3-3 Real-time geomagnetic data acquisition from Siberia region and its application — PURAES project —

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Monitoring and nowcasting of geomagnetic disturbance is necessary for conducting space weather forecast. As the energy from the magnetosphere flows into the ionosphere mainly concentrates on the polar region, it is important to watch the polar region. Developing geomagnetic observation points in the polar region and acquiring data in near real-time way are essentially effective for nowcasting and forecasting. Siberia is a missing region concerning near real-time data acquisition. PURAES Project (Project for Upgrading Russian AE Stations) has been conducted to upgrade magnetometer and set near real-time data transmission instrument in observatories in Siberia. In summer 2002, near real-time data acquisition from four observatories have been accomplished.

AE index is the index which represents the geomagnetic activities in the polar region. Near real-time data acquisition contributes to that the AE index becomes better in its quality and quicker in its calculated output. Moreover, near real-time data is useful for various space weather forecasting application.

Keywords
Geomagnetic observation, Near real-time data acquisition, PURAES project, Siberian region, Auroral Electrojet index, Geomagnetic disturbance

1 Introduction

Global observations of geomagnetic variations and near-real-time data acquisition are necessary for effective research on the processes of energy accumulation in the magnetosphere and energy flowing into the polar region and help us to monitor space weather conditions.

The information about electric currents that flow in the magnetosphere and in the ionosphere are essential to understanding the structure and dynamics of the magnetosphere.

The Earth's magnetosphere is formed by interactions with solar winds. Various electric current systems are generated in the magnetosphere. Some portions of the electric current system are significantly enhanced during periods of geomagnetic disturbances, known as geomagnetic storms and substorms. Because the system is non-uniform, a multipoint observation of the magnetic field variations generated by the electric currents is effective in obtaining information on the spatial distribution and temporal variations of the electric current. Since satellites can make magnetic field observations only at a limited number of points and locations, geomagnetic observation stations distributed around the globe have an important role in such observations.

For nowcasting and forecasting, observation data must be transmitted and collected as quickly as possible for analysis and application. Geomagnetic data and various geomagnetic activity indices calculated from observation data are used as input values to estimate other physical quantities. This data also enables rapid validation of predictions based on theory or numerical simulation, resulting in faster progress in this research field. Nowcasting and forecasting of geomagnetic activity are needed for enabling warnings of potential hazards resulting from induced currents and atmospheric heating. Rapid changes in electric currents flowing in the polar ionosphere induce currents in conductive installations on the ground. In extreme cases, they can induce abnormal currents in power transmission lines, pipelines, and underwater telecommunication cables in polar region. These currents are called geomagnetically induced currents (GICs). Very powerful GICs have been known to damage transformers in power transmission systems. The power blackout in Quebec, Canada, in March 1989 is a typical instance.

The heating of the ionosphere and thermosphere by Joule heating caused by electric currents significantly contributes to atmospheric heating. When the current is exceptionally large, the atmospheric expansion generated by this heating has various effects. Atmospheric heating will increase atmospheric density at a fixed altitude, which in turn increases atmospheric friction on objects passing through at that altitude. This increase in friction alters the courses of low-orbiting satellites and space debris. Along with rapid changes in electric field, atmospheric heating also generates ionospheric storms, which limit the frequencies usable for HF communications. These hazards have led to a demand for near-real-time acquisition of geomagnetic data, for application to space weather studies as well as to forecasting.

Energy influx from the magnetosphere is concentrated in the polar ionosphere, which is the region of origin for GICs, thermospheric atmosphere expansion, and ionospheric storms. During substorms, the electric current in the polar ionosphere rapidly increases, with a rapidly changing distribution. A precise and simple way to monitor these changes has been sought for some time. The most effective method devised to date has been to express these geomagnetic variations as indices. The auroral electrojet (AE) index[1] (see **3** for detailed information) has been proposed as an index of the development, variation, and decay of large-scale electric current systems flowing in the polar ionosphere, based on observation data of geomagnetic variations at 12 stations distributed longitudinally in the polar region at almost uniform intervals. Although stable, reliable determination of this AE index with minimal time lag is considered crucial, it was difficult to pursue this goal without near-real time data from observatories in the Siberian region. To resolve this problem, the PURAES (Project for Upgrading Russian AE Stations) was initiated.

This report will introduce the way how to accomplish near-real-time acquisition of geomagnetic field data and its utilization, mainly in the PUREAS project, of which the first stage is complete. A brief summary of the data transfer method used in the PUREAS project (the INTERMAGNET system) will also be shown. The section on data applications places a particular emphasis on the effectiveness of the AE index and its near-real-time indexing.

This report focuses on geomagnetic variations and index in the polar region. Details of the Dst index, which represents the magnitude of a geomagnetic storm, and the polar cap index (PC index), which is calculated from geomagnetic variations near-pole region, will be omitted here. Readers are referred to the reference material[2][3][4].

2 Near-Real-Time Data Acquisition

Numerous observation and research institutions both in Japan and abroad have shown observation data plots on their Web sites. What, then, is our purpose of collecting data by ourselves? We believe an important goal now is not merely monitoring a phenomenon, but analyzing and processing digital data to extract and identify further physical quantities and properties. This will give us information that cannot be obtained from mere raw data plots. Furthermore, space weather forecasting requires real-time processing for current-state monitoring and predictions. Thus, near-real-time data acquisition by ourselves is essential for realizing instantaneous and advanced utilization and application of data.

A summary of past efforts to achieve near-real-time acquisition of geomagnetic data at CRL is given elsewhere, by Ishibashi et al.[5] in 1997 and Nagatsuma et al.[6] in 2000. Only a brief description will be provided in this report.

2.1 INTERMAGNET

The INTERMAGNET[7] is a joint international project launched in the late 1980s for rapid exchange of data between geomagnetic observatories around the globe and quick derivation of geomagnetic activity indices. INTERMAGNET data has been transferred mainly via meteorological satellites. Data Collection Platforms (DCPs) were installed at the geomagnetic observatories for near-real-time transmission of observation data (1-minute values) to meteorological satellites. The data relayed and downlinked by meteorological satellites is collected at a Geomagnetic Information Node (GIN). Each GIN not only collects data in each region but also responds to requests from users. This system enables stable near-real-time transmission of data from remote observatories which have no other convenient means of such communication. Participating observatories are required to meet specific standards for observation, recording, and transmission, for example, observation with a resolution of 0.1 nT, with at least one absolute value measurement a week. This requirement should ensure high-quality data. As of 2001, the total number of participating observatories was 80. There are 6 GINs around the world, one of which CRL operates.

In Japan, the CRL, the Data Analyses Center for Geomagnetism and Space Magnetism of the Kyoto University, and the Kakioka Magnetic Observatory of the Japan Meteorological Agency (JMA) are INTERMAGNET participants. The region covered by Japanese institutions corresponds to the area in which the Geostationary Meteorological Satellites Himawari-5 (GMS-5) can relay data. A memorandum of understanding exists between the CRL and JMA concerning data transfer via the GMS satellites. The Observations Department, JMA and the Meteorological Satellite Center, JMA cooperate with the CRL. Data is collected every 12 minutes from the Kakioka Magnetic Observatory (geographic coordinates: lat. 36.23˚N and long. 140.18˚E; locations of observatories hereafter will be provided as geographical coordinates, with geographic coordinates in Japan based on the World Geodetic System), Memanbetsu (43.90˚N, 144.20˚E), Dumont d'Urville (66.67˚S, 140.01˚E), Amsterdam Is. (37.80˚S, 77.57˚E), Alibag (18.63˚N, 72.87˚E). The Vostok observation station (78.45˚S, 106.87˚E) also transmits data to GMS-5, although it has some difficulties meeting the specific standards for observation. The observatories in the Siberian region, which are introduced in this report, have been added to these observation points.

2.2 Geomagnetic Data Acquisition System Other Than INTERMAGNET

The CRL is collaborating with other institutions to collect geomagnetic data by systems other than the INTERMAGNET, via routes such as the Internet and telephone lines. Only a brief summary of such systems will be presented here. Readers are referred to Nagatsuma et al.[6] for more detailed information.

The positions and special features of the observation stations are as follows. The Eureka observation station (80.0˚N, 274.10˚E) is located near the north magnetic pole. Data observed there is used to produce an index similar to the PC index[4], an indicator of electric field variations in the polar cap region[8]. The Yap observation station (9.49˚N, 138.09˚E) is located near the magnetic equator. Since the magnetic equator has a peculiar electric conductivity, Yap observation data is used to detect specific magnetic variations. The King Salmon observation station (58.68˚N, 203.35˚E) is located at the same place where the CRL installed a large HF radar in 2001. The St. Paratunka (52.94˚N, 158.25˚E), Hiraiso (36.37˚N, 140.63˚E), Okinawa (26.75˚N, 128.22˚E), Guam (13.58˚N, 144.87˚E), and Yap (9.49˚N, 138.09˚E) observation stations are well-suited to monitoring the penetration of electric fields from the high latitudes into the range from the mid-latitudes to low latitudes, and even into the equator[9], because they are located in almost the same longitudinal zone.

3 The AE Index

This section will describe the AE index, an important indicator for monitoring the current state of geomagnetic disturbances, and closely related to PURAES project. Detailed information on the AE index is provided in the Data Book[10] published by the Data Analyses Center for Geomagnetism and Space Magnetism, Kyoto University.

3.1 Summary

Because the influx of energy from the magnetosphere is concentrated in the polar ionosphere, monitoring of the variations in the ionospheric electric current is critical for understanding the overall variations in energy influx from the magnetosphere. In the polar region, aurora activity sometimes develops explosively (a phenomenon known as auroral breakup), accompanied by sudden increases in ionospheric electric current. Such currents are called auroral electrojets, and the disturbances in the polar regions are called substorms. The AE (Auroral Electrojet) index was proposed as an indicator for the enhancement and decay of auroral electrojets[1]. The geomagnetic data used to calculate the AE index is collected at 12 observatories, which are selected to create the most even distribution possible along the auroral zone encircling the magnetic pole. This distribution usually satisfies the requirement that at least one observatory will be positioned near the region of strong auroral electrojet at any universal time (UT), thereby making the AE index an indicator that closely reflects the enhancement and decay of the auroral electrojet.

3.2 Effectiveness

The AE index has been used by numerous scientists, including studies of the response of the magnetosphere to variations in the solar wind and interplanetary magnetic field (IMF)[11], and studies on the effects of substorms on geomagnetic storms[12].

The AE index is also useful in practical applications such as GIC prediction. Real-time derivations of the AE index are also required to produce an input parameter for real-time predictions of energetic electron flux variations in geostationary orbits[13]. Various other physical quantities have been correlated to the AE index, and numerous empirical models have been proposed based on the relationships. When a correlation between the AE index and a physical quantity has been confirmed statistically, predictions can be made by using the AE index as an input parameter for the empirical model and calculating the physical quantity as the output. As it is

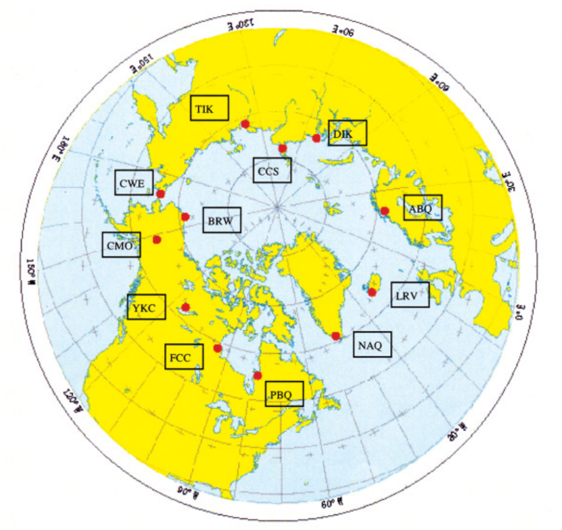
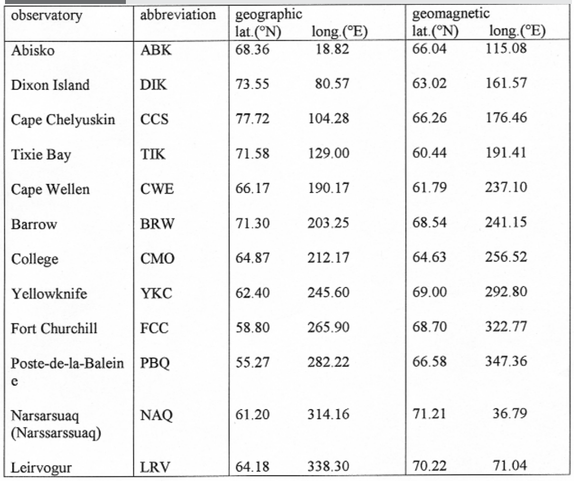


Fig. 1 Distribution of observation stations for AE index. Map shown in geographic coordinates

Table 1 Observing stations for AE index



observatory	abbreviation	geographic lat.(°N)	 long.(°E)	geomagnetic lat.(°N)	 long.(°E)
Abisko	ABK	68.36	18.82	66.04	115.08
Dixon Island	DIK	73.55	80.57	63.02	161.57
Cape Chelyuskin	CCS	77.72	104.28	66.26	176.46
Tixie Bay	TIK	71.58	129.00	60.44	191.41
Cape Wellen	CWE	66.17	190.17	61.79	237.10
Barrow	BRW	71.30	203.25	68.54	241.15
College	CMO	64.87	212.17	64.63	256.52
Yellowknife	YKC	62.40	245.60	69.00	292.80
Fort Churchill	FCC	58.80	265.90	68.70	322.77
Poste-de-la-Baleine	PBQ	55.27	282.22	66.58	347.36
Narsarsuaq (Narssarssuaq)	NAQ	61.20	314.16	71.21	36.79
Leirvogur	LRV	64.18	338.30	70.22	71.04

believed that the number of methods for prompt forecasting will be increased by the adoption of empirical models using near-real-time AE index as input parameters, demand for the realization of the near-real-time derivation of the AE index is increasing.

3.3 Derivation Method

Fig.1 and Table 1 show the distribution of observatories, whose data is used to calculate the AE index. Note that the Cape Wellen (CWE) observatory was closed in 1996, and was replaced by Pebek (PBK) (70.09˚N, 170.93˚E) in 2001.

The input parameters are the 1-minute values of the horizontal (H) geomagnetic field component at each observatory. First, the baseline (the value for the quiet condition) is subtracted from the daily data at each observatory. Then, the data from all the observatories is superposed by aligning the time to universal time, and the maximum and minimum values are determined for each minute to obtain the upper and lower envelope curves. (Fig.2 shows an actual example of the superposition of data for Apr.10, 1978.) The maximum and minimum values are the AU and AL values, respectively. The difference and average of the AU and AL values are the AE and AO values, respectively. In a broad sense, the AE index consists of the AU, AL, AE, and AO indices. This report will discuss the AE index in this broad sense. Fig.3 shows the AE index calculated for April 10, 1978.

The mathematical expression for the AU index is as follows:

$$AU(t) = MAX[H_1(t), H_2(t), \cdots, H_{12}(t)],$$

where $H_i(t)$ is the horizontal component observed at the ith observatory at time t with the baseline subtracted. The AL, AE, and AO indices are:

$$AL(t) = MIN[H_1(t), H_2(t), \cdots, H_{12}(t)],$$

$$AE(t) = AU(t) - AL(t),$$

$$AO(t) = (AU(t) + AL(t)) / 2.$$

The AU and AL indices, respectively, correspond mainly to the eastward and westward auroral electrojets. Since long-term trends affect the baseline, absolute value measurements are required at least once a week to monitor these trends.

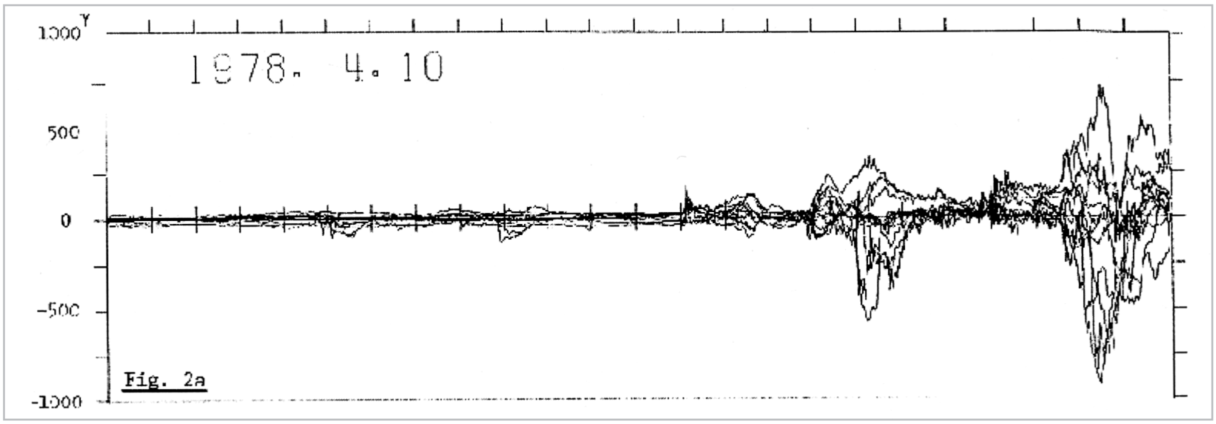


Fig.2 Superposed plot for derivation of AE index on April 10, 1978

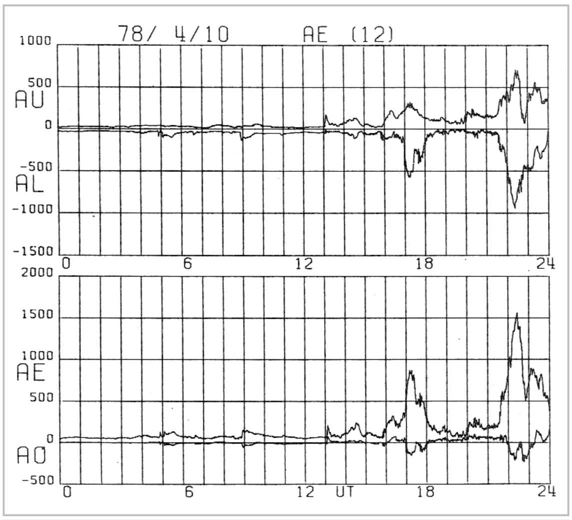


Fig.3 Plot of AU , AL, AE and AO indices on April 10, 1978

The disadvantage of having only a single observatory in each longitudinal zone for calculating the AE index is that the resulting index must be handled with care, especially in the following case. When the geomagnetic activity is extremely high (low), the electrojet tends to flow at lower (higher) latitudes than the observatories. Therefore, the latitude of the observatory does not necessarily coincide with the latitude of the center of the auroral electrojet. In this case, the auroral electrojet estimated by the calculated AE index underestimates the actual current.

3.4 History of the AE Index Derivation and Reduction of the Derivation Time

After the AE index calculation was initially developed at the NASA/Goddard Flight Center (GSFC), the 1-hour values of the AE index from 1957 to 1964 were calculated and published by the Geophysical Institute of the University of Alaska, Fairbanks. 2.5-minute values from Sept. 1964 to 1968 were calculated experimentally at NASA/GSFC. The 2.5-minute values for 1966-1974 and 1-minute values from 1975 to April 1976 were published by the World Data Center for STP, Boulder (NOAA/NGDC). Thereafter, the Data Analyses Center for Geomagnetism and Space Magnetism, Kyoto University, calculated and published the 1-minute values from 1978 to June 1988. (The National Institute of Polar Research has been in charge of the publishing since the late 1980s.) The AE index calculated and published by the above institutions have been strictly controlled in quality, for example, check for anomalous observation values and are referred to as the final AE index. It took months to derive the AE index, a process that required enormous time and effort involving the digitizing of analog observation data and checking for anomalous values.

To promote the calculation and publication of the AE index, the provisional AE index was adopted to reduce the enormous effort needed to convert data into checked digital data. Provisional AE index data is calculated even when no data is available for 1 or 2 observatories. The 1-minute values of provisional AE index from 1990 to 1995 have been calculated in this way by the Data Analyses Center for Geomagnetism and Space Magnetism, Kyoto University and have been published by the National Institute of Polar Research.

Since then, the need for the most current AE index possible has arisen in various fields. The Data Analyses Center for Geomagnetism and Space Magnetism, Kyoto University, tried to fill these demands by making plots of Quick-look AE index on the Web. These are updated as soon as geomagnetic data has been received from observatories. In the past, since it took days or even months for data to arrive from the observatories in the Siberian region, the Quick-look AE index had to be calculated before data for the four Siberian observatories was available. This meant that one-third of the data from the observation circle consisting of 12 observatories was lacking, creating a time period in which it was difficult to monitor the enhancement and decay of the auroral electrojet. Especially if a geomagnetic disturbance develops in the polar region when the Siberian region is on the nightside magnetic local time zone, the disturbance may be underestimated or even missed entirely when monitored by the Quick-look AE index.

A near-real-time transmission of data from the Siberian region over a broad range of longitudes was expected to minimize these inaccuracies by the Quick-look AE index and open the way for speeding up the AE index derivation from the Quick-look to near-real-time AE index. As near-real-time AE index derivation was desired for space weather forecasting and research, near-real-time data acquisition from the Siberian geomagnetic observatories was crucial to its realization. The PURAES project, introduced in the following section, was intended to provide a solution.

4 The PURAES Project

4.1 Background and the Collaboration Framework

As part of the effort to realize near-real-time derivation of the AE index, the 1st PURAES Project Meeting held in Sapporo in Oct. 2000 sought to improve the quality of observation data by upgrading the magnetometer at Siberian observatories, and to establish a way for near-real-time data transmission. Research institutes from Japan, Russia, and the U.S. participated in the discussions, resulting in the official launch of the Project for Upgrading Russian AE Stations/ Space Weather Magnetometer Experiment (PURAES/SWME). The institutes cooperating in the project included the CRL and the Data Analyses Center for Geomagnetism and Space Magnetism, Kyoto University, of Japan, the Institute of Dynamics of Geospheres and the Arctic and Antarctic Research Institute (AARI) of Russia, and the Geophysical Institute of the University of Alaska Fairbanks and the Applied Physics Laboratory of the Johns Hopkins University in the U.S.

4.2 Strategy

The magnetometers at the observatories were upgraded to more reliable models. A DCP, an instrument that can transmit data every 12 minutes, was also installed. Since Siberian observatories are located in remote areas without ready Internet access, data is transmitted to satellite. Data transmitted by DCPs is relayed by the GMS (Himawari satellite) and downlinked to the Meteorological Satellite Center, JMA. Then it is sent to the CRL through the Japan Weather Association (JWA). In short, the transfer method is identical to that used by INTERMAGNET. The data received at CRL is archived and also sent to Kyoto University.

From there, the data is distributed instantly to cooperating institutes. The CRL and Kyoto University are to work together in making near-real-time calculations of the AE index based on this data.

4.3 Project Plans

The positions of the PURAES geomagnetic observatories are shown by stars in Fig.4. The geographical coordinates for each observatory are as follows: Pebek (PBK: 70.09˚N, 170.93˚E); Tixie (TIK: 71.58˚N, 129.00˚E); Cape Chelyuskin (CCS: 77.72˚N, 104.28˚E); and Norilsk (NOK: 69.20˚N, 88.00˚E).

Fig.4 Distribution of PURAES stations with other AE stations

☆mark:PURAES geomagnetic observatories
●mark:Other AE stations
⊗mark:Position of Cape Wellen station, which was closed in 1996.

A PURAES project is given below.

2001 Apr. Installation and adjustment of magnetometers for observation, except for an absolute value measurement, at Pebek. Data Collection Platform (DCP) is also installed. Start of test transmission.

June Data transmission from Pebek becomes part of regular operations.

Sept. Adjustment of magnetometers and DCPs in Japan

Oct. Transport of magnetometers and DCPs to Russia

Nov. Testing is performed on the time calibration function of the instrument at St. Petersburg, where the AARI headquarters is located. Two scientists from Japan are participants in this testing.

Dec. Operation test is performed on the revised sensor of the proton magnetometer near St. Petersburg. Three scientists from Japan are participants.

2002 Feb. Installation and adjustment of magnetometers for observation, including an absolute value measurement, at Tixie. Data Collection Platform (DCP) is also installed. Start of test transmission.

Mar. Installation and adjustment of magnetometer for observation, including an absolute value measurement, at Norilsk. Data Collection Platform (DCP) is also installed. Start of test transmissions.

May Data transmissions from Tixie and Norilsk become part of routine operations.
Installation and adjustment of magnetometer for absolute value measurement at Pebek.

Aug. Installation and adjustment of magnetometer for observations, including an absolute value measurement, at Cape Chelyuskin. Data Collection Platform (DCP) is also installed. Start of test transmission.

Oct. Data transmission from Cape Chelyuskin becomes part of routine operations.

4.4 Outcome of the Availability of Near-Real-Time Geomagnetic Data

Fig.5 shows an example of actual geomagnetic variations data. Both the observation and data transfer are nearly free of interruptions. Data acquisition appears to be commencing smoothly.

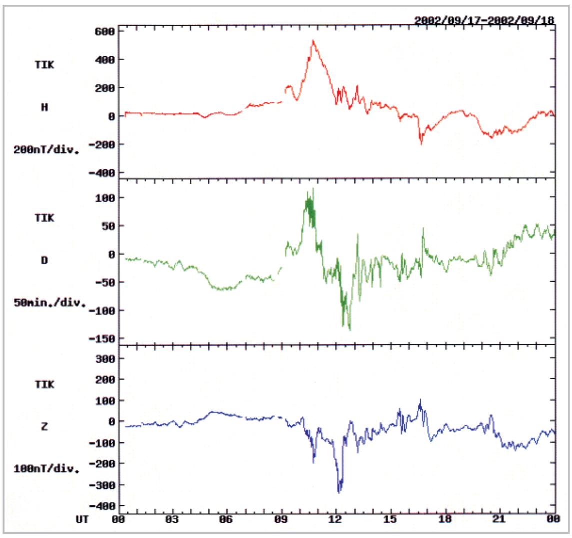


Fig.5 *Geomagnetic variation at Tixie from 0hUT to 24hUT on Sept. 17, 2002. Top panel shows H (horizontal) component. Middle panel shows D component. Bottom panel shows Z component.*

The geomagnetic H component on this day shifts significantly towards the positive during the period of 10:00-12:00 UT, or during the period of 18:00-20:00 in magnetic local time (MLT) at Tixie. This indicates a strong eastward electrojet in the ionosphere.

Fig.6 shows improvements in the underestimated AE index following the availability of near-real-time data from the PURAES observatories. The top two panels show calculated AE indices, excluding data from the PURAES observatories, to simulate conditions prior to PURAES project. The bottom two panels show the AE indices calculated with data from the PURAES observatories, which completion of the project has made available. As can be predicted from the large variations seen in the geomagnetic H component from Tixie data in Fig.5, the AU index during the period of 10:00-12:00 UT in the top panel is estimated with improved precision in the third panel. Fig.7 shows the degree to which the underestimated AU index between 7:00-12:00 UT in the top panel is improved in the third panel. Fig.8 shows the improved accuracy of the AL index during the period of 19:00-22:00 UT. Near-real-time acquisition of data from the Siberian region over a broad longitudinal range has improved the precision of AE index calculations and enabled more accurate now-casting of polar geomagnetic disturbances.

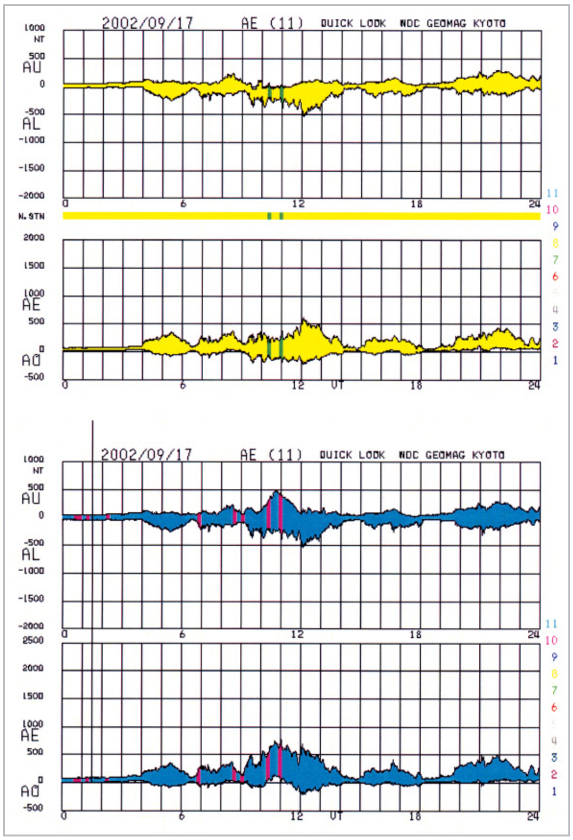


Fig.6 Comparison of conditions on Sept. 17, 2002
Upper half: Simulated calculation of AU, AE, AL, and AO indices, excluding data of PURAES stations.
Lower half: Simulated calculation of AU, AE, AL, and AO indices, including data of PURAES stations.

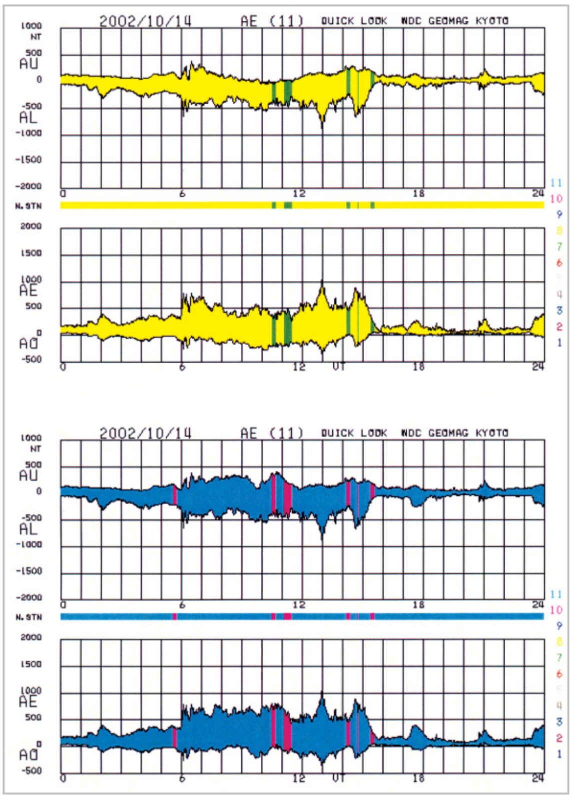


Fig.7 Comparison of conditions on Oct. 14, 2002

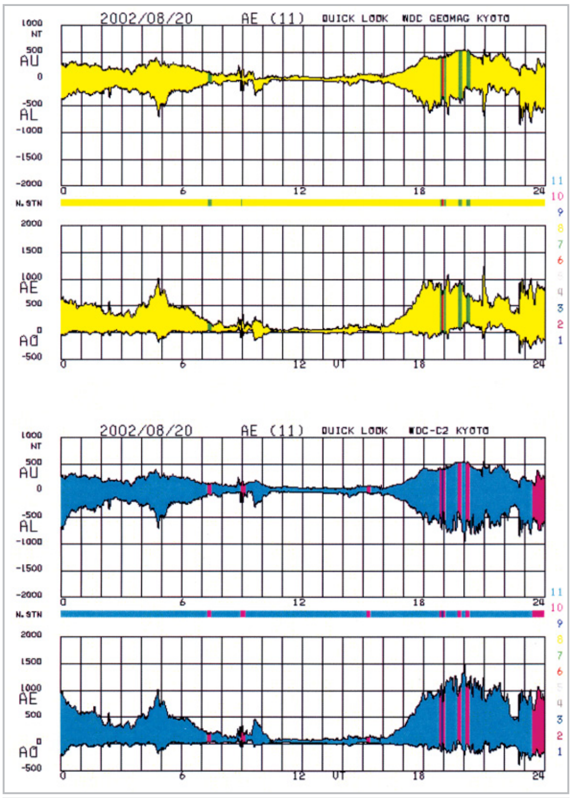


Fig.8 Comparison of conditions on Aug. 20, 2002

5 Other Applications of Near-Real-Time Geomagnetic Data

Essential for near-real-time AE index derivations, the Siberian geomagnetic data also presents the potential for creating new products through advanced utilization of data. Here, two examples of comprehensive use of geomagnetic data are given, as well as one example of geomagnetic data combined with other types of observation data.

Comparing geomagnetic data from the Siberian observatories with geomagnetic data from existing observation station set by CRL from mid-latitude regions to the equator makes it possible to know characteristics of electric field penetration from the polar region to the equator in the eastern Eurasian longitudinal zone[9].

With some additional physical constraints, geomagnetic data from multiple observation stations around the globe has been used as input parameters for near-real-time inversion calculations (KRM algorithm[14]) to estimate the 2-dimensional distribution of ionospheric electric currents, electric fields, Joule heating, and so on. Previously, observation data for input had been confined to North America and Europe. The Siberian region had been devoid of data. The addition of observation data from PUREAS stations is expected to improve the accuracy of estimates.

One example of combining geomagnetic data with data from other observation methods involves combination with data from HF radar observations. In the summer of 2001, the CRL installed a radar in King Salmon, Alaska, as part of SuperDARN, the large HF radar network. The observation area of this radar covers the ionosphere above the Pebek geomagnetic observatory of PUREAS project. However, the other three observatories in the Siberian region are positioned in areas not covered by any radar in the SuperDARN network. A more precise picture of the status of magnetospheric convection can be determined by complementing the SuperDARN radar observations data with geomagnetic data from these three observatories.

6 Conclusions

The PUREAS project has improved the quality of data at geomagnetic observatories in the Siberian region and enabled near-real-time data acquisition. This has improved quality and enabled near-real-time derivation of the AE index, an indicator based on polar geomagnetic data, and contributed significantly to nowcasting of geomagnetic disturbances. The Siberian geomagnetic data can also be used in advanced applications other than the derivation of the AE index. It is expected to prove useful in a wide spectrum of space weather forecasting applications.

Acknowledgments

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