2-1-4 Preceding Monitoring of Solar Wind Toward the Earth Using STEREO

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Acquisition of solar wind information before it reaches the earth is a key to extending the lead time for predicting disturbances in space environment around the earth (called geospace). Since the geospace is an open system, the future status of geospace is unpredictable without having an uninterrupted supply of information about the upstream of the solar wind, as a driving force for the geospace disturbanes. STEREO (Solar TErrestrial RElations Observatory) is the NASA's scientific mission involving two spacecrafts traveling slowly away from the earth basically on the same orbit as the earth to observe the Sun and the solar wind in a stereoscopic view. Like the ACE (Advanced Composition Explorer) mission, STEREO broadcasts real-time beacon signals relevant to the Sun and the solar wind data. NICT is one of the contributing institutions for real-time data receiving networks. Because information on the solar wind reaching the earth can be acquired beforehand using STEREO data (assuming that time-dependent changes in the solar wind structure is negligible), the solar wind and interplanetary magnetic field data from ACE and STEREO were compared. In terms of the solar wind velocity, a good correlation was confirmed between ACE and STEREO data despite a widening elongation. For the north-south component of the interplanetary magnetic field, however, the correlation diminished rapidly with a widening elongation. These findings revealed that the interplanetary magnetic field has time and space scales of several hours and several million kilometers, respectively. These findings also suggest that it is necessary to consider the uncertainties of north-south magnetic field component in using STEREO data for predicting geospace disturbances.

Keywords
The Sun, The solar wind, STEREO, Real time beacon, Preceding monitoring

1 Introduction

The people's understandings for the mechanism and framework of space weather forecasting are often based on the analogies with terrestrial weather forecasting. However, there are a number of significant gaps between both types of weather forecasting. The major difference is whether the system for weather forecasting can be approximated by a closed system. In the case of terrestrial weather forecasting, the system can be practically approximated by a closed system to predict its future status from initial values. This is the reason why the global atmospheric circulation model can be applied for long-term weather forecasting. In the case of space weather forecasting, the causes of disturbances in space environment around the earth (called geospace) originated from the solar activity and the upstream solar wind. If there is no information from the solar activity and the upstream solar wind, the future condition of geospace would be unpredictable, even with an excellent numerical weather forecasting model is provided for operation[1]. Therefore, numerical simulation[2] and data assimilation technology that provides an integrated solution to handling information about the solar activity and solar wind variations and its propagation from the

Sun to the earth is needed to implement quantitative space weather forecasting on a mid- to long-term basis.

NASA's ACE (Advanced Composition Explorer) was launched at the L1 point in the solar-terrestrial system in 1997. Although the main mission of the spacecraft is for scientific research, this is the first interplanetary spacecraft to support a function for continuously broadcasting solar wind and solar energetic particles data in a real-time beacon mode for operational space weather forecasting. The L1 point in the solar-terrestrial system is located about 1.5 million km from the earth toward the Sun, and represents one of the best locations for observing the Sun and the solar wind. Because of a very low bit rate, real-time beacon signals can only carry low-resolution data, but the data being continuously broadcasted by those signals aids in continuous monitoring of the solar wind conditions. A framework for receiving solar wind data around the world has been built and commissioned into service by the National Oceanic and Atmospheric Administration (NOAA) and US Air Force (USAF) with help from NICT and the U.K.'s Rutherford Appleton Laboratory (RAL) to apply such data to space weather forecasting[3][4]. We have used this solar wind monitoring data obtained from ACE in implementing day-to-day forecasting activities, providing space environment information services, conducting real-time MHD simulations, and more.

However, the L1 point - located only about 1.5 million km (or 0.01 astronomical unit) upstream from the earth - only allows predictions of about one hour in advance. Extending the lead time of the prediction requires information on solar wind variations at further upstream region, which we call "inner heliosphere (interplanetary space between the Sun and the earth)". In the past, however, the only available means of observing the inner heliosphere was limited, to the remote sensing of the solar wind by observing interplanetary scintillation (IPS), the Sun, and the solar corona by the ground-based or satellite observation, resulting in an inadequate coverage of inner heliospheric observation.

On October 25, 2006, NASA's STEREO was launched on a scientific research mission to explore the Sun and the inner heliosphere. The two spacecrafts — STEREO-A and STEREO-B — had the primary functions of observing the Sun and inner heliosphere in a stereoscopic view, and measuring the in-situ plasma environment. Although the major purpose of STEREO observation is for scientific research, the data obtained from these spacecrafts is also useful for space weather forecasting. Therefore, NASA decided to equipp real-time space weather beacons on the STEREO explorers to broadcast the Sun and the solar wind data observed by STEREO in real time, though at a low resolution.

Data is also being received from STEREO real-time space weather beacons in cooperation with overseas research institutions and similar organizations. Though the coverage of data acquisition is not 100%, data has thus far been received with reasonable success. At NICT, an antenna facility for VLBI experiment is used to receive such data[1]. Aside from being used in day-to-day forecasting activities, the receiving data is reviewed and analyzed to explore new forecasting applications. We examine the correlation between variations in the solar wind as observed by the STEREO and ACE using the solar wind data, and analyze the characteristic stability of that data for actual monitoring of the solar wind in advance.

2 Preceding monitoring of the solar wind using STEREO-B

Since the period of the Sun's revolution is about 27 days to the earth, the variations of the solar wind parameters are known to show 27-day recurrence (Figure 1). Since STEREO-B is located forward from the earth (ACE) relative to the solar revolution, the solar wind parameters obtained from STEREO-B are expected to arrive at the earth (ACE) after the time lag t_{lag} passed, assuming that the solar

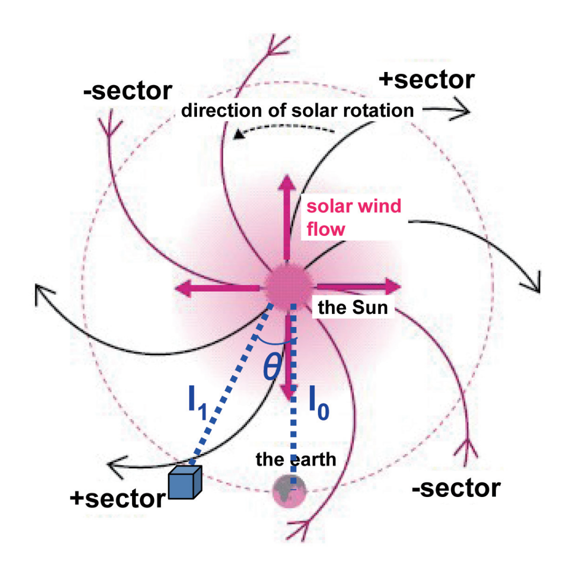

Fig.1 *The sector structure of the solar wind corotation driven by the solar rotation*

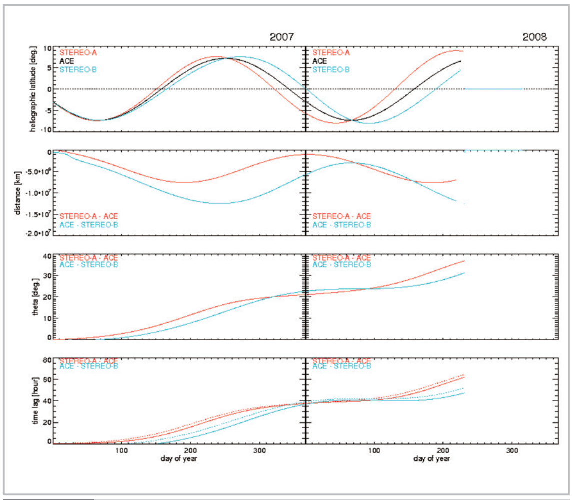

Fig.2 *Orbital trajectories of ACE, and of STEREO (top) heliographic latitude, (middle top) distance difference in the radial direction, (middle bottom) elongation, and (bottom) estimated time lag*

wind has a stationary structure (free from time-dependent changes). The following equation is used to estimate the time lag t_{lag}:

$$t_{lag} = \theta / (\omega_{sun} - \Omega_{earth}) - (\omega_{sun} / (\omega_{sun} - \Omega_{earth})) \cdot ((l_1 - l_0)/V_{sw}) \quad \cdots\cdots (1)$$

where, ω_{sun} denotes the angular velocity of the Sun's rotation, Ω_{earth} the angular velocity of the earth's revolution, l_1 and l_0 is the distance from the Sun to STEREO-B and that from the Sun to the earth, respectively, and V_{sw} is the solar wind velocity observed by STEREO-B. The orbit of STEREO-B somewhat outside the earth's orbit and gradually moves away (rearward) from the direction of the earth's orbital motion. Conversely, The orbit of STEREO-A somewhat inside the earth's orbit and gradually moves away toward the direction of the earth's orbital motion. If the distance between the Sun and the earth, that between the Sun and STEREO-A, and that between the Sun and STEREO-B were equal, the time lag would be determined solely by elongation. However, since there is a difference in each distance in reality, information about the solar wind velocity is necessary to estimate the time lag.

Figure 2 shows (from top to bottom) orbital motions in heliographic latitude, the difference of the distance in the radial direction, elongation, and the time lag of solar wind as estimated by Equation (1). The motions in heliographic latitude are marked by a red line (for STEREO-A), black line (for ACE), and blue line (for STEREO-B). Due to an inclination of 7.15 degrees between the axis of solar rotation and that of the earth's revolution, the heliographic latitude at the base of the solar wind observed by ACE will vary in amplitude of ±7.15 degrees. This essentially holds true with STEREO-A and -B as well. One should therefore keep in mind that one of the possible causes of the difference observed in the solar wind or magnetic field variations between ACE and STEREO is the difference in heliographic latitude. Further, because STEREO-A, ACE, and STEREO-B are located closest to the Sun in this order, both the difference between STEREO-A and ACE and the difference of the distance in the radial direction between ACE and STEREO-B are negative. As for elongation from the earth, both STEREO-A and STEREO-B travel away by about 20 degrees a year. Time lags are found to widen with increases in elongation. A solid line designates a time lag for a solar wind velocity of 400 km/s, and a dotted line designates that for a solar wind velocity of 800 km/s. As shown in the diagram, the higher the solar wind velocity, the wider the time lag.

According to Fig. 2, the time lag of STEREO-B reached a little less than two days from about the end of 2007 to the middle of 2008, suggesting that if the solar wind do have a stationary structure, the variations of the solar wind can be predicted (through preceding monitoring) about two days ahead by using data from STEREO-B.

3 Comparing solar wind variations observed by ACE and STEREO

To examine the feasibility for preceding monitoring of the solar wind based on STEREO data, variations in solar wind observed by ACE and that by STEREO were compared. Figure 3 plots the hourly averages of solar wind variations (in velocity, density and temperature) as observed by ACE and by STEREO during December 2007 without time lag correction. In this study, we used level 2 data. Two fast solar winds flowing at about 600 to 700 km/s were observed during the one-month period, indicating that fast solar winds had been detected by STEREO-B, ACE, and STEREO-A in this order.

Figure 4 similarly plots solar wind variations observed during December 2007, where the times of solar wind variations observed by STEREO-A and STEREO-B were corrected using time lags estimated by using Equation (1) above for comparison with ACE observations. The solar wind variations observed by all three spacecrafts were found in exceptionally good agreement based on the time lag correction process.

For comparison, each observation of the interplanetary magnetic field was plotted with time lag correction as shown in Figure 5. From the top to bottom, the diagram represents the magnetic field strength (BT), the R-component of the RTN (Radial Tangential Normal) coordinate system, the T-component, and the angle of the R-T plane [sector structure] (0 degrees in the R-axis direction and 90 degrees in the T-axis direction). In the diagram, the RTN coordinate system has its R-component points from the center of the Sun to a spacecraft, T-component points cross product of solar rotational axis and R-component, and lies in the solar equatorial plane (towards the west limb). N component points R × T in the right-hand side system. The correlation between magnetic field variations as observed by each spacecraft tends to remain relatively low compared with the solar wind velocity variations. This might be considered as a superposition of MHD waves in the quasi-static interplanetary magnetic field

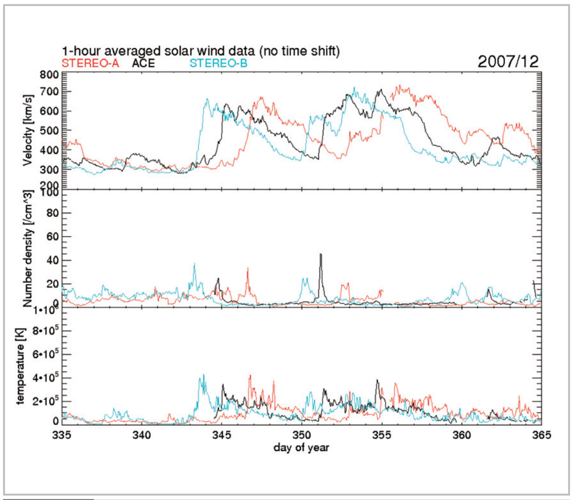

Fig.3 Solar wind variations observed by ACE and STEREO during December 2007 (without time lag correction)

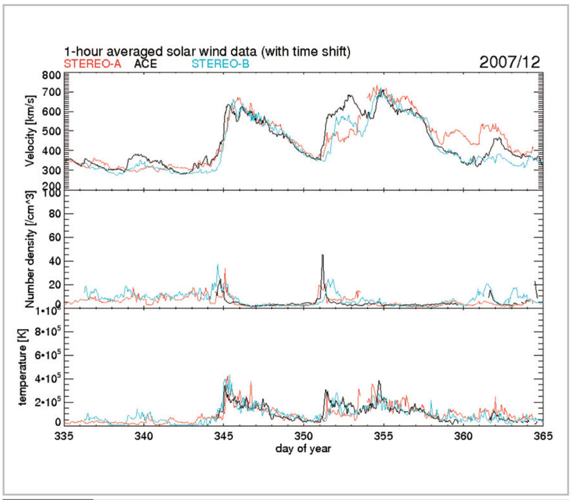

Fig.4 Solar wind variations observed by ACE and STEREO during December 2007 (with time lag correction)

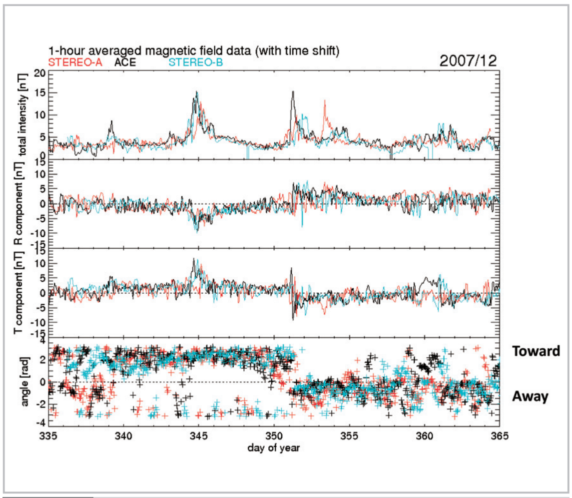

Fig.5 Interplanetary magnetic field variations observed by ACE and STEREO during December 2007 (with time lag correction)

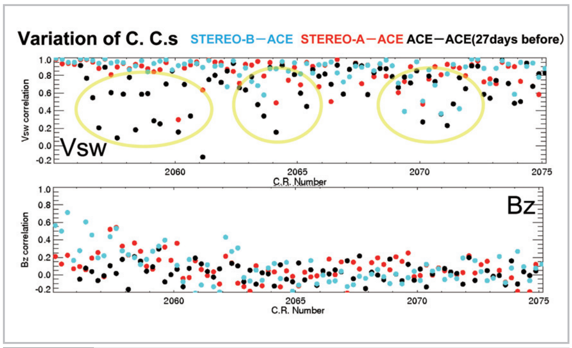

Fig.6 Variations of the correlation coefficient between two different solar wind observations for Carrington rotation periods from #2055 to #2075

Upper panel: Solar wind velocity
Lower panel: North-south component of the interplanetary magnetic field

structure. Moreover, the increased magnetic field intensity observed by STEREO-A around the 353rd day of the year may be associated with magnetic field variations of ICME. On the other hand, a relatively good correlation was found between sector structures observed by ACE and STEREO.

Figure 6 plots variations of the correlation coefficient between two different solar wind observations for Carrington rotation periods numbered from #2055 to #2075. The upper panel in the diagram represents variations in the correlation coefficient of the solar wind velocity; the lower panel represents variations in the correlation coefficient of the north-south component (Bz component) of the interplanetary magnetic field. Each red circle points to a correlation coefficient between STEREO-A and ACE, with each blue circle pointing to a correlation coefficient between ACE and STEREO-B, and each black circle to a correlation coefficient between ACE and the ACE data for the previous Carrington rotation period. As for the solar wind, high correlations evidently exist as a whole, with correlation coefficients of 0.6 or higher generally being observed between STEREO and ACE during the periods of observation, and thus are higher than the correlation with ACE data for the previous Carrington rotation period. However, the correlation coefficient dropped about three periods as marked in yellow open circle. Time-dependent changes in the solar wind structure during this period might be one of the causes. As for variations of Bz, the correlation coefficient down to 0.5 or below about three periods passing after Carrington rotation period #2055. This may reflect the status of the solar wind structure, because the Bz component is directed virtually perpendicularly to the plane of the solar rotation. The widening elongation of STEREO orbit with increases in the Carrington period suggested that the magnetic field structure and time-dependent variations had typical time and space scales of several hours and several million kilometers, respectively.

4 Summary and conclusions

The correlations between the solar wind variations observed by STEREO and by ACE were examined using the solar wind and the magnetic field data obtained from these spacecrafts. As a result, the correlation on the solar wind velocity did not diminish noticeably as a whole, despite a widening elongation, except for the period when time-dependent changes occurred in the solar wind structure. This suggests that the space weather forecasting based on STEREO-B is basically acceptable. As for the Bz component, a key parameter from the perspective of geospace disturbances, the correlation diminished rapidly with a widening elongation, down to 0.5 or below about three periods after Carrington #2055. These findings revealed that typical time and spatial scales for north-south component of interplanetary magnetic field estimated to be several hours and several million kilometers, respectively.Based on these results, information of the solar wind velocity and the sector structure from STEREO-B can be used as input parameters of empirical models and numerical simulation, but not information about Bz in its raw form. For this reason, it is necessary to model the uncertainties of the Bz component and then consider a probabilistic scheme of forecasting. In addition, such tasks as how to assess the impact of time-dependent variations in ICME and the solar wind structure remain to be solved, but the solar wind data provided by the STEREO should prove useful in predicting the status of the magnetosphere and geospace disturbances several days in advance.

We will develop the techniques for removing telemetry noise, calibrating physical quantities, and handling lack of measurements in real-time beacon data, and then perform specific data processing, such as time lag correction and coordinate transformation, by using the resultant solar wind prediction data to conduct a magnetospheric global MHD simulatio[2] and drive an empirical geomagnetic activity forecasting model[5], in order to predict in a quantitative manner the status of the magnetosphere and geospace disturbances several days in advance.

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References

1 M. Akioka, Y. Kubo, T. Nagatsuma, and K. Ohtaka, "Monitoring of the Solar Activity and Solar Energetic Particles", Special issue of this NICT Journal, 2-1-1, 2009.

2 H. Shinagawa, "Significance and Importance of the Integrated Space Weather Simulation", Special issue of this NICT Journal, 2-3-1, 2009.

3 T. Maruyama, S. Watanabe, K. Ohtaka, and H. Shimazu, "Real time solar wind monitor using ACE satellite", Rev. Comm. Res. Lab., Vol. 43, pp. 285–290, Jun. 1997. (in Japanese)

4 E. Sagawa, S. Watanabe, K. Ohtaka, H. Shimazu, and R. D. Zwickl, "Real time data reception of ACE and IMAGE satellites", Vol. 49, pp. 55–67, 2002.

5 T. Nagatsuma, "Monitoring and Forecasting of Geospace Disturbances, and its Importance", Special issue of this NICT Journal, 2-2-1, 2009.

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