The use of environmental data to predict and analyse spacecraft anomalies

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Abstract.
Spacecraft are exposed to a dynamic environment, the space weather. Spacecraft move between different regions and in each region the spacecraft is exposed to different environments. Monitoring the space environment can lead to a better understanding of how spacecraft are affected by the space environment. The data collected by monitoring instruments can be used both for prediction, and for post-analysis of the anomalies. Periods with increased risk for anomalies on geosynchronous satellites are predicted in this study. The input to the models are environmental data that can be accessed in real time. The models are trained to predict whether anomalies will occur within the next 24 hours or not. Models with up to 80% prediction success are presented.

Introduction

Since the mid 1960s, anomalies on geosynchronous orbit (GEO) satellites have been detected and analysed. For instance, the first Meteosat spacecraft anomalies were analysed [*Hoge and Leverington* , 1979] which led to recommendation of design changes and to mount environment monitors on the following satellites. Due to the complex environment non-linear techniques are often used to analyse the data [*Koons and Gorney* , 1991; *Hilgers et al.* , 1998].

Surface charging and internal charging can sometime be distinguished based on the local time dependence *Koons and Gorney* [1991]. The deep dielectric charging effect on GEO satellites are of great concern today *Violet and Fredrickson* [1993]; *Wrenn* [1995]. The deep dielectric charging anomalies are associated with high energy electrons. The high energy electrons at GEO can be created from high-speed solar wind streams *Baker et al.* [1994] which occur mainly near solar minimum *Wrenn and Sims* [1996].

The anomalies

The anomalies that have been used in this study are from two GEO satellites, Meteosat-3 and Tele-X. The Meteosat-3 was launched on June 15, 1988 and

moved several times during it's lifetime before it was put into junk orbit on November 21, 1995. During the 7 year mission, 18 different types of anomalies with a total of 724 anomalies (one anomaly every fifth day) were detected. The second anomaly data set is from the Swedish broadcasting satellite Tele-X. This GEO satellite was launched on April 2, 1989 and put into junk orbit spring 1998. The satellite operators reported 10 different types of anomalies. During the first 8 years of the mission, Tele-X operators detected 192 anomalies, i.e. less than one every tenth day.

The reported anomalies on the two satellites were of minor severeness. For both spacecraft the history of the anomaly frequency is similar, few anomalies in the beginning of the mission and then increasing to 1995. When one spacecraft had many anomalies in a short time frame, the other satellite often also had many anomalies in the same time frame. Both spacecraft had a peak of anomalies during 1994. If one looks on the local time dependence, the satellites have an increased number of anomalies during morning and noon hours (peak at 02-08 local time for Meteosat-3 and 06-18 local time for Tele-X). For Meteosat-3 the number of anomalies during the morning hours is twice the number of anomalies at other local times. The local time dependence is weaker for Tele-X. Both anomaly sets have a seasonal dependence, twice as many anomalies months around the spring and fall equinoxes as compared to the months rest of the year. After October 1996 no more anomalies were detected on the Tele-x satellite, but degradation of different system existed though. The Tele-X satellite was in normal operation until it was replaced and put into junk orbit. The anomaly type that was most frequently occurring during 1994 on Tele-X was not being tracked on in the beginning of the mission. Only the time period from 1992-1995 is used in the models in this study for the Tele-X anomalies.

Input data for the models

The input data for the models were selected so that input data in near real time could have been used. The analysis in this report is based on when the SEM-2 instrument on Meteosat-3 operated. The SEM-2 instrument measures the electron fluxes in five different energy bins covering the range 43 - 300 keV. We have used electron data with two hour resolution. A principal component analysis was made on the electron fluxes and the first principal component that was used as input to the models *Andersson et al.* [1998].

From the solar wind parameters global parameters such as Dst and Kp can be predicted 1 to 3 hours ahead *Wu and Lundstedt* [1998]. In this study Kp and Dst indices are used, since the solar wind data is not completely continuous for this period. If the model is used in real time the Kp and Dst can be derived from solar wind measurements. Dst and Kp are taken from the web (http://nssdc.gsfc.nasa.gov/omniweb) and linear interpolated to two hour resolution.

Daily average particle fluxes from GOES, the NOAA satellites, are used (http://spindr.ngdc.noaa.gov:8080). The input data from the GOES satellites are daily data from the >2 MeV electrons (higher energy than SEM-2), and the >1 MeV and >5 MeV protons.

Cosmic rays which vary with solar cycle, can cause single event upsets (SEU). Cosmic rays are monitored as neutrons on ground. Therefore two hour averaged data from the Climax ground station are included (ftp://ftp.-ngdc.noaa.gov/STP/SOLAR_DATA/COSMIC_RAYS).

Prediction task

Models are built in order to be useful for a satellite operator. A satellite operator need to get an anomaly warning about one day ahead. The model is created to predict if an anomaly will occur within the next 24 hours or not. The satellite operator can not accept too many false alarms. The ratio of days with and without anomalies is about 1:5 for Meteosat-3. To minimise the number of days with false alarms the model is constructed so that 80 % of the days without anomalies are correctly predicted. This leads to that non-anomaly periods will give as many false alarms as the total number of anomalies (for Meteosat-3). If 80% of the non-anomalies are correctly predicted, the warnings from the model can be maximum 50 % correct.

Table 1. *Different periods in solar cycle*

Time period		I	II	III	IV
Trained network					
TEST file Me	no	970	986	1307	1868
model Me all	%	51	53	45	61
model Me short	%	31	36	49	64
model Te	%	14	16	36	54
TEST file Me short	no	585	651	1190	605
model Me all	%	45	44	67	63
model Me short	%	51	51	67	53
model Te	%	35	42	57	50
TEST file Te	no	108	204	491	393
model Me all	%	49	65	68	71
model Me short	%	48	67	60	69
model Te	%	72	87	72	65

Three different models are trained to predict: all Meteosat-3 anomalies (model Me all), Meteosat-3 anomalies but for same time period as Tele-X (model Me short), and Tele-X anomalies (model Te). For each model three data sets are tested (TEST: Me, Me short and Te). The files are tested in four different time periods (I, II, III, IV). Time period I extends over the first quarter of the examples, period II over the second quarter etc. Hence the four periods represent seasonal periods and different periods of the solar cycle. The rows starting with TEST shows the number of warnings for each time period. All models in the table have the same type of input data (see text).

Prediction of the anomalies

In this study, a neural network is trained to find the function that relates input data (the environment data) to the output data (the desired output of the model). In all examples a feed forward neural network with one hidden layer, four hidden neurons and error-back-propagation learning algorithm is used.

For each model a data file is created. Each row in the data files correspond to the two hour time resolution. The first columns contain the input data and the last column the desired output. The desired output is one (1) if an anomaly occur within the next 24 hours and zero (0) if not, thus one anomaly causes 12 rows to be one (1), here on refereed to as warnings. For Meteosat-3 using the full data set, the data file contains about 27000 rows, and for Tele-X about 13000 rows.

When a data file is created all the rows with warnings are separated into one training file (66% of the rows) and one test file (34%). The rows with no warnings are first randomly selected to be reduced to twice the total number of warnings and then split into the training and test file. Since about 50% of the two hour intervals that are associated with no anomaly, is not used at all, a second test file with all the data refereed as 'all' (also the training data is included) is generated. This second test set 'all' will also give information of how the model will behave in real time, and hence what a satellite operator will see.

The output of a back propagation model is a real value. Using the assumption that 80 % of the non-anomaly times shall be correctly predicted, a threshold value must be selected. The result in the report is presented as the success of predicting the warnings when no warnings are predicted with 80% accuracy.

The input data in this study are: the last 24 hours from the first principal component (12 inputs), every second value for the last 24 hours of Kp, Dst and neutrons (3 x 6 inputs) and the last five days from the GOES data (electrons, low and high energy protons) (3 x 5 inputs). This gives 45 inputs to the models.

For the Meteosat-3 54 % of the warnings were predicted when 80 % of the non-anomalies were predicted. For a model that is trained for Tele-X anomalies 82 % of the warnings were predicted *Andersson et al.* [1998].

Different time periods

Three different models are trained on three different anomaly data sets: all Meteosat-3 anomalies, Meteosat-3 data only from the same period as Tele-X, and all Tele-X anomalies. Each model (Table 1) is then tested using the test files that contains all data, 'all'. The test files are divided into four separate time periods, having equal number of data points (due to time gaps this is not exactly equally to time periods). Each time period has a different threshold so that the periods of non-anomalies are predicted to 80% for all four periods.

When testing the three models with the Meteosat-3 'all' test file, all three models predict the last time period best. Since the models trained with "Meteosat-3 short" and Tele-X data are not trained on data from the first period, these models underestimate the output from the first time periods. This shows that it is necessary to have a model that is trained with data from the same period in the solar cycle as the model will be used in.

Table 2. *Local time dependence*

	Meteosat-3		Tele-X	
LT	pre	unp	pre	unp
00-02	24	26	1	0
02-04	41	23	3	1
04-06	41	20	4	4
06-08	39	21	13	2
08-10	45	15	9	1
10-12	26	18	8	6
12-14	17	17	10	1
14-16	18	15	10	3
16-18	15	20	7	4
18-20	14	18	5	2
20-22	16	23	5	2
22-24	20	31	4	3

The anomalies have been divided into two-hour local-time (LT) sectors. Two models, for Meteosat-3 and Tele-X are trained to predict anomalies two hour in advance. The result from the models are presented as the number of predicted (pre) and unpredicted (unp) anomalies.

Different local times

To investigate in which local time the best predictions are made, models were trained to predict 24 hours ahead. In Table 2 the results from 2 hour ahead predictions presented in order not to confuse the reader with warnings and anomalies. The result from both 2 hour and 24 hour prediction is the same. The models (for Meteosat-3 and Tele-X) predict most warnings in

Table 3. *Anomaly types*

no	Anomaly type	%	no
1	Radiometer stops	64	244
2	Radiometer position jump	33	57
3	Radiometer jump & stops	67	100
4	Other radiometer anom.	0	1
5	Battery charger 1	60	5
6	Battery charger 2	42	31
7	Battery charger off	42	12
8	Battery charger rate anom.	0	4
9	Digital multiplexer 1 off/2 on	71	7
10	Corrupted/lost image line	65	52
11	Command counter anom.	0	1
12	Temperature reading anom.	11	9
13	SIC anom.	45	22
14	EDA bias & SIC lid jump, rad gain	20	5
15	VIS 2 gain jump	50	2
16	Regulator loop voltage anom.	0	2
17	Spurious mem. reconfig.	50	2
18	Other anomalies	0	7

A model is trained to predict Meteosat-3 anomalies. The table shows how well the individual anomaly types are predicted. The model is trained to predict the anomalies within the next two hours. The number of anomalies for each anomaly type (column 4) and the prediction result (column 3) are presented.

the morning-midday section where most of the anomalies occurred. The anomalies that are not predicted are more randomly distributed and hence the non-predicted anomalies are probably causes by other mechanism than those that are predicted.

Different anomaly types

On Meteosat-3, there are many different anomaly types. A test of which anomalies that are easier to predict is made in table 3. Again the model is made to only predict 2 hour ahead but the result is the same as if 24 hour ahead prediction were made. The poor statistics (even though 740 anomalies were detected on Meteosat-3) limits the possibility to do proper evaluation. The three largest and best predicted anomaly types are the radiometer stops, stops & jump and the corrupted/lost image line (rows 1,3 & 10).

In Table 4 results using one model trained with only

Table 4. *Selected anomaly types*

Trained model / Test files	only 1,3 & 10	other
individual test files	64	38
anomalies 1,3 & 10	66	20
all other anomalies	21	29
All Meteosat-3 data	55	34
All Tele-X data	62	32

One model is trained with the best predicted anomalies (1, 3 & 10 from Table 3) and then compared with a model trained with the other anomalies. Both are trained to predict anomalies within the next 24 hours. Different test files are tested with the two models; first, from the respectively test file for the two trained models; second, all data with only the anomalies 1,3 & 10; third, all data with only the other anomalies; forth, all the Meteosat-3 anomalies; and the last, all the Tele-X data set.

these anomalies and one model trained with all the other anomalies are presented. The two models are tested with different test files. The model that is trained with only the 1, 3 & 10 anomalies have the same result as when all Meteosat-3 anomalies are used to train a model.

The results in Table 4 indicate that all anomalies do not have the same cause. Earlier studies *Rodgers et al.* [1997] which have used all anomalies associated with the radiometer also show anomalies caused by at least two different mechanism.

Discussion & Summary

From *Andersson et al.* [1998] it is clear that no energy range is preferable from the SEM-2 instrument on board Meteosat-3. The best parameter to predict anomalies is the high energy electrons, from the GOES > 2 MeV electron data. To predict Tele-X, only GOES electron measurements are needed. For Meteosat-3, a combination of electron measurements is recommended. Both energy ranges of the electrons measured by GOES and Meteosat-3 are energetic enough to cause deep dielectric charging *Wrenn* [1995].

When a model is created for one GEO satellite it can be used with good result on the other satellite. This indicates that the created models uses the same properties to predict the anomalies. The electron flux can be measured by another satellite giving a good result of the model. The latest measurement of the environment is the most important parameter, but a time sequence of measured parameters increase the prediction result.

Deep dielectric charging is the main candidate for the anomalies, especially for Tele-X. For Meteosat-3, the data indicate that other causes are also possible for some of the anomalies. The on board electron monitor helps to predict anomalies for Meteosat-3. This indicates that either this energy range is of importance and/or that the high energy electrons measured on GOES do not totally correlate with the high energy electrons at Meteosat-3 position. In an earlier study of Meteosat-3 anomalies *Rodgers* [1991] the anomalies were divided into two groups. The 'Morning' anomalies occurred at 3-8 local time and could be associated to less than 3 days charge accumulation of electron energies > 200 keV. The anomaly occurred after a burst of high flux. The other group of anomalies was 'Afternoon' anomalies associated with 16-24 local time and charge accumulation of 8 days. Again the anomalies were associated to electrons above 200 keV but the trigger to the anomalies was not known. In this study it seems that the predicted anomalies are correlated with the 'Morning' anomalies and the 'Afternoon' anomalies to the unpredicted anomalies. Also in this study the trigger mechanism for 'Afternoon' anomalies was not found, but the spread in the unpredicted anomalies is found to be slightly wider, 15-06 local time. A new study is planned to look into if surface charging can be a cause to the unpredicted anomalies.

The anomalies from the two satellites are well correlated with periods of high speed solar wind streamers. Solar wind streamers can produce high energy electrons *Baker et al.* [1998] that exist at GEO for long time periods. These high energy particles can cause deep dielectric charging which is the proposed cause for the predicted anomalies in this study. Therefore from this study deep dielectric charging is expected to occur more frequently during the declining phase of at solar cycle than at the solar maximum.

ACKNOWLEDGEMENTS

Part of this work was made under an ESTEC contract no 11974/96/NL(SC). Many thanks to NSSDC OMNIWeb database and Space Physics Interactive Data Resource (SPIDR) which have put their data on the web for public use.

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This preprint was prepared with AGU's LaTeX macros v5.01, with the extension package 'AGU++' by P. W. Daly, version 1.6b from 1999/08/19.