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LA-UR-85-1305

CONF-8410170--2

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TITLE: LINEAR FILTERS AS A METHOD OF REAL-TIME PREDICTION OF GEOMAGNETIC ACTIVITY

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SUBMITTED TO: Chapman Conference on Solar Wind-Magnetosphere Coupling

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Linear Filters as a Method of Real-Time Prediction of Geomagnetic Activity

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March 20, 1984

ABSTRACT

Important factors controlling geomagnetic activity include the solar wind velocity, the strength of the inteplanetary magnetic field (IMF), and the field orientation. Because these quantities change so much in transit through the solar wind, real-time monitoring immediately upstream of the earth provides the best input for any technique of real-time prediction. One such technique is linear prediction filtering which utilizes past histories of the input and output of a linear system to create a time-invariant filter characterizing the system. Problems of nonlinearity or temporal changes of the system can be handled by appropriate choice of input parameters and piecewise approximation in various ranges of the input. We have created prediction filters for all the standard magnetic indices and tested their efficiency. The filters show that the initial response of the magnetosphere to a southward turning of the IMF peaks in 20 minutes and then again in 55 minutes. After a northward turning, auroral zone indices and the midlatitude ASYM index return to background within 2 hours, while Dst decays exponetially with a time constant of about 8 hours. This paper describes a simple, real-time system utilizing these filters which could predict a substantial fraction of the variation in magnetic activity indices 20 to 50 minutes in advance.

INTRODUCTION

Information concerning the level of magnetic disturbance at a given moment is useful in a variety of activities. An obvious example in scientific studies is where balloon or rocket payloads need to be launched some time before magnetic activity begins. A commerical example is exploration geophysics, where it is useless to fly magnetic surveys if the magnetic field is varying too rapidly. ~~For~~ In the military context, radio communications, radar reflections, navigation, satellite orbits, and communciation spacecraft are all affected by strong magnetic activity.

Usually, Measures of the level of magnetic activity are not calculated until long after the ~~activity is well past~~ fact. This is simply because data from a world-wide collection of stations ~~is~~ are required to obtain adequate measures such as the AE or Dst indices ~~discussed earlier~~ (Baumjohann, this volume). Because of the need for such measures in various real-time applications, estimates of activity are sometimes made with data from only one station. It is possible to do considerably better than this if data from a solar wind monitor are available. The technique of linear prediction filtering described by Clauer (this volume) provides the method whereby an empirical filter can be convolved with a measured solar wind parameter to predict a given index. This paper illustrates the nature of such filters and their predictions.

EXAMPLES OF INDEX PREDICTIONS

In recent years it has been well documented that the immediate cause of geomagnetic activity is the interplanetary magnetic field (IMF). A southward orientation of the IMF at the subsolar magnetopause allows the IMF to merge with the earth's field. Subsequent transport of dayside magnetic flux to the tail and its return to the dayside are the main phenomena which drive the currents creating magnetic activity. As we show elsewhere (see articles by Bargatze et al., this volume), the parameter in the solar wind most linearly related to magnetic activity indices is the rectified solar wind electric field. This single parameter is able to account for more than 40% of the variance in the AL index and 50% of the variance in Dst.

A prediction filter relating the rectified solar wind electric field to the AL index is plotted in Figure 1. This filter was calculated from a 52-day data set of 2.5-minute values recorded in 1967-1968. The filter has a duration of 2 hours, an initial delay of 20 minutes, and a peak between 40-60 minutes. Its rise time is more rapid than its decay, giving it the appearance of a Rayleigh function pulse. As we show below, the filter includes an approximate 10-minute delay caused by solar wind propagation from the solar wind monitor 40 Re upstream of the subsolar magnetopause.

A comparison of the observed and predicted AL index is made in the middle panel of Figure 2. A thin line denotes the observed index, and a heavy line the index predicted by the filter in Figure 1 convolved with the input. The top panel shows the rectified solar wind electric field (VBs) which was assumed to be the primary cause of electrojet activity. As readily apparent, magnetic calm is produced by the absence of a southward IMF, and hence a zero rectified electric field. The bottom panel presents the prediction residual, the difference between observed and predicted AL. The general trends of the predicted and observed indices are in agreement with the predicted index, appearing to be a low-pass filtered version of the observed index. Details are not well predicted; in particular substorm expansion onsets (vertical dashed lines) do not appear to be directly related to the solar wind. Occasionally, weak disturbances occur during intervals of northward IMF (zero VBs), suggesting that energy is stored in the magnetosphere for later release by intervals of southward IMF.

Filters required to predict the Dst index are presented in Figure 3. Since Dst measures effects of both the magnetopause currents and the ring current, two filters are needed. The first, the dynamic pressure filter, predicts a constant value of Dst proportional to the square root of solar wind dynamic pressure. The greater the pressure, the closer to the earth are the magnetopause currents causing enhanced values of Dst. Although not clear on the time scale of the plot, the filter is peaked at 10 minutes' delay and has a width of about 10 minutes. The delay represents the average ~~propagation~~ time for the solar wind to propagate from the position of the solar wind monitor to the mangetopause. The width represents variations in this delay over the data set used to define the filters. The second filter, the solar wind electric field filter, predicts decreases in Dst during intervals of southward IMF. This filter represents two effects, injection into the ring current and subsequent decay. Because of the long time constants associated with the decay, the filter has a very long duration. Its initial behavior is very similar to the AL filter, however, with an initial delay of about 20 minutes and a peak at about 60 minutes.

Figure 4 illustrates predictions of Dst made by these filters for data from the CDAW-6 workshop. The top two panels show the solar wind inputs, the middle two panels the variation in Dst predicted by the respective inputs, and the bottom panel a comparison of the observed and predicted Dst index. Although on average these two filters predict 70% of the Dst variance, there are obvious discrepancies. These include an initial observed Dst higher than predicted, and a final Dst lower than predicted, as well as an incorrect magnitude for the initial phase of the magnetic storm. Despite these problems the general trend of the predictions is quite similar to the observations.

DISCUSSION

In the preceding section we have illustrated the nature of the filters relating the two most commonly used magnetic indices, AL and Dst, to the solar wind. Filters have also been calculated for two other indices, ASYM, which measures the longitudinal deviation of the midlatitude magnetic perturbation in H from its world-wide average Dst, and AU, which measures the strength of the eastward auroral electrojet (Ref.). The ASYM filter is virtually identical to the AL filter and predicts a similar fraction of the index variance. In contrast, the AU filter is very poorly defined and predicts only about 20% of the index variance.

It should be pointed out that if the solar wind measurements are made just upstream of the bowshock, there will be virtually no warning about impending activity other than the inherent delay in the magnetospheric response functions. This is simply a consequence of the causal nature of the prediction filters. The situation can be improved by moving the monitor upstream of the earth to measure solar wind parameters well before they arrive at the earth. For example, at the location of ISEE-3 (230 R_e upstream), as much as one-hour advance warning is provided (e.g. Tsurutani and Baker, p 702, EOS, 1979). Unfortunately, if the monitor is too far upstream, the quality of the predictions is degraded because small-scale structures in the solar wind evolve as they convect and propagate. Thus, a balance must be struck between the need for accurate prediction of [illegible] activity onsets and the need for early warning of impending activity as provided by measurements far upstream

CONCLUSIONS

Linear prediction filters provide a technique whereby historical data may be used to define predictors of geomagnetic activity indices. The technique is based on the assumption that a linear, time-invariant system couples the solar wind to a particular magnetic activity index. Past records are used to construct the filters which can then be convolved with later measurements to predict the activity index. A real-time system to make such predictions consists of several elements. First is the properly instrumented spacecraft monitoring the solar wind. The second is a real-time communication link between the monitor and a computer system that stores the measured quantities and computes the indices. Within this computer system, the current and preceding values of the calculated solar wind parameters are convolved with the filters to predict the indices. If the measurements are made upstream of the earth, the prediction at a given instant corresponds to a later time ~~calculated~~ from the current solar wind velocity. The calculated indices are stored in the system for examination by remote dial-up.

The proposed system can be improved in a variety of ways. First, it is possible that parameters other than those discussed above affect geomagnetic activity indices. Further research may determine ~~what~~ these ~~are~~ and may calculate corresponding filters. Inclusion of measurements of these parameters in the real-time system would then improve the estimated indices. Second, it may be possible to improve the quality of the predictions by more complex models such as piecewise approximations of nonlinear systems by linear relations in restricted ranges or by filters whose constants change with time in predictable ways. Third, further research on the propagation of disturbances in the solar wind may improve the quality of the estimates of the solar wind at the magnetospause from measurements made upstream. Finally, there remains hope that further research on the origins of the solar wind at the sun will enable researchers to predict the existence of regions of southward IMF in the solar wind from optical measurements.

ACKNOWLEDGEMENTS

This work was supported at UCLA by grant ATM 83-18200 from the National Science Foundation, grant N00014-84-C-0158 from the Office of Naval Research, and grant NGL-05-007-004 from the National Space and Aeronautics Administration. A grant from the Institute of Geophysics and Planetary Physics at Los Alamos National Laboratory also provided partial support.

FIGURE CAPTIONS

Figure 1:

Linear prediction filter relating the 2.5-minute AL index to the rectified solar wind electric field (product of velocity and southward magnetic field strength).

Figure 2:

A comparison c the observed AL index with that predicted by the rectified solar wind electric field. The top panel shows the input electric field, the middle panel compares the observed (thin line) and calculated (heavy line) AL index, and the bottom panel displays the prediction residual. Vertical dashed lines denote onset of substorm expansions.

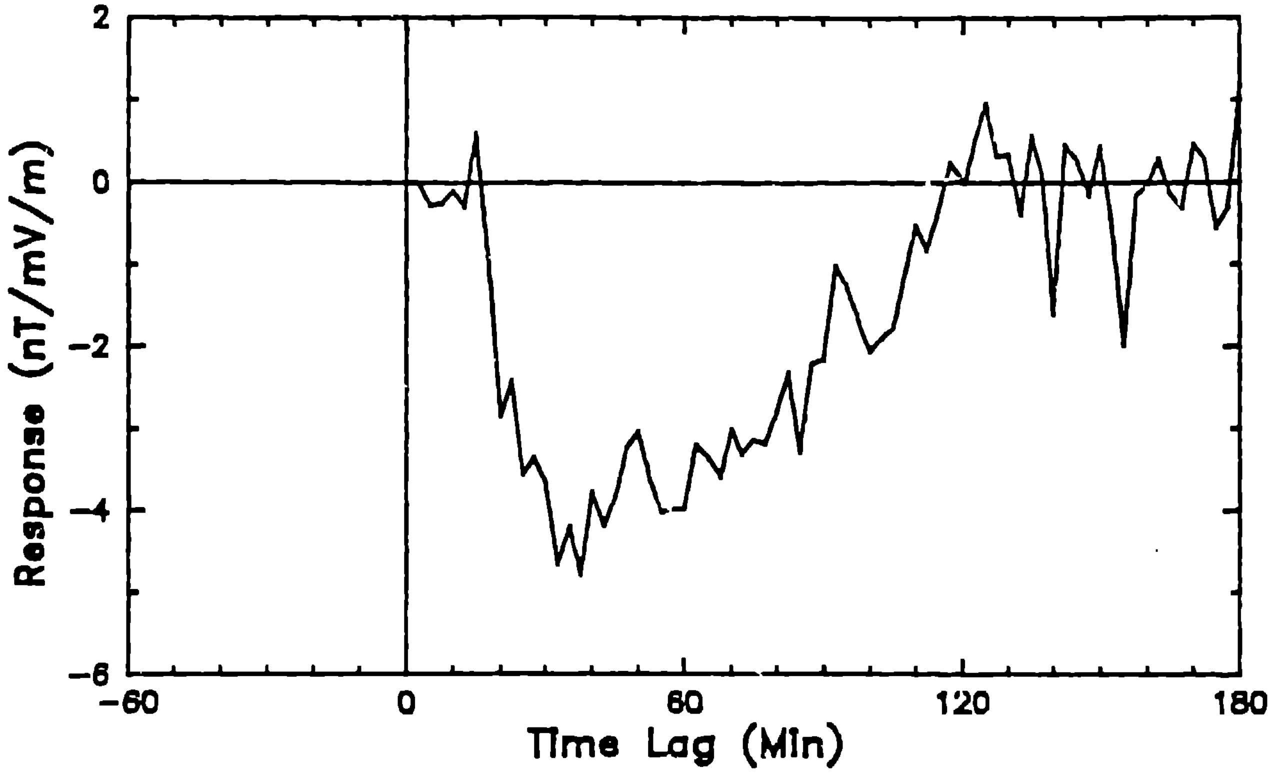
Figure 3:

Prediction filters for the Dst index. Top panel shows the filter relating the square root of dynamic pressure to Dst. Bottom panel shows the filter relating the rectified solar wind electric field to Dst.

Figure 4:

An example of the prediction of the Dst index from solar wind measurements. Top two panels are the electric field and pressure inputs; middle panels are the separate predictions. Bottom panel compares the prediction (dotted) to the observations (solid).

FILTER PREDICTING THE AL INDEX FROM THE SOLAR WIND ELECTRIC FIELD — VB_s



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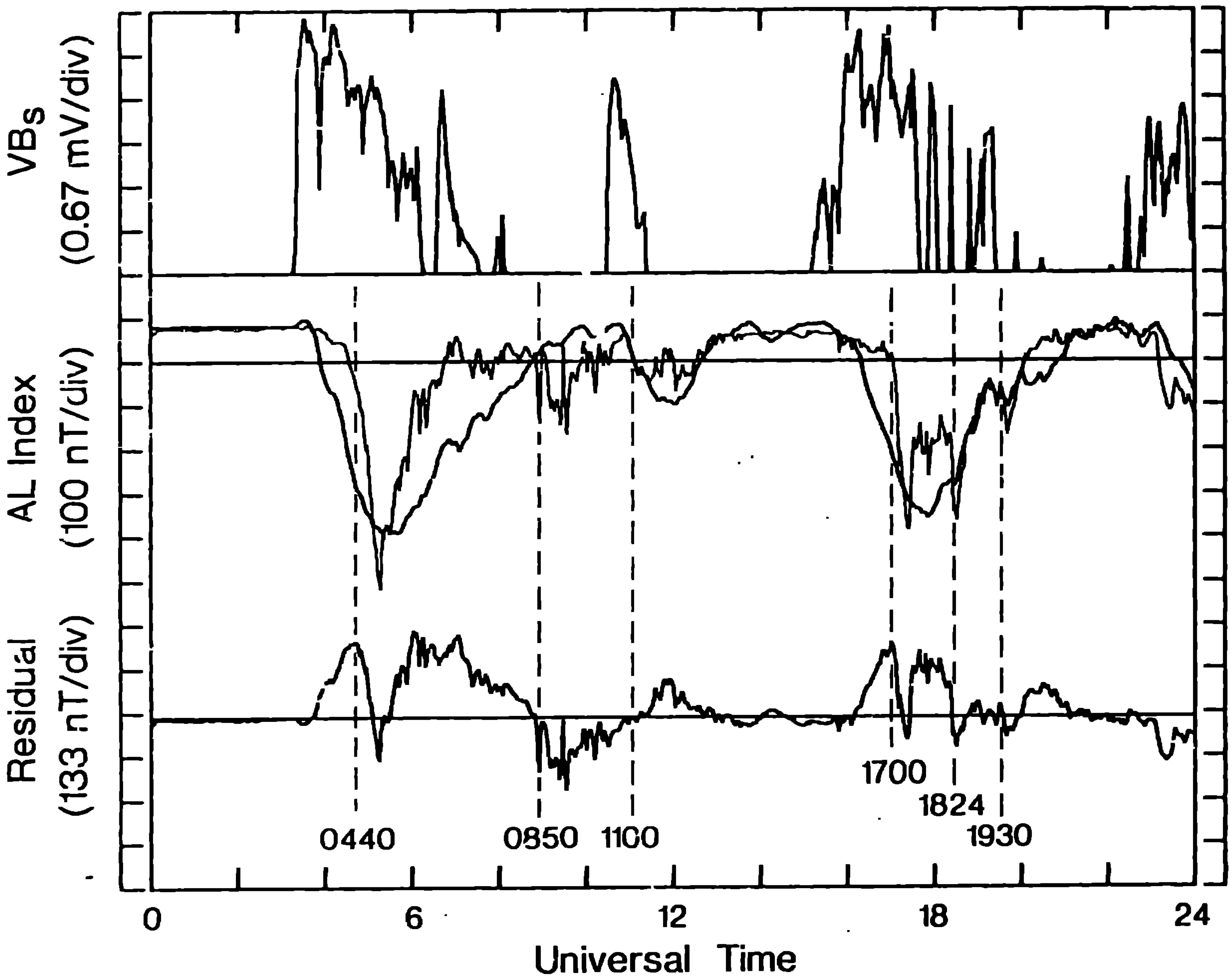
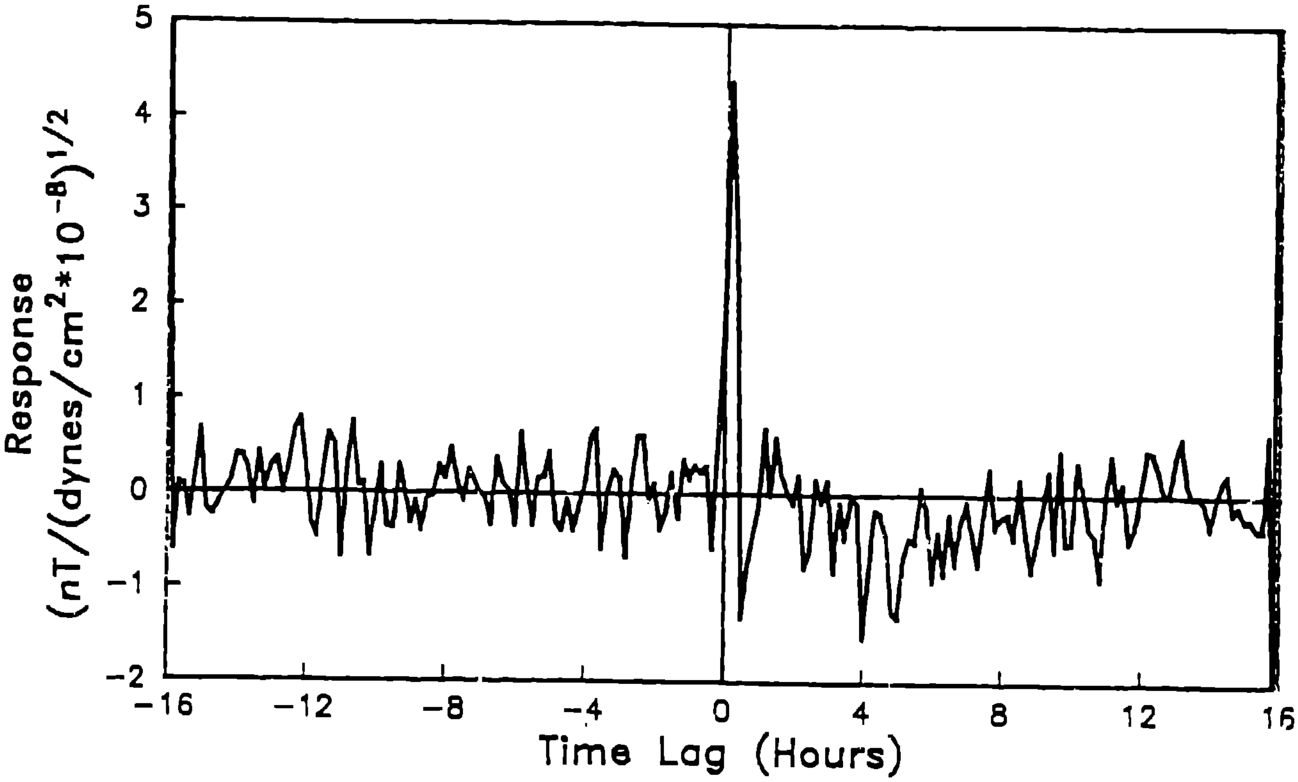
COMPARISON OF OBSERVED AND PREDICTED AL INDEX
February 25, 1967



FILTER RELATING D_{st} INDEX
TO SOLAR WIND DYNAMIC PRESSURE



FILTER RELATING D_{st} INDEX
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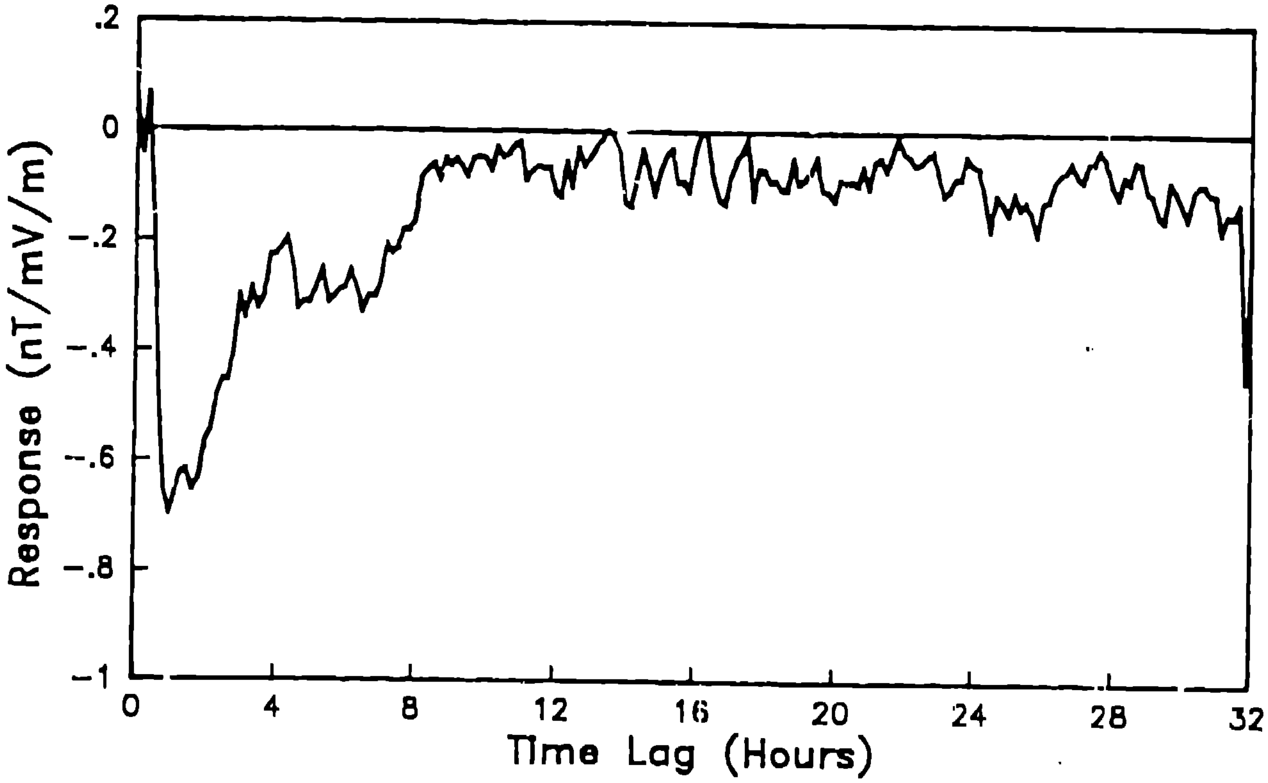

COMPARISON OF OBSERVED AND PREDICTED D_{st} INDEX

March 21–23, 1979