AN EXPERT SYSTEM FOR DIAGNOSING ANOMALIES OF SPACECRAFT

Michael Lauriente, NASA Goddard Space Flight Center, Code 400
Greenbelt, Maryland 20771

N95- 23684

Rick Durand and Al Vampola, University Research Foundation
Greenbelt, Maryland 20771

Harry C. Koons and David Gorney, The Aerospace Corporation, P.O. Box 92957
Los Angeles, CA 90009

Telephone (301)286-5690, Fax (301)286-1742
E-Mail Address: lauriente@envnet.gsfc.nasa.gov

KEY WORDS AND PRASES

Artificial Intelligence, rule-based expert system, spacecraft anomalies, space environment interactions

INTRODUCTION

Although the analysis of anomalous behavior of satellites is difficult because it is a very complex process, it is important to be able to make an accurate assessment in a timely manner when the anomaly is observed. Spacecraft operators may have to take corrective action or to "safe" the spacecraft, space-environment forecasters may have to assess the environmental situation and issue warnings and alerts regarding hazardous conditions, and scientists and engineers may want to gain knowledge for future designs to mitigate the problems. Anomalies can be hardware problems, software errors, environmentally induced, or even the cause of workmanship. Spacecraft anomalies attributable to electrostatic discharges have been known to cause command errors. A goal is to develop an automated system based on this concept to reduce the number of personnel required to operate large programs or missions such as Hubble Space Telescope (HST) and Mission to Planet Earth (MTPE). Although expert systems to detect anomalous behavior of satellites during operations are established, diagnosis of the anomaly is a complex procedure and is a new development.

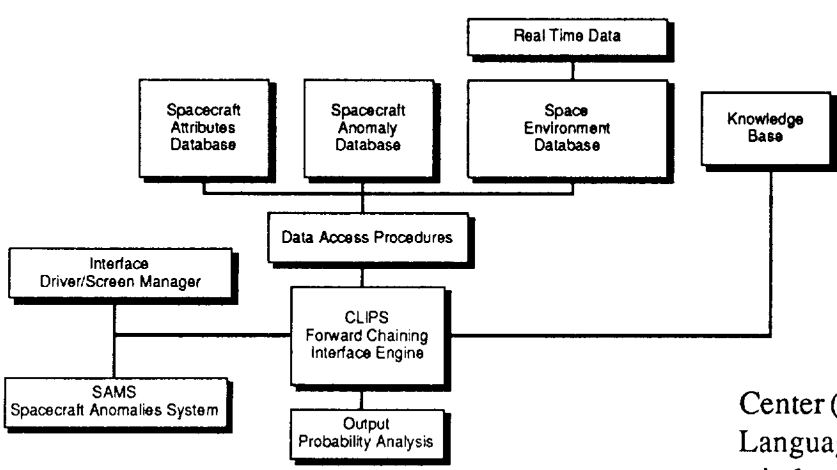

Figure 1. Expert System Architecture.

DESCRIPTION

The tool that is being proposed is a rule-based online expert system for diagnosing in-flight spacecraft anomalies that has the future of simplifying the complex task of analyzing spacecraft anomalies. It uses heuristics in addition to algorithms which allow approximate reasoning and inference and has the ability to attack problems not rigidly defined. The expert system provides scientists with needed risk analysis and confidence not found in the usual programs. The system currently runs on an IBM RISC 6000 at Goddard Space Flight Center (GSFC). The inference engine used is NASA's C Language Integrated Production System (CLIPS).[1,2] A window implementation makes it a more effective tool.

The architecture of the system is shown in Figure 1. The real time link shown is an option available to

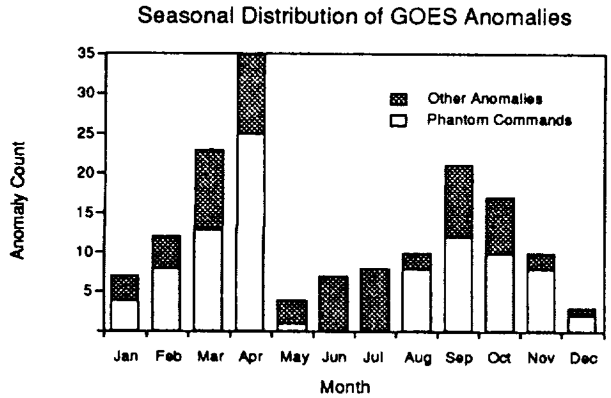

Figure 2. Seasonal distribution of GOES anomalies

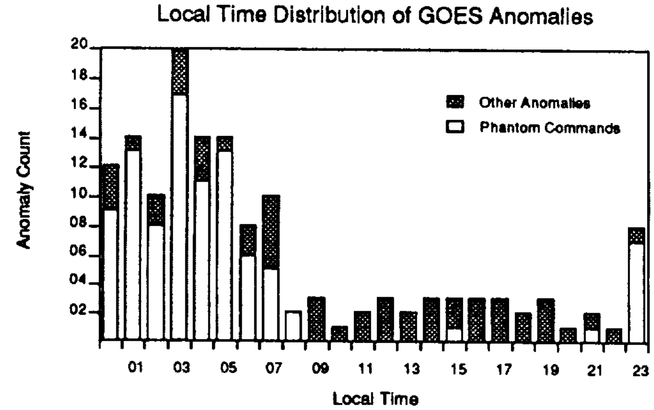

Figure 3. Local-time distribution of GOES anomalies

collect quasi-real time satellite broadcasts by NOAA's Space Environments Services Center (SESC) in Boulder, Colorado. Also available is an option to link up with the interactive space modeling facilities at EnviroNET.[3] The interface driver shown provides a graphing capability. An example is the seasonal distribution of all the GOES spacecraft anomalies as shown in Figure 2, plotted from data in the Spacecraft Anomaly Database using IDL™ graphics.[4] This file was provided by NOAA's National Geophysical Data Center (NGDC). Phantom command anomalies show a bimodal distribution by season. The other anomalies do not. As the phantom commands have been correlated to substorms, it follows that phantom commands also exhibit a seasonal trend.

Figure 3 is a plot of the local time-observed anomalies for the GOES spacecraft. The clustering of phantom commands shows the extent of the particle injection and the subsequent discharging due to high surface potentials.

The block shown as SAMS in Figure 1 was developed by NGDC as a utility to provide a full range of functions for managing, displaying and analyzing data, including functions to examine single anomalies or sets of anomalies for environmental relations. Histograms of local time and seasonal occurrence frequency provided by this utility can reveal distinct patterns for spacecraft which are susceptible to static charge buildup and electrostatic discharge.

Over 300 events are in the database going back to 1971. The contributions to this database were made by cooperation on a world-wide scale and 80 per cent of the spacecraft are at geosynchronous orbit. The four databases shown represent different techniques for storing

RULE 201

SUBJECT : : BULK CHARGING-RULES
DESCRIPTION : : (recurs when fluence high)

If 1) the recurrence of the anomaly, and
2) the recurrence is of HIGH_PENETRATING-FLUX, and
3) 1) the seven-day accumulated fluence of penetrating electrons is HIGH, or
2) the seven-day accumulated fluence of penetrating electrons is VERY_HIGH,

Then there is suggestive evidence (60%) that the cause of the anomaly is BULK_CHARGING

```
IF      ::      (RECURRENCE AND PERIODICITY = OF_HIGH-      PENETRATING_FLUXAND
                        (ACCUM_FLUEN = HIGH OR ACCUM_FLUEN = VERY_HIGH) )
THEN : : (CAUSE = BULK_CHARGING CF 60)
```

RULE 110

SUBJECT : : TOTAL_DOSE-RULES
DESCRIPTION : : (Local time recurrence rules out total radiation dose.)

If 1) the recurrence of the anomaly, and
2) the recurrence of an anomaly in a specific local-time sector,

Then it is definite (100%) that the cause of the anomaly is not TOTAL_DOSE.

```
IF      ::      (RECURRENCE AND LT_RECUR
THEN : : (CAUSE ! = TOTAL_DOSE)
```

Figure 4. Rule Format

Spacecraft Environmental Anomalies

Select all of the types of problems that are associated with this anomaly:

Yes	
<>	PHANTOM COMMAND
<>	LOGIC UPSET
<>	ELECTRICAL
<>	MECHANICAL
<>	SENSOR
<>	SOFTWARE
<>	MEMORY
<>	THERMAL
<>	PART FAILURE
<>	TELEMETRY ERROR
<>	SYSTEM FAILURE
<>	MISSION FAILURE
<>	OTHER

Figure 5. Expert system query screen

and accessing data. The architecture of the system was designed to emulate the way the user normally looks at data to diagnose anomalies. The expert system not only consolidates expertise in a uniform, objective, and logical way, but it also offers "smart" ways of accessing various databases which are transparent to the user. Then by applying various rules in its knowledge base, the system is queried, as appropriate, to arrive at a conclusion. The current development of the system is able to attribute the causes of satellite anomalies to one of several possible categories, including surface charging, bulk charging, single event upsets (SEUs), and total radiation dose. The architecture is such that other causes could be added if a satisfactory rule base were developed. The rule base includes the expert system rules that will be "fired" under control of the inference engine. The rules are entered in a defined "if-then" format as shown in Figure 4. The user interface links to databases which include past environmental data, satellite data and known anomalies.

The knowledge base consists of over 200 rules and provides links to historical and environmental databases. Unlike its algorithmic predecessors, it can be flexible in the way it attacks complex problems. The system output was verified by referring to historical case studies and historical databases.

The anomaly database is an ASCII file provided by the NGDC which contains information on approximately 300 historical anomalies. Figure 5 is a listing of the types of problems considered for anomalous behavior. The attributes database is an ASCII file for launch and orbital information on satellites as shown in Figure 6 is an abbreviated format. The actual listing has 35 satellites.

The environment database is an ASCII text file of the historical record of the geophysical parameter known as Kp, the planetary magnetic index, used to estimate the severity of magnetic storms within the Earth's magnetosphere. The solar flare database is an ASCII data file on the date and time-of-occurrence of X-class solar x-rays These files are accessed by a C-language interface between the expert system and the ASCII file.

The Attributes Database is an ASCII file for launch and orbital information on satellites. It is possible to anticipate anomalies based on particular orbits. These probable causes have been summarized for classes of orbits in the tutorial paper on spacecraft anomalies.[5] These probable causes are also covered by rules and facts in the Knowledge Base.

FUTURE WORK

The graphical outputs of the Anomaly Database were used as illustrations merely to make the point that these fact resources are readily accessed. They lend to the tool an advantage for analyzing and interpreting large data sets. The development of the engine or driver is considered adequate for the task. The fact base and

NAME	INCLINATION	APOGEE	PERIGEE	LONGITUDE	LAUNCH DATE
SAMPEX	82°	520 km	670 km	-1°	07/03/92
UARS	57.0	579	573	-1	09/15/91
TOMS	82.6	1203	1185	-1	08/15/91
TDRS 5	0.0	35805	35774	-1	08/02/91
TDRS 1	1.4	35798	35785	-1	04/05/83

Figure 6: Launch and orbital information for satellites contained in the database

knowledge base, on the other hand, need to be expanded. The correlation of cause and effects of solar terrestrial effects is a young science. Enough evidence has been collected by NOAA's NGDC that these environmental effects need to be considered as serious.[6] Workshops and special publications that update our knowledge on these environmental interactions should be used as resources for the knowledge base. New frames are also needed. Orbital debris has been recognized as a threat and algorithms exist that are easily accommodated by the expert system. Scintillation related to noisy telemetry links and commanding errors are also candidates to be considered ionospheric.[7] The facility has been improved by the speed of the IBM RISC 6000, and with the use of X Windows, the system will also be enhanced. The Spacecraft Attributes Database does not presently contain information on electrical parts which is certainly an area that needs pursuing.

A new initiative under study is a spin-off expert system for diagnosing anomalies during the early phase of the spacecraft life. The present operation depends on a contingency manual for guidance when anomalies occur. This expert system is an ideal candidate to host a "lessons learned" archive to improve on the facilities now available to ground operators.

Wilkinson has found a solar cycle dependence for SEUs on the Tracking and Data Relay Satellite (TDRS-1),which are caused by cosmic rays.[6] Anomalously high rates of SEUs were correlated with solar flares. We are now collecting SEU data from the Total Ozone Mapping Spectrometer (TOMS) and the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) satellites in a cooperative effort with NOAA. According to NOAA's Joe Allen, every satellite is a potential monitor of the space environment.[8] By continuing to study the SEUs of spacecraft in different orbits, we hope to get a better understanding of the anomalous behavior of spacecraft for incorporation into the rules of the expert system.

The incorporation of real-time or near real-time data would permit a much more efficient resolution of the causes of satellite anomalies. For this to be achieved, major interagency cooperation will be needed. A long range goal is to reduce the number of personnel needed to monitor and control the large NASA missions. The present development can be incorporated as a baseline for subsystem for ground operators. The implementation of this concept will hold great promise for reducing cost of operations throughout NASA.

ACKNOWLEDGMENTS

We have been fortunate enough to receive outstanding support through a cooperative agreement with the University Research Foundation by Chris O'Callaghan, John Ruby, Tom Wehrung, Mark Rolincik, and Peter Messore, who are students. We are indebted to the staff of NASA Johnson Space Center's AI Laboratory for their cooperation in the use of CLIPS. The technical discussions with Dan Wilkinson and Dr. Joe H. Allen at NOAA were very helpful.

REFERENCES

[1] Giarratano, J. C. (1989, May). "Artificial Intelligence Section," CLIPS User's Guide, Version 4.3 of CLIPS, Lyndon B. Johnson Space Center.

[2] Rolinick, Mark; Lauriente, Michael; Koons, Harry, C.; Gorney, David; "An On-Line Expert System For Diagnosing Environmentally Induced Spacecraft Anomalies Using Clips," NASA Conference Publication 3187, SOAR '92, Vol.1.

[3] Lauriente, Michael, "An On-Line Spacecraft Environment Interactions Information System, J. Spacecraft and Rockets, 31, No. 2, Mar- Apr 1994.

[4] Wilkinson, Daniel C., "National Oceanic and Atmospheric Administration's Spacecraft Anomaly Database and Examples of Solar Activity Affecting Spacecraft," J. Spacecraft and Rockets, 31. No. 2, Mar-Apr 1994.

[5] Vampola, A.L. "Environmentally Included Spacecraft Anomaly Analysis," Spacecraft and Rockets, 31, No. 2, Mar-Apr 1994

[6] Wilkinson, Daniel C., TDRS-1 Single Event Upsets And The Effect Of The Space Environment," IEEE Transactions on Nuclear Science, Vol. 38, No. 6, Dec., 1991.

[7] Koons, H. C., and Gorney, D. J., "Spacecraft Environmental Anomalies Expert System," J. Spacecraft and Rockets, 31. No.2, Mar-Apr 1994.

[8] Allen, Joe, Private Communication, May 1989