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Magnetospheric Response to Solar Wind Variations

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ABSTRACT

The time lagged response of the magnetosphere to solar wind variations has been determined using the linear prediction filtering method and 34 intervals of high time resolution IMP-8 solar wind data and auroral electrojet AL index data. The linear prediction filtering method is a powerful time series analysis technique which is utilized to produce a filter of time lagged response coefficients which estimates the most general linear relationship between magnetospheric activity and solar wind variations. This study uses the AL index to monitor the magnetosphere's response and VB_s to monitor the solar wind input. Before analysis, the median value of the AL index for each of the 34 intervals was utilized to rank the intervals according to the level of geomagnetic activity. It is found that the VB_s-AL filters are composed of two response pulses peaking at time lags of 20-minutes and 60-minutes. Our interpretation associates the 20-minute pulse with activity driven directly by solar wind-magnetosphere interaction and it associates the 60-minute pulse with activity driven by the release of stored energy from the magnetotail. Thus, the filter results suggest that both the directly driven and the unloading models of magnetospheric response are important in describing the time lagged response of the magnetosphere to solar wind variations.

INTRODUCTION

An active topic of research in solar-terrestrial physics is the study of the magnetosphere's response to variations in the upstream solar wind conditions. Indeed, this is a topic of some controversy since two competing models have been proposed to describe the response of the magnetospheric system to the solar wind. One of these, the directly driven model, suggests that the magnetosphere responds directly to interactions with the solar wind. That is, one need only to prescribe the boundary conditions on the magnetopause to predict the behavior of the magnetospheric system. The other model which is often called the unloading model concludes that processes internal to the magnetosphere are important in determining when enhanced geomagnetic activity occurs. The hypothesis is that the release of stored energy from the earth's magnetotail gives rise to the energy dissipation processes commonly associated with magnetospheric substorms.

The technique of linear prediction filtering provides a means of testing the relative efficacies of the directly driven and unloading models of magnetospheric response. This technique uses a filter of time lagged response coefficients to quantify the relationship between the input and output of a linear, time-invariant system. The linear prediction filtering method has a major advantage over conventional cross-correlation methods. Once a filter is obtained, it can be convolved with the input time series to directly predict the output time series of the system. Then, comparison of the predicted and observed time series reveals valuable clues as to what signals are transferred through the system from the input to the output. For a history of the application of linear prediction filtering to the problem of solar-terrestrial physics and a self-contained description of the technique, please refer to the review by Clauer (this volume).

In this study, we shall use VB_s which is equal to the solar wind bulk speed multiplied by the magnitude of the interplanetary magnetic field (IMF) southward component to monitor the solar wind input to the magnetosphere. We shall also use the AL index to monitor the response of the magnetosphere to the solar wind. A study by Clauer et al. (1981) has already used VB_s and the AL index in a preliminary study using linear prediction filtering. They report that the VB_s-AL filters have a single response pulse which peaks after a time lag of about 40 to 60 minutes and which decays to zero after about 2.5 hours. Furthermore, Clauer et al. (1981) found that the character of the filters describing the relationship between the solar wind and the AU and AL indices change depending on the magnitude of the geomagnetic disturbance in the data sets used for analysis. They suggest that the response of the magnetosphere is not completely linear; otherwise, the filter characteristics would not vary depending on the level of geomagnetic activity. Of course, the magnetosphere is a very complicated system which is not likely to behave in a completely linear fashion. This latter complication will be addressed here by organizing the data with respect to the level of geomagnetic activity before analyzing them with the filtering routines. The study presented here is a brief summary of the essential points reported in Bargatze et al., (1985).

DATA AND DATA SET PREPARATION

This study utilizes IMP-8 solar wind plasma data, IMP-8 IMF measurements, and the auroral electrojet AL index from the time interval between November 1973 and December 1974. The IMF measurements are expressed in geocentric solar magnetospheric (GSM) coordinates. All of the data is at 2.5-minute time resolution and they are the same data used by Baker et al. (1981) to study the correlation between the AE index and interplanetary parameters.

A series of five steps were required to prepare a data set suitable for analysis. First, the solar wind data were time shifted to account for the transit time of the solar wind from the point of observation at IMP-8 to the subsolar point of the magnetopause. This correction takes into account both the radial and azimuthal drift of solar wind plasma in the GSM coordinate system. The time shift has the effect of setting the fiducial zero time lag for the linear filtering analysis. A more complete description of the time shifting formula is given by Baker et al. (1983).

Second, the AL index which we use to model the response of the magnetospheric system and VB_s which we use to model the solar wind input to the system were scanned to identify intervals which contained at least one day's worth of nearly continuous data. The list of intervals was then modified on the basis of the following criteria: each data interval must be temporally bounded at beginning and end by 3-hour segments of weak solar wind input and weak geomagnetic activity; each data interval may contain one or more events of geomagnetic activity if and only if the events are of the same level of activity; and any data interval must be split into two separate intervals if the two new intervals independently satisfy the above criteria. These latter conditions aid in the prevention of time aliasing caused by inputing concatenated data intervals into the linear filtering routines and they aid us later when we sort the intervals with respect to the level of geomagnetic activity.

Third, the integral occurrence percentages of the AL index for each data interval was calculated to find the median value of the index in each interval. The median AL index values were then used to order the data intervals from weakest levels of geomagnetic activity (small, negative AL index medians) to strongest levels of geomagnetic activity (large, negative AL index medians).

In the final two steps, the data gaps in the solar wind time series were interpolated and then, the data intervals were concatenated end-to-end in the order prescribed by activity levels. The interpolation was done since the linear filtering routines cannot accept missing data in the input or output time series; few data gaps were longer than 10-minutes long.

LINEAR FILTERING RESULTS

As mentioned above, the Clauer et al. (1981) study found evidence that the response of the magnetosphere shows some nonlinear behavior. They note that the VB_s-AL and VB_s-AU filters change character depending on the level of geomagnetic disturbance in the data sets they used to calculate them. In particular, the time lag to peak response tends to shorten with increasing levels of disturbance. To study this feature, we input each set of five activity ordered data intervals into the linear filtering routines to obtain VB_s-AL filters which describe the magnetosphere's response to the solar wind over limited ranges of geomagnetic activity. In all, thirty filters were calculated using the 34 intervals in the analysis data set. These filters were numbered from 1 to 30 with #1 and #30 representing the impulse response of the magnetosphere during weakest and strongest levels of geomagnetic activity respectively.

In Figure 2, filter #10 and filter #27 are displayed. Both of these filters have a response pulse which rises quickly from near zero response at zero time lag, which reaches a peak value near 20-minutes time lag, and which decays thereafter. In addition, filter #10 possesses a second response pulse which reaches a peak value at a time lag of about 60-minutes. If filter #27 has a corresponding pulse, it is not well resolved. Both filters decay back to near zero response at a time lag of about 2.5-hours.

Figure 3 is a stack plot of all of the VB_s-AL filters we calculated. In general, filters #1 through #18 possess the same response features which were described for filter #10 above. Likewise, filters #19 through #30 have nearly the same response character as that described for filter #27. Note, however, that there is a degree of variability in the time lag to peak magnitude of the first and second response pulses. It is likely that this variability is related to incomplete correction for solar wind transit effects. It may, however, represent some real variability in the response of the magnetosphere to the solar wind.

Figure 4 is a plot of the VB_s solar wind input time series, the original AL index output time series, the predicted AL index output time series, and the residual AL index time series (= original - predicted) for the data sets used to calculate filter #10 (top three panels) and filter #27 (bottom three panels). In both cases, the predicted AL index time series appears to be a low pass averaged version of the original AL index time series. And in both cases, about 45% of the variance in the original AL index time series is modeled by the predicted AL index time series. However, there are high frequency variations in the original AL index that are not predicted using the VB_s solar wind input. Some of these variations, the sharp negative residuals, appear to be systematic response signatures of the magnetosphere. McPherron et al. (this volume) have correlated the occurrence of such signatures with the onset times of magnetospheric substorms. The fact that this component of the AL index is not predicted using solar wind data alone suggests that magnetospheric variables do exercise some control over the response of the magnetosphere to the solar wind.

DISCUSSION AND CONCLUSION

The VB_s-AL filter results presented here in Figures 2 and 3 are in good agreement with the results presented by Clauer et al. (1981). However, by ordering our data set with respect to activity level and by correcting for the transit time of the solar wind from IMP-8 to the magnetopause, we have been able to distinguish two response pulses in our VB_s-AL filters whereas, the Clauer et al. study only found one pulse. These two pulses peak at time lags of about 20-minutes and 60-minutes and, their relative magnitudes depend on the level of geomagnetic activity in the data sets used to calculate them. This change in relative magnitude is responsible for the differences that Clauer et al. (1981) reported in their moderate and strong activity level filters.

Likewise, our filter results are in agreement with the results of a cross-correlation study performed by Baker et al. (1981) which used the same data set analyzed here. They found that the time lag for peak correlation between VB_s and the AL index maximizes near a time lag of about 40-minutes. This is intermediate between the time lags of the 20-minute and 60-minute pulses found using linear filtering which is understandable since they did not separate their analysis data set depending on the level of geomagnetic activity.

Our present interpretation of these results is that the 20-minute and 60-minute pulses each correspond to a separate response mode of the magnetosphere. It is possible that the 20-minute pulse corresponds to the enhancement of current flow in the ionosphere in response to magnetospheric convection driven directly by solar wind interaction. Also, it is possible that the 60-minute pulse corresponds to the enhancement of current flow in the ionosphere in reponse to the release of stored electromagnetic energy from the magnetotail. There is observational support for this intepretation. For

instance, Meng (1979), Holzer and Reid (1975), and Reid and Holzer (1975) reported that motions of the auroral oval respond to changes in the solar wind with an exponential time constant of about 20 minutes. Furthermore, Iyemori (1980) found that the onset of a substorm is typically delayed one hour after a southward turning of the IMF. Many cross-correlation studies find a similar time lag.

If the present interpretation is correct, then the linear filtering results suggest that both the directly driven and unloading models of magnetospheric response are important in describing the complete response of the magnetosphere to solar wind variations. In the future, we hope to improve upon our capability to predict geomagnetic activity. To do this, it appears that we must identify magnetospheric variables which are readily monitored and which accurately predict the onset times of all facets of magnetospheric substorms.

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Iyemori, T., Time delay of the substorm onset from the IMF southward turning, J. Geomag. Geoelectr., 32, 267, 1980.

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Reid, G. C., and T. E. Holzer, The response of the dayside magnetosphere-ionosphere system to time varying field line reconnection at the magnetopause: 2. Erosion event of March 27, 1968, J. Geophys. Res., 80, 2050, 1975.

FIGURE CAPTIONS

Figure 1. A plot of filter #10 and filter #27. These filters correspond to moderately and strongly active data intervals respectively. The vertical axis is plotted using the units of the AL index (nT) divided by units of the solar wind electric field (mV/m) and normalized by the data sampling period (150 seconds).

Figure 2. A stack plot of linear prediction filters for all levels of geomagnetic activity. The geomagnetic "activity level," based on the distributions in Figure 1, increases unevenly from filter #1 through #30. A dashed baseline and a vertical scale are included for filter #1 and a vertical scale is included for filter #30. Each successive filter is plotted after a cumulative, vertical displacement of one tick mark. Note that the filter coefficients were multiplied by a hundred before plotting.

Figure 3. A plot of the VB_s, original AL index, predicted AL index, and residual AL index time series for moderate (top three panels) and strong (bottom three panels) geomagnetic activity levels. The moderate and strong activity data shown here correspond to a 5-day subset of the data used to calculate filter #10 and filter #27. Note that the predicted AL index time series is the more smoothly varying function plotted in the middle panel of each set of panels.

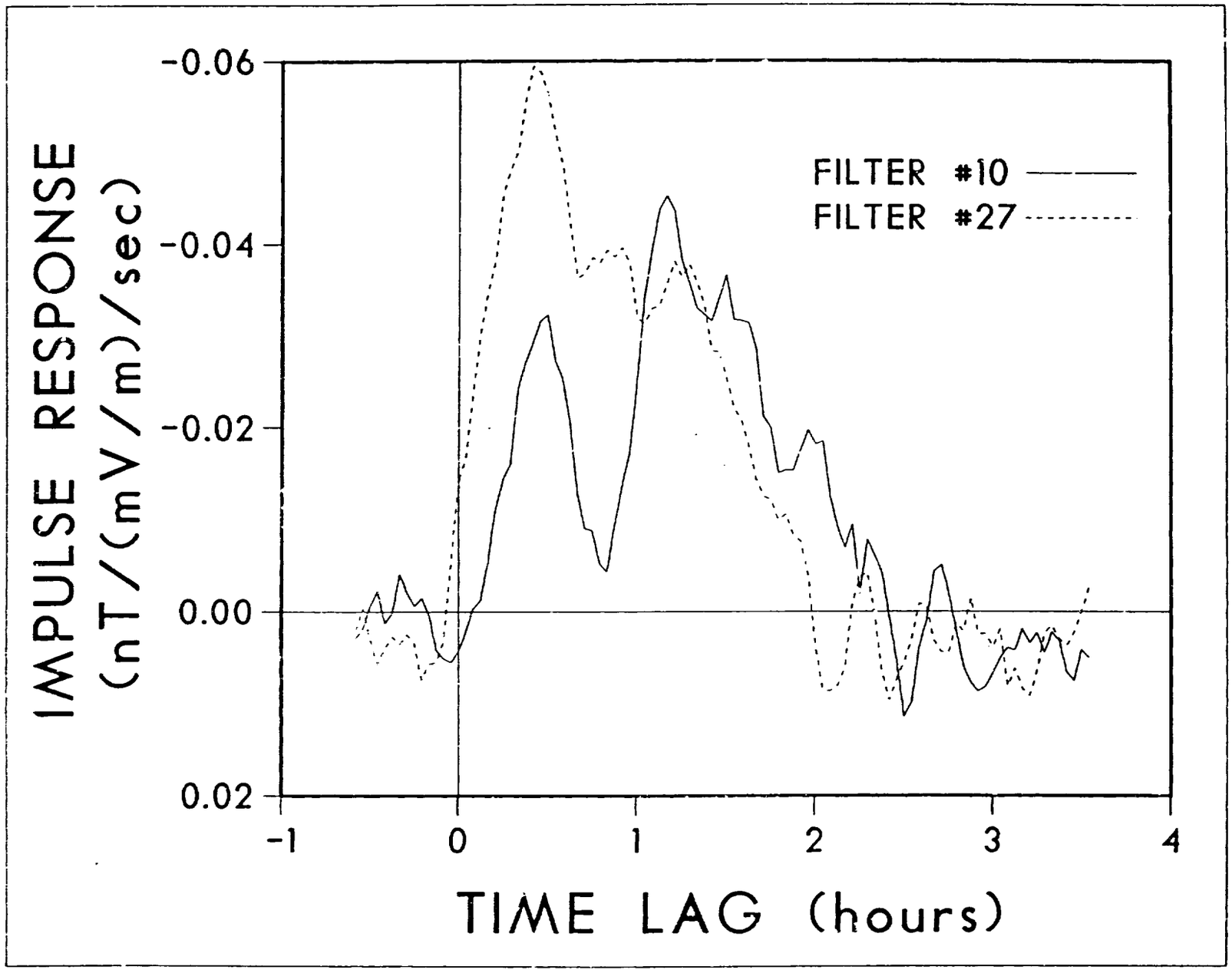
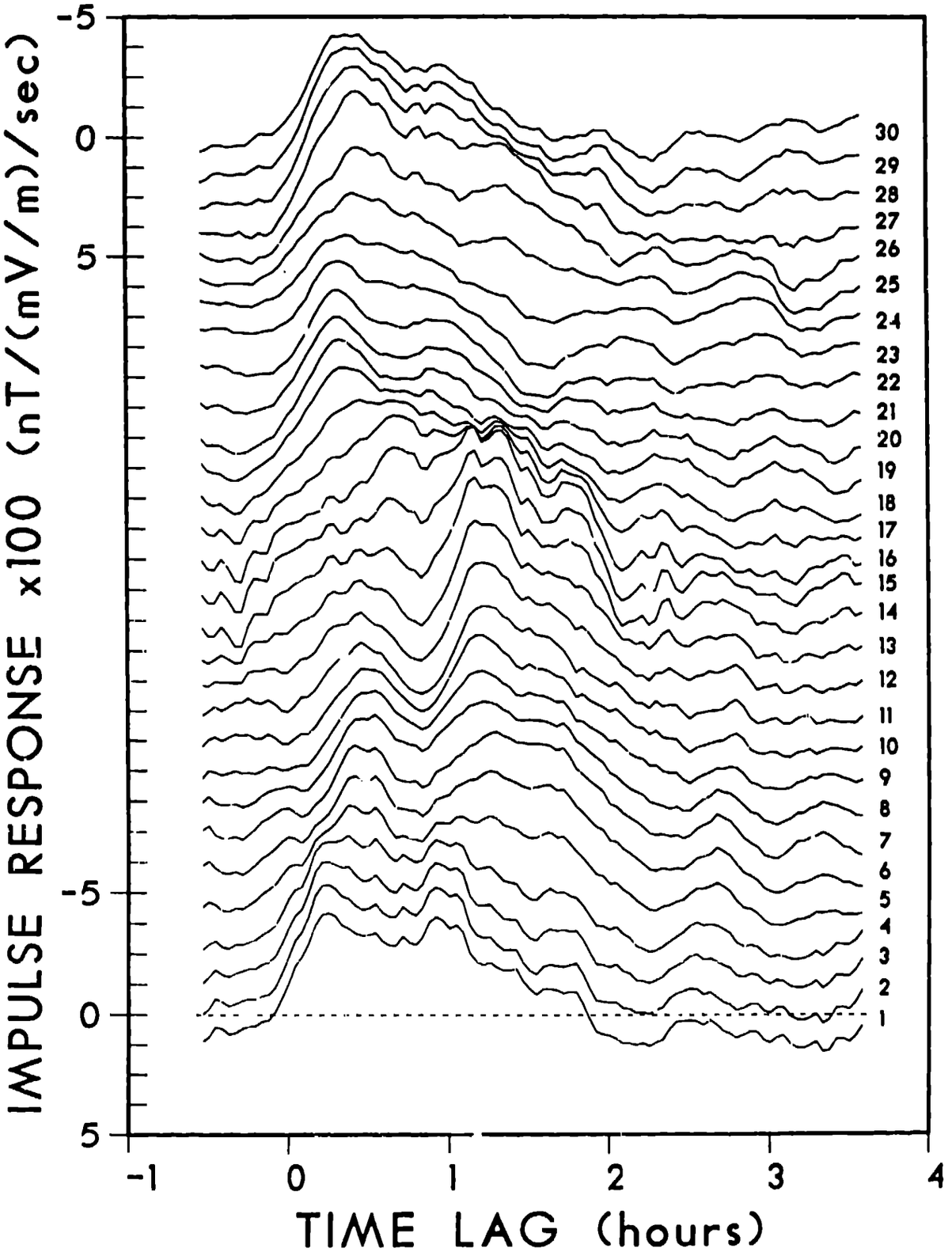
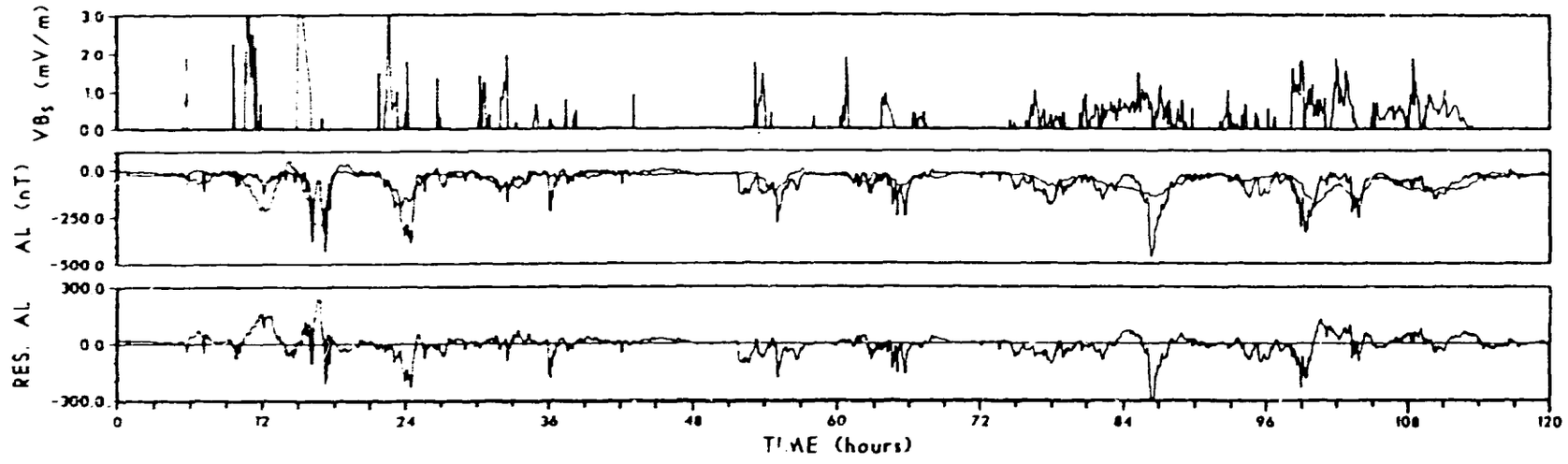
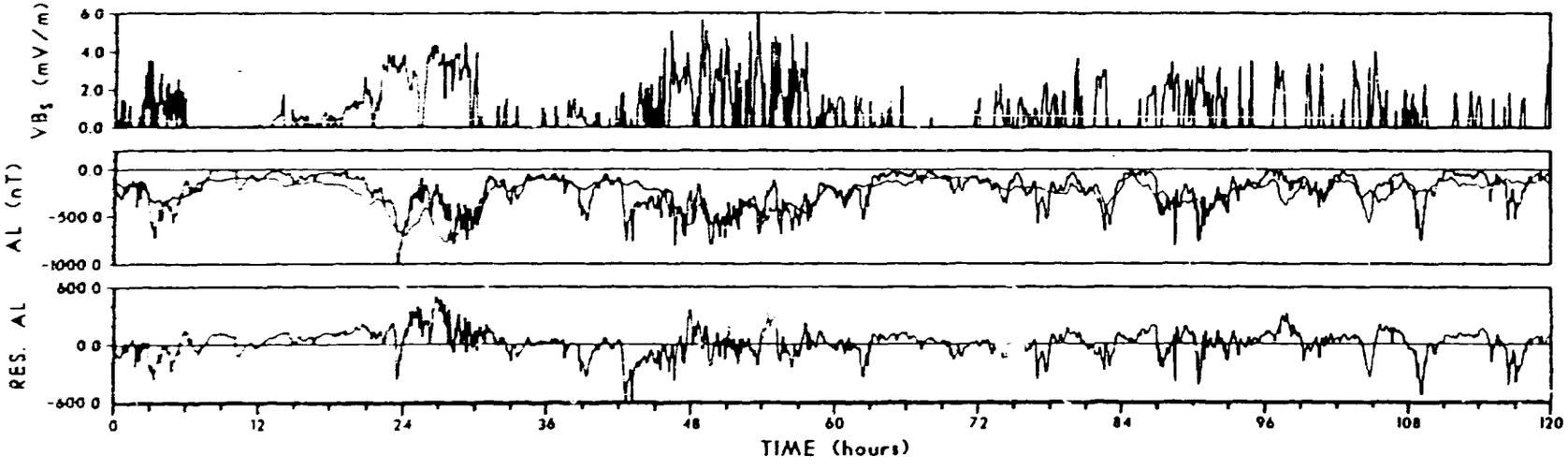

IMPULSE RESPONSE
(nT/(mV/m)/sec)
-0.06
-0.04
-0.02
0.00
0.02
-1
0
1
2
3
4
TIME LAG (hours)
FILTER #10
FILTER #27

FIGURE 1.

FIGURE 2.


IMPULSE RESPONSE x100 (nT/(mV/m)/sec)
-5
0
5
-5
0
5
-1
0
1
2
3
4
TIME LAG (hours)
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1


VBs (mV/m)
3.0
2.0
1.0
0.0
AL (nT)
0.0
-250.0
-500.0
RES. AL
300.0
0.0
-300.0
0
12
24
36
48
60
72
84
96
108
120
TIME (hours)


VBs (mV/m)
6.0
4.0
2.0
0.0
AL (nT)
0.0
-500.0
-1000.0
RES. AL
600.0
0.0
-600.0
0
12
24
36
48
60
72
84
96
108
120
TIME (hours)