Automatic Realtime Detection of Sudden Commencement of Geomagnetic Storms

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By using realtime magnetometer data, we developed an automatic realtime detection system of sudden commencements (SC) of the geomagnetic storms. The geomagnetic storm is a major disturbance that often cause troubles on the operational satellites and telecommunications. The SC is a good indicator of onset of the geomagnetic storm. Therefore, it is important to automatically detect the SC and to inform space weather forecasters of the onset time and its magnitude. We have been operating this automatic detection system since June 2003.

Keywords
Sudden commencement, Geomagnetic storm, Automatic detection system, Space weather

1 Introduction

Geomagnetic storms form one of the major types of space-weather disturbance. When a Coronal Mass Ejection (CME) occurs on the Sun and the solar wind is ejected at high speed toward Earth, disturbances in the solar wind reach Earth in one to two days. The resultant "interplanetary shock" reaching Earth compresses the magnetosphere such that a rapid increase in the magnetic field is observed over the entire surface of the Earth. Subsequent to the interplanetary shock, a geomagnetic storm will occur if the magnetic field of the solar wind features a large component pointing south. The initial change in the magnetic field in this case is referred to as the "sudden commencement" (SC). A geomagnetic storm that occurs directly after the SC is also referred to as a "geomagnetic storm with sudden commencement". After the interplanetary shock passes over the Earth, the magnetic field of the solar wind sometimes continues to point north, and geomagnetic storms do not occur. The initial change in the magnetic field in these cases is referred to as the "sudden impulse" (SI).

In contrast to geomagnetic storms featuring sudden commencement, some geomagnetic storms are referred to as "geomagnetic storms with gradual commencement". This term is used for geomagnetic storms that do not accompany SCs, such as those arising due to the high-speed solar wind generated by coronal holes. Such high-speed solar winds change gradually, so that corresponding geomagnetic storms also tend to develop gradually.

Solar wind disturbances due to CME can sometimes be exceedingly strong, as can geomagnetic storms with sudden commencement following CME. These events often damage equipment sensitive to space weather, such as satellites and high-frequency communication equipment. Thus it is necessary to develop a system that detects and provides notice of geomagnetic storms with sudden commencement at the earliest possible point. If this operation were to be performed manually, people would have to monitor the data continuously 24 hours a day, which would be extremely inefficient. It would be better to establish a system in which detection is automated via personal computer (PC), with people then estimating the scale of the detected event to determine the required actions in response. Moreover, events that occur at night are currently neglected until the following morning. Thus, we believe that it would be worthwhile to construct an automatic reporting system as a means of providing space-weather information to users requiring such information.

The Space Weather Group of the National Institute of Information and Communications Technology (NICT) has constructed a magnetometer network that collects data in near-real-time (in 12-minute intervals). Through use of this data we have constructed a system incorporating a software application that automatically detects SC/SI. When SC/SI is detected, notification is instantly issued via email, and a web page is automatically generated to display the latest data on the web. Users anywhere can then browse this information as they wish.

The system began operations in June 2003. This article reports on the details of the detection method and the current status of detection activities.

2 SC detection criteria

Figure 1 shows the five low-latitude observation sites used in automatic SC/SI detection, among the observation sites constituting NICT's near-real-time magnetometer network[1]. Three sites are on the same side of the Earth as Japan: Okinawa (OKI), the islands of Guam (GAM), and Yap (YAP); the two remaining sites are situated approximately on the opposite side of the Earth: Sao Luis (SLZ) and Santa Maria (SMA) in Brazil. As discussed later, it is important that the detection network include observation sites distributed widely

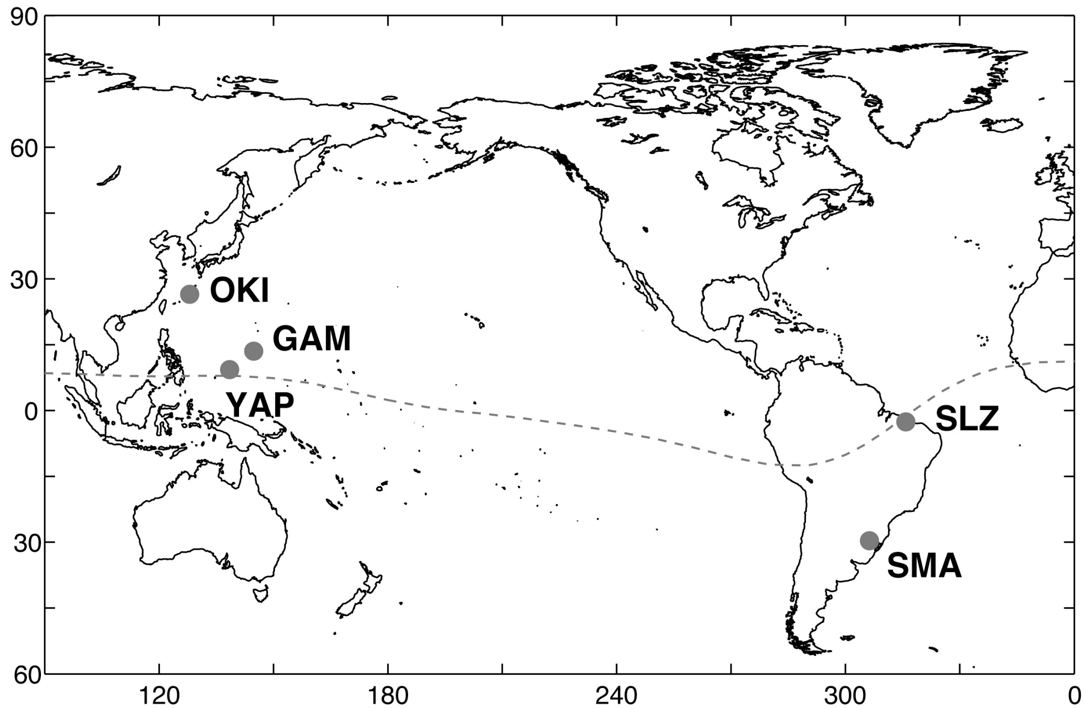


Fig.1 *NICT geomagnetism observation sites used in automatic SC/SI detection*

Five sites are employed: OKI, GAM, and YAP are in or near Japan, and SLZ and SMA are in Brazil, located in the opposite hemisphere. The dashed line indicates the geomagnetic equator.

(on the day and night sides of the Earth) and that there are at least two sites on each side, for backup in the event of failure. The present system of automatic detection uses H-component (northward component) data, as such data tends to reflect changes in the magnetic field of the SC/SI in low latitudes.

Figure 2 shows an example of SC occurring at 8 UT on January 31, 2001. In this case it was evening in OKI and GAM and morning in SMA. Similar changes were observed in both hemispheres. The magnetic field suddenly increased at the time indicated by the vertical dashed line. The inverted triangular mark indicates the point at which OKI data peaked. The magnetic field peaked at approximately five minutes and then decreased slowly. The first sudden increase is designated as the SC or the SI. This event was followed by a small-scale geomagnetic storm, and was therefore categorized as an SC event. If such an event is not accompanied by a geomagnetic storm, it is categorized as an SI event.

We decided to implement automatic SC/SI detection to identify events matching conditions set for several quantities selected from this characteristic change. The most conspicuous characteristic of the change in the magnetic field with an SC/SI event is the rapid increase in the strength of the magnetic field within a short time. We focused our attention on this point and selected the following three quantities drawn from the change, from the start of the SC (dashed line) to its peak (inverted triangular mark).

- Amplitude
- Time required for increase
- Maximum time variation

We listed 89 SC events between January 2000 and October 2003 based on the Solar-Geophysical Data[2] provided by the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA). Of the available NICT observation sites, Okinawa was selected as the source of data for the three quantities above for each event. Each of these quantities was statistically analyzed and upper or lower limits were set.

Some natural phenomena yield extremely low or high measurement values. If the limiting values are set here to include all SCs, additional phenomena similar to SCs are also likely to be detected. An SC is in principle characterized by a sharp increase in magnetic field intensity within a short time. Nevertheless, if the SC is less intense, other events will reflect this lesser degree of change. Consequently, the number of erroneous detections will increase.

The automatic detection system that is the subject of this study was developed for a space-weather monitoring system. The aim is to establish a system that will unfailingly detect disturbances exceeding a certain scale—i.e., those that will have a significant effect on space weather—and that informs the user of their occurrence. Yet if comprehensive detection of SCs is given higher priority and the number of erroneous detections increases as a result, the system will prove impractical. Settings should therefore be made with a view

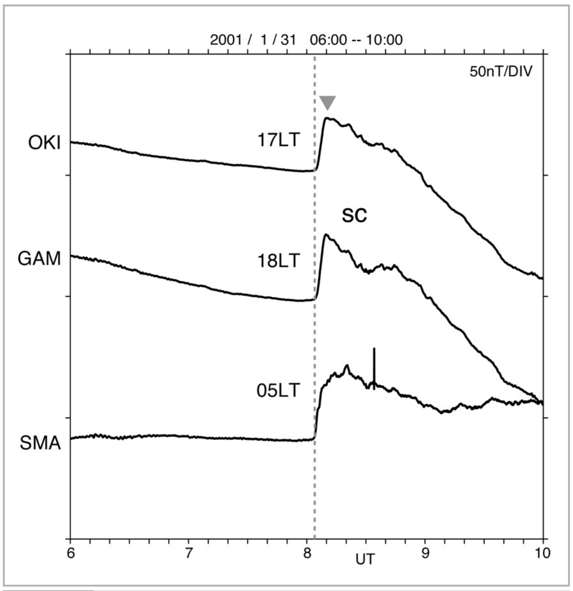


Fig.2 *SC observed on January 31, 2001*

The vertical axis is the H-component (northward component) of the magnetic field for OKI, GAM, and SMA. The scale is in units of 50 nT. The horizontal axis represents universal time (UT).Simultaneous changes are observed on the evening side (OKI, GAM) and morning side (SMA) of the Earth.

to minimizing the frequency of erroneous detection, even if doing so allows small SCs to go undetected. The values for upper and lower limits defined in the discussion below are set to achieve a balance between SC/SI detection and the frequency of erroneous detection.

2.1 Amplitude of SC

Figure 3 shows the amplitude distribution of the SC observed at OKI. The horizontal axis is the date of SC occurrence, and the vertical axis is the amplitude in logarithmic scale. As the circles do not appear near the bottom of the graph (where the amplitude is small), the figure indicates that there is a certain minimum amplitude value for an event to be recognized as an SC. The asterisks in the figure represent events with a Dst lower than −100 nT in a geomagnetic storm following the SC (indicating the development of a large geomagnetic storm). The scale of a geomagnetic storm is influenced by the state of the solar wind (e.g., velocity, magnetic field intensity, and particularly the southward component) after the SC occurs (in other words, after the interplanetary shock has passed). Thus, there is no direct relationship between the amplitude of the SC (the onset of the geomagnetic storm), and the scale of the geomagnetic storm, which is determined by the disturbance following the SC. Nevertheless, a large geomagnetic storm requires a certain degree of disturbance in the solar wind, and consequently, the SC is also considered to be of corresponding scale. Although the dispersion is large, in Fig.3 the asterisks are mainly distributed where the amplitude is relatively large. Thus, the lower limit for amplitude is set as 7.5 nT, which allows for detection of all asterisked SCs, though not of certain SCs of extremely low amplitude.

2.2 Period of SC Increase

Figure 4 shows the time (in minutes) required for the SC to peak after initiation. An SC occurs when the interplanetary shock of the solar wind compresses the magnetosphere of the Earth, and in this case the SC usually peaks within a short time. The distribution of the asterisks indicates the tendency of events followed by larger geomagnetic storms to increase within shorter periods. Based on this figure, we decided to set the upper limit for the period of SC increase at 10 minutes.

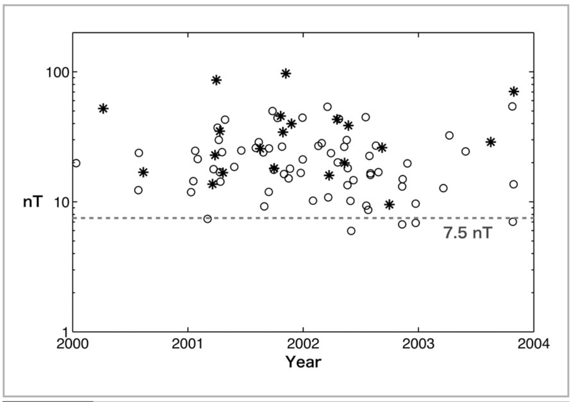


Fig.3 *Amplitude distribution of SCs observed at OKI*

The vertical axis is the amplitude in nT. The horizontal axis is the date on which the SC occurred. The asterisks (*) indicate events in which Dst (in geomagnetic storms) developed to −100 nT or below after the SC. The circles (o) indicate events in which Dst did not reach −100 nT after the SC. The lower limit of SC amplitude detection is set at 7.5 nT.

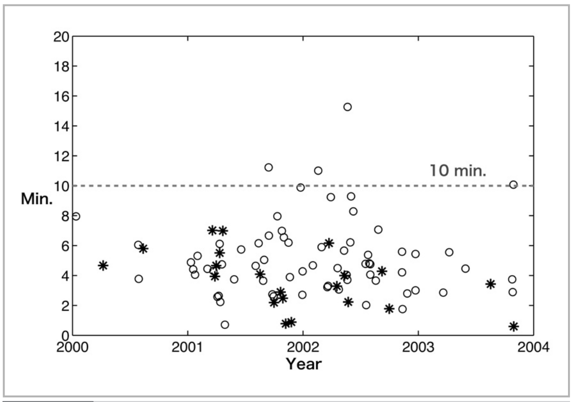


Fig.4 *Periods of SC increase observed at OKI*

The vertical axis is the period of SC increase in minutes. The horizontal axis is the date on which the SC occurred. The asterisks (*) indicate events in which Dst (in geomagnetic storms) developed to −100 nT or below after the SC. The circles (o) indicate events in which Dst did not reach −100 nT after the SC. The upper limit for detection of the period of SC increase is set at 10 minutes.

2.3 Maximum time variation of SC

Figure 5 shows the maximum change in the magnetic field per minute (in nT/minute) observed within the period of SC increase. The vertical axis is in the logarithmic scale. The period of SC increase varies widely. Some events slowly rise at 1 nT/minute, and some vigorous events reach 40 nT/minute. Based on the results shown in this figure, we excluded the extremely slow group and elected to detect events featuring a maximum variation in the SC period of 2.5 nT/minute or greater.

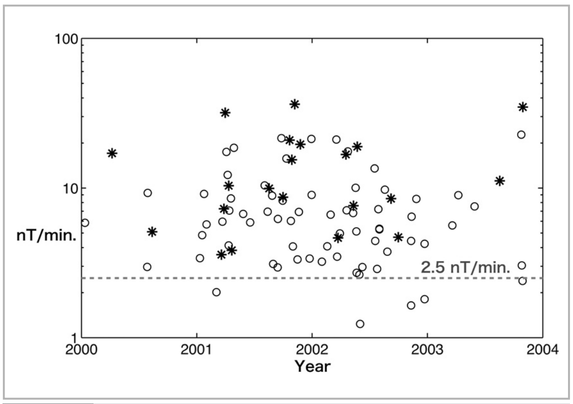


Fig.5 *Maximum SC time variations observed at OKI*

The vertical axis is the change in the magnetic field H component per minute in nT/minute. The asterisks (*) indicate events in which Dst (in geomagnetic storms) developed to –100 nT or below after the SC. The circles (o) indicate events in which Dst did not reach –100 nT after the SC. The lower limit of detection for variation in the SC period was set at 2.5 nT/minute.

3 Detection and notification of SC/SI

Based on the above statistical analyses, we set the criteria for SC/SI as follows:

- Amplitude: ≧ 7.5 nT or greater
- Increase period: ≦ 10 minutes or less
- Maximum time variation: ≧ 2.5 nT/minute or more

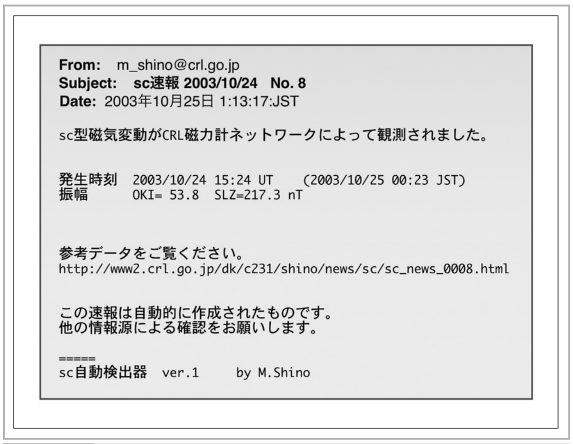
Specifically, the system will search for changes that satisfy the criteria among the data collected in real time. The process involves the following procedures:

(1) Detection of an event meeting the upper limit of time variation
(2) Determination of the start and end points
(3) Judgment of the amplitude and the increase time

The start and end points of an event are determined by the time variation in the magnetic field. The start point is the time at which the intensity of the magnetic field begins to increase, and the end point is the time at which the increase ceases.

When an SC/SI is detected, the system notifies registered users of the SC/SI via email and automatically creates and publishes a web page presenting details of the event, including solar-wind and magnetic-field data. Further, the PC activates an alarm within the laboratory. As stated at the beginning of this report, the value of automatic detection lies in its elimination of the need for continuous human monitoring. When an event is detected, the use of an audible alarm appears to be the simplest and most reliable means of informing people of the event.

Figure 6 shows an example of the notification email when an SC/SI is detected.



From: m_shino@crl.go.jp
Subject: sc速報 2003/10/24 No. 8
Date: 2003年10月25日 1:13:17:JST

sc型磁気変動がCRL磁力計ネットワークによって観測されました。

発生時刻 2003/10/24 15:24 UT (2003/10/25 00:23 JST)
振幅 OKI= 53.8 SLZ=217.3 nT

参考データをご覧ください。
http://www2.crl.go.jp/dk/c231/shino/news/sc/sc_news_0008.html

この速報は自動的に作成されたものです。
他の情報源による確認をお願いします。

=====
sc自動検出器 ver.1 by M.Shino

Fig.6 *Example of SC automatic-detection email*

The email gives the onset time of the SC/SI, the observation sites at which the event was detected, the amplitude of the SC/SI, and other information.The email is automatically generated and sent to registered users directly after the automatic detection system has identified the event.

This email was sent to users when the detection system automatically detected the SC/SI that occurred directly before the ensuing problems on ADEOS-II. The email notes the detection time, the amplitude of the SC/SI observed at each observation site, and the link to the web page with the detailed data.

With the amplitude information of the SC/SI included in this email, one can roughly estimate the scale of the interplanetary shock. Compared to the values in Fig.3, the amplitude of 53.8 nT at OKI indicates that the SC/SI was considerably large. By going to the indicated web page, users who received the email could promptly investigate the SC/SI occurrence with reference to the original data.

4 Operational status of automatic detection

The automatic detection system began operations in June 2003. The system detected 71 SC/SI events by May 2004, within a single year. Among these events, 55 were concentrated in October and November 2003. Solar-flare activity was extremely energetic during these two months and the solar wind showed significant disturbance. The concentration of detection counts to this extent is abnormal and indicates that space-weather conditions were themselves abnormal. Section **4.2** discusses the results of detection during this period. Below we evaluate the relevance of the 16 remaining events during the normal period.

The 16 detection results are analyzed as follows:

SC	4
SI	8
Disturbance due to geomagnetic storm	3
Erroneous detection	1

Four SC events and eight SI events are detected. Out of four SC events, one event could not be detected in real time due to problems in the initial operation of the system, but instead were detected through reprocessing involving a slight delay. Categorization as either SC or SI depends on the occurrence or absence of a geomagnetic storm after the interplanetary shock passes Earth. This system detects only the initial increase in the magnetic field and does not include a mechanism to distinguish between these two types of event. Nor can the current system distinguish between a disturbance due to a geomagnetic storm from one attributable to SC, as discussed in more detail below. Thus, the system can be said to have operated as planned for these 15 events.

The developed system successfully detected seven out of 10 SC events listed in the Solar-Geophysical Data[2] for the same period. The three events that went undetected were all SIs with small amplitudes, and were indicated as events of low detection within the Solar-Geophysical Data[2]. These events fell within the range below our established detection limit—a range within which it was acknowledged that some events of small amplitude would inevitably go undetected.

4.1 Example of erroneous detection

The only case of erroneous detection involved a change in the positive bay generated by a substorm. Figure 7 shows the magnetic field change observed at 16 UT, January 31, 2001, a phenomenon similar to, though not the same as, the erroneously identified event. A sharp increase in the magnetic field was observed at two observation sites, OKI and GAM, similar to that corresponding to an SC (see Fig.2). This is the positive bay, a change in the magnetic field created by a substorm generated at the magnetospheric tail. As a large-scale electric current is rapidly formed connecting the magnetospheric tail and the nighttime hemisphere, a sharp increase in the rate of change in the magnetic field occurs as a result.

Substorms occur extremely frequently compared to SC/SI; many times a day, in fact, under certain circumstances. If these substorms cannot be distinguished from SC/SI events under automatic detection, frequent errors are inevitable. However, there is a sig-

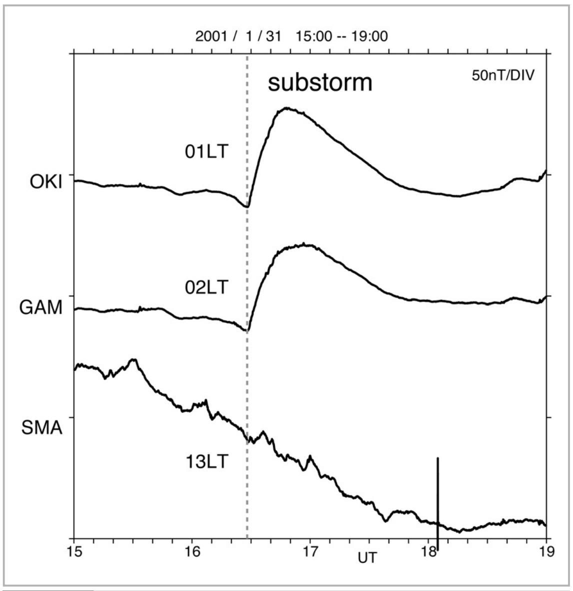


Fig.7 *Substorm observed on January 31, 2001*

The vertical axis is the H (northward)-component of the magnetic field at OKI, GAM, and SMA. The scale is in units of 50 nT.The horizontal axis represents universal time (UT).Changes are observed at observation sites on the night side (OKI and GAM) but not at the observation site (SMA) on the day side.

nificant difference between these types of events: an SC/SI occurrence is a compression phenomenon involving the entire magnetosphere, such that the change is observed in all time zones regardless of whether it is day or night; a substorm, on the other hand, is a nighttime phenomenon in which the positive bay is observed in a relatively limited time zone on the night side. In the example shown in Fig.7, the positive bay was observed at OKI and GAM, approximately at midnight, whereas no corresponding magnetic field change was observed at SMA on the day side. As such, the spatial distribution of the change in the magnetic field can serve as a basis for distinguishing SC/SI from the positive bay.

As shown in Fig.1, the observation sites employed in automatic detection are widely distributed near Japan and in Brazil. This large spatial distribution usually prevents erroneous detection of positive bays. In the example of erroneous detection cited above, some data was missing among real-time observations; in this case, only nighttime data was collected, so that it was impossible to determine whether the detected magnetic field change was global or whether it occurred only on the night side. For accurate automatic detection of SCs, it is important to ensure the stable collection of simultaneously observed data over a wide area.

4.2 Geomagnetic storm disturbances

A geomagnetic storm disturbance refers to an event in which a change in the magnetic field similar to SC/SI is observed during a geomagnetic storm. For example, an extremely energetic flare erupted on the Sun from October 2003 to November 2003. This caused large geomagnetic storms resulting in low-latitude auroras in Hokkaido. During this period, the automatic detection system detected 55 events of SC/SI-type magnetic field change. Most of these detections were due to circumstances arising from geomagnetic storm disturbances.

Below we discuss the details of such detection with reference to an example of observations that took place on October 21, 2001, when many SC/SI-type events were detected, though this was prior to the period in 2003 referred to above.

Figure 8 shows the solar wind dynamic pressure (P), the magnetic field data at OKI, and the Dst index from 15 UT, October 21, 2001 to 01 UT, October 22, 2001. The solar wind data is shifted to line up with the later initiation of SC on the ground. The Dst index is superposed on magnetic field data from OKI.

Next, from the data in this period we show the onset time of the SC/SI-type change in the magnetic field identified by the automatic detection system. The six vertical dashed lines in Figure 7 indicate the detection times.

10/21/2001 16:47 ←SC
10/21/2001 18:30
10/21/2001 20:29
10/21/2001 21:48
10/21/2001 22:34

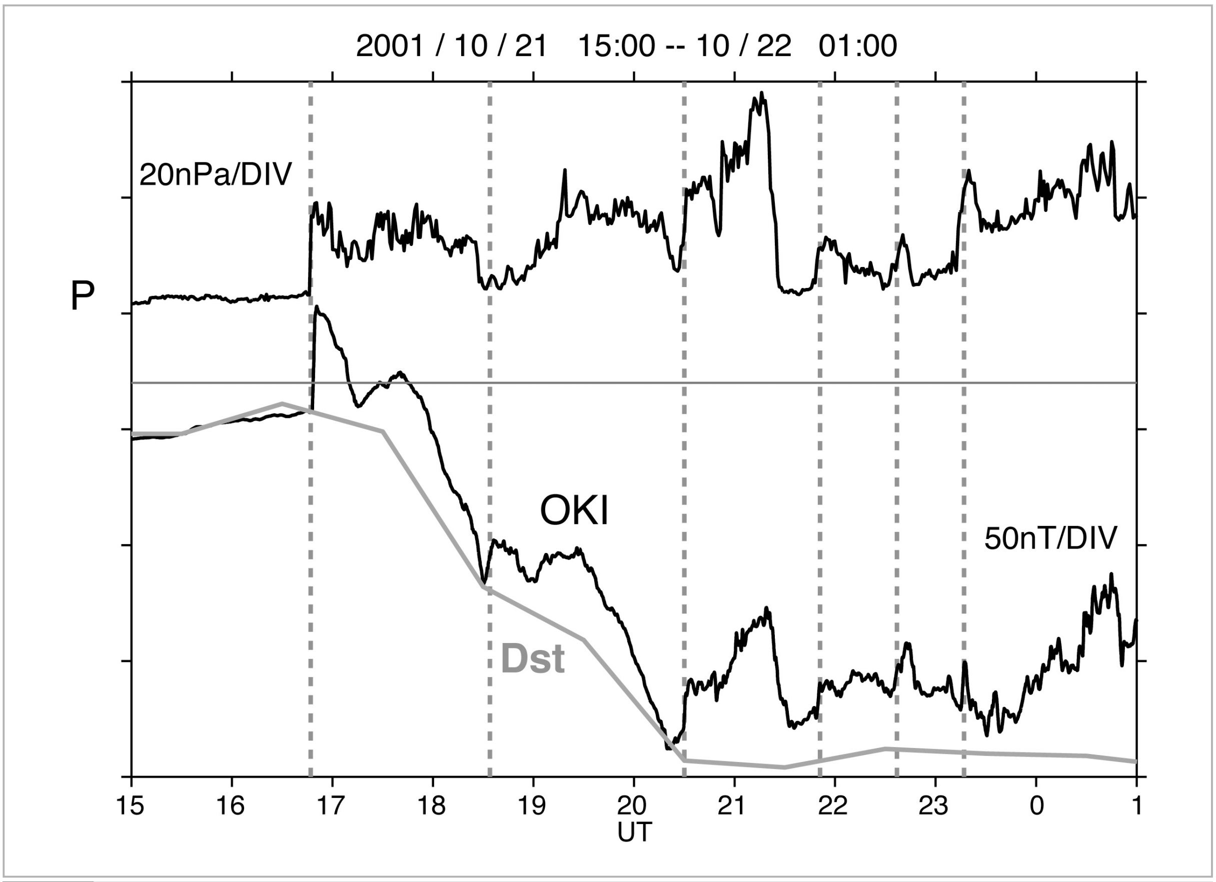


Fig.8 *Solar wind dynamic pressure (P), H component of the magnetic field at OKI, and Dst index on October 21, 2001*

The horizontal axis represents universal time (UT). The vertical scale of the solar wind dynamic pressure is 20 nPa.The solar wind data is according to ACE. This is shifted along the time axis to match the initiation of SC on the ground.The vertical scale of the H component at OKI and Dst is 50 nT.With the horizontal line in the plot as the reference line (0 nT), lower values of Dst indicate larger geomagnetic storms. The vertical dashed lines indicate points at which the SC/SI automatic detection system identified events.

ACE data was provided by the ACE SWEPAM instrument team and the ACE Science Center.

10/21/2001 23:15

Among these detection events, the only change that can be referred to as an SC is that occurring at 16:47 UT. The first (leftmost) dashed line in the figure corresponds to this event. At this point the solar wind dynamic pressure increased rapidly.

The superposed Dst index decreases rapidly after SC onset, which indicates that a geomagnetic storm developed after the SC. Following the SC, five changes in the magnetic field were detected, but the third to sixth events also involved a rapid increase in the dynamic pressure of the solar wind, in addition to the increase in the magnetic field noted at OKI. In other words, the same changes are observed in terms of the solar wind dynamic pressure, for the initial SC and for the third to sixth events. Thus, a similar SC/SI-type magnetic field change is observed for all cases on the ground. However, as indicated in the Dst, a single geomagnetic storm has already developed covering the period of the second and subsequent events, so these events are not deemed SC occurrences.

Therefore, to identify an SC correctly, the system should be able to judge whether geomagnetic storm conditions currently apply. The current detection algorithm, which detects only a rapid increase in the magnetic field, cannot accomplish this.

5 Conclusions

A system of automatic detection of SC/SI-type magnetic field change has been developed to detect geomagnetic storms with sudden commencement, based on near-real-time magnetic field data obtained by NICT. The system detects SC/SI by sensing a rapid increase in the magnetic field in accordance with a number of criteria. When the system detects an event, it sends emails to registered users and automatically generates a web page showing the corresponding data. This detection system has been in operation since June 2003.

The system has erroneously detected similar phenomena such as positive bays. For this type of error, we feel that an SC/SI can be distinguished from local phenomena using data distributed widely over the day and night sides of the Earth, as an SC/SI is a globally observed phenomenon. Thus, in order to reduce erroneous detection, it is important to obtain stable data from remotely separated areas, with two or more observation sites within each area.

We should also work toward a system that can recognize whether a geomagnetic storm has developed after the SC/SI. Such a system would be able to distinguish an SC from an SI and could prevent detection reports during geomagnetic storms. It could also provide more detailed disturbance information, including the scale of the developing geomagnetic storm and the extent of the risk. These features would ultimately result in a more useful detection system.

In terms of space weather, we cannot predict when disturbances will occur, so data must be monitored continuously. However, a system in which people continue monitoring 24 hours a day would be inefficient. We believe that we ought to work in the long term toward a system in which detection is automated via PC and in which people then respond to the detected events. We have built the present SC/SI automatic detection system under these assumptions, though the current system represents only partial implementation of our overall aims.

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