ANALYSIS AND PREDICTION OF SATELLITE ANOMALIES

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ABSTRACT

The Satellite Anomaly Analysis and Prediction System (SAAPS) is a software containing a database of space weather data and satellite anomaly data, tools for plotting and analysis, and models for the prediction of anomalies. The system uses real-time data and can run stand-alone on a computer or remotely over the Internet. The anomaly prediction models use neural networks that have been trained on specific anomaly sets that are related to either surface or internal ESDs. The predictions range from nowcasting up to one-day forecasts. Generally, the predictions are correct in slightly more than 70% of the events. The model also gives the probability that a specific forecast is correct, which range from poor (50%) to very good (90%). A user can also submit anomaly data for further analysis. Visit http://www.irfl.lu.se/saaps for more information.

1. INTRODUCTION

This paper describes the development of the *Spacecraft Anomaly Analysis and Prediction System*, hereafter called SAAPS. SAAPS is the software implementation of the ESA funded project *Development of AI methods in spacecraft anomaly predictions* (ESTEC contract 13561/99/NL/SB). The project is a continuation of the ESA *Study of plasma and energetic electron environment and effects* [1].

Many years experience exists on how spacecraft are affected by the space environment. These findings have been included in the design of spacecraft to reduce the risks of anomalies related to surface charging [2] and internal charging [3]. However, the properties of the plasma and radiation that surrounds the spacecraft vary dramatically both over space and in time. Thus, it is difficult to completely remove anomalies related to the space weather [4].

On most spacecraft anomalies occur regularly. Their impacts are often not dramatic, but they still have to be dealt with, and may also include intervention from on-board systems or ground control. However, there are also severe events such as the failures of the momentum wheel control systems on ANIK E1 and E2 in 1994 [5,6] and the loss of solar power on E1 in 1996 [7].

There are several related projects that study the space weather and its effects on spacecraft. The Space Environment Information System (SPENVIS) [8,9] contains an impressive number of models, and not only for spacecraft charging purposes. The intended users of SPENVIS are spacecraft engineers, scientists, and educators and students. A specific model to study internal charging is DICTAT [10]. DICTAT is also one of the models included in SPENVIS.

In the rest of the paper we will describe SAAPS and its subsystems and also discuss the results of the analysis and prediction of a few selected anomaly sets.

2. SAAPS

SAAPS consists of a database, analysis module, prediction module, and various interfaces as shown in Fig. 1. The database contains solar wind data, electron and proton flux data at geostationary orbit, geomagnetic indices, and satellite anomaly data. The data comes from different sources. The OMNI database [11] is included so that historic solar wind data can be accessed. From about 1998 and onwards the ACE [12] one minute resolution plasma and magnetic field data are included providing real-time operation. Electron flux for the >0.6 MeV and >2 MeV energy levels are included from the GOES-8 and –10 satellites [13], also providing real time access. LANL electron data are included for a three-year period [14]. The data are available in 7 energy levels from 22 eV to 11 MeV with a time resolution of 1 hour. Geomagnetic indices that are included are *Kp*, *Dst*, and *AE*. The *Kp* index exists in four different versions. The final *Kp* comes from NGDC [15], the close to real time estimated *Kp* from SEC [16], the nowcasted *Kp* from Lund, and the forecasted *Kp* also from Lund [17]. Finally, the satellite anomaly data come from both public and private sources. The NGDC anomaly database [18] with over 5000 anomalies has been used. Also ESA anomaly sets [19] and other data sets from commercial satellites have been included.

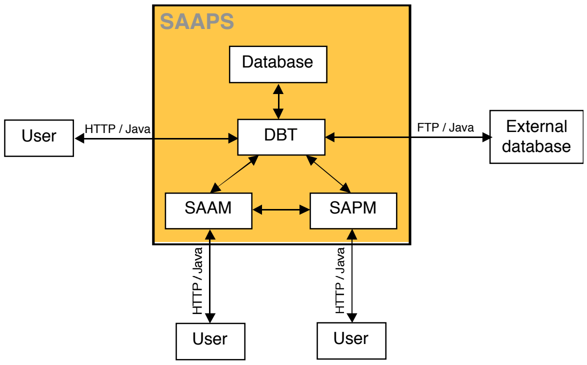

Fig. 1. SAAPS with subsystems and interfaces.

The database tool (DBT, Fig. 1) updates the database with real-time data from various external sources. On the system level the database can also be manipulated using the DBT. The analysis and prediction modules can only access data from the database via the DBT.

The analysis module (SAAM, Fig. 1) operates on the data in the database. The module contains tools to plot data from the database, plot anomaly data, estimate the best prediction model from user submitted anomaly data, perform superposed epoch analysis, find energetic electron flux levels that may cause internal charging, and to find *Kp* levels that may be related to surface charging anomalies.

The prediction module (SAPM, Fig. 1) contains different models that can be used for the prediction of specific satellite anomalies, caused by surface charging or internal charging, with a daily resolution based on daily summed *Kp* or daily >2 MeV electron fluence.

SAAPS has been implemented in Java and runs on a Sun Workstation. Solar wind data, geostationary electron flux data, and geomagnetic indices are updated in real time from: the *Space Environment Center*, Boulder, USA (ACE, GOES-8 and –10, estimated *Kp*); the *World Data Center C2*, Kyoto, Japan (near real time *Dst*); and the *Regional Warning Center*, Lund, Sweden (nowcasted and forecasted *Kp*). As the compiled Java code is platform independent it can be run on virtually all computer systems. It has been successfully tested on Mac OSX, Windows, and Linux platforms. The analysis and prediction tools have also been implemented as Java Applets, which means that they can be run from a web browser over the Internet. The Java Applets offer another degree of user interaction.

3. DEMONSTRATIONS AND RESULTS

In the following we demonstrate a few examples of how SAAPS can be used.

In Fig. 2 the local time histogram is shown for a satellite that has experienced surface charging anomalies. The expected clustering of anomalies in the local morning sector is seen. As indicated by the button "Edit Anomaly Data …" in the figure the user can enter his own anomaly data and produce the various plots.

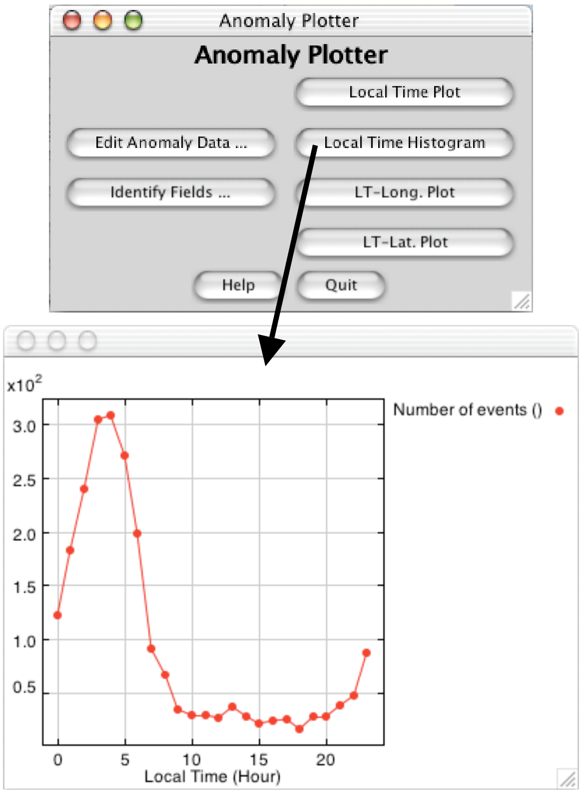

Fig. 2. An example of a local time histogram using the anomaly plotter tool.

In Fig. 3 the data plotter interface is shown together with an example plot of the GOES-8 data. The top panel shows the interface from which the data are selected. In the top left scroll pane the database items are listed with the GOES-8 particle data currently selected. The user enters the start and end dates over which the data should be studied. After the data has been downloaded the user selects the parameters that should be on the x-axis and y-axis, respectively. In this example the x-axis represents time and the y-axis represents the >0.6 MeV and >2 MeV electron flux data. The bottom panel of Fig. 3 shows the resulting plot. The user can then further manipulate the plot by choosing linear or logarithmic scales, changing the axis limits and zooming in and out of the plot. As the data have already been loaded into the applet in the web browser it is also possible to select other data fields to be plotted without having to reload any data.

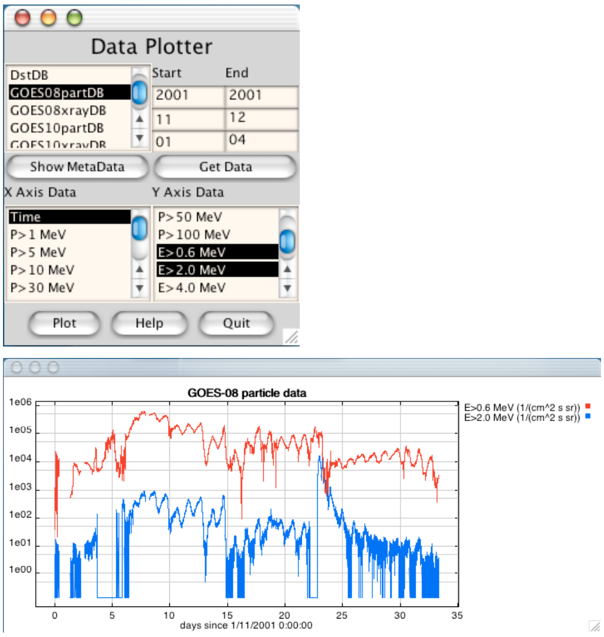

Fig. 3. The bottom part of the figure shows a plot of GOES-8 electron flux data created with the data plotter tool.

As a final demonstration we give an example of a tool in the prediction module. One model in the prediction tool consists of a neural network targeted at predicting anomalies with a daily resolution for one specific satellite at geostationary orbit. The neural network uses daily sums of *Kp* extending over the past eight days at its inputs. The network has been trained in the standard way using three independent data sets: training set, validation set, and test set. The optimal network architecture, i.e. the number of hidden neurons and the length of the time delay line, is determined from the validation set. On average, this model makes a correct prediction in about 70% of the events on a balanced test set, i.e. a set with equal number of “anomaly” events as “no anomaly” events. However, it was found that the output value from the neural network not only gives the predicted class, but also the probability that the prediction is correct [20]. In Fig. 4 it is shown that the absolute value |y| of the network output is directly related to the probability that the prediction is correct. At one end we get probabilities close to 50% which we would also achieve with a model always predicting “no anomalies” or with a model always predicting “anomalies”. At the other end we reach probabilities between 80% to 90%. The dashed line shows the fraction of events in each bin. Taking the last two bins we see that almost 50% of the events are predicted with an accuracy of 80% or higher.

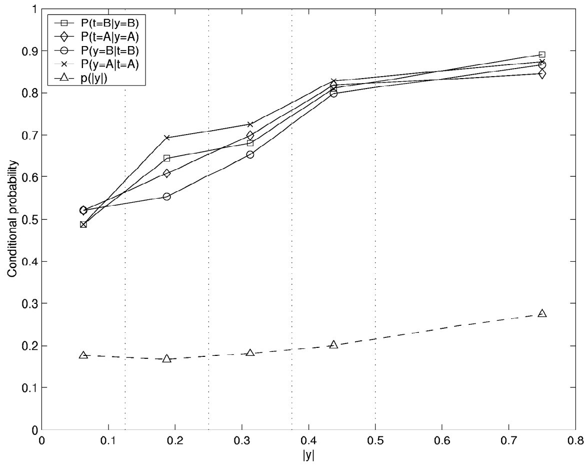

Fig. 4. The figure shows how the probability for correct prediction varies with the absolute value of the network output |y|.

In Fig. 5 the anomaly prediction tool is shown. The plot extends over a period of 14 days in November-December 2001. In the top left scroll pane different prediction models can be selected. The type of anomalies that the model has been trained to predict and other information can be retrieved by pushing the “Inspect model” button. The date of the day to be predicted is entered and then the model is run for a 14-day period ending on the selected date. The plot gives the probability for an anomaly and goes from 0% to 100%. The probabilities are derived from the output value and Fig. 4. If the prediction is 20%, as for 22 November, then there is an 80% probability for a “no anomaly” event. November 24th predicts an “anomaly” event with a 85% probability.

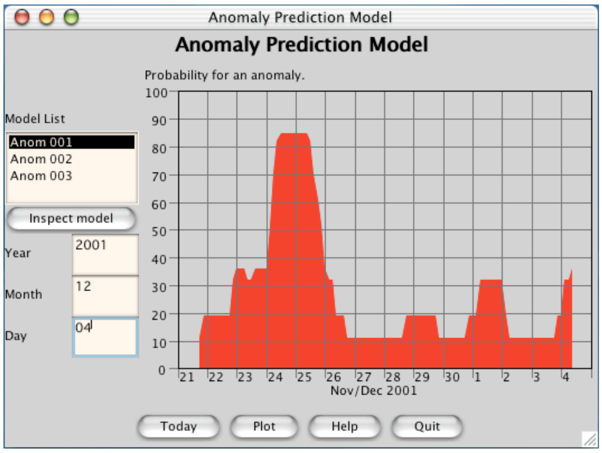

Fig. 5. The figure shows the prediction of anomalies for one model over the 14-day period 21 November to 4 December 2001.

4. DISCUSSION AND CONCLUSIONS

The main features of SAAPS are the possibilities to quickly and easily analyse the space environment, and to make predictions of specific charging related anomalies. SAAPS will be further developed by including more models to forecast anomalies as there still are many anomaly data sets that have not yet been studied. It also seems to be difficult to find *one* model that can predict anomalies of a certain class but for different satellites. Instead, the prediction models should be targeted for specific satellites. It is also planned to merge SAAPS with the *Lund Space Weather Forecast Service* [21]. During the development of SAAPS we have had discussions with a few selected satellite operators. They have provided input on what kind of information they need and what kind of actions they might take during hazardous events. In the future we plan to deepen the collaboration with the operators so that SAAPS can mature into a useful system for real-time operation.

5. ACKNOWLEDGEMENTS

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