days of data. Fluxgate magnetometer data from the Chichijima station of the Kakioka Magnetic Observatory are obtained by the same logging system. Time pulses (1 min, 1 h, 24 h) from the time signal generator are also recorded on the digital cassette tape as a way of checking the crystal clock inside the data logger. The accuracy of the time signal generator is maintained to within ±25 ms by automatic comparisons with standard radio transmissions (WWVH, JJY, and WWV) from Maui, Hawaii; Koganei, Japan; and Boulder, Colorado, respectively.

Figures 2(a) and 2(b) show one example of the H and D components of ordinary magnetograms from the 210° MM chain stations Tixie ($L = 5.89$, $\Lambda = 197.06°$), Chokurdakh (5.46, 212.12°), Kotzebue (5.40, 249.72°), Magadan ($L = 2.83$), Paratunka (2.10), Moshiri (1.59), Onagawa (1.38), Kagoshima (1.22), Chichijima (1.14), Ewa Beach (1.17, 269.36°), Muntinlupa (1.00), and Guam (1.01) in the Northern Hemisphere and stations Biak (1.05), Darwin (1.18), Learmonth (1.46), Birdsville (1.55), Dalby (1.57), Adelaide (2.11), and Macquarie Island ($L = 5.40$, $\Lambda = 247.84°$) in the Southern Hemisphere. In latitudes lower than $|\Phi| = 55°$, the H-component magnetic bay variations around 1800 UT at the northern and southern stations show an in-phase relation, while the D components at the northern and southern stations show a 180° out-of-phase relation. Amplitude ranges of the H components are of almost the same order at the lower latitudes, but the D components increase exponentially from the magnetic equator to higher latitudes.

Table 1. (continued).

Station name*	Abbreviation	Geographic coordinates		Geomagnetic** coordinates		L**	Associ. Inst.***	Date of onset
		Lat (deg)	Long (deg)	Lat (deg)	Long (deg)			
Kotel'nyy	KTN	75.94	137.71	69.94	201.02	8.50	IKFIA	94/10–
Chokurdakh	CHD	70.62	147.89	64.67	212.12	5.46	IKFIA,IFZ	92/8–
Zyryanka	ZYK	65.75	150.78	59.62	216.72	3.91	IKFIA	94/4–
Magadan	MGD	59.97	150.86	53.56	218.66	2.83	IKIR	92/8–
St. Paratunka	PTK	52.94	158.25	46.34	225.91	2.10	IKIR	92/8–
Moshiri	MSR	44.37	142.27	37.61	213.23	1.59	STEL	90/7–
Onagawa	ONW	38.43	141.47	31.65	212.51	1.38	THU	91/6–
Kagoshima	KAG	31.48	130.72	25.13	202.24	1.22	STEL	90/7–
Chichijima	CBI	27.15	142.30	20.59	213.00	1.14	KMO	90/7–
Guam	GUA	13.58	144.87	4.57	214.76	1.01	USGS	91/6–
Yap	YAP	9.3	138.5	−0.3	209.0	1.00	UK	93/1–
Koror	KOR	7.33	134.48	−2.64	205.21	1.00	UAF	94/8–
Biak	BIK	−1.08	136.05	−12.18	207.30	1.05	LAPAN	92/5–
Wewak	WEW	−3.33	143.74	−13.94	215.37	1.06	PWH, UPNG	91/6–
Darwin	DAW	−12.40	130.90	−23.13	202.68	1.18	TERC, UNC	91/8–
Weipa	WEP	−12.68	141.88	−22.99	214.34	1.18	WNSS, UNC	90/7–
Birdsville	BSV	−25.54	139.21	−36.58	212.96	1.55	POB	90/7–
Dalby	DAL	−27.18	151.20	−37.09	226.80	1.57	DAC, UNC	91/8–
Canberra	CAN	−35.30	149.00	−45.98	226.14	2.07	IPS	94/8–
Adelaide	ADL	−34.67	138.65	−46.46	213.66	2.11	DSTO	90/7–
Kotzebue	KOT	66.88	197.40	64.52	249.72	5.40	UAF	93/11–
Cape Shmidt	CST	68.88	180.55	64.51	236.29	5.40	IKIR	
Ewa Beach	EWA	21.32	202.00	22.67	269.36	1.17	PTWC/USGS	91/1–
American Samoa	ASA	−14.28	170.70	−20.60	245.05	1.14		
Macquarie Isl.	MCQ	−54.50	158.95	−64.50	247.84	5.40	AAD, UNC	92/11–

*Includes established stations at which additional instruments with a high time resolution will be installed during the STEP period.

**The IGRF-90 model was used to calculate corrected geomagnetic coordinates and L values for 100-km altitude at each station on January 1, 1993.

***The Department of Earth and Planetary Sciences, Kyushu University and the Solar-Terrestrial Environment Laboratory, Nagoya University (STEL), are conducting multinationally coordinated magnetic observations in cooperation with and/or courtesy of the following institutes and organizations: University of Newcastle (UNC), Electronics Research Laboratory (DSTO), CSIRO Tropical Ecosystems Research Centre (TERC), Learmonth Solar Observatory and Canberra Observatory of IPS Radio and Space Services (IPS), Weipa North State School (WNSS), Birdsville Police Station (POB), Dalby Agriculture College (DAC), Katanning Research Station (KRS), and Australian Antarctic Division (AAD) in Australia; National Institute of Aeronautics and Space (LAPAN), in Indonesia; Tohoku University (THU), Tohoku Institute of Technology (TIT), Kakioka Magnetic Observatory (KMO), Tokai University (TKU), University of Tokyo (GRL), and Kyushu University (UK) in Japan; Paradise New Wewak Hotel (PWH) and University of Papua New Guinea (UPNG) in Papua New Guinea; Coast & Geodetic Survey Department (CGSD) in the Philippines; Institute of Space Research and Radiowaves Propagation (IKIR), Institute of Cosmophysical Research and Aeronomy (IKFIA), Institute of Physics of Earth (IFZ), and Pacific Oceanological Institute (POI), Academy of Science in Russia; Lunping Observatory (LNP), and National Central University (NCU) in Taiwan; and Guam Magnetic Observatory, U.S. Geological Survey (USGS), Pacific Tsunami Warning Center (PTWC), Koror Observatory of the U.S. National Weather Service and University of Alaska, Fairbanks (UAF) in the United States.

3. Data Exchanges

Routine magnetic observations at the 190°, 210°, and 250° MM chain stations will continue during the entire STEP period (1990–1997). For effective data exchanges and analyses, the magnetic data are being compiled at the STEL, Nagoya University, for STEP investigators. Data catalogue, one minute-averaged plots, and 4 second-averaged pulsation data for 1990–1995 can be found through the STEL homepage at World Wide Web (http://www.stelab.nagoya-u.ac.jp/, and click "STEP Database Catalog" and "210 Magnetic Data"). One-min digital data are open by Internet file transfer through the STEP networks of a UNIX workstation (NEC EWS/4800). The data are available by means of 3.5- and 5-in. diskettes for NEC or IBM personal computers, magnetic tapes in the IBM format, copies of an optical disk for NEC personal computers, and copies of quick-look summary plots.

The one minute-averaged daily magnetogram and pulsation data from the 210° MM network are distributed to STEP investigators. The data are not calibrated and are only for quick-look. The plots cannot used at any publication or presentation without the permission by the principal investigator of the 210° MM team, K. Yumoto (yumoto@geo.kyushu-u.ac.jp). The user is requested to offer an authorship to the PI and members of the 210° MM team when the 210° MM data are essential in the publication and presentation. If no one on the 210° MM team participates as an author, the paper should acknowledge the 210° MM team and the STEL for the use of the database and should refer to the following papers: Yumoto *et al.*, *J. Geomag. Geoelectr.*, **44**, 261–276, 1992 and **47**, 1197–1213, 1995. High-time-resolution (1-s) data can ordinarily be used for collaborative studies with the 210° MM team. Scientists conducting research using the 210° MM data must contact the PI of the 210° MM Network Project, who will organize the joint studies.

4. Initial Results

The 210° MM Magnetic Observation Project was outlined by Tanaka and Yumoto (1993), Yumoto (1994), and Yumoto *et al.* (1991, 1992, 1993b). The importance and effectiveness of multistation network observations for obtaining spatiotemporal information on solar-terrestrial phenomena are emphasized. Using data from the 210° MM network stations and satellites, we are studying the STEP objective and obtaining preliminary results (see Yumoto, 1995). The scientific items and related publications are as follows: (1) magnetospheric response to interplanetary shocks and discontinuities (sudden commencements [sc] and sudden impulses [si]) (Araki *et al.*, 1997; Yumoto *et al.*, 1994b, 1996a, 1996b; Petrinec *et al.*, 1996), (2) the global dynamics of low- and high-latitude auroras (Shiokawa *et al.*, 1994, 1995a, 1995b, 1996a, 1996b, 1996c, 1996d; Yumoto *et al.*, 1994a, 1994c; Yumoto, 1995), (3) relations between in situ and ground (or separated ground) observations of substorm phenomena (Kawano *et al.*, 1994, 1996; Kokubun *et al.*, 1996; Nakamura *et al.*, 1996; Shiokawa *et al.*, 1996), (4) global characteristics of Pc 3 waves (Yumoto *et al.*, 1992; Menk and Yumoto, 1994; Pilipenko *et al.*, 1995; Matsuoka *et al.*, 1997) and Pi 2 waves (Yumoto *et al.*, 1994d; Osaki *et al.*, 1996; Shiokawa *et al.*, 1996c), (5) mass loading effect on Pc 3 waves in the low-latitude ionosphere (Yumoto *et al.*, 1993a; Yumoto, 1995; Pilipenko *et al.*, 1996), and (6) miscellaneous (earthquake-related ULF waves (Hayakawa *et al.*, 1996) and geophysical induction current (Yumoto and Utada, 1993; Seto *et al.*, 1996)).

In particularly, we obtained new findings from analyses of coordinated ground-based observation data from the 210° MM stations. The main results (cf. Yumoto, 1995) are summarized here.

4.1 North-south asymmetry of sc/si disturbances

North-south asymmetry of sc and si disturbances at low and middle latitudes indicates that the *DP* component of sc and si is larger than the *DL* component; i.e., electric field penetration into the equatorial ionosphere plays an important role on energy transfer from high latitudes to the magnetic equator (Yumoto *et al.*, 1996a).

sc are a global magnetospheric phenomenon caused by interplanetary shocks and other discontinuities. When the interplanetary magnetic field (IMF) turns southward or becomes turbulent behind an interplanetary shock or discontinuity, geomagnetic storms can develop following so-called storm sudden commencements (ssc). When the IMF remains to the north behind the shocks or discontinuities, sc are not followed by geomagnetic storms. Although such sc have been called si, there is no difference between the physical mechanisms producing ssc and si. The sc can be used to study transient responses of the magnetosphere, ionosphere, and conducting Earth system to dynamic pressure variations in the solar wind.

The disturbance fields of sc and si observed on the ground can be decomposed into two subfields, *DL* and *DP*. The *DL* field is produced by electric currents flowing on the magnetopause and a propagating compressional wave front in the magnetosphere. *DP* fields are produced by twin vortex-type ionospheric currents, which are caused by a dawn-to-dusk electric field transmitted to the polar ionosphere. In order to examine which components of the *DL* and *DP* fields dominate sc and si magnetic variations on the ground, i.e., to investigate transfer processes and latitudinal structures of sc and si disturbances from the magnetopause through the magnetosphere to the Earth's surface and/or from the magnetopause to the polar ionosphere and thence to the magnetic equator, we analyzed magnetic field data from the 210° MM chain of stations. We statistically analyzed 41 events of sc and si magnetic variations and long-period (around 1-h) variations in the initial phases of magnetic storms observed along the 210° meridian during the 15 months from November 1992 through January 1994 and found that the amplitudes of sc and si at low and middle latitudes are larger in the summer hemisphere than in the winter hemisphere. We also used the 210° MM data to confirm the enhancement of sc and si amplitudes near the dayside equator.

The north-south asymmetry of sc and si disturbances at middle and low latitudes cannot be explained by invoking the Chapman-Ferraro current on the magnetopause but can be interpreted by invoking an asymmetry in the Northern and Southern Hemisphere twin vortex-type ionospheric currents, i.e., by invoking enhanced ionospheric conductivities in the summer hemisphere.

4.2 Transfer of solar wind energy to the magnetosphere

Low-latitude aurorae provide evidence that solar wind energy can be transferred into the inner magnetosphere around $L = 2.5$ during magnetic storms (Yumoto and Utada, 1993; Yumoto *et al.*, 1994a, 1994c; Shiokawa *et al.*, 1994, 1995a, 1996b, 1996d).

Recent optical and magnetic observations at Moshiri ($\theta = 44°22'$ N, $\phi = 142°16'$ E) of the STEL indicate that even during moderate magnetic storms, invisible low-latitude aurorae sometimes occur in concert with $\Delta H \gtrsim 50$ nT positive magnetic excursions and large-amplitude Pi magnetic pulsations around a minimum *D*st index of ~–200 nT and/or in concert with sudden decreases in *D*st at a rate of $\gtrsim$30 nT/h (Yumoto *et al.*, 1994a, 1994c). Optical instrumentations (photometers, all-sky television cameras) were used to identify six events of invisible low-latitude aurorae at Moshiri and Rikubetsu ($\theta = 43.46°$, $\phi =$ 143.77°E, $L = 1.6$) in Hokkaido, Japan, that occurred between February 1992 and September 1993 (Shiokawa *et al.*, 1994).

All low-latitude aurorae observed in 1992 exhibited a vortical equivalent ionospheric current patterns, and four of them also showed westward movement (Yumoto *et al.*, 1994a). Although we don't yet have sufficient evidence to provide it, we still propose that the magnetic perturbations associated with low-latitude aurorae correspond to changes in substorms and local overhead currents that involve strong perturbing forces that act on the trapped-particle population and precipitate large fluxes of low-energy electrons into the thermosphere. The large oscillations in the *D* component of the magnetic field can be explained by the intensification of upward (and downward) field-aligned currents (FACs) within an ionospheric Hall current vortex (or vortices) and their spatial movement, as shown in Fig. 15 of Yumoto *et al.* (1994c). The upward FAC must be associated with intense precipitation of energetic electrons at latitudes below that which is normal for the auroral oval. The direct injection of energy from the ring current in the form of particle precipitation into the upper thermosphere must be very significant and must affect the dynamics of the thermosphere and ionosphere during magnetically disturbed times. Particle precipitations into the low- and mid-latitude thermosphere and the occurrence of low-latitude aurorae coincide with large values of the *D*st index, which are proportional to the total energy content of the trapped particles that constitute the ring current.

Shiokawa *et al.* (1996b, 1996d) recently used plasma particle observations made by the DMSP-F10 satellite to confirm the intense precipitation of energetic electrons associated with the May 10, 1992, low-latitude auroral event. The electron precipitation did not appear in an expanded auroral oval but rather in an isolated region around 50° magnetic latitude. This precipitation exhibited an unusual acceleration process in which electrons at all energies measured (32 eV to 30 KeV) were intensified. Nevertheless, we conclude that the intensity variations of optical emissions and magnetic perturbations during low-latitude auroral events are associated with variations of the upward FAC (and/or electron precipitation) in a localized region of $L = 2.5$ and on a shorter time scale.

4.3 Cavity-mode-like oscillations

Interplanetary impulses can readily stimulate a standing Pc 3-4 field line oscillation in the inner magnetosphere but don't easily excite cavity resonance oscillations at low latitudes. Only great sc and si can stimulate cavity-mode-like oscillations within the daytime plasmasphere (Yumoto *et al.*, 1992, 1994b).

The 210° magnetometer network data were also analyzed to determine whether or not global cavity-mode and localized field line oscillations can be excited in the inner magnetosphere by interplanetary impulses (sc/si) (Yumoto *et al.*, 1994b). Two types of Pc 3-4 magnetic pulsations were stimulated at low latitudes just after 13 sc and si events. Most of the Pc 3-4 pulsations were standing field line oscillations with maximum power densities around $L = 1.6$ and/or higher latitudes, while only four global cavity-mode-like oscillations with larger amplitudes at lower latitudes ($|\Phi| < 30°$) were stimulated by extremely large sc and si within the dayside plasmasphere.

Spectral peak power densities of the 38 oscillations measured at Moshiri ($L = 1.59$) just after the sc and si events as a function of magnetohydrodynamic mode and local time when the events happened show that cavity-mode-like oscillations tend to be observed only when the 210° MM chain stations are located within the daytime sector from 0900 to 1500 LT, where the level of magnetic activity is $Kp > 7_+$ and the stimulated power density just after the sc event is larger than 600 nT^2/Hz (see Table 2 of Yumoto *et al.* (1994b)). This result implies that the interplanetary impulses must be sufficiently large to drive cavity-mode-like waves. We conclude that Pc 3-4 cavity-mode-like oscillations at low latitudes are not easily stimulated by the external impulses in the solar wind and tend to be excited within the dayside plasmasphere only by great sc and si.

4.4 Mass loading effect at near-equatorial latitudes

Pc 3 magnetic pulsations at low latitudes indicate an abnormal dependence of the resonant period on L and a drastic increase in ionospheric damping, i.e., a so-called mass loading effect on Pc 3 oscillations in the near-equatorial latitude ionosphere ($|\Phi| < 30°$) (Yumoto *et al.*, 1993a; Yumoto, 1995; Pilipenko *et al.*, 1996).

Magnetospheric ULF field line oscillations at middle and high latitudes have been thoroughly studied for many years with the numerous facilities of modern geophysics, but much less is known about the physical nature of ULF waves at low and near-equatorial latitudes. Low-latitude magnetic field line oscillations may have a number of characteristic features that distinguish them from the well-known midlatitude geomagnetic pulsations (e.g., Yumoto, 1995; Pilipenko *et al.*, 1996). These peculiarities are related to the primary influence of ionospheric ions on field line oscillations. New facilities for the experimental study of the spatiospectral structure of ULF pulsations became available after the 210° MM project began. In these studies we have found a peculiarity of Pc 3 pulsations at low latitudes, i.e., increasing period with decreasing magnetic latitude, and we have compared the observations with the results of numerical models of the magnetospheric resonator.

Although a detailed comparison between various ionospheric plasma models and observational data is required, ULF observations could be used as a low-latitude extension of whistler observations to monitor plasma density variations in the plasmasphere, where in situ plasma data are not easily obtained by satellites (Yumoto *et al.*, 1995).

4.5 Latitudinal profiles of Pi 2 pulsations

The latitudinal profiles of Pi 2 phase relations and amplitudes imply that Pi 2 pulsations observed at low and high latitudes consist of different mode oscillations (Yumoto *et al.*, 1994d; Osaki *et al.*, 1996; Shiokawa *et al.*, 1996c).

At the onset of a magnetospheric substorm, transient hydromagnetic oscillations with periods of 40–150 s, called Pi 2 magnetic pulsations, are excited globally in the magnetosphere. One possible source of nighttime Pi 2 pulsations is a sudden change in magnetospheric convection or configuration during the substorm expansive phase. This change would be caused by a plasma flow from the reconnection (or current disruption) region or by the formation of a substorm current wedge. Many workers have studied Pi 2 magnetic pulsations on the ground and in space, but the generation and propagation mechanisms of these pulsations are still only partly understood.

In order to check the existing Pi 2 model, we analyzed data from stations along the 210° MM. We found the followings for "low"-latitude Pi 2 pulsations: (1) Pi 2 pulsations have similar wave forms at lower latitudes; (2) H-component Pi 2 pulsations at the northern and southern stations show an in-phase relation, and D components at the northern and southern stations show a 180° out-of-phase relation; (3) amplitudes of the H components are independent of geomagnetic latitudes and are almost the same at all stations, but D components depend on latitude and increase exponentially from the magnetic equator to higher latitudes. The first two of these observational facts suggest that the field line resonance theory is inadequate to explain all of the characteristics of low-latitude Pi 2 pulsations. If each field line oscillated with its own eigenperiod, then the dominant period of magnetic pulsations would vary from place to place.

The observed latitudinal characteristics indicate that Pi 2 magnetic pulsations may be explained by a global cavity-mode oscillation with phase reversal near the plasmapause, the substorm current wedge model-like oscillation, and auroral field line oscillations with field-aligned and ionospheric current variations. However, whether the existing Pi 2 models are consistent with these observational results is still an open question. In order to answer the question, in the near future we will further analyze the 210° MM chain data, including data from around the plasmapause and simultaneously obtained by the AKEBONO, GEOTAIL, and CLUSTER satellites.

5. Conclusion

A review of some initial 210° MM network observations demonstrates the usefulness of multistation observations. Imaging the Earth's magnetosphere by using ground-based magnetometer arrays can be reaffirmed as one of the major techniques for investigating the dynamical features of solar wind-magnetosphere interactions. Magnetic field 1-s data from coordinated ground stations make it possible to study magnetospheric processes by distinguishing between temporal changes and spatial variations in the phenomena, to clarify global and latitudinal structures and propagation characteristics of magnetospheric variations from higher to equatorial latitudes, and to understand the global generation mechanisms of the solar-terrestrial phenomena. Considering the essential importance of simultaneous satellite-ground observations and also the cost-effectiveness of expensive satellites, we propose that any in situ measurements by the GEOTAIL, WIND, POLAR, SOHO, CLUSTER, and INTERBALL satellites should be coordinated with the COMOSM networks for observing fundamental geophysical phenomena such as magnetic storms, magnetospheric substorms, and global-mode ULF waves.

After the STEP period (1990–1997), coordinated ground-based observations along the 190°, 210°, and 250° MMs will be continued by adding various remote-sensing techniques. The scientific objectives of the new phase will be to investigate the effects of high-energy particles on the middle atmosphere during solar proton and low-latitude auroral events, relationships between the eastward auroral electrojet at high latitudes and the equatorial electrojet in daytime, and long-term variations of the core magnetic field. The 210° MM observation network will be further connected to the Chinese meridian chain along the 120° geographic longitude that is organized by the Institute of Geophysics, Chinese Academy of Science; with the Yakutsk meridian chain along the Lena river, organized by IKFIA, Russia; with the AE-index stations in Siberia, Alaska, and Canada; and with island stations in the Pacific ocean that will be supported by the Earthquake Research Institute, University of Tokyo. Campaign-based ground observations with 1-s time resolutions will be also organized for comparison with observations by the multiple satellites.

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REFERENCES

Araki, T., S. Fujitani, M. Emoto, K. Yumoto, K. Shiokawa, T. Ichinose, H. Lühr, D. Orr, D. K. Milling, H. Singer, G. Rostoker, S. Tsunomura, Y. Yamada, and C. F. Liu, Anomalous sudden commencement on March 24, 1991, *J. Geophys. Res.*, **102**, 1997 (in press).

Hayakawa, M., R. Kawate, O. A. Molchanov, and K. Yumoto, Results of ultra-low-frequency magnetic field measurements during the Guam earthquake of 8 August 1993, *Geophys. Res. Lett.*, **23**, 241–244, 1996.

Kawano, H., T. Yamamoto, S. Kokubun, K. Tsuruda, A. T. Lui, D. J. Williams, K. Yumoto, H. Hayakawa, M. Nakamura, T. Okada, A. Matsuoka, K. Shiokawa, and A. Nishida, A flux rope followed by recurring encounters with traveling compression regions: Geotail observations, *Geophys. Res. Lett.*, **21**, 2891–2894, 1994.

Kawano, H., A. Nishida, M. Fujimoto, T. Mukai, S. Kokubun, T. Yamamoto, T. Terasawa, M. Hirahara, Y. Saito, S. Machida, K. Yumoto, H. Matsumoto, and T. Murata, A quasi-stagnant plasmoid observed with Geotail on October 15, 1993, *J. Geomag. Geoelectr.*, **48**, 525–539, 1996.

Kokubun, S., L. A. Frank, K. Hayashi, Y. Kamide, R. P. Lepping, T. Mukai, R. Nakamura, T. Yamamoto, and K. Yumoto, Large field events in the distant magnetotail during magnetic storms, *J. Geomag. Geoelectr.*, **48**, 561–575, 1996.

Matsuoka, H., K. Takahashi, S. Kokubun, K. Yumoto, T. Yamamoto, S. I. Solovyev, and E. F. Vershinin, Phase and amplitude structure of Pc 3 magnetic pulsations as determined from multipoint observations, *J. Geophys. Res.*, **102**, 1997 (in press).

Menk, F. W. and K. Yumoto, Conjugate and meridional phase structure of low latitude ULF pulsations, *Adv. Space Res.*, **5**, 425–428, 1994.

Nakamura, R., S. Kokubun, Y. Kamide, K. Yumoto, T. Yamamoto, L. A. Frank, W. R. Paterson, E. Friis-Christensen, K. Hayashi, T. Iyemori, H. Lühr, and O. A. Troshichev, Observations of the magnetosheath near the nominal tail axis during the geomagnetic storm of January 25, 1993, *J. Geomag. Geoelectr.*, **48**, 577–588, 1996.

Osaki, H., K. Yumoto, K. Fukao, K. Shiokawa, F. W. Menk, B. J. Fraser, and the 210° MM Magnetic Observation Group, Characteristics of low-latitude Pi 2 pulsations along the 210° magnetic meridian, *J. Geomag. Geoelectr.*, **48**, this issue, 1421–1430, 1996.

Petrinec, S. M., K. Yumoto, H. Lühr, D. Orr, D. Milling, K. Hayashi, S. Kokubun, and T. Araki, The CME event of February 21, 1994: Response of the magnetic field at the Earth's surface, *J. Geomag. Geoelectr.*, **48**, this issue, 1341–1379, 1996.

Pilipenko, V. A., N. G. Kleimenova, O. V. Kozyreva, K. Yumoto, and J. Bittery, Is Cusp the source of mid-latitude Pc 3 pulsations ?, *Geomagn. Aeron.*, **36**, 39–48, 1995.

Pilipenko, V. A., K. Yumoto, E. Fedorov, N. Kurneva, and F. Menk, Some peculiarities of field line Alfven oscillations at low latitudes, *Ann. Geophys.*, 1996 (to be submitted).

Seto, M., K. Yumoto, Y. Kitamura, and the 210° MM Magnetic Observation Group, Induction arrow computed for the 210° MM magnetic observation stations in Australia, *Mem. Fac. Sci., Kyushu Univ.*, **29**, 1996 (in press).

Shiokawa, K., K. Yumoto, Y. Tanaka, T. Oguti, and Y. Kiyama, Low-latitude auroras observed at Moshiri and Rikubetsu (L = 1.6) during magnetic storms on February 26, 27, 29, and May 10, 1992, *J. Geomag. Geoelectr.*, **46**, 231–252, 1994.

Shiokawa, K., K. Yumoto, Y. Tanaka, Y. Kiyama, Y. Kamide, and M. Tokumaru, A low-latitude aurora observed at Rikubetsu (L = 1.6) during the magnetic storm of September 13, 1993, *Proc. NIPR Symp. Upper Atmos. Phys.*, **8**, 17–23, 1995a.

Shiokawa, K., K. Yumoto, K. Hayashi, T. Oguti, and D. J. McEwen, A statistical study of the motions of auroral arcs on the high-latitude morning sector, *J. Geophys. Res.*, **100**, 21979–21983, 1995b.

Shiokawa, K., K. Yumoto, N. Nishitani, K. Hayashi, T. Oguti, D. J. McEwen, Y. Kiyama, F. J. Rich, and T. Mukai, Quasi-periodic poleward motions of Sun-aligned auroral arcs in the high latitude morning sector—A case study, *J. Geophys. Res.*, **101**, 19789–19800, 1996a.

Shiokawa, K., K. Yumoto, C.-I. Meng, and G. Reeves, Broadband electrons observed by the DMSP satellites during storm-time substorms, *Geophys. Res. Lett.*, **23**, 2529–2532, 1996b.

Shiokawa, K., K. Yumoto, Y. Tanaka, H. Osaki, M. Sato, T. Kato, Y. Kato, M. Sera, Y. Ikegami, S.-I. Akasofu, K. Hayashi, T. Oguti, and Y. Kiyama, Auroral observations using automatic optical instruments: Relations with multiple Pi 2 magnetic pulsations, *J. Geomag. Geoelectr.*, **48**, this issue, 1407–1419, 1996c.

Shiokawa, K., C.-I. Meng, G. Reeves, F. J. Rich, and K. Yumoto, Broadband electrons observed by the DMSP satellites during storm-time substorms, A multi-event study, *J. Geophys. Res.*, 1996d (to be submitted).

Tanaka Y. and K. Yumoto, Study on the magnetospheric processes at low latitudes by means of magnetic meridian networks, *Gakujyutsu Geppou*, **46**(9), 846–852, 1993.

Yumoto, K. and 210° Magnetic Meridian Observation Group, Collaborative GB magnetometer observations along 210° and 250° magnetic meridians, in *COSPAR Colloquia Ser. 5 on Solar Terrestrial Energy Program*, edited by D. N. Baker, V. O. Patitashvili, and M. J. Teague, pp. 639–642, Pergamon Press, New York, Oxford, 1994.

Yumoto, K. and the 210° MM Magnetic Observation Group, Initial results from the 210° magnetic meridian project—Review, *J. Geomag. Geoelectr.*, **47**, 1197–1213, 1995.

Yumoto, K. and H. Utada, Geophysical study of western Pacific region by means of undersea cables and magnetometer network, *Proc. Conductivity Anomaly*, 229–245, 1993.

Yumoto, K., Y. Tanaka, T. Oguti, and K. Shiokawa, Globally coordinated magnetic observations along 210° magnetic meridian during STEP period, *STER Jpn.*, **15**, 100–105, 1991.

Yumoto, K., Y. Tanaka, T. Oguti, K. Shiokawa, Y. Yoshimura, A. Isono, B. J. Fraser, F. W. Menk, and the 210° MM Magnetic Observation Group, Globally coordinated magnetic observations along 210° magnetic meridian during STEP period, 1, Preliminary results of low-latitude Pc 3's, *J. Geomag. Geoelectr.*, **44**, 261–276, 1992.

Yumoto, K., B. A. Pilipenko, E. H. Fedorov, and H. A. Kurneva, Mechanism of damping of geomagnetic pulsations at low latitudes, *Geomagn. Aeron.*, **33**, No. 5, 34–41, 1993a.

Yumoto, K., K. Shiokawa, Y. Tanaka, S. Kokubun, M. Seto, T. Sakurai, T. Takahashi, S. Tsunomura, F. W. Menk, K. J. W. Lynn, L. Corbett, J. A. Kennewell, A. W. Green, P. Hattori, M. Blackford, D. Yeboah-Amankwah, S. L. Manurung, E. F. Vershinin, V. F. Osinin, G. Krymskij, S. I. Solovyev, V. A. Pilipenko, and R. J. Morris, Daily magnetograms: (STEP) 210° MM network, *STER Jpn.*, **17**, 45–53, 1993b.

Yumoto, K., T. Endo, K. Shiokawa, Y. Tanaka, and the 210° MM Magnetic Observation Group, Ionospheric current and magnetic variations caused by low latitude aurorae, in *COSPAR Colloqa Ser. Vol. 7 on Low-Latitude Ionospheric Physics*, edited by Fu-Shong Kuo, pp. 241–250, Pergamon Press, New York, Oxford, 1994a.

Yumoto K., A. Isono, K. Shiokawa, H. Matsuoka, Y. Tanaka, F. W. Menk, B. J. Fraser, and the 210° MM Magnetic Observation Group, Global cavity mode-like and localized field-line Pc 3-4 oscillations stimulated by interplanetary impulse (si/sc): Initial results from the 210° MM magnetic observations, *AGU Geophysical Monograph on Solar Wind Sources of Magnetospheric ULF Waves*, **81**, 335–344, 1994b.

Yumoto, K., K. Shiokawa, Y. Tanaka, and T. Oguti, Characteristics of magnetic variations caused by low-latitude aurorae observed around 210° magnetic meridian, *J. Geomag. Geoelectr.*, **46**, 213–229, 1994c.

Yumoto, K., H. Osaki, K. Fukao, K. Shiokawa, Y. Tanaka, S. I. Soloveyev, G. Krymskij, E. F. Vershinin, V. F. Osinin, and 210° MM Magnetic Observation Group, Correlation of high- and low-latitude Pi 2 magnetic pulsations observed at 210° magnetic meridian chain stations, *J. Geomag. Geoelectr.*, **46**, 925–935, 1994d.

Yumoto, K., V. A. Pilipenko, E. Fedorov, N. Kurneva, and K. Shiokawa, The mechanisms of damping of geomagnetic pulsations, *J. Geomag. Geoelectr.*, **47**, 163–176, 1995.

Yumoto, K., H. Matsuoka, H. Osaki, K. Shiokawa, Y. Tanaka, T.-I. Kitamura, H. Tachihara, M. Shinohara, S. I. Solovyev, G. A. Makarov, E. F. Vershinin, A. V. Buzevich, S. L. Manurung, Obay Sobari, Mamat Ruhimat, Sukmadradjat, R. J. Morris, B. J. Fraser, F. W. Menk, K. J. W. Lynn, D. G. Cole, J. A. Kennewell, J. V. Olson, and S.-I. Akasofu, North/south asymmetry of sc/si magnetic variations observed along the 210° magnetic meridian, *J. Geomag. Geoelectr.*, **48**, this issue, 1333–1340, 1996a.

Yumoto, K., V. Pilipenko, E. Fedorov, N. Kurneva, and M. De Lauretis, Magnetospheric ULF phenomena stimulated by ssc, *J. Geomag. Geoelectr.*, 1996b (to be submitted).