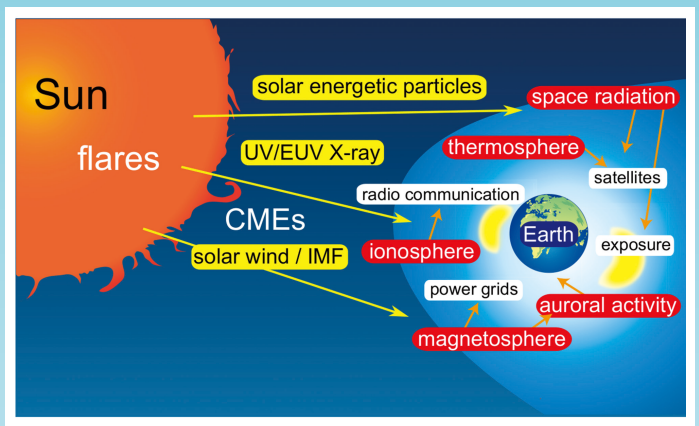
Earth, Planets and Space

Solar-Terrestrial Environment Prediction: Toward the Synergy of Science and Forecasting Operation of Space Weather and Space Climate



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Yours sincerely,

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Earth, Planets and Space

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PREFACE

Open Access

Special issue "Solar–terrestrial environment prediction: toward the synergy of science and forecasting operation of space weather and space climate"

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The space environmental variability (widely called "space weather") can influence the electromagnetic environment around the earth and human life. In particular, a severe space weather event caused by a large solar eruption is a potential risk to social infrastructures such as artificial satellites, aviation, electric power, communications, and positioning systems. Furthermore, it has been pointed out that long-term variation in the solar cycle may affect the global environment. Therefore, predicting the solar–terrestrial environment is important not only as scientific research, but also for sustaining a safe and secure modern society. However, the mechanism of solar–terrestrial environmental dynamics and its influence on the socio-economic system is not yet fully understood.

The special issue "Solar–Terrestrial Environment Prediction: Toward the Synergy of Science and Forecasting Operation of Space Weather and Space Climate" is a comprehensive summary of the current status of research on this issue. In Japan, a nation-wide joint project "the Project for Solar–Terrestrial Environment Prediction (PSTEP)" was conducted from 2015 to 2019 in order to improve this situation through synergy between the basic science research and the forecast operation. In this special issue, the various research papers of this project and the related studies are compiled as follows.

Kusano et al. (2021) summarized the major research achievements of PSTEP about the space weather forecasting system, the prediction of solar storm and geospace dynamics, solar cycle activity and its climate impact. The scale of space weather events and their occurrence rate in Japan was surveyed by Ishii et al. (2021), in which the information for the space weather disaster defense was assembled.

One of the major space weather impacts on the society is caused by geomagnetic induced current (GIC). Watari et al. (2021) overviewed GIC measurement systems and reported several examples of the measurements in substations around Tokyo, Japan. Yagova et al. (2021) analyzed GIC in a transformer at the terminal station at Vykhodnoy, Russia, during the entire year of 2015 and found that large-scale pulsations are more effective in GIC generation than small-scale pulsations. Kikuchi et al. (2021) observed the electromagnetic disturbance caused by the geomagnetic sudden commencement (SC) using the high-frequency (HF) Doppler sounders at middle and low latitudes and confirmed that the electric field signal propagates near-instantaneously (within 10 s) over the globe.

The evaluation of the influence of energetic particles on satellites and aircraft is an important task for the space weather forecast. Nagatsuma et al. (2021) developed the Space Environment Customized Risk Estimation for Satellites (SECURES) system by combining models of the space environment and those of spacecraft charging.

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Saito et al. (2021) estimated the economic impact of atmospheric radiation storm associated with solar energetic particle (SEP) events on aircraft operations by using the Warning System for AVIation Exposure to Solar energetic particle (WASAVIES). Oka et al. (2021) analyzed an unusual short-duration SEP event and found that the higher-energy (>30 MeV) protons were detected about four hours after the shock arrival of ICME. The impact of energetic particle precipitation on atmospheric chemistry was investigated by Tsuda et al. (2021) and they found that the Na loss around the topside of Na layer would be induced by the energetic particle precipitation.

Many papers on the ionospheric dynamics and its prediction are published by this special issue. Nishioka et al. (2021) statistically analyzed the extreme states of ionospheric total electron content (TEC) in Japan. Tao et al. (2020b) also analyzed the statistics of short-wave fadeout for extreme space weather event estimation. Otsuka et al. (2021) studied the solar activity dependence of medium-scale traveling ionospheric disturbances (MSTID) using GPS receivers in Japan. Hosokawa et al. (2020) monitored the anomalous propagation of aeronautical VHF radio waves due to sporadic E layer in Japan.

The Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) is a powerful tool to simulate and predict the dynamics of ionosphere and atmosphere. Shinagawa et al. (2021) developed the numerical prediction of sporadic E layer occurrence using the GAIA. Ghosh et al. (2020) investigated the day-to-day variation of pre-reversal enhancement in the equatorial ionosphere based on GAIA model simulations. Sivakandan et al. (2021) compared the seasonal and longitudinal variation of daytime MSTID activity using GPS observation and GAIA simulations. Tao et al. (2020a) reported the numerical forecast of the upper atmosphere and ionosphere using GAIA, in particular for ionospheric storms and sudden stratospheric warming.

The solar cycle dynamics and solar eruptions are the major cause of space weather variation in the long term and short term, respectively, and their prediction is one of the most important subjects in this special issue. The variability of solar differential rotation and meridional flow were analyzed by Imada et al. (2020) using the magnetic element feature tracking technique. Seki et al. (2021) studied the relationship between three-dimensional velocity of filament eruptions and CME based on the Doppler observations. A new infrared observation for solar polarimetry was developed by Hanaoka et al. (2020).

Nishizuka et al. (2021) reported the operational solar flare prediction model using Deep Flare Net. Watanabe et al. (2021) reported the model-based reproduction and validation of the total spectra of a solar flare and their impact on the global environment. Nishimoto et al. (2021) examined the computed extreme ultraviolet emission spectra during solar flares. The advanced method for the CME arrival-time forecasts was developed based on the assimilation of magnetohydrodynamic simulations and the interplanetary scintillation observations by Iwai et al. (2021).

It is also crucial to investigate the details of the severe space weather phenomena that occurred in the past from the literature and records for considering countermeasures against future space weather disasters. Hayakawa et al. (2020) reported the record of south American aurora during the Carrington storm. Oliveira et al. (2020) investigated a possible case of sporadic aurora observed at Rio de Janeiro. Kataoka (2020) statistically analyzed extreme geomagnetic activities.

As mentioned already, solar–terrestrial environment prediction is necessary to protect the future society. However, for its development, the cooperation between various related research fields and their applications is essential. This special issue summarizes the latest efforts for it. We hope that further study will progress through the synergy between scientific research and the operational forecast of space weather.

Acknowledgements
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Authors' contributions
KK, MI, TB, YM, SY, HL, TO, and KI served as guest editors for this special issue. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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References

Ghosh P, Otsuka Y, Mani S, Shinagawa H (2020) Day-to-day variation of pre-reversal enhancement in the equatorial ionosphere based on GAIA model simulations. Earth Planets Space 72:93. https://doi.org/10.1186/s40623-020-01228-9

Hanaoka Y, Katsukawa Y, Morita S, Kamata Y, Ishizuka N (2020) A HAWAII-2RG infrared camera operated under fast readout mode for solar polarimetry. Earth Planets Space 72:181. https://doi.org/10.1186/s40623-020-01318-8

Hayakawa H, Ribeiro JR, Ebihara Y, Correia AP, Sôma M (2020) South American auroral reports during the Carrington storm. Earth Planets Space 72:122. https://doi.org/10.1186/s40623-020-01249-4

Hosokawa K, Sakai J, Tomizawa I, Saito S, Tsugawa T, Nishioka M et al (2020) A monitoring network for anomalous propagation of aeronautical VHF radio waves due to sporadic E in Japan. Earth Planets Space 72:88. https://doi.org/10.1186/s40623-020-01216-z
Imada S, Matoba K, Fujiyama M, Iijima H (2020) Solar cycle-related variation in solar differential rotation and meridional flow in solar cycle 24. Earth Planets Space 72:182. https://doi.org/10.1186/s40623-020-01314-y
Ishii M, Shiota D, Tao C, Ebihara Y, Fujiwara H, Ishii T et al (2021) Space weather benchmarks on Japanese society. Earth Planets Space 73:108. https://doi.org/10.1186/s40623-021-01420-5
Iwai K, Shiota D, Tokumaru M, Fujiki K, Den M, Kubo Y (2021) Validation of coronal mass ejection arrival-time forecasts by magnetohydrodynamic simulations based on interplanetary scintillation observations. Earth Planets Space 73:9. https://doi.org/10.1186/s40623-020-01345-5
Kataoka R (2020) Extreme geomagnetic activities: a statistical study. Earth Planets Space 72:124. https://doi.org/10.1186/s40623-020-01261-8
Kikuchi T, Chum J, Tomizawa I, Hashimoto KK, Hosokawa K, Ebihara Y et al (2021) Penetration of the electric fields of the geomagnetic sudden commencement over the globe as observed with the HF Doppler sounders and magnetometers. Earth Planets Space 73:10. https://doi.org/10.1186/s40623-020-01350-8
Kusano K, Ichimoto K, Ishii M, Miyoshi Y, Yoden S, Akiyoshi H et al (2021) PSTEP: project for solar–terrestrial environment prediction. Earth Planets Space 73:159. https://doi.org/10.1186/s40623-021-01486-1
Nagatsuma T, Nakamizo A, Kubota Y, Nakamura M, Koga K, Miyoshi Y et al (2021) Development of space environment customized risk estimation for satellites (SECURES). Earth Planets Space 73:26. https://doi.org/10.1186/s40623-021-01355-x
Nishimoto S, Watanabe K, Kawai T, Imada S, Kawate T (2021) Validation of computed extreme ultraviolet emission spectra during solar flares. Earth Planets Space 73:79. https://doi.org/10.1186/s40623-021-01402-7
Nishioka M, Saito S, Tao C, Shiota D, Tsugawa T, Ishii M (2021) Statistical analysis of ionospheric total electron content (TEC): long-term estimation of extreme TEC in Japan. Earth Planets Space 73:52. https://doi.org/10.1186/s40623-021-01374-8
Nishizuka N, Kubo Y, Sugiura K, Den M, Ishii M (2021) Operational solar flare prediction model using Deep Flare Net. Earth Planets Space 73:64. https://doi.org/10.1186/s40623-021-01381-9
Oka M, Obara T, Nitta NV, Yashiro S, Shiota D, Ichimoto K (2021) Unusual enhancement of ~ 30 MeV proton flux in an ICME sheath region. Earth Planets Space 73:31. https://doi.org/10.1186/s40623-021-01362-y
Oliveira DM, Hayakawa H, Bhaskar A, Zesta E, Vichare G (2020) A possible case of sporadic aurora observed at Rio de Janeiro. Earth Planets Space 72:82. https://doi.org/10.1186/s40623-020-01208-z
Otsuka Y, Shinbori A, Tsugawa T, Nishioka M (2021) Solar activity dependence of medium-scale traveling ionospheric disturbances using GPS receivers in Japan. Earth Planets Space 73:22. https://doi.org/10.1186/s40623-020-01353-5
Saito S, Wickramasinghe NK, Sato T, Shiota D (2021) Estimate of economic impact of atmospheric radiation storm associated with solar energetic particle events on aircraft operations. Earth Planets Space 73:57. https://doi.org/10.1186/s40623-021-01377-5
Seki D, Otsuji K, Ishii TT, Asai A, Ichimoto K (2021) Relationship between three-dimensional velocity of filament eruptions and CME association. Earth Planets Space 73:58. https://doi.org/10.1186/s40623-021-01378-4
Shinagawa H, Tao C, Jin H, Miyoshi Y, Fujiwara H (2021) Numerical prediction of sporadic E layer occurrence using GAIA. Earth Planets Space 73:28. https://doi.org/10.1186/s40623-020-01330-y
Sivakandan M, Otsuka Y, Ghosh P, Shinagawa H, Shinbori A, Miyoshi Y (2021) Comparison of seasonal and longitudinal variation of daytime MSTID activity using GPS observation and GAIA simulations. Earth Planets Space 73:35. https://doi.org/10.1186/s40623-021-01369-5
Tao C, Jin H, Miyoshi Y, Shinagawa H, Fujiwara H, Nishioka M et al (2020a) Numerical forecast of the upper atmosphere and ionosphere using GAIA. Earth Planets Space 72:178. https://doi.org/10.1186/s40623-020-01307-x
Tao C, Nishioka M, Saito S, Shiota D, Watanabe K, Nishizuka N et al (2020b) Statistical analysis of short-wave fadeout for extreme space weather event estimation. Earth Planets Space 72:173. https://doi.org/10.1186/s40623-020-01278-z
Tsuda TT, Tanaka Y-M, Tozu R, Takizawa K, Ejiri MK, Nishiyama T et al (2021) Relationship between Na layer and CNA variations observed at Syowa. Antarctic Earth Planets Space 73:7. https://doi.org/10.1186/s40623-020-01335-7
Watanabe K, Jin H, Nishimoto S, Imada S, Kawai T, Kawate T et al (2021) Model-based reproduction and validation of the total spectra of a solar flare and their impact on the global environment at the X93 event of September 6. Earth Planets Space 73:96. https://doi.org/10.1186/s40623-021-01376-6
Watari S, Nakamura S, Ebihara Y (2021) Measurement of geomagnetically induced current (GIC) around Tokyo, Japan. Earth Planets Space 73:102. https://doi.org/10.1186/s40623-021-01422-3
Yagova NV, Pilipenko VA, Sakharov YA, Selivanov VN (2021) Spatial scale of geomagnetic Pc5/Pi3 pulsations as a factor of their efficiency in generation of geomagnetically induced currents. Earth Planets Space 73:88. https://doi.org/10.1186/s40623-021-01407-2

Publisher's Note

FRONTIER LETTER Open Access

PSTEP: project for solar–terrestrial environment prediction

Kanya Kusano*, Kiyoshi Ichimoto, Mamoru Ishii, Yoshizumi Miyoshi, Shigeo Yoden, Hideharu Akiyoshi, Ayumi Asai, Yusuke Ebihara, Hitoshi Fujiwara, Tada-Nori Goto, Yoichiro Hanaoka, Hisashi Hayakawa, Keisuke Hosokawa, Hideyuki Hotta, Kornyanat Hozumi, Shinsuke Imada, Kazumasa Iwai, Toshihiko Iyemori, Hidekatsu Jin, Ryuho Kataoka, Yuto Katoh, Takashi Kikuchi, Yûki Kubo, Satoshi Kurita, Haruhisa Matsumoto, Takefumi Mitani, Hiroko Miyahara, Yasunobu Miyoshi, Tsutomu Nagatsuma, Aoi Nakamizo, Satoko Nakamura, Hiroyuki Nakata, Naoto Nishizuka, Yuichi Otsuka, Shinji Saito, Susumu Saito, Takashi Sakurai, Tatsuhiko Sato, Toshifumi Shimizu, Hiroyuki Shinagawa, Kazuo Shiokawa, Daikou Shiota, Takeshi Takashima, Chihiro Tao, Shin Toriumi, Satoru Ueno, Kyoko Watanabe, Shinichi Watari, Seiji Yashiro, Kohei Yoshida and Akimasa Yoshikawa

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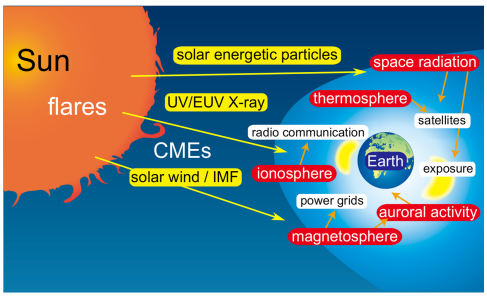
Abstract

Although solar activity may significantly impact the global environment and socioeconomic systems, the mechanisms for solar eruptions and the subsequent processes have not yet been fully understood. Thus, modern society supported by advanced information systems is at risk from severe space weather disturbances. Project for solar–terrestrial environment prediction (PSTEP) was launched to improve this situation through synergy between basic science research and operational forecast. The PSTEP is a nationwide research collaboration in Japan and was conducted from April 2015 to March 2020, supported by a Grant-in-Aid for Scientific Research on Innovative Areas from the Ministry of Education, Culture, Sports, Science and Technology of Japan. By this project, we sought to answer the fundamental questions concerning the solar–terrestrial environment and aimed to build a next-generation space weather forecast system to prepare for severe space weather disasters. The PSTEP consists of four research groups and proposal-based research units. It has made a significant progress in space weather research and operational forecasts, publishing over 500 refereed journal papers and organizing four international symposiums, various workshops and seminars, and summer school for graduate students at Rikubetsu in 2017. This paper is a summary report of the PSTEP and describes the major research achievements it produced.

Keywords: Solar physics, Solar–terrestrial environment, Space weather, Earth environmental system



Graphical abstract

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FULL PAPER Open Access

Extreme geomagnetic activities: a statistical study

Ryuho Kataoka

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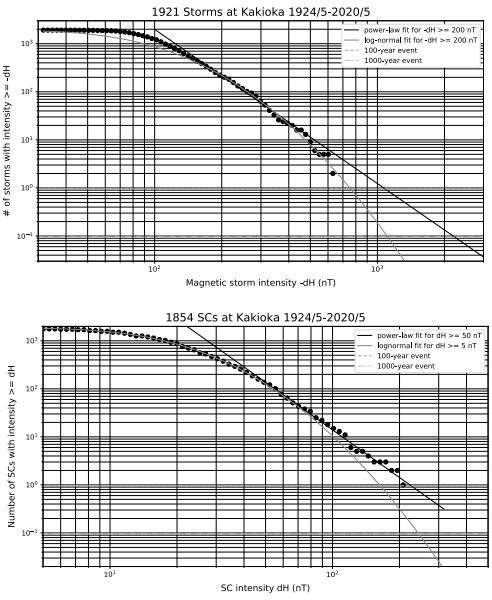
Abstract

Statistical distributions are investigated for magnetic storms, sudden commencements (SCs), and substorms to identify the possible amplitude of the one in 100-year and 1000-year events from a limited data set of less than 100 years. The lists of magnetic storms and SCs are provided from Kakioka Magnetic Observatory, while the lists of substorms are obtained from SuperMAG. It is found that majorities of events essentially follow the log-normal distribution, as expected from the random output from a complex system. However, it is uncertain that large-amplitude events follow the same log-normal distributions, and rather follow the power-law distributions. Based on the statistical distributions, the probable amplitudes of the 100-year (1000-year) events can be estimated for magnetic storms, SCs, and substorms as approximately 750 nT (1100 nT), 230 nT (450 nT), and 5000 nT (6200 nT), respectively. The possible origin to cause the statistical distributions is also discussed, consulting the other space weather phenomena such as solar flares, coronal mass ejections, and solar energetic particles.

Keywords: Magnetic storms, Sudden commencements, Substorms, Solar flares, Coronal mass ejections, Solar energetic particles, Log-normal distributions, Power-law distributions



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Statistical analysis of short-wave fadeout for extreme space weather event estimation

Chihiro Tao*, Michi Nishioka, Susumu Saito, Daikou Shiota, Kyoko Watanabe, Naoto Nishizuka, Takuya Tsugawa and Mamoru Ishii

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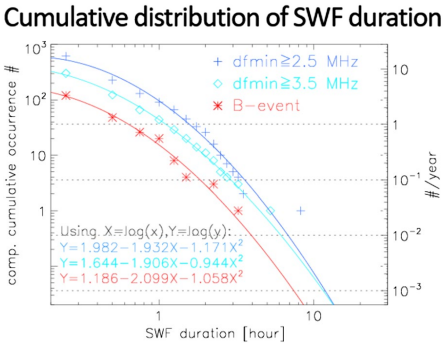
Abstract

Solar flares trigger an increase in plasma density in the ionosphere including the D region, and cause the absorption of radio waves, especially in high-frequency (HF) ranges, called short-wave fadeout (SWF). To evaluate the SWF duration and absorption statistically, we analyze long-term (36 years) ionosonde data observed by the National Institute of Information and Communications Technology (NICT). The minimum reflection frequency, *f*min, is used to detect SWFs from 15-min-resolution ionosonde observations at Kokubunji, Tokyo, from 1981 to 2016. Since *f*min varies with local time (LT) and season, we refer to d*f*min, which is defined as *f*min subtracted by its 27-day running median at the same LT. We find that the occurrence of SWFs detected by three criteria, (i) d*f*min ≥ 2.5 MHz, (ii) d*f*min ≥ 3.5 MHz, and (iii) blackout, during daytime associated with any flare(s) greater than the C1 class is maximized at local noon and decreases with increasing solar zenith angle. We confirm that the d*f*min and duration of SWFs increase with the solar flare class. We estimate the absorption intensity from observations, which is comparable to an empirical relationship obtained from sudden cosmic noise absorption. A generalized empirical relationship for absorption from long-distance circuits shows quantitatively different dependences on solar flare flux, solar zenith angle, and frequency caused by different signal passes compared with that obtained from cosmic noise absorption. From our analysis and the empirical relationships, we estimate the duration of extreme events with occurrence probabilities of once per 10, 100, and 1000 years to be 1.8–3.6, 4.0–6.8, and 7.4–11.9 h, respectively. The longest duration of SWFs of about 12 h is comparable to the solar flare duration derived from an empirical relationship between the solar flare duration and the solar active area for the largest solar active region observed so far.

Keywords: Short-wave fadeout (SWF), Dellinger effect, Ionosphere, Solar flare, Ionosonde, HF radio, Space weather



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Numerical forecast of the upper atmosphere and ionosphere using GAIA

Chihiro Tao*, Hidekatsu Jin, Yasunobu Miyoshi, Hiroyuki Shinagawa, Hitoshi Fujiwara, Michi Nishioka and Mamoru Ishii

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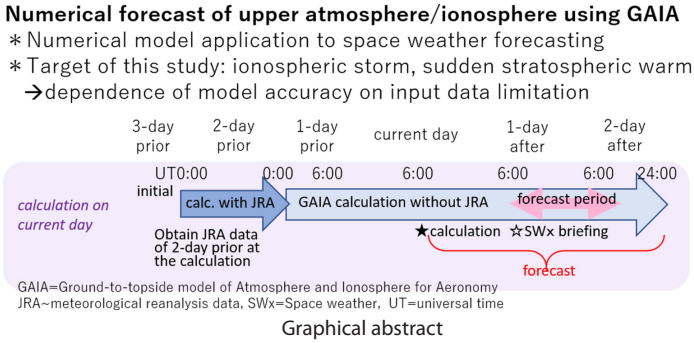
Abstract

Upper atmospheric conditions are crucial for the safe operation of spacecraft orbiting near Earth and for communication and positioning systems using radio signals. To understand and predict the upper atmospheric conditions, which include complex variations affected by both low altitude and upper surrounding environments, we have developed a quasi-real-time and forecast simulations using a physical global model, the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA). The GAIA simulation system provides a global distribution of ionospheric total electron content (TEC) with background atmospheric and electric distributions including a few-days prediction. The prediction accuracy for the detection of significant ionospheric storms decreases with increasing lead time, i.e., the duration of the model simulation which is not constrained by realistic input parameters. Similar characteristic variations associated with sudden stratospheric warmings (SSWs) are reproduced with the full or limited input of meteorological data at least the prior 3 days. This is a first step toward the usage of GAIA for space weather forecasting.

Keywords: GAIA, Ionosphere, Upper atmosphere, Space weather, Real-time simulation



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Solar cycle-related variation in solar differential rotation and meridional flow in solar cycle 24

Shinsuke Imada*, Kengo Matoba, Masashi Fujiyama and Haruhisa Iijima

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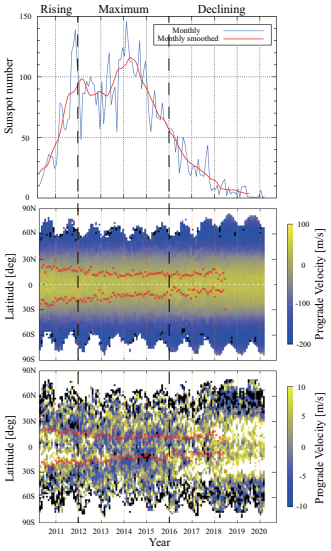
Abstract

We studied temporal variation of the differential rotation and poleward meridional circulation during solar cycle 24 using the magnetic element feature tracking technique. We used line-of-sight magnetograms obtained using the helioseismic and magnetic imager aboard the Solar Dynamics Observatory from May 01, 2010 to March 26, 2020 (for almost the entire period of solar cycle 24, Carrington rotation from 2096 to 2229) and tracked the magnetic element features every 1 h. We also estimated the differential rotation and poleward meridional flow velocity profiles. The observed profiles are consistent with those of previous studies on different cycles. Typical properties resulting from torsional oscillations can also be observed from solar cycle 24. The amplitude of the variation was approximately ±10 m s^{-1}. Interestingly, we found that the average meridional flow observed in solar cycle 24 is faster than that observed in solar cycle 23. In particular, during the declining phase of the cycle, the meridional flow of the middle latitude is accelerated from 10 to 17 m s^{-1}, which is almost half of the meridional flow itself. The faster meridional flow in solar cycle 24 might be the result of the weakest cycle during the last 100 years.

Keywords: Solar surface flow, Solar cycle



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FULL PAPER Open Access

Relationship between Na layer and CNA variations observed at Syowa, Antarctic

T. T. Tsuda*, Y. -M. Tanaka, R. Tozu, K. Takizawa, M. K. Ejiri, T. Nishiyama, T. D. Kawahara and T. Nakamura

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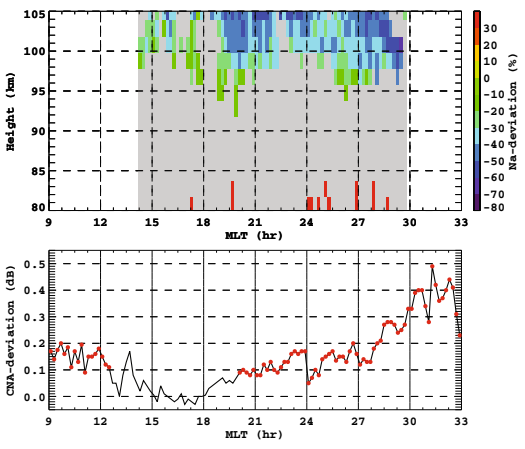
Abstract

We have performed a statistical data analysis on relationship between simultaneous Na density data and cosmic noise absorption (CNA) data, which is an indicator for energetic particle precipitation, obtained at Syowa, Antarctic in 2000–2002. It is found that the Na densities around the topside of Na layers (above ~95km height) tended to be smaller when the CNA was larger. The amounts of Na density responses, i.e., Na density decrease or Na loss, were increasing with magnetic local time (MLT) from dusk hours to dawn hours, and those of CNA responses, i.e., CNA increase, were also increasing with MLT. Thus, there were clear negative correlations between the Na density and CNA variations. These results indicate that the Na loss around the topside of Na layer would be induced by the energetic particle precipitation, and its effect would be more severe in dawn hours.

Keywords: Na layer, CNA, Energetic particle precipitation, Geomagnetic activity, Polar region, Syowa



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Penetration of the electric fields of the geomagnetic sudden commencement over the globe as observed with the HF Doppler sounders and magnetometers

Takashi Kikuchi*, Jaroslav Chum, Ichiro Tomizawa, Kumiko K. Hashimoto, Keisuke Hosokawa, Yusuke Ebihara, Kornyanat Hozumi and Pornchai Supnithi

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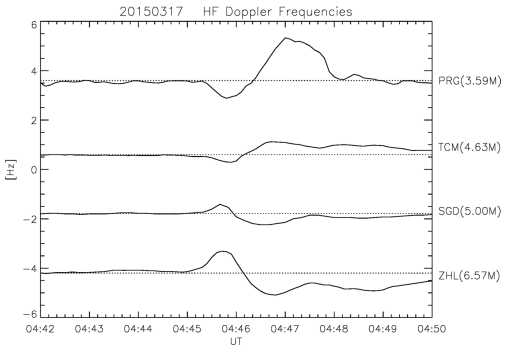
Abstract

Using the HF Doppler sounders at middle and low latitudes (Prague, Czech Republic; Tucuman, Argentina; Zhongli, Republic of China, and Sugadaira, Japan), we observed the electric fields of the geomagnetic sudden commencement (SC) propagating near-instantaneously (within 10 s) over the globe. We found that the electric fields of the preliminary impulse (PI) and main impulse (MI) of the SC are in opposite direction to each other and that the PI and MI electric fields are directed from the dusk to dawn and dawn to dusk, respectively, manifesting the nature of the curl-free potential electric field. We further found that the onset and peak of the PI electric field are simultaneous on the day and nightsides (0545, 1250, 1345 MLT) within the resolution of 10 s. With the magnetometer data, we confirmed the near-instantaneous development of the ionospheric currents from high latitudes to the equator and estimated the location of the field-aligned currents that supply the ionospheric currents. The global simultaneity of the electric and magnetic fields does not require the contribution of the magnetohydrodynamic waves in the magnetosphere nor in the F-region ionosphere. The global simultaneity and day–night asymmetry of the electric fields are explained with the ionospheric electric potentials transmitted at the speed of light by the TM_0 mode waves in the Earth-ionosphere waveguide.

Keywords: HF Doppler sounder, Penetration electric field, Geomagnetic sudden commencement, Preliminary impulse, Global simultaneous onset, TM_0 mode wave in the earth-ionosphere waveguide, Polar-equatorial ionospheric currents



Graphical abstract

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FULL PAPER Open Access

Solar activity dependence of medium-scale traveling ionospheric disturbances using GPS receivers in Japan

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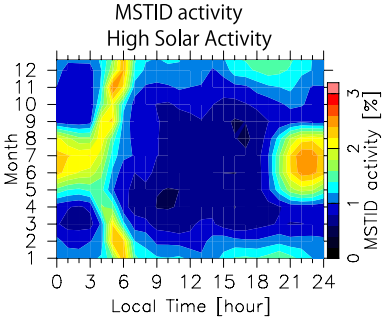
Abstract

In order to reveal solar activity dependence of the medium-scale traveling ionospheric disturbances (MSTIDs) at midlatitudes, total electron content (TEC) data obtained from a Global Positioning System (GPS) receiver network in Japan during 22 years from 1998 to 2019 were analyzed. We have calculated the detrended TEC by subtracting the 1-h running average from the original TEC data for each satellite and receiver pair, and made two-dimensional TEC maps of the detrended TEC with a spatial resolution of 0.15° × 0.15° in longitude and latitude. We have investigated MSTID activity, defined as $\delta I/\bar{I}$, where δI and $\bar{I}$ are standard deviation of the detrended TEC and the average vertical TEC within the area of 133.0°–137.0° E and 33.0°–37.0° N for 1 h, respectively. From each 2-h time series of the detrended TEC data within the same area as the MSTID activity, auto-correlation functions (ACFs) of the detrended TEC were calculated to estimate the horizontal propagation velocity and direction of the MSTIDs. Statistical results of the MSTID activity and propagation direction of MSTIDs were consistent with previous studies and support the idea that daytime MSTIDs could be caused by atmospheric gravity waves, and that nighttime MSTIDs were caused by electro-dynamical forces, such as the Perkins instability. From the current long-term observations, we have found that the nighttime MSTID activity and occurrence rate increased with decreasing solar activity. For the daytime MSTID, the occurrence rate increased with decreasing solar activity, whereas the MSTID activity did not show distinct solar activity dependence. These results suggest that the secondary gravity waves generated by dissipation of the primary gravity waves propagating from below increase under low solar activity conditions. The mean horizontal phase velocity of the MSTIDs during nighttime did not show a distinct solar activity dependence, whereas that during daytime showed an anticorrelation with solar activity. The horizontal phase velocity of the daytime MSTIDs was widely distributed from 40 to 180 m/s under high solar activity conditions, whereas it ranged between 80 and 200 m/s, with a maximum occurrence at 130 m/s under low solar activity conditions, suggesting that gravity waves with low phase velocity could be dissipated by high viscosity in the thermosphere under low solar activity conditions.

Keywords: Ionosphere, Traveling ionospheric disturbance, TID, MSTID, GPS, Total electron content, TEC, Gravity wave, Perkins instability



Graphical abstract

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FULL PAPER Open Access

Development of space environment customized risk estimation for satellites (SECURES)

Tsutomu Nagatsuma*, Aoi Nakamizo, Yasubumi Kubota, Masao Nakamura, Kiyokazu Koga, Yoshizumi Miyoshi and Haruhisa Matsumoto

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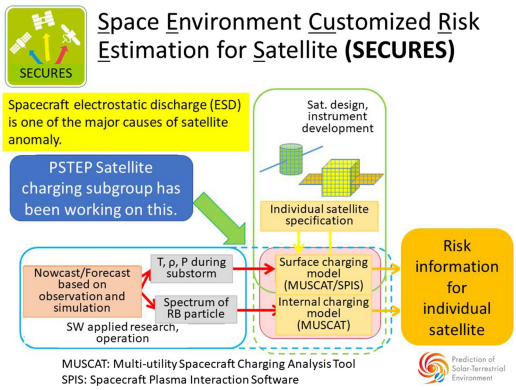
Abstract

Plasma variations in the geospace environment driven by solar wind–magnetosphere interactions are one of the major causes of satellite anomaly. To mitigate the effect of satellite anomaly, the risk of space weather disturbances predicted by space weather forecasting needs to be known in advance. However, the risk of satellite anomaly owing to space weather disturbances is not the same for all satellites, because the risk depends not only on the space environment itself but also on the design and materials of individual satellites. From the viewpoint of satellite operators, it is difficult to apply a general alert level of the space environment to the risk of individual satellites. To provide tailored space weather information, we have developed SECURES (Space Environment Customized Risk Estimation for Satellites) by combining models of the space environment and those of spacecraft charging. In SECURES, we focus on the risk of spacecraft charging (surface/internal) for geosynchronous satellites. For the risk estimation of surface charging, we have combined the global magnetosphere magnetohydrodynamics (MHD) model with the satellite surface charging models. For the risk estimation of internal charging, we have combined the radiation belt models with the satellite internal charging models. We have developed prototype products for both types of charging/electrostatic discharge (ESD). The development of SECURES and our achievements are introduced in this paper.

Keywords: Space weather forecasting, Geospace, Satellite anomaly, Satellite charging, Customized risk estimation



Graphical abstract

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FULL PAPER Open Access

Numerical prediction of sporadic E layer occurrence using GAIA

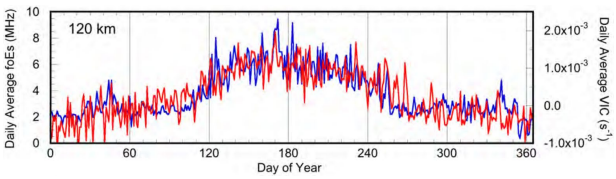
Hiroyuki Shinagawa*, Chihiro Tao, Hidekatsu Jin, Yasunobu Miyoshi and Hitoshi Fujiwara

Earth, Planets and Space 2021, **73**:28 DOI: 10.1186/s40623-020-01330-y
Received: 19 July 2020, Accepted: 3 December 2020, Published: 27 January 2021

Abstract

A sporadic E layer has significant influence on radio communications and broadcasting, and predicting the occurrence of sporadic E layers is one of the most important issues in space weather forecast. While sporadic E layer occurrence and the magnitude of the critical sporadic E frequency (*foEs*) have clear seasonal variations, significant day-to-day variations as well as regional and temporal variations also occur. Because of the highly complex behavior of sporadic E layers, the prediction of sporadic E layer occurrence has been one of the most difficult issues in space weather forecast. To explore the possibility of numerically predicting sporadic E layer occurrence, we employed the whole atmosphere–ionosphere coupled model GAIA, examining parameters related to the formation of sporadic E layer such as vertical ions velocities and vertical ion convergences at different altitudes between 90 and 150 km. Those parameters in GAIA were compared with the observed *foEs* data obtained by ionosonde observations in Japan. Although the agreement is not very good in the present version of GAIA, the results suggest a possibility that sporadic E layer occurrence can be numerically predicted using the parameters derived from GAIA. We have recently developed a real-time GAIA simulation system that can predict atmosphere–ionosphere conditions for a few days ahead. We present an experimental prediction scheme and a preliminary result for predicting sporadic E layer occurrence.

Keywords: Sporadic E layer, Wind shear, Occurrence, Prediction, GAIA, Model, Vertical ion convergence



Relationship between daily average *foEs* (blue) and daily average vertical ion convergence (red) at 120 km altitude.

Graphical abstract

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FULL PAPER Open Access

Comparison of seasonal and longitudinal variation of daytime MSTID activity using GPS observation and GAIA simulations

Mani Sivakandan*, Yuichi Otsuka, Priyanka Ghosh, Hiroyuki Shinagawa, Atsuki Shinbori and Yasunobu Miyoshi

Earth, Planets and Space 2021, **73**:35 DOI: 10.1186/s40623-021-01369-5
Received: 7 September 2020, Accepted: 23 January 2021, Published: 4 February 2021

Abstract

The total electron content (TEC) data derived from the GAIA (Ground-to-topside model of Atmosphere Ionosphere for Aeronomy) is used to study the seasonal and longitudinal variation of occurrence of medium-scale traveling ionospheric disturbances (MSTIDs) during daytime (09:00–15:00 LT) for the year 2011 at eight locations in northern and southern hemispheres, and the results are compared with ground-based Global Positioning System (GPS)-TEC. To derive TEC variations caused by MSTIDs from the GAIA (GPS) data, we obtained detrended TEC by subtracting 2-h (1-h) running average from the TEC, and calculated standard deviation of the detrended TEC in 2 h (1 h). MSTID activity was defined as a ratio of the standard deviation to the averaged TEC. Both GAIA simulation and GPS observations data show that daytime MSTID activities in the northern and southern hemisphere (NH and SH) are higher in winter than in other seasons. From the GAIA simulation, the amplitude of the meridional wind variations, which could be representative of gravity waves (GWs), shows two peaks in winter and summer. The winter peak in the amplitude of the meridional wind variations coincides with the winter peak of the daytime MSTIDs, indicating that the high GW activity is responsible for the high MSTID activity. On the other hand, the MSTID activity does not increase in summer. This is because the GWs in the thermosphere propagate poleward in summer, and equatorward in winter, and the equatorward-propagating GWs cause large plasma density perturbations compared to the poleward-propagating GWs. Longitudinal variation of daytime MSTID activity in winter is seen in both hemispheres. The MSTID activity during winter in the NH is higher over Japan than USA, and the MSTID activity during winter in the SH is the highest in South America. In a nutshell, GAIA can successfully reproduce the seasonal and longitudinal variation of the daytime MSTIDs. This study confirms that GWs cause the daytime MSTIDs in GAIA and amplitude and propagation direction of the GWs control the noted seasonal variation. GW activities in the middle and lower atmosphere cause the longitudinal variation.

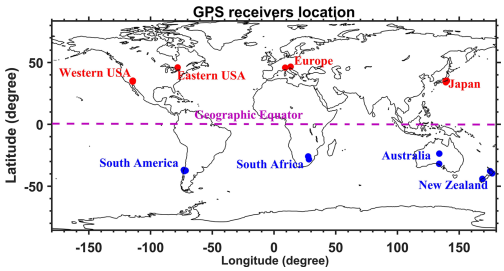

Fig. 1

Keywords: Daytime MSTIDs, GAIA model, GPS, Gravity waves, Meridional wind, TEC

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FULL PAPER Open Access

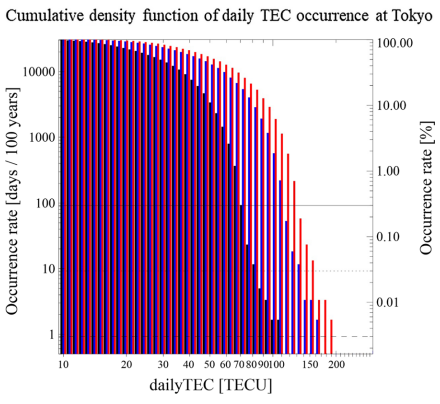
Statistical analysis of ionospheric total electron content (TEC): long-term estimation of extreme TEC in Japan

Michi Nishioka*, Susumu Saito, Chihiro Tao, Daikou Shiota, Takuya Tsugawa and Mamoru Ishii

Earth, Planets and Space 2021, **73**:52 DOI: 10.1186/s40623-021-01374-8
Received: 12 July 2020, Accepted: 2 February 2021, Published: 15 February 2021

Abstract

Ionospheric total electron content (TEC) is one of the key parameters for users of radio-based systems, such as the Global Navigation Satellite System, high-frequency communication systems, and space-based remote sensing systems, since total ionospheric delay is proportional to TEC through the propagation path. It is important to know extreme TEC values in readiness for hazardous ionospheric conditions. The purpose of this study is to estimate extreme TEC values with occurrences of once per year, 10 years, and hundred years in Japan. In order to estimate the extreme values of TEC, a cumulative distribution function of daily TEC is derived using 22 years of TEC data from 1997 to 2018. The extreme values corresponding to once per year and 10 years are 90 and 110 TECU, respectively, in Tokyo, Japan. On the other hand, the 22-year data set is not sufficient to estimate the once-per-100-year value. Thus, we use the 62-year data set of manually scaled ionosonde data for the critical frequency of the F-layer (foF2) at Kokubunji in Tokyo. First, we study the relationship between TEC and foF2 for 22 years and investigate the slab thickness. Then the result is applied to the statistical distribution of foF2 data for 62 years. In this study, two methods are applied to estimate the extreme TEC value. In the first method, the distribution of slab thickness is artificially inflated to estimate extreme TEC values. In the second method, extreme slab thicknesses are applied to estimate extreme TEC values. The result shows that the once-per-100-year TEC is about 150–190 TECU at Tokyo. The value is also estimated to be 180–230 TECU in Kagoshima and 120–150 TECU in Hokkaido, in the southern and northern parts of Japan, respectively.



Graphical abstract

Keywords: Total electron content (TEC), Extreme TEC, Long-term ionosonde observation, Manually scaled foF2, Slab thickness

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FULL PAPER Open Access

Estimate of economic impact of atmospheric radiation storm associated with solar energetic particle events on aircraft operations

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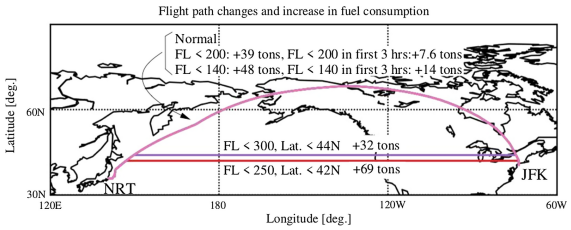
Earth, Planets and Space 2021, **73**:57 DOI: 10.1186/s40623-021-01377-5
Received: 6 August 2020, Accepted: 8 February 2021, Published: 23 February 2021

Abstract

A solar energetic particle (SEP) event generates a shower of secondary generated particles in the Earth's atmosphere down to lower altitudes to cause an atmospheric radiation storm (ARS). The high-energy secondary particles cause additional radiation dose at altitudes where aircraft flies. The space weather information provided by the International Civil Aviation Organization (ICAO) designated space weather centers includes advisories on the solar radiation storm. The Warning System for AVIation Exposure to Solar energetic particle (WASAVIES), we can estimate the effective dose rate (EDR) along the flight path of the aircraft. However, it has not been well established how the operators of aircraft should react with the space weather advisories on the solar radiation storm. By using a flight trajectory generation algorithm and the global EDR distribution, the economic impacts of ARS associated with SEP events on aircraft operation, namely the flight path length, flight time, and fuel consumption, are estimated. The conditions of the peak of the ARS event on 20 January 2005 are used. The economic impacts for a flight route from New York, US to Tokyo, Japan, are estimated with constraints in flight routes to avoid the hazard of radiation and compared with those of the reference case without the ARS effects. The fuel consumption is shown to increase by 39–69 tons (33–58%) for a twin-engine, wide-body jet passenger aircraft, when a constraint is imposed on the flight altitude only. When the constraints are set on the aircraft altitude and the latitude, the flight time and the fuel consumption are both increased by 2.2–2.8 h (17–20%) and 32–48 tons (27–41%), respectively. If the ARS event duration is limited for 3 h, the increase in the fuel consumption is about 7.6–14 tons (6.4–12%). This economic impact may be reduced, if the space weather nowcast and forecast for the ARS and an optimal flight trajectory generation algorithm are used together. Setting more flexible constraints on the flight route and generating optimal flight trajectories with minimal economic impacts by fully utilizing the global EDR distribution is the next step.

Keywords: Solar energetic particle event, Radiation, Impact on airplane operation



Graphical abstract

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FULL PAPER Open Access

Relationship between three-dimensional velocity of filament eruptions and CME association

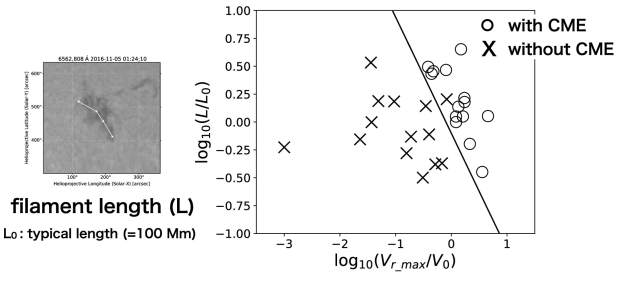
Daikichi Seki*, Kenichi Otsuji, Takako T. Ishii, Ayumi Asai and Kiyoshi Ichimoto

Earth, Planets and Space 2021, **73**:58 DOI: 10.1186/s40623-021-01378-4
Received: 2 September 2020, Accepted: 10 February 2021, Published: 26 February 2021

Abstract

It is widely recognised that filament disappearances or eruptions are frequently associated with Coronal Mass Ejections (CMEs). Since CMEs are a major source of disturbances of the space environment surrounding the Earth, it is important to investigate these associations in detail for the better prediction of CME occurrence. However, the proportion of filament disappearances associated with CMEs is under debate. The estimates range from ~10 to ~90% and could be affected by the manners to select the events. In this study, we aim to reveal what parameters control the association between filament eruptions and CMEs. We analysed the relationships between CME associations and the physical parameters of filaments including their length, maximum ascending velocity, and direction of eruptions using 28 events of filament eruptions observed in Hα. We found that the product of the maximum radial velocity and the filament length is well correlated with the CME occurrence. If the product is larger than 8.0×10^6 km^2 s^{-1}, the filament will become a CME with a probability of 93%, and if the product is smaller than this value, it will not become a CME with a probability of 100%. We suggest a kinetic-energy threshold above which filament eruptions are associated with CMEs. Our findings also suggest the importance of measuring the velocity vector of filament eruption in three-dimensional space for the better prediction of CME occurrence.

Keywords: Filaments, Filament eruptions, Coronal Mass Ejections, Hα observation, 3D velocity



Graphical abstract

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FULL PAPER Open Access

Operational solar flare prediction model using Deep Flare Net

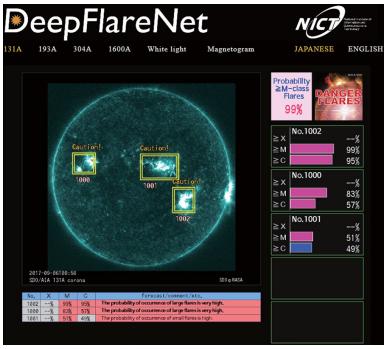
Naoto Nishizuka*, Yûki Kubo, Komei Sugiura, Mitsue Den and Mamoru Ishii

Earth, Planets and Space 2021, **73**:64 DOI: 10.1186/s40623-021-01381-9
Received: 7 August 2020, Accepted: 17 February 2021, Published: 5 March 2021

Abstract

We developed an operational solar flare prediction model using deep neural networks, named Deep Flare Net (DeFN). DeFN can issue probabilistic forecasts of solar flares in two categories, such as ≥ M-class and < M-class events or ≥ C-class and < C-class events, occurring in the next 24 h after observations and the maximum class of flares occurring in the next 24 h. DeFN is set to run every 6 h and has been operated since January 2019. The input database of solar observation images taken by the Solar Dynamic Observatory (SDO) is downloaded from the data archive operated by the Joint Science Operations Center (JSOC) of Stanford University. Active regions are automatically detected from magnetograms, and 79 features are extracted from each region nearly in real time using multiwavelength observation data. Flare labels are attached to the feature database, and then, the database is standardized and input into DeFN for prediction. DeFN was pretrained using the datasets obtained from 2010 to 2015. The model was evaluated with the skill score of the true skill statistics (TSS) and achieved predictions with TSS = 0.80 for ≥ M-class flares and TSS = 0.63 for ≥ C-class flares. For comparison, we evaluated the operationally forecast results from January 2019 to June 2020. We found that operational DeFN forecasts achieved TSS = 0.70 (0.84) for ≥ C-class flares with the probability threshold of 50 (40)%, although there were very few M-class flares during this period and we should continue monitoring the results for a longer time. Here, we adopted a chronological split to divide the database into two for training and testing. The chronological split appears suitable for evaluating operational models. Furthermore, we proposed the use of time-series cross-validation. The procedure achieved TSS = 0.70 for ≥ M-class flares and 0.59 for ≥ C-class flares using the datasets obtained from 2010 to 2017. Finally, we discuss the standard evaluation methods for operational forecasting models, such as the preparation of observation, training, and testing datasets, and the selection of verification metrics.

Keywords: Solar flares, Space weather forecasting, Prediction, Operational model, Deep neural networks, Verification



Graphical abstract

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FULL PAPER Open Access

Validation of computed extreme ultraviolet emission spectra during solar flares

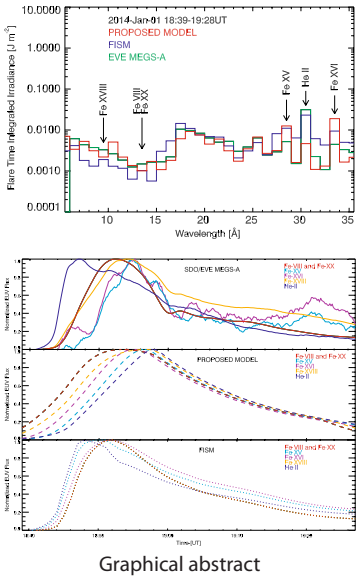
Shohei Nishimoto*, Kyoko Watanabe, Toshiki Kawai, Shinsuke Imada and Tomoko Kawate

Earth, Planets and Space 2021, **73**:79 DOI: 10.1186/s40623-021-01402-7
Received: 5 August 2020, Accepted: 18 March 2021, Published: 25 March 2021

Abstract

X-rays and extreme ultraviolet (EUV) emissions from solar flares rapidly change the physical composition of the Earth's thermosphere and ionosphere, thereby causing space weather phenomena such as communication failures. Numerous empirical and physical models have been developed to estimate the effects of flare emissions on the Earth's upper atmosphere. We verified the reproduction of the flare emission spectra using a one-dimensional hydrodynamic calculation and the CHIANTI atomic database. To validate the proposed model, we used the observed EUV spectra obtained by the Extreme ultraviolet variability experiment (EVE) on board the Solar Dynamics Observatory (SDO). We examined the "EUV flare time-integrated irradiance" and "EUV flare line rise time" of the EUV emissions for 21 events by comparing the calculation results of the proposed model and observed EUV spectral data. The proposed model successfully reproduced the EUV flare time-integrated irradiance of the Fe VIII 131 Å, Fe XVIII 94 Å, and Fe XX133 Å, as well as the 55–355 Å and 55–135 Å bands. For the EUV flare line rise time, there was an acceptable correlation between the proposed model estimations and observations for all Fe flare emission lines. These results demonstrate that the proposed model can reproduce the EUV flare emission spectra from the emitting plasma with a relatively high formation temperature. This indicates that the physics-based model is effective for the accurate reproduction of the EUV spectral irradiance.

Keywords: Solar flare, X-ray emission, EUV emission, Space weather



Graphical abstract

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FULL PAPER Open Access

Spatial scale of geomagnetic Pc5/Pi3 pulsations as a factor of their efficiency in generation of geomagnetically induced currents

Nadezda V Yagova*, Vyacheslav A Pilipenko, Yaroslav A Sakharov and Vasily N Selivanov

Earth, Planets and Space 2021, **73**:88 DOI: 10.1186/s40623-021-01407-2
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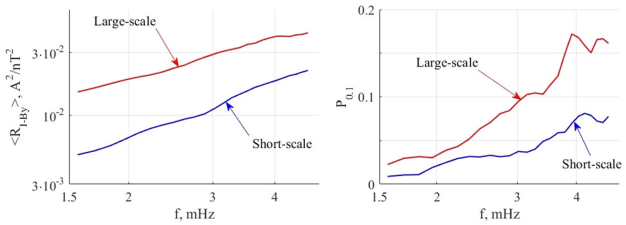
Abstract

Geomagnetically induced currents (GICs) in a quasi-meridional power transmission line on the Kola Peninsula are analyzed during the intervals of Pc5/Pi3 (frequency range from 1.5 to 5 mHz) pulsations recorded at the IMAGE magnetometer network. We have analyzed GIC in a transformer at the terminal station Vykhodnoy (68° N, 33° E) during the entire year of 2015, near the maximum of the 24th Solar cycle. To quantify the efficiency of GIC generation by geomagnetic pulsations, a ratio between power spectral densities of GIC and magnetic field variations is introduced. Upon examination of the geomagnetic pulsation efficiency in GIC generation, the emphasis is given to its dependence on frequency and spatial scale. To estimate pulsation spatial scales in latitudinal and longitudinal directions, the triangle of stations KEV-SOD-KIL has been used. Large-scale pulsations (with a high spectral coherence, low phase difference, and similar amplitudes at latitudinally separated stations) are found to be more effective in GIC generation than small-scale pulsations. The GIC response also depends on the pulsation scale across the electric power line.

Keywords: Geomagnetically induced currents, Pc5/Pi3 geomagnetic pulsations



Graphical abstract

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FULL PAPER Open Access

Model-based reproduction and validation of the total spectra of a solar flare and their impact on the global environment at the X9.3 event of September 6, 2017

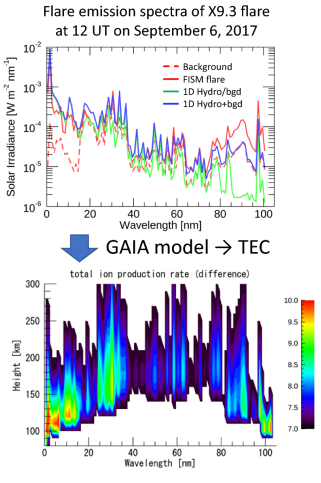
Kyoko Watanabe*, Hidekatsu Jin, Shohei Nishimoto, Shinsuke Imada, Toshiki Kawai, Tomoko Kawate, Yuichi Otsuka, Atsuki Shinbori, Takuya Tsugawa and Michi Nishioka

Earth, Planets and Space 2021, **73**:96 DOI: 10.1186/s40623-021-01376-6
Received: 2 August 2020, Accepted: 8 February 2021, Published: 20 April 2021

Abstract

We attempted to reproduce the total electron content (TEC) variation in the Earth's atmosphere from the temporal variation of the solar flare spectrum of the X9.3 flare on September 6, 2017. The flare spectrum from the Flare Irradiance Spectral Model (FISM), and the flare spectrum from the 1D hydrodynamic model, which considers the physics of plasma in the flare loop, are used in the GAIA model, which is a simulation model of the Earth's whole atmosphere and ionosphere, to calculate the TEC difference. We then compared these results with the observed TEC. When we used the FISM flare spectrum, the difference in TEC from the background was in a good agreement with the observation. However, when the flare spectrum of the 1D-hydrodynamic model was used, the result varied depending on the presence or absence of the background. This difference depending on the models is considered to represent which extreme ultraviolet (EUV) radiation is primarily responsible for increasing TEC. From the flare spectrum obtained from these models and the calculation result of TEC fluctuation using GAIA, it is considered that the enhancement in EUV emission by approximately 15–35 nm mainly contributes in increasing TEC rather than that of X-ray emission, which is thought to be mainly responsible for sudden ionospheric disturbance. In addition, from the altitude/wavelength distribution of the ionization rate of Earth's atmosphere by GAIA (Ground-to-topside Atmosphere and Ionosphere model for Aeronomy), it was found that EUV radiation of approximately 15–35 nm affects a wide altitude range of 120–300 km, and TEC enhancement is mainly caused by the ionization of nitrogen molecules.

Keywords: Solar flares, Dellinger effect, Total electron content, Space weather



Graphical abstract

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FULL PAPER Open Access

Space weather benchmarks on Japanese society

Mamoru Ishii*, Daikou Shiota, Chihiro Tao, Yusuke Ebihara, Hitoshi Fujiwara, Takako Ishii, Kiyoshi Ichimoto, Ryuho Kataoka, Kiyokazu Koga, Yuki Kubo, Kanya Kusano, Yoshizumi Miyoshi, Tsutomu Nagatsuma, Aoi Nakamizo, Masao Nakamura, Michi Nishioka, Susumu Saito, Tatsuhiko Sato, Takuya Tsugawa and Shigeo Yoden

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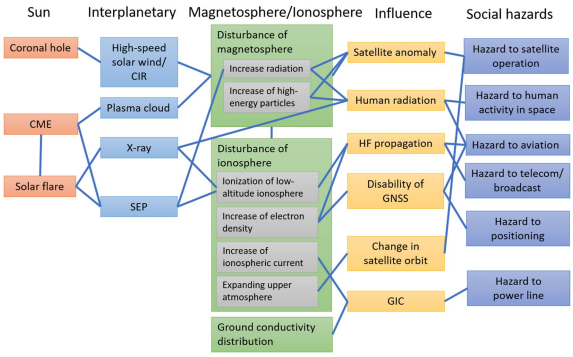
Abstract

We surveyed the relationship between the scale of space weather events and their occurrence rate in Japan, and we discussed the social impact of these phenomena during the Project for Solar–Terrestrial Environment Prediction (PSTEP) in 2015–2019. The information was compiled for domestic users of space weather forecasts for appropriate preparedness against space weather disasters. This paper gives a comprehensive summary of the survey, focusing on the fields of electricity, satellite operations, communication and broadcasting, satellite positioning usage, aviation, human space activity, and daily life on the Earth's surface, using the cutting-edge knowledge of space weather. Quantitative estimations of the economic impact of space weather events on electricity supply and aviation are also given. Some topics requiring future research, which were identified during the survey are also described.

Keywords: Space weather, Benchmark, Extreme event, Societal impact, Economic impact estimation



Graphical abstract

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EXPRESS LETTER Open Access

A possible case of sporadic aurora observed at Rio de Janeiro

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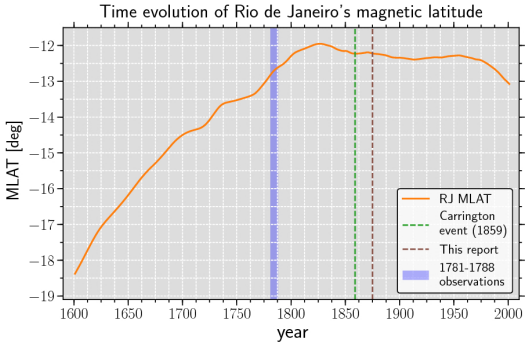
Abstract

Being footprints of major magnetic storms and hence major solar eruptions, mid- to low-latitude aurorae have been one of the pathways to understand solar–terrestrial environments. However, it has been reported that aurorae are also occasionally observed at low latitudes under low or even quiet magnetic conditions. Such phenomena are known as "sporadic aurorae". We report on a historical event observed by a scientist of the Brazilian Empire in Rio de Janeiro on 15 February 1875. We analyze this event on the basis of its spectroscopic observations, along with its visual structure and coloration, to suggest this event was a possible case of sporadic aurorae. Given the absence of worldwide aurora observations on that day as a consequence of low magnetic activity recorded on the days preceding the observation, in addition to a detailed description, the event observed can most likely be classified as a sporadic aurora. We discuss the geographic and magnetic conditions of that event. Thus, we add a possible case of sporadic aurora in the South American sector.

Keywords: Space weather, Sporadic aurora, Analysis of historical data



Graphical abstract

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EXPRESS LETTER Open Access

Day-to-day variation of pre-reversal enhancement in the equatorial ionosphere based on GAIA model simulations

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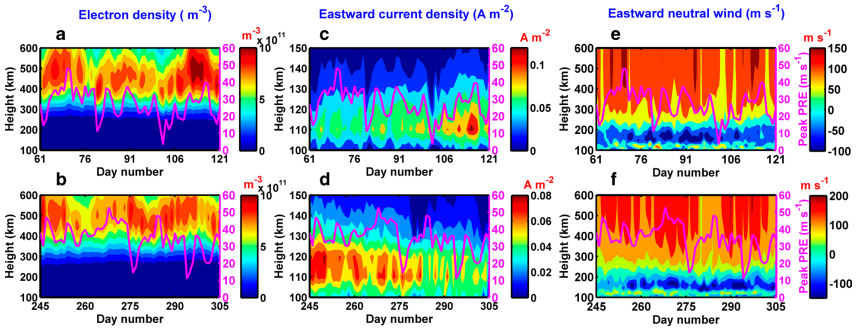
Abstract

Using a whole atmosphere–ionosphere coupled model GAIA (ground-to-topside model of atmosphere and ionosphere), we have investigated which parameters mainly control day-to-day variation of vertical plasma drift at the evening terminator over magnetic equator, so-called pre-reversal enhancement (PRE). Day-to-day variations of the peak PRE are compared with those of electron density, eastward current density and eastward neutral wind in the E- and F-region over Chumphon (10.7° N, 99.4° E; 0.86° N magnetic latitude), Thailand during equinoctial months in 2011–2013. Eastward neutral wind in the F-region shows positive correlation with peak PRE, indicating that the F-region winds control the peak PRE through the mechanisms of the F-region dynamo (including E- and F-region coupling processes). Daytime eastward electric current at an altitude of 110 km, corresponding to equatorial electro jet (EEJ), is also positively correlated with the peak PRE. Correlation between the EEJ and PRE is the largest at 1700 LT, approximately 1.5 h prior to the peak PRE.

Keywords: Pre-reversal enhancement, Eastward neutral wind, Eastward current density, Electron density, GAIA



Graphical abstract

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EXPRESS LETTER Open Access

South American auroral reports during the Carrington storm

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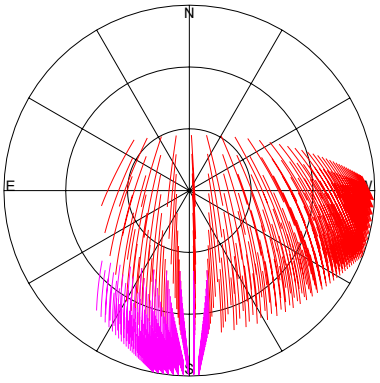
Abstract

The importance of the investigation of magnetic superstorms is not limited to academic interest, because these superstorms can cause catastrophic impact on the modern civilisation due to our increasing dependency on technological infrastructure. In this context, the Carrington storm in September 1859 is considered as a benchmark of observational history owing to its magnetic disturbance and equatorial extent of the auroral oval. So far, several recent auroral reports at that time have been published but those reports are mainly derived from the Northern Hemisphere. In this study, we analyse datable auroral reports from South America and its vicinity, assess the auroral extent using philological and astrometric approaches, identify the auroral visibility at −17.3° magnetic latitude and further poleward and reconstruct the equatorial boundary of the auroral oval to be 25.1° ± 0.5° in invariant latitude. Interestingly, brighter and more colourful auroral displays were reported in the South American sector than in the Northern Hemisphere. This north–south asymmetry is presumably associated with variations of their magnetic longitude and the weaker magnetic field over South America compared to the magnetic conjugate point and the increased amount of magnetospheric electron precipitation into the upper atmosphere. These results attest that the magnitude of the Carrington storm indicates that its extent falls within the range of other superstorms, such as those that occurred in May 1921 and February 1872, in terms of the equatorial boundary of the auroral oval.

Keywords: Low-latitude aurorae, Auroral oval, Geomagnetic storms, Coronal mass ejections, Historical records, Space weather, Extreme space weather events, Carrington storm



Graphical abstract

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EXPRESS LETTER Open Access

Validation of coronal mass ejection arrival-time forecasts by magnetohydrodynamic simulations based on interplanetary scintillation observations

Kazumasa Iwai*, Daikou Shiota, Munetoshi Tokumaru, Ken'ichi Fujiki, Mitsue Den and Yûki Kubo

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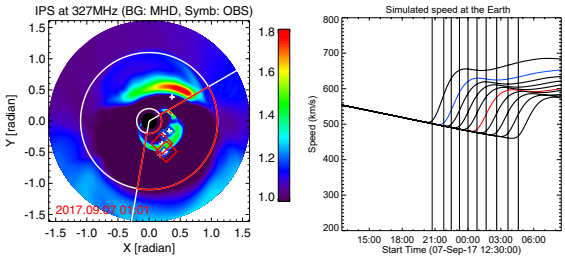
Abstract

Coronal mass ejections (CMEs) cause various disturbances of the space environment; therefore, forecasting their arrival time is very important. However, forecasting accuracy is hindered by limited CME observations in interplanetary space. This study investigates the accuracy of CME arrival times at the Earth forecasted by three-dimensional (3D) magnetohydrodynamic (MHD) simulations based on interplanetary scintillation (IPS) observations. In this system, CMEs are approximated as spheromaks with various initial speeds. Ten MHD simulations with different CME initial speed are tested, and the density distributions derived from each simulation run are compared with IPS data observed by the Institute for Space-Earth Environmental Research (ISEE), Nagoya University. The CME arrival time of the simulation run that most closely agrees with the IPS data is selected as the forecasted time. We then validated the accuracy of this forecast using 12 halo CME events. The average absolute arrival-time error of the IPS-based MHD forecast is approximately 5.0 h, which is one of the most accurate predictions that ever been validated, whereas that of MHD simulations without IPS data, in which the initial CME speed is derived from white-light coronagraph images, is approximately 6.7 h. This suggests that the assimilation of IPS data into MHD simulations can improve the accuracy of CME arrival-time forecasts. The average predicted arrival times are earlier than the actual arrival times. These early predictions may be due to overestimation of the magnetic field included in the spheromak and/or underestimation of the drag force from the background solar wind, the latter of which could be related to underestimation of CME size or background solar wind density.

Keywords: Interplanetary scintillation, Coronal mass ejection, Space weather forecasting, Magnetohydrodynamics, Data assimilation



Graphical abstract

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EXPRESS LETTER Open Access

Unusual enhancement of ~30 MeV proton flux in an ICME sheath region

Mitsuo Oka*, Takahiro Obara, Nariaki V. Nitta, Seiji Yashiro, Daikou Shiota and Kiyoshi Ichimoto

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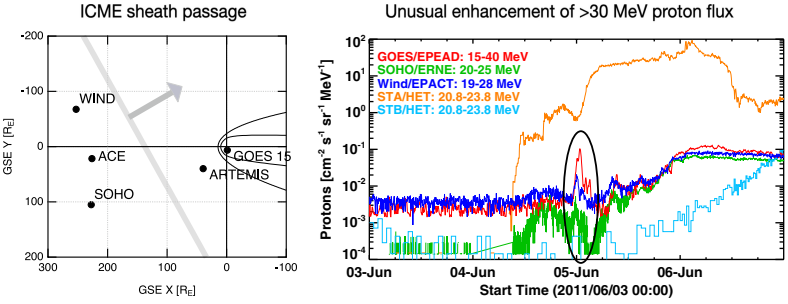
Abstract

In gradual Solar Energetic Particle (SEP) events, shock waves driven by coronal mass ejections (CMEs) play a major role in accelerating particles, and the energetic particle flux enhances substantially when the shock front passes by the observer. Such enhancements are historically referred to as Energetic Storm Particle (ESP) events, but it remains unclear why ESP time profiles vary significantly from event to event. In some cases, energetic protons are not even clearly associated with shocks. Here, we report an unusual, short-duration proton event detected on 5 June 2011 in the compressed sheath region bounded by an interplanetary shock and the leading edge of the interplanetary CME (or ICME) that was driving the shock. While < 10 MeV protons were detected already at the shock front, the higher-energy (> 30 MeV) protons were detected about four hours after the shock arrival, apparently correlated with a turbulent magnetic cavity embedded in the ICME sheath region.

Keywords: Particle acceleration, Solar energetic particles, Turbulence, Coronal mass ejections, Interplanetary shocks



Graphical abstract

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TECHNICAL REPORT Open Access

A monitoring network for anomalous propagation of aeronautical VHF radio waves due to sporadic E in Japan

Keisuke Hosokawa*, Jun Sakai, Ichiro Tomizawa, Susumu Saito, Takuya Tsugawa, Michi Nishioka and Mamoru Ishii

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Abstract

We introduce a network observation of anomalous long-distance propagation of aeronautical navigation (NAV) very high-frequency (VHF) radio waves due to sporadic E layer (Es). The system has been operative since May 2019 at 6 stations in Japan. The receiver consists of a log-periodic antenna, air-band filter, software-defined radio and small computer which is capable of recording the strength of radio signals in the frequency band from 98 to 118 MHz with a temporal resolution of 2 s. The receiver covers not only the NAV band including VHF omnidirectional radio range (VOR), instrument landing system localizer (ILS LOC) and ground-based augmentation system VHF data broadcast (GBAS VDB) from 108 to 118 MHz, but also broadcasting channels from 98 to 108 MHz. Soon after the start of the full operation of the network observation, a strong Es event was detected by an ionosonde in Tokyo during the daytime on July 4, 2019, in which foEs (critical frequency of Es) was sometimes higher than 15 MHz. The VHF radio wave monitoring system detected multiple signatures of Es anomalous propagation (EsAP) at all the stations extending from Okinawa to Hokkaido. At some stations, the EsAP signatures continued for a few hours with some brief intervals of disappearance. The observed correspondence between the enhancement of foEs and the occurrence of anomalous propagation confirmed that an extreme electron density enhancement within Es caused the anomalous long-distance propagation of VHF NAV signals. The data from this network observation can be browsed at http://gwave.cei.uec.ac.jp/cgi-bin/vor/vhf.cgi in near real-time basis. This near real-time monitoring capability allows people in the aeronautical operation community such as air navigation service providers, pilots, and airline engineers to check the propagation environment of VHF NAV signals online, which contributes to a mitigation of ionospheric space weather impacts on the aeronautical navigation systems. Not only that the current method for detecting Es in a wide area can be used to visualize the spatial distribution of Es in two-dimensional fashion through a combination of other observation techniques such as ionosondes and total electron content (TEC) measurements using Global Navigation Satellite System (GNSS) signals.

Keywords: Ionosphere, Sporadic E, Radio propagation, Aeronautical navigation system, Software radio

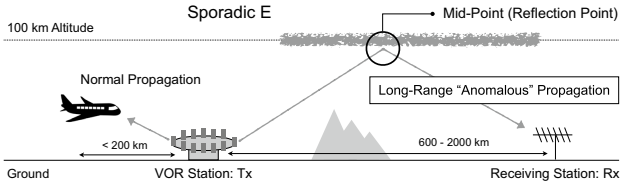

Fig. 1

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TECHNICAL REPORT Open Access

A HAWAII-2RG infrared camera operated under fast readout mode for solar polarimetry

Yoichiro Hanaoka*, Yukio Katsukawa, Satoshi Morita, Yukiko Kamata and Noriyoshi Ishizuka

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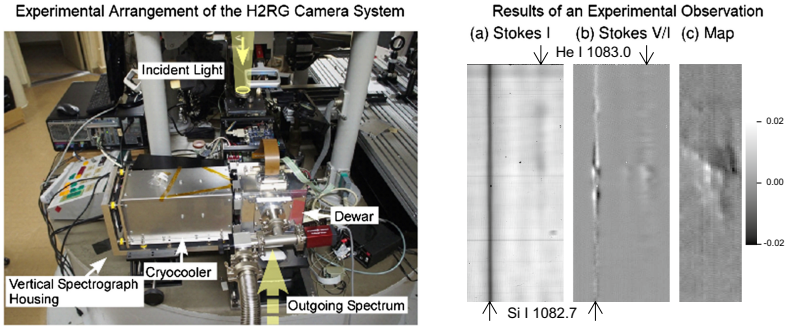
Abstract

Polarimetry is a crucial method to investigate solar magnetic fields. From the viewpoint of space weather, the magnetic field in solar filaments, which occasionally erupt and develop into interplanetary flux ropes, is of particular interest. To measure the magnetic field in filaments, high-performance polarimetry in the near-infrared wavelengths employing a high-speed, large-format detector is required; however, so far, this has been difficult to be realized. Thus, the development of a new infrared camera for advanced solar polarimetry has been started, employing a HAWAII-2RG (H2RG) array by Teledyne, which has 2048 ×2048 pixels, focusing on the wavelengths in the range of 1.0–1.6 μm. We solved the problem of the difficult operation of the H2RGs under "fast readout mode" synchronizing with high-speed polarization modulation by introducing a "MACIE" (Markury ASIC Control and Interface Electronics) interface card and new assembly codes provided by Markury Scientific. This enables polarization measurements with high frame-rates, such as 29–117 frames per seconds, using a H2RG. We conducted experimental observations of the Sun and confirmed the high polarimetric performance of the camera.

Keywords: Solar observation, Polarimetry, Magnetic field, Space weather, Near-infrared, H2RG



Graphical abstract

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TECHNICAL REPORT Open Access

Measurement of geomagnetically induced current (GIC) around Tokyo, Japan

Shinichi Watari*, Satoko Nakamura and Yusuke Ebihara

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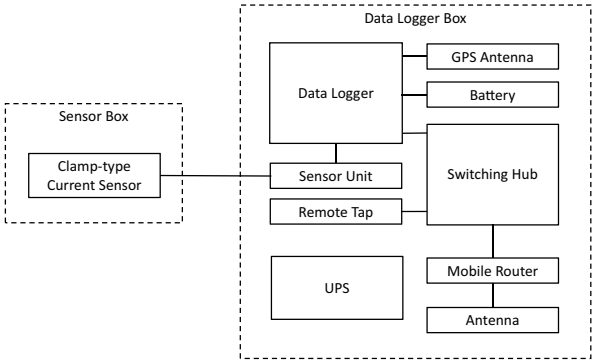
Abstract

We need a typical method of directly measuring geomagnetically induced current (GIC) to compare data for estimating a potential risk of power grids caused by GIC. Here, we overview GIC measurement systems that have appeared in published papers, note necessary requirements, report on our equipment, and show several examples of our measurements in substations around Tokyo, Japan. Although they are located at middle latitudes, GICs associated with various geomagnetic disturbances are observed, such as storm sudden commencements (SSCs) or sudden impulses (SIs) caused by interplanetary shocks, geomagnetic storms including a storm caused by abrupt southward turning of strong interplanetary magnetic field (IMF) associated with a magnetic cloud, bay disturbances caused by high-latitude aurora activities, and geomagnetic variation caused by a solar flare called the solar flare effect (SFE). All these results suggest that GIC at middle latitudes is sensitive to the magnetospheric current (the magnetopause current, the ring current, and the field-aligned current) and also the ionospheric current.

Keywords: Geomagnetically induced current (GIC), Equipment, Storm sudden commencement (SSC), Sudden impulse (SI), Geomagnetic storm, Bay disturbance, Solar flare effect (SFE), Magnetic cloud, Space weather



Block diagram of the GIC measurement system

Graphical abstract

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