A NON-LINEAR APPROACH TO SATELLITE ANOMALY PREDICTION

R.J.K. Smith [1], D.J. Rodgers [2], C.S. Dyer [3]

[1] Space Department, DERA, Farnborough, UK, +44 1252 393164, +44 1252 396330, rjsmith@scs.dera.gov.uk
[2] Space Department, DERA, Farnborough, UK, +44 1252 394297, +44 1252 396330, djrodgers@scs.dera.gov.uk
[3] Space Department, DERA, Farnborough, UK, +44 1252 393774, +44 1252 396310, csdyer@scs.dera.gov.uk

ABSTRACT

Prediction of periods of increased risk to anomalies would be invaluable in the operational planning process. Many studies have used self-adaptive techniques to model particle populations and their effects in space. However, few address the problem of non-stationary data characteristics, despite the widely-accepted idea of the solar cycle. Linear studies have identified relationships and timescales in particle propagation and acceleration processes in solar-terrestrial data. Progress has been made towards constructing non-linear models, using parameters from linear analysis as a logical starting point.

BACKGROUND

Satellites orbiting the Earth are subjected to a highly dynamic environment of charged particles trapped in the magnetosphere. The configuration of this system and the motions of the particles are not easily predictable due to the non-linear nature of the solar wind and its interaction with the Earth's magnetic field.

Previous studies [1,2] have shown clear links between certain particle populations, geomagnetic activity indices and databases of anomaly times, indicating electrostatic discharges. However, due to the complexity of the solar processes and the magnetospheric system, and the lack of understanding of the mechanisms responsible for the particle acceleration and propagation, the times of these anomalies are notoriously difficult to predict with any accuracy.

AIM

As communications satellites in geostationary orbit are particularly susceptible to electrostatic anomalies, this study has concentrated on this area of the problem. The aim is to forecast the risk of suffering such an anomaly near geostationary regions using whatever space- and ground-based data are available.

The ultimate goal is to use solar observations in the predictions, in order to take advantage of the inherent delay between electromagnetic emissions and subsequent disturbance propagation in the solar wind and particle acceleration in the magnetosphere.

TIMESCALES

Satellite anomaly databases have limited availability and coverage, but previous work [1,2] has shown strong links between anomalies, energetic electron populations and geomagnetic activity indices. As the Sun strongly affects the Earth's magnetospheric environment, analysis of solar data could yield dividends.

An examination of the physics of the system gave an initial estimate of the timescales involved in the particle transport processes, shown in figure 1. The Sun-Earth transport time for electrons was estimated at two days, from typical solar wind speeds, and the acceleration mechanisms of the magnetosphere to yield MeV electrons near geostationary Earth orbits (GEO) were estimated at further two days. As soft X-rays travel at the speed of light, there is a typical inherent prediction of four days built into the scheme. This may be further enhanced by the persistence of features on the Sun for two or three 27-day solar rotations.

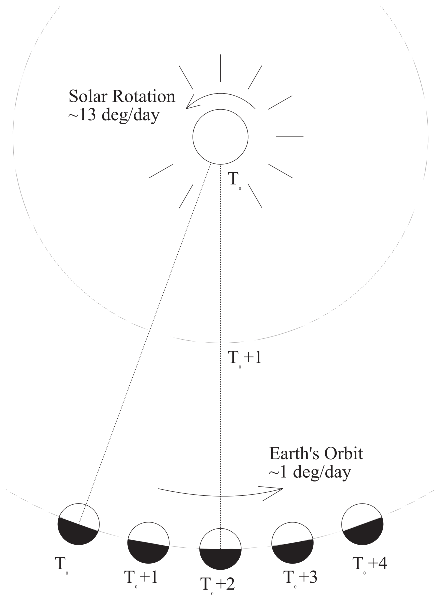

Figure 1: *Timescales Involved in Physical Processes Linking Solar Features with Satellite Anomalies*

LINEAR ANALYSIS

The timescales identified from physical reasoning can be verified by linear analysis of the data. Several representative data sets were investigated using correlation techniques.

GOES-7 >2MeV electron flux data were correlated with time-offset copies of themselves to produce the results shown in figure 2. The data exhibit a short-term memory of a few days and a recurrence relationship after a solar rotation period, due to the persistence of features on the Sun over timescales longer than the spin period. The two periods (1991-5 and 1994-8) considered are in different phases of the solar cycle, which explains the differences in shape of the two curves.

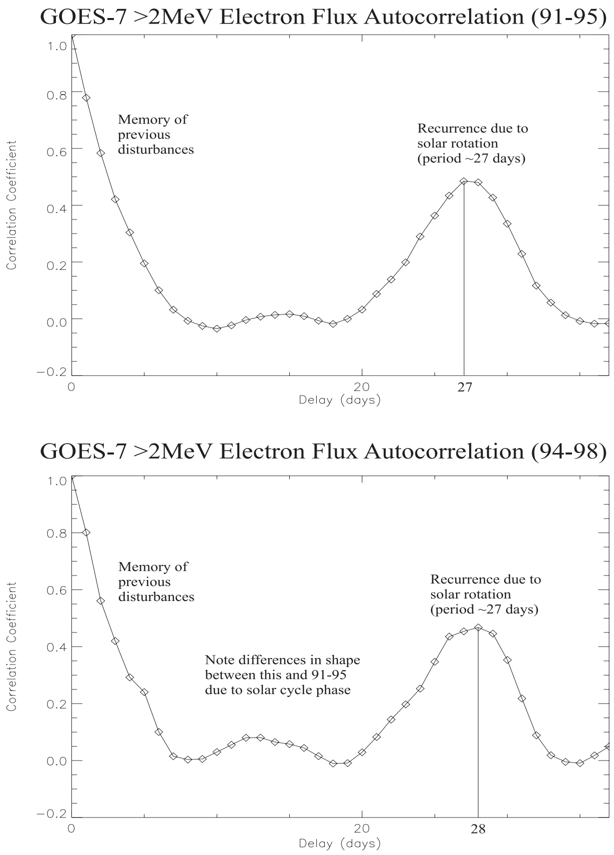

Figure 2: *Linear Analysis of GOES Electron Flux Data*

Data on the solar wind speed obtained from the WIND satellite, were analysed and show similar characteristics to GOES electron flux data, though with a shorter memory (figure 3). These data sets were compared to examine the acceleration processes of the Earth’s magnetosphere and show these take 1-2 days, connecting the two data sets quite strongly, though not as much as autocorrelation.

Soft X-ray telescope (SXT) data from the Yohkoh satellite were processed from full-disc images into a synoptic map (solar latitude against visible longitude) to simplify analysis. This map (figure 4) clearly shows the declining solar cycle during 1992-5. When compared with GOES electron flux data (figure 5), the results show weak anti-correlations, indicating that enhancements in electron fluxes at GEO are connected with coronal holes on the Sun, and a characteristic delay of around 6 days.

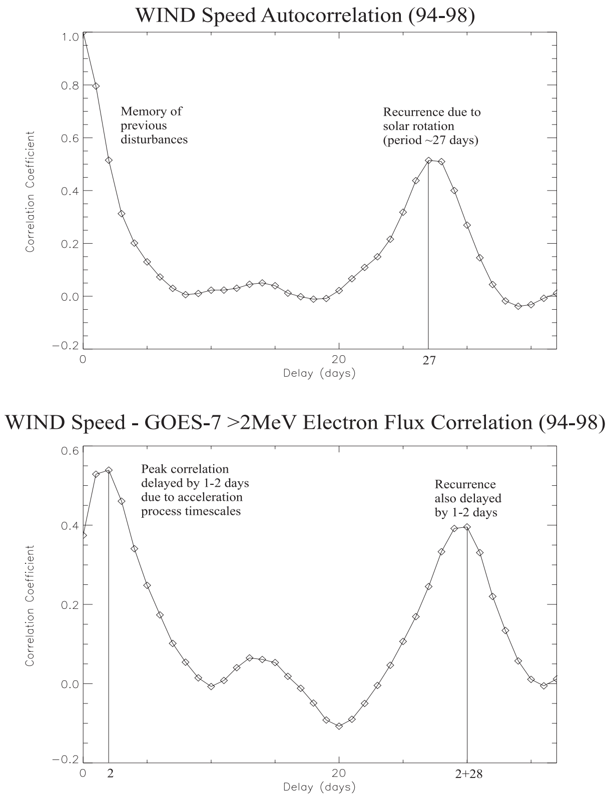

Figure 3: *Linear Analysis of Solar Wind Speed Data*

Kp gives an indication of magnetospheric disturbance globally across the Earth. Correlation with GOES electron flux data shows a weak relationship with a typical delay of 2-3 days (figure 5). This connection is weaker than that between solar wind speed and electron flux (c.f. figure 3).

All these linear results confirm the conclusions reached by physical reasoning and provide a valuable insight to resolutions and regions of influence to consider in subsequent analysis.

NON-LINEAR METHODS

A non-linear approach has been taken using Radial Basis Functions (RBF) as described by Broomhead et al [3,4]. This is a self-adaptive method with strong parallels to Multi-Layer Perceptrons (MLP). However unlike MLPs, RBFs have a unique solution and do not require iterative training. Non-linear systems have not often been used to analyse noisy systems, so it was suggested that the data should be filtered using a Singular Value Decomposition (SVD) to help reduce any noise present.

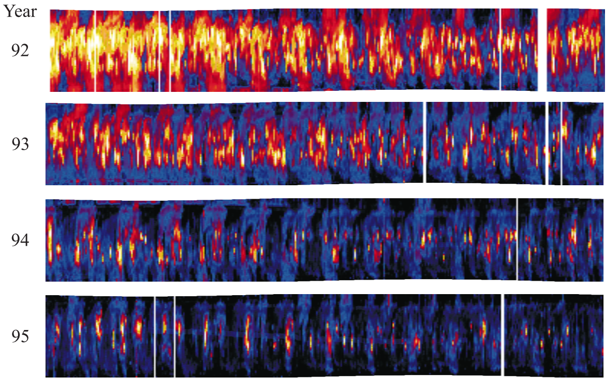

Figure 4: *Processed Yohkoh Synoptic Maps Showing Solar Cycle Progression*

SVD relies on a mathematical theorem that allows an orthogonal co-ordinate system to be constructed, for any set of points, with an associated importance for each dimension. A Principal Component Analysis (PCA) can then be performed to decide which dimensions can be ignored, on the basis that they contain little useful information, reducing the noise in the data. The noise is also reduced within the remaining dimensions due to the effects of averaging and application of the Central Limit Theorem.

The RBF method requires a training data set and a test data set, possessing similar characteristics. Centres, i.e. points, are chosen representatively throughout the data space and radially-symmetric functions fitted to each one using the training data. The model is then tested, using the test data, to ensure that it generalises well. The process uses a linear, least-squares fit which requires no iteration, giving it a significant advantage over MLP methods.

The prediction problem is a type of time-series analysis, a genre which requires a continuous data set with fixed temporal spacing. Real data sets, particularly space-related data sets, seldom satisfy these criteria and so a method was devised to deal with 'missing data' using an associated measure of 'confidence'. Clearly, the value of this confidence depends on the amount and distribution of the missing data, but in certain circumstances it may be possible to 'predict' the contents of the gaps.

The combination of PCA and RBF techniques results in a method with many different parameters and variations. Many of these choices directly affect each other, and their net result can be observed only at the end of the prediction process. Consequently, there can be a potentially infinite number of possible permutations, from which the optimum choice should be selected. An exhaustive search is seldom possible due to the numbers and complexity of the calculations involved, so a strategy must be formed for optimising the system.

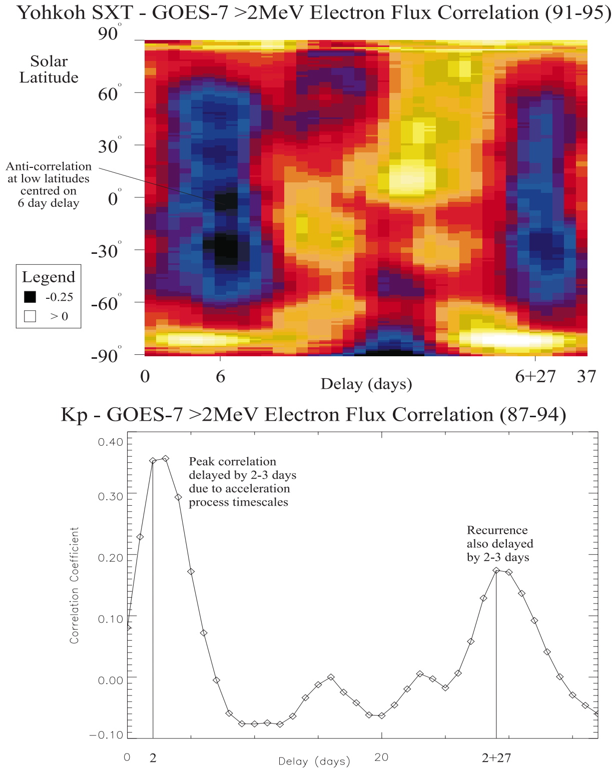

Figure 5: *Flux Comparison with Solar Disturbances*

Preliminary linear studies of the data were performed to attempt to identify trends and features to help choose appropriate parameters for the non-linear analysis and understand the physics behind the observations.

NON-LINEAR RESULTS

The key data set for analysis of anomalies is the satellite's local environment, reflected by >2 MeV electron flux data obtained from GOES-7. Linear analysis of these data and their relationships with other representative data sets has given valuable insight into timescales and resolutions for further analysis, and ensured that suitable information value is present.

The non-linear analysis is still at an early stage, but two self-predictive models have been constructed from GOES-7 electron flux data. An exhaustive search of low-dimensional models was used to identify a suitable choice of parameters.

The first model uses daily average fluxes, to alleviate diurnal variation, with an input window of three consecutive days and output one day ahead. A visual comparison of the modelled output with the real data (figure 6) shows that the prediction is of a similar shape and magnitude to its real counterpart, even for the test data. However, the normalised root mean squared error (NRMSE) is disappointingly high, though it does indicate that the model is learning information from the data.

The second model is identical to the first, except that the electron flux data has been transformed (log10) prior to modelling. The results (figure 7) show that the NRMSE has been reduced significantly and that the model is concentrating more on the temporal location of the peaks than their magnitude. As satellite anomalies coincide with electron enhancement above a certain threshold value, this model may be providing information more relevant to the aim of this study.

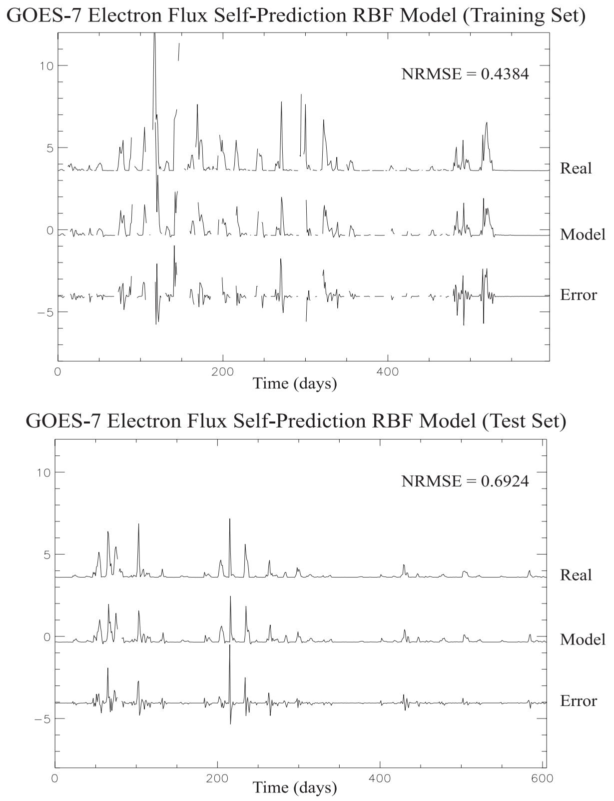

Figure 6: *RBF Model-Real Data Comparison*

CONCLUSIONS

Linear techniques have demonstrated understandable and physically explainable results, and shown that suitable information value is present in the data. Recent results have shown that transforming the data prior to modelling can serve to emphasise particular characteristics and concentrate the model on these. This approach will allow models to be constructed for a specific purpose, ignoring irrelevant information.

The non-linear techniques being used and the software to implement them have now matured sufficiently to allow their application to a wide variety of data. This will allow future investigation of more diverse and complex problems, and more selective control of input data focussing the learning process on the areas of most significance to the problem under scrutiny.

Future activities will attempt to create models relating GOES electron flux to solar wind parameters from WIND and ultimately to direct solar observations, e.g. Yohkoh.

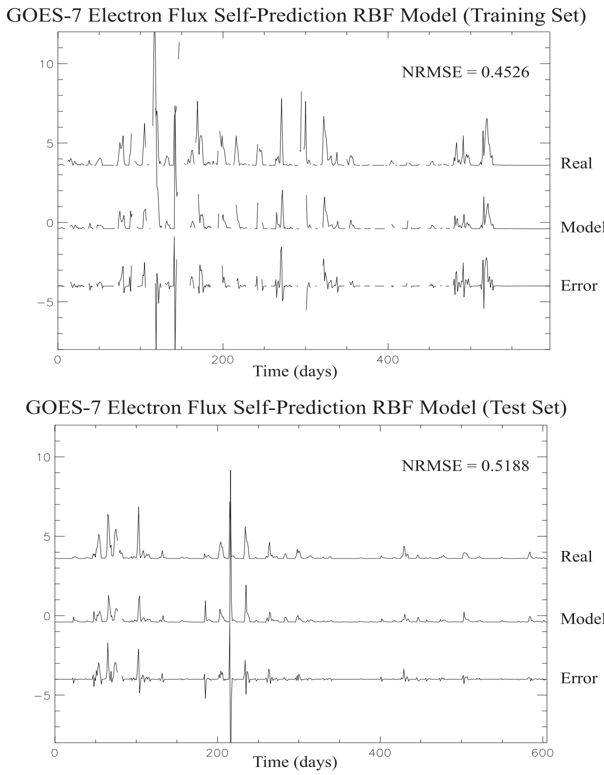

Figure 7: *RBF Model Using Logged Data*

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