Investigation of substorms during geomagnetic storms using wavelet techniques

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Abstract. The variations in the geomagnetic field during intense geomagnetic storms can be reproduced by changes in the interplanetary magnetic field and the solar wind velocity. Both the solar wind velocity enhancement and the magnitude of the southward component of IMF are important in enhancing the ring current. During geomagnetic storm periods, variety of fluctuations exist in the IMF components and that in solar wind velocity which initiate the similar fluctuations in geomagnetic field. If solar wind pressure oscillations with periods comparable to the substorm cycle time are imposed on the magnetosphere, some magnetospheric resonant state may be excited, and substorms can be triggered. In this work, the evolution of short quasi-periods are investigated using wavelet cross spectral method and decomposition techniques to study the interlink between geomagnetic field fluctuation and the solar wind velocity and IMF using cross wavelet spectral method. In the wavelet decomposition process, these signals are broken down into many lower resolution components with successive approximations being decomposed in turn. Multi-resolution techniques (MRA) due to their time-frequency flexibility are particularly suited to the study of transient structures like those associated with geomagnetic storms. From the details, the transient nature of solar disturbances characterized by intermittent bursts during geomagnetic storm is seen. The fluctuations in IMF Bz and H are much similar during the main phase which are stable for many levels of decomposition, whereas those fluctuations in solar wind velocity are similar to H only during the initial phase. It is also seen that the high frequency fluctuations that are present during the progress of the storm are stable for many levels of decomposition in the reconstructed signal. So these fluctuations may be due to high frequency signals that are present in the parameters as a result of the disturbed conditions which play a leading role in the solar terrestrial energy coupling.

Index Terms. Ionosphere, IMF, periodicity, solar wind, substorm.

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1. Introduction

The energy and momentum carried by solar wind is transferred into the magnetosphere at the magnetopause boundary layer when conditions are favorable. The solar wind plasma can cross the magnetopause and enter the magnetosphere either by a direct entry due to flow along reconnected open field lines or by cross-field transport due to scattering across closed magnetopause field lines. The first process is more likely to be important when the interplanetary magnetic field is directed southward i.e., when solar wind and magnetospheric magnetic field lines are antiparallel. Solar wind-magnetosphere interaction is highly evolving with time and the parameters associated with it exhibits variety of transient and periodic fluctuations. The magnetospheric responses to the solar wind input is highly nonlinear and produce very different outputs for a slight difference in the input (Baker and McPherron, 1990; Klimas et al., 1994). The physical interaction of the interplanetary medium with Earth’s magnetosphere generates a variety of global processes in the ionosphere-thermosphere-magnetosphere system. Transient changes in the solar wind parameters generate enhanced geomagnetic activity when interplanetary magnetic field have a prolonged and strong southward component. During geomagnetic storm periods, the fluctuations in IMF and that in solar wind velocity can initiate the substorms. If solar wind pressure oscillations imposed on the magnetosphere are comparable to the substorm cycle, some magnetospheric resonant state may be excited, and periodic substorms can be triggered. If the solar wind oscillations are too fast, not enough energy is accumulated in the magnetotail for substorms to occur. If the period of solar wind oscillations are too long, magnetospheric energy will be released through other processes including internally triggered substorms. In this work, the evolution of short quasi-periods in geomagnetic activity and solar wind are investigated using wavelet cross spectral method and decomposition techniques to study the interlink between them. The wavelet transform provides a flexible time-frequency window that automatically narrows when focusing on high-frequency oscillations and widens on the low-frequency background in a manner analogous to a zoom lens. The wavelet transform permits identification of the main periodicities in a time series and to study the evolution in time of each frequency (Torrence and Compo, 1998). The cross-wavelet power at a particular frequency provides qualitative information about the strength of the relation between oscillations present in each time series. The large values of the cross-wavelet modulus reflects the combined effects of large fluctuations of the signals in both parameters at that time and of a good matching of the shape between the signal and the wavelet. A given data set is divided into components with different scales, which allows the investigation of each component with a resolution matched to its scale. This property is especially useful for signals that are non-stationary, short-lived transient components and have features at different scales, or have singularities (Kumar and Foufoula-Georgiou, 1997). In the present work, Daubechies wavelet is taken as mother wavelet for multi resolution analysis and Morlet wavelet for spectral analysis. Daubechies wavelets have a fractal structure and they include both highly localized wavelets and highly smooth wavelets. Wavelet decomposition of each parameter is also taken for comparison to analyze the high frequency components present in each parameter during the progress of a geomagnetic storm. Wavelet decomposition method is also used to investigate the relation between solar wind parameters and geomagnetic field. Daubechies (db3) wavelet is used to decompose each parameter and they are reconstructed for 9 levels of decomposition. Then a cross correlation between the filtered and time shifted solar wind velocity and IMF with H is performed. The time lag corresponding to maximum cross correlation is noted (Kelley et al., 2003).

2. Magnetic storm on 6-7 April 2000

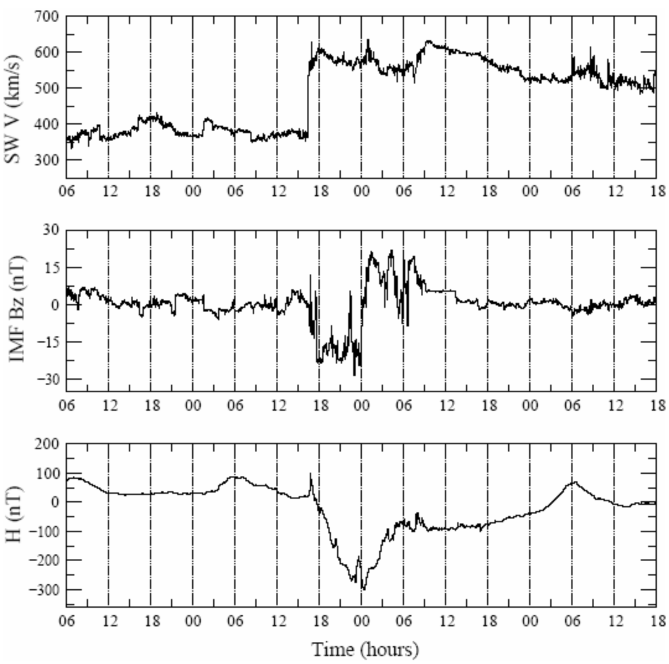

Fig. 1. The solar wind velocity, IMF Bz component and horizontal field at Alibag during the magnetic storm on April 6-7, 2000.

Fig. 1 shows solar wind velocity (top) and IMF Bz component (middle) measured by WIND satellite and geomagnetic H (bottom) at Alibag (ABG, Geog. lat. 18.6^0 N, Geog. long. 72.9^0 E and Dip lat. 12.9^0 N) during 5 - 8 April, 2000, around the period of the magnetic storm of April 7, 2000. The position of WIND satellite during the period of study was at distance of approximately 50 R_E along the Sun-Earth direction and 40 R_E in east-west direction. It takes almost 12 minutes for the disturbances at the WIND satellite position to reach the magnetosheath. An interplanetary shock headed toward Earth is detected by WIND around 1600 UT on 6 April, 2000. This shock was caused by a solar coronal mass ejection observed by SOHO at 1541 UT on April 4, 2000. The solar wind was so strong (~ 620 km/s) that it compressed the magnetosphere and triggered a great

3. Spectra of solar terrestrial parameters during magnetic storm

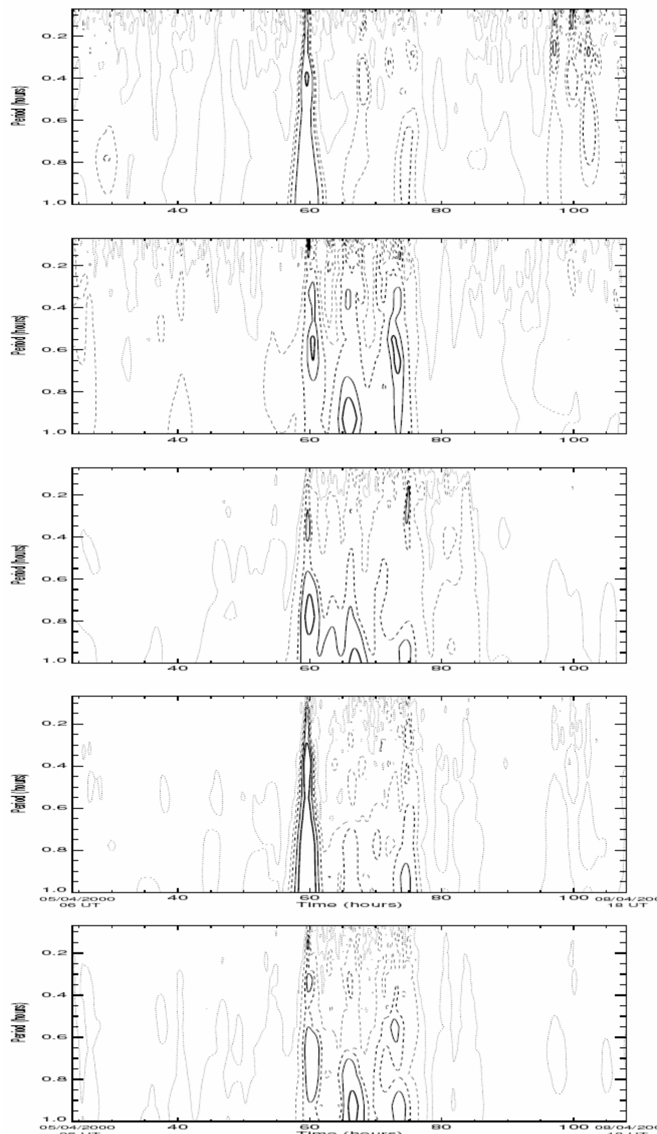

Fig. 2. Wavelet spectrum of solar wind velocity (top), IMF Bz (second), horizontal component of geomagnetic field (H) (third), cross spectrum between solar wind velocity and H (fourth) and Bz and H (bottom) during 0600 UT April 05 to 1800 UT, April 08, 2000.

geomagnetic storm. Dst initially dropped to - 85 at 0300 UT, reached a minimum of - 207 at 10.00 UT, and recovered to - 50 by the end of the day. The large values of By and Bz in the solar wind led to enhanced reconnection on the dayside and to enhanced magnetospheric convection. The solar wind velocity increased by 230 km/s and Bz changes from near zero to almost 10 nT. After some rapid fluctuations the IMF

Bz remained southward for a long period and exhibited a number of oscillations. These oscillations are reflected in the variations of geomagnetic field component. The initial phase of the storm started with a sudden commencement on 6 April, 17.00 UT. After the initial phase, Dst started becoming more negative during the main phase and reached -321 nT at 01.00 UT on 7 April, 2000. IMF Bz remained southward for almost 6 hours and then turned northward. The corresponding changes in Alibag H is also shown in the bottom panel of fig. 1.

Fig. 2 presents the wavelet spectra of solar wind velocity, IMF Bz and H (top three panels) and also the cross spectrum (bottom two panels) of solar wind velocity and Bz with H. The data plotted here is during 06.00 UT April 5 to 18.00 UT April 8, 2000 which includes the initial phase, main phase and beginning of recovery phase. From the cross spectrum, it is evident that there is large covariance in the period range of about 50-60 minutes during the initial phase and the main phase. There are also some enhancements around 25 minutes in the cross spectrum during the initial phase. The analysis is restricted to the period range 0 to 1 hour. It is noticed that in solar wind velocity the wavelet power corresponding to the period less than one hour is highly evolving during storm time and the parameters show strong short period features during the storm. The main periodicities present are near 12 minutes, 25-30 minutes and one hour. The periods near 25 minutes and 1 hour are highly covariant in the cross spectra of solar wind velocity and H, compared to other periods. The cross wavelet spectrum between solar wind velocity and H and Bz and H are depicted in the bottom two panels of figure 2. The covariance between periodic variations in solar wind velocity and H is very prominent during the initial phase of the storm and less prominent during the main phase of the geomagnetic storm. Whereas, the cross wavelet spectrum between Bz and H depicted in the bottom panel of fig. 2 shows that during the main phase of the storm the covariance between H and Bz is very prominent.

4. Multi scale analysis of solar terrestrial parameters

The Multi resolution analysis (MRA) enables to look hierarchically at the embedded fluctuations in detail by successively removing the smaller scale (high frequency) fluctuations while leaving a coarser signal (Malinga and Poole, 2002). In order to study the variability of solar wind parameters and H, this filtering procedure using wavelet analysis is employed here. The original signal (s) is decomposed into two orthonormal components, frequency component (details). The approximations (shown on the left side of fig.3 represent the long term trend of data which is almost identical to original signal, and the detail coefficients represent the short period fluctuations in a given period range. For the wavelet decomposition analysis, the data of solar wind velocity, Bz and H around three geomagnetic storms are used. Each set of resolution 2 minutes. So the detailed components D3, D4, D5, D6, D7 are in the period range 4 - 8 minutes, 8 - 16 minutes, 16 - 32 minutes, 32 - 64 minutes and 1 - 2 hours.

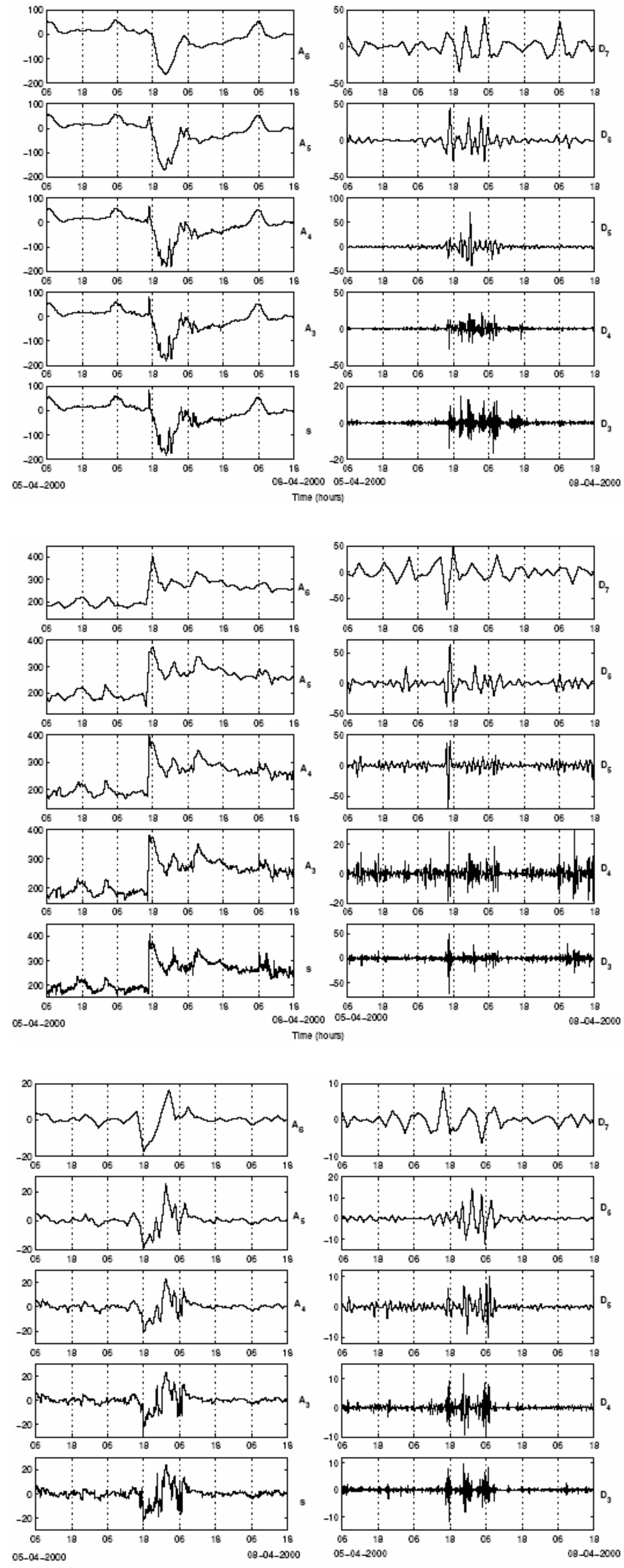

Fig.3. Signal (s), Approximations at levels A6, A5, A4 and A3 and details at D7, D6, D5, D4 and D3 of H (top), solar wind velocity (middle) and IMF Bz (b0tt0m) during the storm on April 7, 2000

Fig. 3 (top) presents the wavelet decomposition of H and solar wind velocity during April 7, 2000 magnetic storm. The approximations and the details at different levels of decomposition of the horizontal intensity H during the magnetic storm are presented. Similarly middle panel of fig. 3 shows the approximation and details of solar wind velocity. Comparison of detail coefficients of these two parameters depict the relation between fluctuations of different periods present in H and solar wind velocity and their time evolution. The detail coefficients of H show that high frequency components present during the initial and main phases of the storm are having high amplitudes in the period range from few minutes to two hours and they are existing for higher levels of decomposition. It is observed that the fluctuations in solar wind velocity during the initial phase of the storm are very strong and persistent for different levels of decomposition. Here it is observed that very high frequency components present only during the initial phase of the storm and are very strong in amplitude and stable for higher levels of decomposition. Even though there are some strong fluctuations in the main phase and recovery phase, they are not so persistent as that present during the initial phase. The wavelet decomposition of Bz (Fig. 3) indicates that the short period fluctuations are highly significant during the initial phase and main phase of the storm. The presence of high frequency components in the detail coefficients are observed near the sub-storms appeared during the progress of the storm. The fluctuations are almost identical to that of H for about 5 levels of decomposition in the period range of few minutes to one hour as in the case of cross wavelet spectrum.

5. Results and discussion

Wavelet analysis employed in the present work helps to decompose the time series of solar wind and geomagnetic field parameters in to different scales. There may be different dominant scales at different times in the solar terrestrial parameters, depending on the regularity of their variation. The wavelet spectrum presented in fig.2. reveals the time at which there is large covariance and hence important in the investigation of solar wind magnetosphere coupling. During the magnetic storm, the solar wind velocity enhanced by more than 200 km/s and remained comparatively higher for a longer period. The IMF Bz component changed orientation north and south several times with comparable magnitudes and it triggered many substorms during the storm period. It is often difficult to separate the solar wind effect from the IMF Bz effect. In general, the wavelet power of solar wind velocity and IMF parameters are more prominent during the initial and main phase. The cross spectrum between solar wind velocity and H has higher magnitudes during the initial and main phases of storm with varying strength. At other times, the cross spectrum do not exhibit prominent covariant features. This means that the solar wind and interplanetary disturbances during the storms are being mapped to terrestrial environment noted by the variations in geomagnetic H, during the progress of the storm. In fig. 3, it is seen that the spectral power of periods in the range 0 to 1 hour are highly enhanced due to the passage of interplanetary shock. Due to the transfer of energy and momentum, the geomagnetic field also get affected and leads to a storm. These features are reproduced in the cross spectrum also. During the recovery phase, though the spectral amplitude of the periods is not at all stronger as initial phase but shows many characteristic short period features.

The Bz component of IMF has important role in determining the variations in H during the main phase of the storm. The presence of highly covariant features in the spectra of solar wind velocity and H during the initial phase of the storm shows that the high dynamic pressure of solar wind is instantly communicated to geomagnetic field and hence caused the initial phase of storm. But during main phase, the spectral features in H are similar to Bz rather than solar wind velocity, indicating that the fluctuations during the main phase are due to the variations in Bz. Multi-resolution techniques, due to their time-frequency flexibility, are particularly suited to the study of transient structures like those associated with storms. In the detail-coefficients the transient nature of solar disturbances characterized by intermittent bursts during geomagnetic storm are seen. As in the wavelet spectra presented in fig. 2, the decomposition also shows that fluctuations in the period range of few minutes to one hour in IMF Bz and H simultaneously. They are much similar during the main phase and are stable for many levels of decomposition. Whereas, the fluctuations in solar wind velocity are similar to H only during the initial phase. It is also seen that the high frequency fluctuations that are present during the progress of the storm are stable for many levels of decomposition in the reconstructed signal. So these fluctuations may be due to high frequency signals that are present in the parameters as a result of the disturbed conditions which plays a leading role in the solar terrestrial energy coupling.

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