JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 31, No. 2, March–April 1994

Spacecraft Environmental Anomalies Expert System

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An expert system has been developed by The Aerospace Corporation, Space and Environment Technology Center for use in the diagnosis of satellite anomalies caused by the space environment. The expert system is designed to determine the probable cause of an anomaly from the following candidates: surface charging, bulk charging, single-event effects, total radiation dose, and space-plasma effects. Such anomalies depend on the orbit of the satellite, the local plasma and radiation environment (which is highly variable), the satellite-exposure time and the "hardness" of the circuits and components in the satellite. The expert system is a rule-based system that uses the Texas Instrument's Personal Consultant Plus™ expert-system shell. The expert-system's knowledge-base includes about 200 rules, as well as a number of data bases which contain information on spacecraft and their orbits, previous spacecraft anomalies, and the environment.

Introduction

THE spacecraft environmental anomalies expert system (SEAES) is a microcomputer-based expert system that has been developed by The Aerospace Corporation, Space and Environment Technology Center (SETC) to aid in the objective analysis of environmentally induced satellite anomalies. An early version of the system (a prototype system) is described by Koons and Gorney.[1] At its present stage of development SEAES is a rule-based research system.[2]

On-orbit anomalies in satellite systems or subsystems occur quite often (several hundred are reported each year), and the number, frequency, and severity of the anomalies are likely to grow with the inevitable increases in spacecraft complexity in the future.[3] Spacecraft anomalies have a wide variety of causes and a wide range of effects and severity. Design errors and inadequate quality control in parts selection and workmanship are examples of preflight engineering and construction errors that can lead to later anomalous behavior of components on orbit. Naturally, all mechanical and electrical components are susceptible to failure from excessive wear. Such failures and their effects can be difficult or impossible to anticipate. Many satellite anomalies result directly from improper commanding or operation (human error or ground-system error). For military space systems, the possibility of hostile action must be a consideration as well. Recent studies have shown that adverse interactions between spacecraft components and the natural space environment can have deleterious consequences comparable in severity and frequency to those caused by any other factor.[3] Indeed, spacecraft anomalies attributable to electrostatic discharges (just one form of environmental interaction) have been known to cause command errors, spurious signals, phantom commands, degraded sensor performance, part failure and even complete mission loss.[3] Regardless of the severity of the anomaly, it is important to assess the cause of the problem in a timely and accurate manner so that appropriate corrective action can be taken.

Various aspects of the space environment can cause on-orbit satellite anomalies. The plasma environment (especially around geosynchronous orbit) can cause differential charging of satellite components on the surface of the vehicle.[4-6] Surface charging can exceed breakdown voltages, and electrostatic discharges (ESDs) can occur with the potential to disrupt electronic circuits. Medium-energy electrons in the space-radiation environment can penetrate and become embedded in dielectric components such as cable insulation and circuit boards.[7] This "bulk charging" phenomenon can result in ESD within the dielectric components, disrupting signals or devices within the affected subsystem.[8,9] High-energy, trapped, radiation-belt particles, solar-flare protons, and galactic cosmic rays can cause single-event upsets (SEU) within microelectronic devices. The total-radiation dose of this same high-energy radiation leads to degradation of microelectronic devices and sensors. Other aspects of the environment, such as micrometeorites and debris, can cause mechanical disruption of the vehicle.[10] Anomalies which result from any of these environmental causes can lead to transient malfunction or even to nonrecoverable loss of the component or subsystem.

Typically, various agencies and individuals become involved in the identification and resolution of spacecraft anomalies. These include 1) the civilian or military satellite operators who must evaluate the anomaly in near real time in order to take the proper corrective action or to "safe" the vehicle; 2) space-environment forecasters, such as the Air Force Space Forecast Center (AFSFC) or the National Oceanic and Atmospheric Administration (NOAA) Space Environment Services Center (SESC), who must assess the environmental situation in real time and issue warnings and alerts regarding hazardous condi-

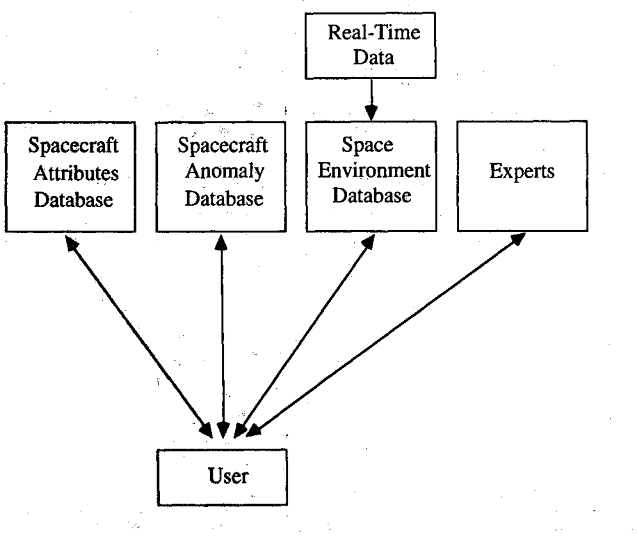

Fig. 1 Typical user environment without the benefit of an expert system.

Received Nov. 14, 1992; revision received March 3, 1993; accepted for publication March 13, 1993.

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tions; 3) satellite contractors, who must assess the susceptibility of their vehicle and incorporate design modifications if the vehicle's on-orbit reliability proves to be inadequate; and 4) scientists and engineers who develop an understanding of the processes by which the environment interacts with the satellite, with the goal of recommending mitigating procedures for future missions. A major difficulty with spacecraft anomaly diagnosis is that many of the people who must quickly and accurately diagnose the anomaly do not have immediate access to the required data or to the scientific or engineering expertise required to properly assess the role of the space environment in the anomaly. Thus, real-time spacecraft-anomaly diagnosis appears to be an ideal application for an expert system which can gather, format, display, and utilize appropriate data consistent with logical rules based on state-of-the-art engineering and scientific expertise. The objectivity in this approach is obtained by applying a consistent set of rules, the knowledge base, to the inputs provided by the user. The results of consultations may differ as the user inputs or the data bases available to the user differ.

System Description

SEAES has been developed using a commercial expert-system shell, Texas Instrument's Personal Consultant Plus™, and has been implemented for development and test on an IBM compatible personal computer. The basic architecture of the system is designed to conform as much as possible to the working environment in which the system will ultimately be used while taking advantage of the data-processing, data-display and decision-making functions of the personal-computer system. The design makes use of existing data sets.

Figure 1 shows the typical user environment without the benefit of an expert system. A user (anyone who is responsible for the diagnosis of a satellite anomaly) generally has access to a number of data bases and to some amount of expertise. The data bases might be computer based or in the form of technical literature; the data might be on site or at other agencies. The most pertinent data are the space-environment data, which include historical and real-time data on the space environment; the spacecraft-attributes data , which contain information on the vehicles (this might include component information, ephemerides, etc.); and spacecraft-anomaly data containing records of previous anomalies on the vehicle in question. Expert opinions are usually available over the phone or in consultations after the fact. Even under the best of circumstances the user has a formidable task to acquire and digest the information pertinent to his diagnosis. Often the user is not an expert in the space environment and its interaction with space vehicles and, thus, may not know what information is available or even what information is pertinent.

SEAES contains both an expert and a novice mode. The novice mode contains more descriptive material and an-

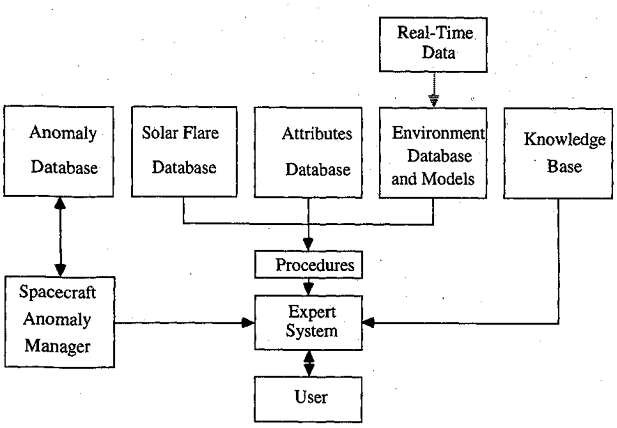

Fig. 2 Architecture of the space environmental anomalies expert system.

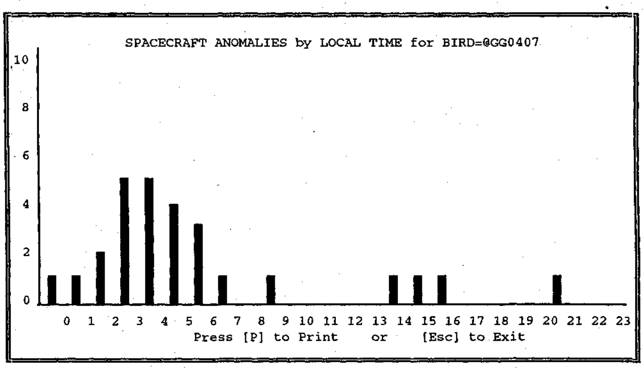

Fig. 3 Example of the graphical output available from SAM.

tecedent rules that explain the conclusions reached by the system. It is primarily intended as a learning tool. Figure 2 shows the architecture of SEAES. The expert system not only provides access to a consolidated interactive knowledge base, but also provides procedures to access and display information from the data bases. The four data bases shown in Fig. 2 represent different techniques for storing and accessing data. The anomaly data base is a dBASE III PLUS™ file provided by the National Geophysical Data Center in Boulder, CO. It presently contains information on approximately 3000 historical anomalies. The attributes data base consists of a dBASE III PLUS™ file for a small selection of satellites. It contains launch dates and orbital information. The environment data base is an ASCII text file that contains an historical record of the geophysical parameter known as Kp, the planetary magnetic index. Kp is a measure of the severity of magnetic storms within the Earth's magnetosphere. This file is accessed by a C-language interface between the expert system and the ASCII file.

The environment data base can be automatically updated for recent values of Kp. This feature has been tested but not yet implemented in the research system. Recent data can be collected by a remote computer from the satellite broadcasts by the Space Environment Services Center, Boulder, CO. They are stored in a text file similar to the environment data base. When requested by a user, the most recent data in the file can be automatically transferred via telephone modem to the consultation computer for consideration in the consultation.

The solar flare data base is a dBASE III PLUS™ data file containing the date and time of occurrence of X-class solar x-ray flares. The user can request a report of such flares that occurred near the time of the anomaly.

The user selects the data bases that he wishes to use during the consultation. This permits a flexible configuration at different sites where one or more of the data bases may not be available. In practice, the expert system could be operated (albeit with diminished effectiveness) even if one or more of the prescribed data bases were unavailable.

If the user chooses to use the anomaly data base, the expert system automatically queries the data base via a dBASE III interface and obtains a list of the satellites that are contained in the data base. It then presents the satellite selection screen to the user. Many of the names are coded to conceal the identity of the actual vehicle. Two types of reports are generated. A satellite report lists all of the anomalies in the data base for a single vehicle. This can be used to search for the recurrence of similar anomalies on the same or related spacecraft. The recurrence of anomalies in specific local-time sectors or in limited regions of the orbit, for example, is an indication of a possible environmental cause. A date report lists of all of the anomalies in the data base for a 3-day time period around the date entered by the user. Frequently, more than one vehicle is affected by a severe geomagnetic storm. The occurrence of similar anomalies on more than one vehicle in a short time period is another indication of a possible environmental cause.

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

     Yes
↔    ■    PHANTON_COMMAND
↔         LOGIC_UPSET
↔         ELECTRICAL
↔         MECHANICAL
↔    ■    SENSOR
↔         SOFTWARE
↔         MEMORY
↔         THERMAL
↔         PART_FAILURE
↔         TELEMETRY_ERROR
↔         SYSTEM_FAILURE
↔         MISSION_FAILURE
↔         OTHER

 1. Use arrow keys or first letter of item to position cursor.
 2. Select all applicable responses.
3. After making selections, press RETURN/ENTER to continue.
```

Fig. 4 Screen for selecting one or more types of problems associated with the anomaly under study.

The expert system provides the user access to the spacecraft anomaly manager (SAM) software which has been developed by the National Geophysical Data Center. The SAM program provides a full range of functions for managing, displaying, and analyzing the data, including functions to examine single anomalies or sets of anomalies for environmental relationships. Histograms of local time and seasonal frequency of occurrence provided by this program can reveal distinct patterns for spacecraft which are susceptible to static-charge buildup and ESD. Figure 3 shows one example of the graphical output available from SAM. The SAM program also provides a means of updating the anomaly data base after the expert-system consultation.

The knowledge base, currently consisting of about 200 rules, has been constructed based on personal interviews with space scientists and engineers who are experts in each of the fields covered by the expert system. The expert system is arranged into frames which allow the knowledge-base structure to be divided into logically different, but related, segments. The frames include the causes of the anomaly such as surface charging, bulk charging, single-event effects, total-radiation dose, and space-plasma effects, as well as frames to instantiate the various reports and graphs produced by the system. This organization allows the system to be easily expanded to include a broader range of environmental causes of anomalies.

Expert users prefer to see a graphical display of the environmental parameters in addition to the values extracted by the expert system in its normal processing of the rules. This assists them in understanding the state of the environment at the time of an anomaly. For this purpose the expert system provides a graphic display of *Kp* for the time period from 12 days before the date of the anomaly to 1 day after the date of the anomaly. This allows the user to see recent levels of activity, thus putting the time period of the anomaly in perspective.

As progress is made through the consultation a number of specific questions are asked. Figure 4 shows the screen for selecting one or more types of problems associated with the anomaly under study. The responses to this screen are used to instantiate one or more of the frames for the five environmental causes of anomalies.

The expert system uses the backward-chaining inference method to establish the facts that it needs to determine the probable cause or causes of an anomaly. The knowledge is contained in a set of rules in the form: IF *premise* THEN *conclusion*. It also uses certainty factors to measure the certainty or confidence that one has in a fact or a rule. A typical rule relating the magnetically disturbed conditions to the cause surface charging is shown in Fig. 5. The rule uses three parameters: RECURRENCE, PERIODICITY, and MAG_STATE_CURRENT. The definition of the recurrence parameter is also shown in Fig. 5. The expert system collects facts from the user by means of questions. Figure 6 shows a technical question regarding the level for the accumulation of energetic electrons in the vehicle. This requires access to satellite environmental data plus an analysis or expert opinion to relate the measurements from the satellite making the measurements to the one experiencing the anomaly. Help is always available by pressing a function key on the computer keyboard. The help window then appears as shown in Fig. 6. The help window contains a more detailed explanation of the question and a person or organization to contact for assistance.

If the accumulated fluence is unknown, the user is asked if he wishes to view a graph of the daily average flux of relativistic electrons at geosynchronous orbit. If the response is yes, then a graph of the flux of >3 MeV electrons is displayed for a time period from 12 days prior to the anomaly to 1 day after the anomaly. The flux is calculated using a neural-network model that predicts the daily averaged electron flux based on the daily sum of the planetary magnetic index ΣKp (Ref. 11). The graph assists the user in determining if bulk charging is the cause of the anomaly.

Single-event upsets are caused by the deposition of energy in digital devices when a very energetic particle passes through the device. The probability of an anomaly thus depends on the hardness of the device as well as on the environment. A list of device types is presented for the users selection if the single event upset frame is instantiated. A series of rules in this frame contains qualitative information on the hardness of each type of technology as determined by laboratory measurements of their upset cross sections.

The result of a consultation is given on a conclusions screen such as the one shown in Fig. 7. A confidence level is given for each possible cause. Note that a negative conclusion is listed whenever a specific cause can be ruled out. Unknown is also a possible and plausible conclusion, depending on the amount of data available.

```
     RULE059
     =======
       SUBJECT :: SURFACE_CHARGING-RULES
       DESCRIPTION :: (anomalies recur during magnetically disturbed
times)
If    1) the recurrence of the anomaly, and
      2) the recurrence is MAGNETICALLY_DISTURBED, and
      3) the level of magnetic activity in the magnetosphere is
DISTURBED,
Then there is suggestive evidence (50%) that the cause of the anomaly is
SURFACE_CHARGING.

       IF    :: (RECURRENCE AND PERIODICITY = MAGNETICALLY_DISTURBED AND
                 MAG_STATE_CURRENT = DISTURBED )
       THEN :: (CAUSE = SURFACE_CHARGING CF 50)


     RECURRENCE
     ==========
       TRANSLATION :: (the recurrence of the anomaly)
       PROMPT :: ("Has this type of anomaly occurred several times (at
least 4 or 5 times) on this spacecraft?" )
       TYPE :: YES/NO
       USED-BY :: (RULE024 RULE025 RULE040 RULE059 RULE019 RULE020
RULE110 RULE165 RULE054 RULE188 RULE189 RULE190 RULE191 RULE192 RULE193
RULE194 RULE039 RULE201 RULE043 )
       CERTAINTY-FACTOR-RANGE :: UNKNOWN
```

Fig. 5 Typical rule relating magnetically disturbed conditions to the cause of surface charging.

```
Select the appropriate level for the accumulated fluence of energetic
electrons above 300 keV for several days prior to the anomaly.

   VERY_HIGH        Help:
   HIGH
   INTERMEDIATE     The accumulated fluence of penetrating electrons
   LOW              is the integral of the electron flux above 300
   UNKNOWN          keV for several days before the anomaly.  It is
                    measured in units of [electrons/cm^2].  For
                    assistance in determining the fluence contact D.
                    Gorney (310/336-6821) at the Aerospace Corp.

                    VERY_HIGH    >10^12          HIGH   10^11 - 10^12
                    INTERMEDIATE 10^10 - 10^11   LOW     <10^10

                      ** End  -  RETURN/ENTER to continue

 1. Use the arrow keys or first letter of item to position the cursor.
 2. Press RETURN/ENTER to continue.
```

Fig. 6 Technical question regarding the level for the accumulation of energetic electrons in the vehicle.

The user may then review the consultation with the option to modify one or more of his responses to see how they affect the conclusion. Also, the user may choose to re-enter the spacecraft anomaly manager program to update the anomaly data base based on the results of the consultation.

The performance and functionality of the system has been tested on historical cases from the anomaly data base, on anomalies that occurred on the SCATHA spacecraft, and on a number of operational spacecraft.

Confidence Factors Within the Spacecraft Environmental Anomalies Expert System

In addition to determining the likely cause or causes of a satellite anomaly based on available data, SEAES expresses its conclusions in terms of a confidence (or certainty) factor (CF). A tabulation of the confidence factors for each cause is maintained throughout the consultation as a standard feature of the expert system shell. Confidence factors offer valuable information to a user. In satellite-anomaly diagnoses, conclusions are rarely black or white, and it is informative to know whether a given conclusion is merely suggestive or fairly certain. In SEAES, the confidence factors are displayed only at the conclusion of a consultation. They are expressed in percentage units, ranging from −100% (a certain negative result) through 0% (no information) to 100% (a certain positive result).

In a consultation, uncertainty can arise in two ways. First, the facts or data can have some associated uncertainty. For example, when a user is asked if a set of satellite anomalies tends to recur in a particular pattern, he might wish to qualify his response with a confidence factor. Second, even when data are certain, the implication of the data might be somewhat uncertain. For example, an expert might regard a positive response to the recurrence pattern of satellite anomalies as providing only suggestive evidence to the conclusion that the anomalies can be attributed to a particular cause. From the standpoint of a logical rule (IF: *data*, THEN: *conclusion*), the first source of uncertainty arises from the "if" portion of the rule, whereas the second type of uncertainty arises from the "then" portion of the rule. Thus, the confidence factor associated with a particular rule (CF_{rule}) is

$$CF_{rule} = (CF_{if}*CF_{then})/100 \quad (1)$$

where CF_{if} represents the uncertainty of the input and CF_{then} represents the uncertainty in the conclusion given that the input is absolutely true. For example, if the user is 60% confident in the validity of his input, and an affirmation of the rule implies 50% confidence in a particular conclusion, then the resulting confidence factor is 30%.

In practice, many individual rules combine to determine a final conclusion. Therefore, confidence factors are updated continuously throughout a consultation in order to increase or decrease confidence in a particular conclusion as inputs are provided that either corroborate or contradict the conclusion. Within the expert system, a previous confidence level ($CF_{previous}$) is modified on the basis of a new rule through the following relationship:

$$CF_{new} = CF_{previous} + CF_{rule}*(100 - CF_{previous})/100 \quad (2)$$

```
Conclusions:

The cause of the anomaly is as follows:  SURFACE_CHARGING  (90%)
                                         Not BULK_CHARGING (72%)




** End - RETURN/ENTER to continue
```

Fig. 7 Conclusions screen showing the result of a consultation.

Perform exponential fit to Gabbard diagram:
If b < 2.0 then CAUSE=COLLISION CF25
If b > 2.0 then CAUSE=EXPLOSION CF25

Perform polynomial fit to Gabbard diagram:
If A_1 < .15 then CAUSE=COLLISION CF25
If A_1 > .15 then CAUSE=EXPLOSION CF25

Dispersion of large pieces: If any fragments larger than 1 m^2 are dispersed over 50% of the total range of fragments, then CAUSE=EXPLOSION CF10 ELSE CAUSE=COLLISION CF10.

Asymmetry of large fragments: If fragments larger than 1 m^2 are asymmetrically distributed about the parent, then CAUSE=EXPLOSION CF15 ELSE CAUSE=COLLISION CF15.

Orderedness of dispersion: If the Gabbard diagram is very ordered, then CAUSE=COLLISION CF15 ELSE CAUSE=EXPLOSION CF15.

Velocity analysis: If average velocity imparted decreases as fragment size increases, then CAUSE=COLLISION CF10 ELSE CAUSE=EXPLOSION CF10.

Fig. 8 Sample rule set for a Gabbard diagram.

Here CF_{new} represents the updated (or cumulative) confidence factor. For example, if the previous confidence factor had been 30%, and a new rule introduced an added confidence of 50%, then the cumulative confidence factor would be $CF_{new} = 30 + 50*(100-30)/100 = 65\%$. Confidence factors for each cause are updated in this manner by every rule that fires that pertains to the cause.

In practice, conclusions with confidence factors less than 20% are not displayed. Conclusions with confidence factors between 20% and 50% are considered to represent a weakly suggestive result, 50–80% a suggestive result, and 80–100% a strongly suggestive result.

Potential for Future Additions to the Spacecraft Environmental Anomalies Expert System

The architecture of SEAES is such that other causes could be added if a satisfactory rule base were developed. Some examples that have been considered are ionospheric scintillation (pertinent to commanding errors and noisy telemetry links) and orbital debris (pertinent to mechanical breakups or damage). Rules and data bases are being compiled for each of these categories, and frames will be added to the expert system after verification and testing has been completed.

As an example of our approach to the addition of new frames, consider the case of orbital debris diagnosis. The rationale for including orbital debris in the analysis of satellite anomalies is that debris is an ever increasing threat to spacecraft.[10] The effects of orbital debris on spacecraft range from minor erosion of surfaces to more severe mechanical damage or even breakup in the case of collisions with large objects. From a system design standpoint, it is useful to understand the cause of a mechanical breakup. For example, breakups can be caused by internal component ruptures or explosions of pressurized systems such as fuel, attitude control gases, or batteries. Design changes would be called for in these cases. However, design mitigation would not be appropriate for collisional breakups. Although orbital debris data bases offer some guidelines for assessing the probabilities of collisions for spacecraft, they do not offer any insight into a particular occurrence of a breakup. An expert system would be able to help the user interpret the available data bases in terms of the particular anomaly under study. Furthermore, it is possible to examine orbital data on the resulting fragments to specifically identify the cause of the breakup as being due to collision or explosion.

A common and useful data display for understanding satellite breakups is the Gabbard diagram.[10] The Gabbard diagram plots orbital data (specifically, the apogee and perigee altitudes vs the orbital period) for each of the trackable fragments

Table 1 Application of the sample rule set to two example breakups

Satellite	Exponential	Polynomial	Dispersion	Asymmetry	Order	Delta V	Cause
1981-53A	$b = 1.07$	$A1 = -0.064$	Yes	Yes	Yes	Yes	Collision[a]
1977-65B	$b = 4.13$	$A1 = -0.207$	Yes	No	No	No	Explosion[b]

[a]Confidence factor for satellite 1981-53A is 69%. [b]Confidence factor for satellite 1977-65B is 63%.

following a breakup. The distribution, symmetry, and scatter of the points can all be used in analysis of the event. These rules can be incorporated into a knowledge base which, when applied to actual data, can be used to assess the nature of a breakup.

A sample rule set (not yet verified within the context of an expert system) is shown in Fig. 8 (Ref. 10). This rule set is meant to discriminate between the breakup of a spacecraft caused by a collision or by an explosion. The quantities b and A_1 are parameters of a numerical fit to a Gabbard diagram.

A set of rules such as those shown in Fig. 8 can be added easily as a separate frame of the expert system. Similarly, rule sets for other causes, such as ionospheric scintillation or others, can be added as well. The individual rules would be addressed independently, and confidence factors for the cause of the breakup would be computed as discussed earlier. Table 1 shows example applications of this rule set to two breakups, one thought to be due to collision and the other to an explosion. Note that the cumulative confidence factors for the cause produces a suggestive result in each case.

Summary

The spacecraft environmental anomalies expert system has been developed and tested by The Aerospace Corporation, Space and Environment Technology Center. The system is a research system which aids in the analysis of satellite anomalies which may be caused by interactions with the space environment. Currently, the system deals with anomalies caused by electrostatic discharges resulting from surface or bulk charging, single-event upsets, total radiation dose, and space-plasma effects. It includes four data bases and a knowledge base consisting of about 200 rules. The system also contains software to access, display, and modify the data. Frames can be added easily to the expert system. It is anticipated that orbital debris and ionospheric scintillation are likely topics for treatment in future versions of this system. The expert system is now being tested at operational sites and is available on EnviroNET, a centralized computer-based information data base on natural and induced space environments.[12] (For information on EnviroNET contact the EnviroNET Office at the Goddard Space Flight Center.) Potential users of the system include space environment forecasters at the Air Force Space Forecast Center, civilian and military satellite operators, and spacecraft contractors.

Acknowledgments

This work was supported by the Aerospace Sponsored Research Program and by the U. S. Air Force Space and Missile Systems Center under Contract F04701-88-C-0089. We benefited greatly from technical discussions with J. H. Allen, G. Heckman, and D. Wilkinson at NOAA, M. Lauriente at NASA Goddard Spaceflight Center, and with J. Fennell, A. L. Vampola, and W. A. Kolasinski at The Aerospace Corporation. The spacecraft anomaly manager software used in our expert system is provided by the NOAA National Geophysical Data Center.

References

[1]Koons, H. C., and Gorney, D. J., "Spacecraft Environmental Anomalies Expert System," *Proceedings of the NASA Conference on Artificial Intelligence for Space Applications*, NASA CP-3013, 1988, pp. 457–467.

[2]Waterman, D. A., *A Guide to Expert Systems*, Addison-Wesley, New York, 1986, pp. 95–105.

[3]Robinson, P. A., "Spacecraft Environmental Anomalies Handbook," Air Force Geophysics Lab., AFGL-TR-89-0222, Hanscom AFB, MA, Aug. 1989.

[4]Fennell, J. F., Koons, H. C., Leung, M. S., and Mizera, P. F., "A Review of SCATHA Satellite Results: Charging and Discharging," European Space Agency, ESA-SP-198, Noordwijk, The Netherlands, Nov. 1983.

[5]Mullen, E. G., Gussenhoven, M. S., and Garret, H. B., "A Worst-Case Spacecraft Environment as Observed by SCATHA on 24 April 1979," Air Force Geophysics Lab., AFGL-TR-81-0231, Hanscom AFB, MA, July 1981.

[6]Mizera, P. F., and Boyd, G., "A Summary of Spacecraft Charging Results," *Journal of Spacecraft and Rockets*, Vol. 20, No. 5, 1983, pp. 438–443.

[7]Vampola, A. L., "Thick Dielectric Charging on High-Altitude Spacecraft," *Journal of Electrostatics*, Vol. 20, Jan. 1987, pp. 21–30.

[8]Wennaas, E. P., "Spacecraft Charging Effects by the High Energy Natural Environment," *IEEE Transactions on Nuclear Science*, Vol. NS-24, No. 6, 1977, pp. 2281–2284.

[9]Beers, B. L., "Radiation Induced Signals in Cables," *IEEE Transactions on Nuclear Science*, Vol. NS-24, No. 6, 1977, pp. 2429–2434.

[10]Johnson, N. L., and McNight, D. S., *Artificial Space Debris*, Orbit, Malabar, FL, 1987, pp. 38–52.

[11]Koons, H. C., and Gorney, D. J., "A Neural Network Model of the Relativistic Electron Flux at Geosynchronous Orbit," *Journal of Geophysical Research*, Vol. 96, No. A4, 1991, pp. 5549–5556.

[12]Vampola, A. L., Hall, W. N., and Lauriente, M., "EnviroNET: An Interactive Space Environment Information Resource," *Proceedings of the Conference on High-Energy Radiation Background in Space*, American Inst. of Physics, CP 186, Sanibel, FL, 1987.

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