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DIAGNOSING ANOMALIES OF SPACECRAFT FOR SPACE MAINTENANCE AND SERVICING

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ABSTRACT

Very often servicing of satellites is necessary to replace components which are responsible for anomalous behavior of satellite operations due to adverse interactions with the natural space environment. A major difficulty with this diagnosis is that those responsible for diagnosing these anomalies do not have the tools to assess the role of the space environment causing the anomaly. To address this issue, we have under development a new rule-based, expert system for diagnosing spacecraft anomalies. The knowledge base consists of over two-hundred (200) rules and provides links to historical and environmental databases. Environmental causes considered are bulk charging, single event upsets (SEU), surface charging, and total radiation dose. The system's driver translates forward chaining rules into a backward chaining sequence, prompting the user for information pertinent to the causes considered. When the user selects the novice mode, the system automatically gives detailed explanations and descriptions of terms and reasoning as the session progresses, in a sense teaching the user. As such it is an effective tutoring tool. The use of heuristics frees the user from searching through large amounts of irrelevant information and allows the user to input partial information (varying degrees of confidence in an answer) or 'unknown' to any question. The system is available on-line and uses C Language Integrated Production System (CLIPS), an expert shell developed by the NASA Johnson Space Center AI Laboratory in Houston.

INTRODUCTION

What is proposed is a system for diagnosing spacecraft anomalies which will provide an intelligence for servicing of satellites. The analysis of components responsible for anomalous behavior of satellites due to adverse interactions with the natural space environment is a very complex process. It is important to be able to make an accurate assessment in a timely and accurate manner when the problem becomes serious enough to requiring servicing. This approach that is being proposed is to take advantage of the new tools that have been developed to analyze, display, and interpret large data sets. Significant progress has been made to the extent that some are even suggesting that these powerful tools may even lead to schemes to predict flares and geomagnetic activity. An international workshop on artificial intelligence applications on solar-terrestrial physics to be held at Lund, Sweden, September 22-24, 1993, sponsored by NOAA, NASA/GSFC, Lund Observatory and the Swedish Science Research Institute has made such a suggestion.[1] Although prediction may be an optimistic long term goal for scientists, the engineers responsible for design and building the hardware would be satisfied if early warning schemes were available. Vampola, as Guest Editor for a collection of papers on solar effects on space systems found a consensus that the solar output of radiation, solar wind, and energetic particles depends on the solar magnetic cycle.[2] This fits in with viewpoint that radiation belt models should be based on years of magnetic activity maximum and minimum instead of sun spot maximum and minimum.[3] NOAA's National Geophysical Data Center, (NGDC), has responsibility for collecting, archiving, analyzing, and disseminating solar-terrestrial data and information.[4] NGDC makes a deliberate effort to apply these data resources to the problem of spacecraft interaction with space environment.

Historical records that have been started fairly recently by NOAA, indicate that the anomalous behavior of spacecraft occurs when the elements of the upper atmosphere become unstable. Trends alone do not provide the answers to the anomaly, but they help focus on the problem. On-board instruments will improve the ability to forecast or provide early warning of events leading to the environments responsible for some of the anomalies.[4] Design errors and quality control problems, workmanship, and wear can also lead to anomalies but these are in a category that engineers understand and can cope with.

The expert system that is under development will help those who have a need to diagnose the anomaly with the scientific and engineering expertise to assess the interaction that is taking place by the environment. As result of the heightened interest in spacecraft anomalies, no doubt due to the high geomagnetic activity that has been observed for solar cycle 22, the 1990 AIAA Sciences meeting included a special session at which seven papers related to spacecraft anomalies were presented. Since then these papers were updated and recently accepted for publication as a special collection on environmentally induced spacecraft anomalies.[5] It is anticipated that these coordinated activities to update the knowledge base of the system will lead to a useful engineering tool for space maintenance.

DESCRIPTION

The tool that is being proposed is a rule-based online expert system for diagnosing inflight spacecraft anomalies system. It has features that provide an effective method for saving knowledge, allow sifting through large amounts of data, and home in on significant information. Most importantly, it uses heuristics in addition to algorithms which allow approximate reasoning and inference, and the ability to attack problems not rigidly defined. A microcomputer-based version that has essentially the same features is also under development by The Aerospace Corporation as a research system to accomplish the same results.[6]

The modularity of the expert system allows for easy updates and modifications. It not only provides scientists with needed risk analysis and confidence not found in the usual programs. but the window implementation makes it a more effective tool. 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).[7,8] CLIPS is not only compatible with both C and Fortran languages, but it has features which include the ability to compile the rules and save them in a binary image file, thus allowing faster execution than a typical rule interpretive system. This feature qualifies CLIPS to be used as an expert shell, i.e., an environment where the rules can reside and be accessed.The architecture of the system is shown in Figure 1.

Besides the interactive knowledgebase, the system also provides access and display of information from the databases. As shown in Figure 1, the system has four databases, but more can be added as needed. This is the fact base for the collection of informative sources related to the topic of interest.

The attributes database is an ASCII file for launch and orbital information on satellites. Figure 2 shows the launch and orbital information in the Attributes database. While anomalies can occur in almost any orbit, it is possible to anticipate environmentally induced anomalies based on orbits. Vampola has summarized these probable causes for classes of orbits in his tutorial paper on spacecraft anomalies.[9] These probable causes are also covered by rules and facts on the Knowledge Base.

Some examples of the nature of the anomaly database are given in Figures 3-6. The anomaly database, an ASCII file provided by the NGDC, contains information on about 300 historical anomalies. Figure 3 is a listing of the types of problems considered for anomalous behavior. Figure 4 lists the satellites that are in the database. Some of the names are coded to hide the identity of the actual spacecraft. The seasonal distribution of TDRSS anomalies shown in Figure 5 was plotted from data in the Spacecraft Anomaly Database using IDL™ graphics. This file was provided by NGDC. The TDRSS-1 anomalies show no distinct seasonal variation in anomaly occurrence. This distribution has a very good probability of being random.[4] Figure 6 is a plot of the TDRSS weekly SEU count for all observed SEUs. Since some of the SEUs are unobserved, the rate shown is considered a minimum. The spikes in August, September and October are due to solar flares. This experience led to changes to hardened devices for the following TDRSS spacecraft whence the problem ceased.[10] The exception was TDRSS, which was lost with *Challenger*. Part of the problem of TDRSS-1 was an innocent desire to take advantage of advance technology. It was not realized at the time that as technology advances towards faster and lower power devices on a chip, the sensitivity to SEUs increases.[11]

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.

KNOWLEDGE BASE

The knowledge base consists of over two-hundred (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. It more closely simulates the methods of human experts who use a combination of known empirically derived formulae, hunches based on degrees of certainty and experience, and even judicious "fudging when specific data is lacking. The system output was verified by referring to historical case studies and historical 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 (SEU), and total radiation dose. ("Unknown" is also a possible and plausible conclusion, depending on the quantity of of data available. 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. The user interface links to databases which include past environmental data, satellite data and previous known anomalies. Information regarding satellite design, specifications and orbital history need to be assimilated with previous anomalies data and environmental conditions, while addressing the specific circumstances of individual users.

LEARNING TOOL

One of the most beneficial aspects of the system is its use as a learning tool for diagnosing spacecraft anomalies. A user is initially given a choice between either 'novice' or 'expert' mode for the current session. If the user selects the novice mode the system automatically gives detailed explanations and descriptions of terms and reasoning as the session progresses, in a sense teaching the user about the topic or topics. The expert mode, on the other hand, simply executes the session without giving these extra explanations, unless the user specifically requests them.

The user is also given the option of selecting which causes are to be considered.This selection determines a knowledge base sub-group, so that only rules in this specific environmental area are considered. In this way the user can learn what variables, information and data affect, and are important to, that cause. In addition to this, in the features described next, the user is actually able to access the relevant rules him/herself and other variables and facts which were determined by using these rules.

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 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 serious. 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 accomodated by the expert system. Ionic scintillation related to noisy telemetry links and commanding errors are also candidates to be considered.that should be used.[12] We are improving our EnviroNET network with the addition of an IBM Risc 6000. Once there, not only will the speed of the Expert System be increased, but with the use of X Windows the system will also be enhanced. The PC system is able to access the Spacecraft Anmomaly Manager (SAM) software which was developed by the National Geophysical Data Center. The SAM program provides a full range of functions for managing, displaying and analyzing data. The on-line system does not have this type of data management as yet but it is something to consider. The Spacecraft Attributes Database does not presently contain information on electrical parts which is certainly an area that needs pursuing. It is noted that no GSFC scientific satellites are listed in Figure 2. This omission also should be rectified. The last issue is that of updating Kp values. Recent data can be received from satellite broadcasts by the Space Environment Center, Boulder, CO.

CONCLUSION:

A useful tool for diagnosing anomalies of spacecraft for space maintenance and servicing has been described. This tool combines the algorithmic capabilities of mathematical programs and diagnostic models with expert heuristic knowledge, and uses confidence factors in variables and rules to calculate results with degrees of human confidence associated with them. Since the causes of environmentally induced spacecraft anomalies depend not only on algorithms, but also on environmental conditions, rules and information can rarely be known with 100% certainty. Based on present experiences, the role for the expert system is for either quasi-real time, or post analysis. There is a need to greatly improve the knowledge base and rules in view of the correlation observations that are emerging out of NOAA's NDGC.

ACKNOWLEDGMENTS

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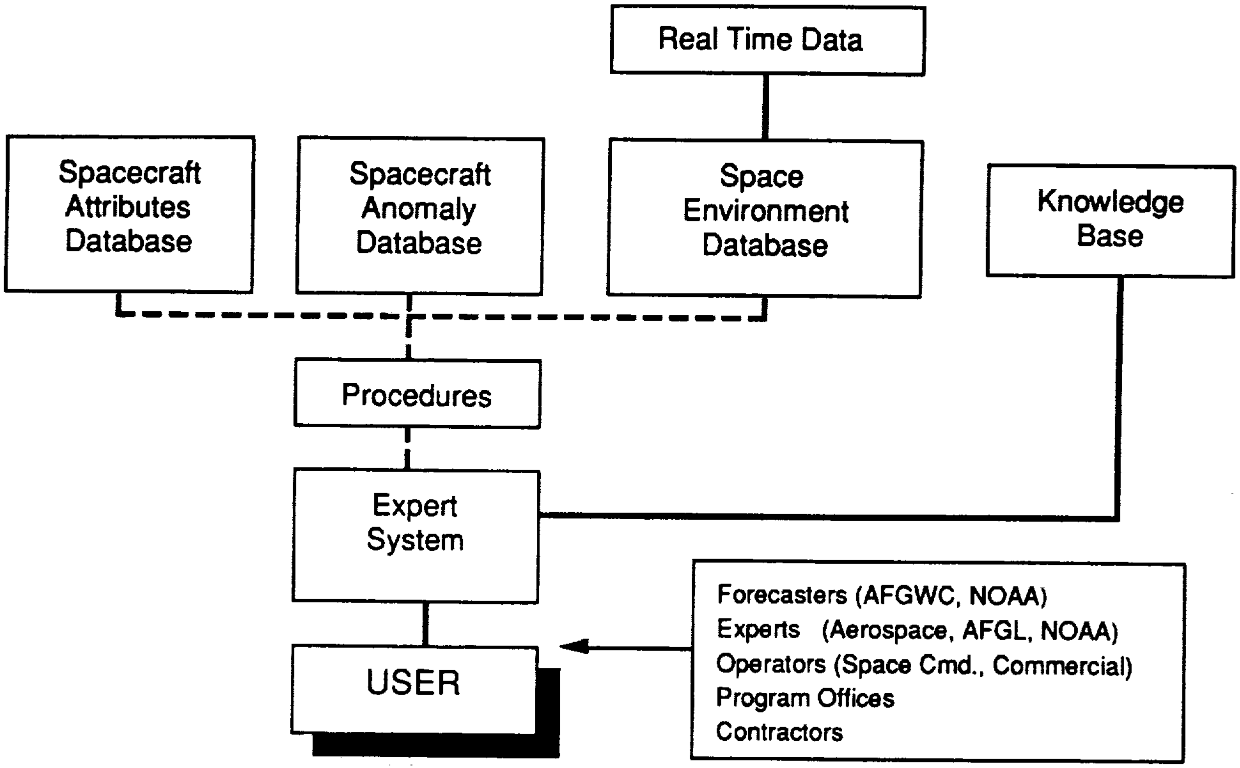

Figure 1. Expert System Architecture.

NAME	INCL	APOGEE	PERIGEE	LONG	LAUNCH DATE
OSCAR_32	90.3	1185	1017	-1	9-16-87
OSCAR_31	90.3	1183	1018	-1	9-16-87
DMSP	0.0	0	0	-1	6-20-87
GOES_7	0.1	37796	35783	277	2-26-87
FLTSCOM_7	4.3	35875	35703	-1	12-05-86
PLOAR_BEAR	89.6	1015	960	-1	11-14-86
NOAA_10	98.7	826	808	-1	9-17-86
GSTAR_2	0.1	35800	35775	255	3-28-86
SATCOM_K1	0.0	35794	35781	279	1-12-86
SATCOM_K2	0.0	35801	35774	279	11-28-85
NAVSTAR_11	63.4	20474	19887	-1	10-09-85
ASC_1	0.1	35791	35782	81	8-27-85
OSCAR_30	89.8	1260	1000	-1	8-03-85
OSCAR_24	89.8	1259	1001	-1	8-03-85
TELSTAR_3D	0.0	35804	35770	284	6-19-85
GSTAR_1	0.0	35779	35778	257	5-08-85
LEASAT_3	1.4	35809	35768	178	4-13-85
SCATHA	4.9	42577	28205	-1	1-30-79

Figure 2. Launch and orbital information on satellites contained in the database.

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 3. Description of types of problems considered in anomaly database.

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Select the name of the satellite that has experienced the anomaly.

   OSCAR_32          TELSTAR_3D
   OSCAR_31          GSTAR_1
   DMSP              LEASAT_3
   GOES_7            SCATHA
   FLTSATCOM_7       UNKNOWN
   POLAR_BEAR
-> NOAA_10
   GSTAR_2
   SATCOM_K1
   SATCOM_K2
   NAVSTAR_11
   ASC_1
   OSCAR_30
   OSCAR_24
```

Figure 4. Names of satellites that are in the anomaly database.

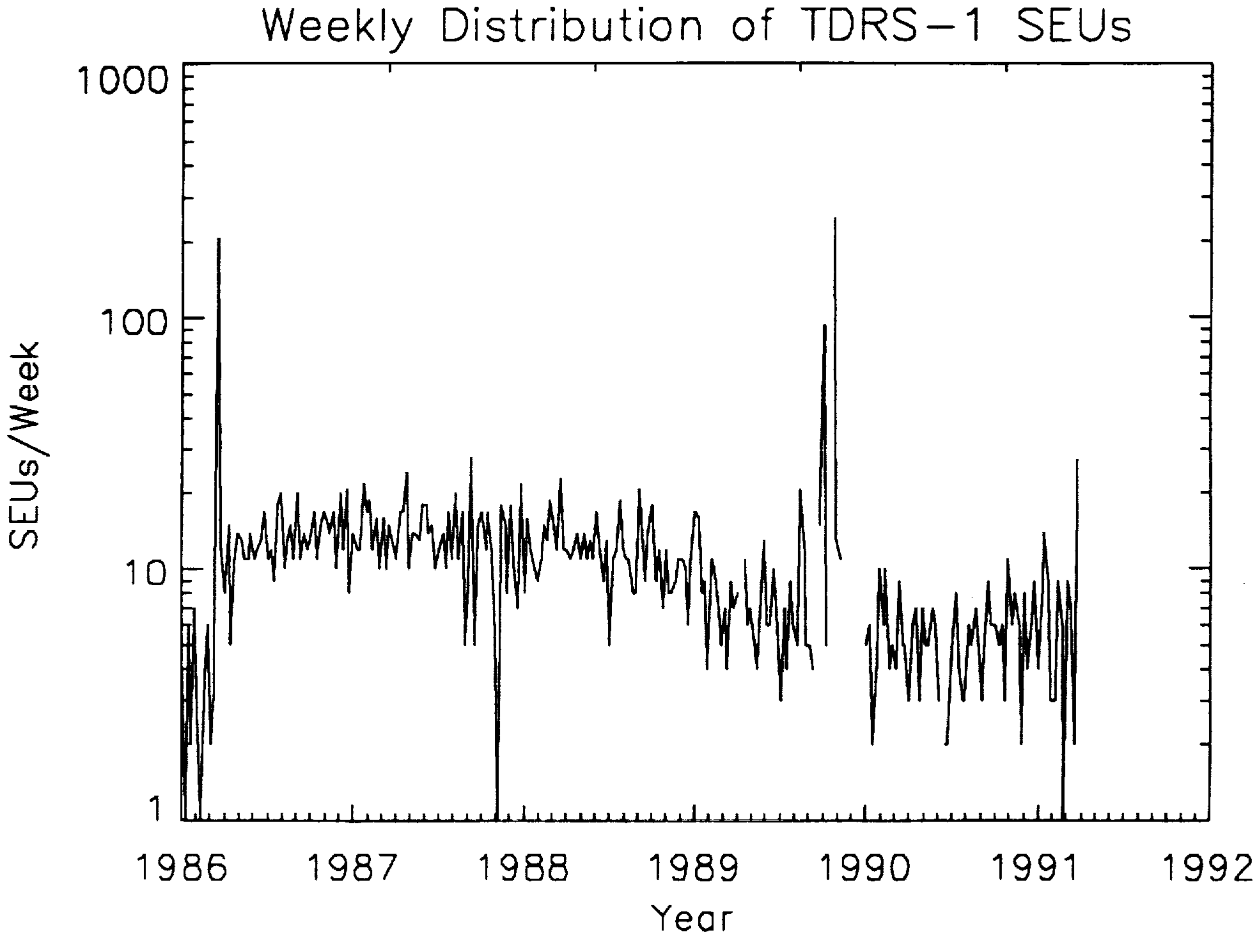

Figure 5. Graph made from data in seasonal distribution of TDRSS anomalies. The distribution is considered random. (Source NGDC)

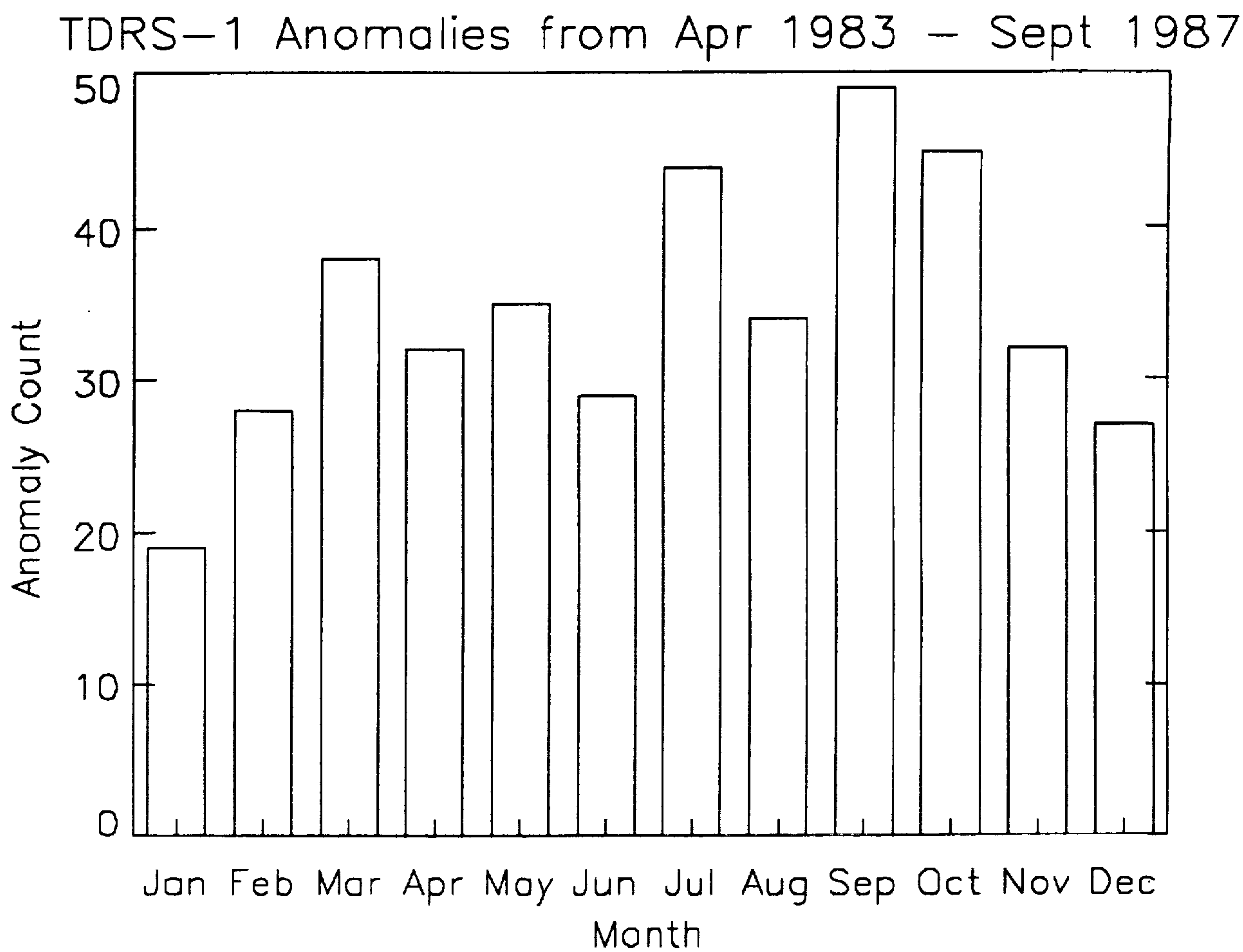

Figure 6. Graph made from data in anomaly database of anomalies on TDRS-1 weekly count for all observed SEU's. The rate shown is a minimum. The spikes in August, September and October are due to flares. (Source NGDC)