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AN ON-LINE EXPERT SYSTEM FOR DIAGNOSING ENVIRONMENTALLY INDUCED SPACECRAFT ANOMALIES USING CLIPS

by

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ABSTRACT

A new rule-based, expert system for diagnosing spacecraft anomalies is under development. 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. 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 expert system not only provides scientists with needed risk analysis and confidence estimates not available in standard numerical models or databases but is also an effective learning tool. In addition, the architecture of the expert system allows easy additions to the knowledge base and the database. For example, new frames concerning orbital debris and ionospheric scintillation are being considered. The system currently runs on a MicroVAX and uses C Language Integrated Production System (CLIPS), an expert shell developed by the NASA Johnson Center AI Laboratory in Houston.

BACKGROUND

The Air Force (1) and NASA (2) jointly are designing a new rule-based, on-line expert system for diagnosing in-flight spacecraft anomalies. This system provides an effective method for saving knowledge and allows computers to sift through large amounts of data, homing in on significant information. Most importantly, it uses heuristics in addition to algorithms which allows approximate reasoning and inference, and the ability to attack problems not rigidly defined.

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 it is also an effective learning tool, and the window implementation makes it very easy to use. The system currently runs on a microVAX II at Goddard space Flight Center (GSFC). The inference engine used is NASA's C Language Integrated Production System (CLIPS) (3). 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 expert system is divided into frames, something most programmers would call "modules," and each frame relates to one of the causes of the satellite anomaly.

DESCRIPTION

The knowledge base consists of over two-hundred (200) rules and provides links to historical and environmental databases. Initially, recognized experts in the field were queried on how to diagnose anomalies. The "rules of thumb" they provided were formatted into logical rules. 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 version of the Space Environment Anomalies Expert system (SEAES) 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 data available. The architecture of SEAS is such that other causes could be added if a satisfactory rule base were developed. Some examples that have been considered are ionospheric scintillation (e.g., pertinent to commanding errors or telemetry link failures) and orbital debris (pertinent to mechanical breakups or damage). Rule bases and data bases are being compiled for each of these categories, and these new frames will be added to the SEAES after verification and testing has been completed. The system goes through a "decision tree" based on these rules in order to arrive at the likely cause of anomaly. The rule base includes the expert system rules that will be "fired" under control of the inference engine and 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.

NEW FRAMES

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 an analysis of satellite anomalies is that debris is an ever-increasing threat to spacecraft. 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, while design mitigation would not be appropriate for collisional breakups. While 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 debris 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(4), Figure 1. The Gabbard diagram plots an apogee and perigee height against its orbital period for each of the trackable fragments following breakup. In an elliptical orbit a Gabbard diagram will have two points: The apogee and perigee heights aligned above its orbital period. To denote apogee, "x" symbols are used and "+" symbols are used for perigee. In a circular orbit, the Gabbard diagram is a single point for each fragment. Figure 1, shows a Gabbard diagram, plotting the apogee and perigee heights versus orbital period for fragments following 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

Sample Gabbard Diagram

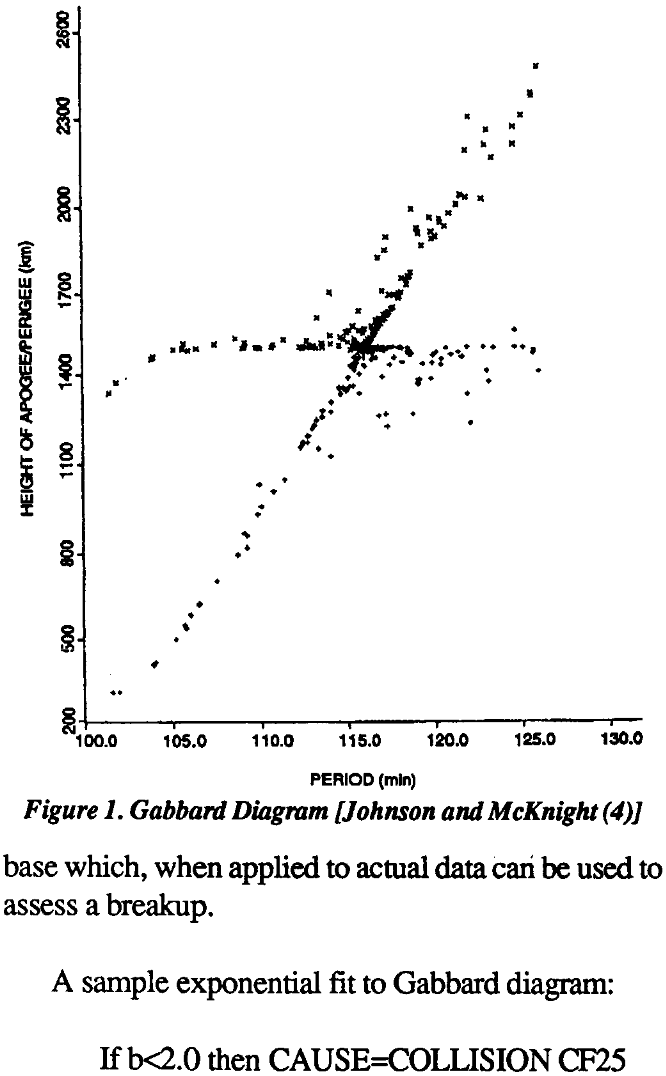

Figure 1. Gabbard Diagram [Johnson and McKnight (4)]

base which, when applied to actual data can be used to assess a breakup.

A sample 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.

A set of rules as these 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.

RESEARCH TOOL

The on-line feature was considered a natural communication tool for educating the users on this innovative venture. In addition, the opportunity was there for the users to feedback information to improve on the system. The key to advancement in this endeavor is communication between users. The user here is either a forecaster, a scientist, an engineer, an operator, or perhaps a contractor, who needs to know something about the effects of the environment on a satellite or a satellite subsystem, recognizing that they will have access to a variety of databases and knowledge. As of the present, we call it a "research system." That is a technical name for an expert system at a specific state of development beyond the prototype stage, where it has been shown to produce useful answers. It doesn't contain all the possible rules it could, but it is getting close to being ready for other people to start evaluating it. We are interested in granting accounts to users for the purpose of evaluation.

KNOWLEDGE BASE

Unlike its algorithmic predecessors, an expert system can be flexible in the way that it attacks complex problems. By virtue of its three basic parts (a knowledge base, a fact base, and a driver interface) an expert system 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. Figure 2 shows the expert system configuration.

The knowledge base, with its set of rules, is what makes a rule-based expert system unique. Best thought of as an independent collection of "if...then" statements, the rules are created by experts in their respective fields and reflect the current level of human experience, along with its uncertainties. Under the weight of these rules, and by the use of multi-field variables, an expert system

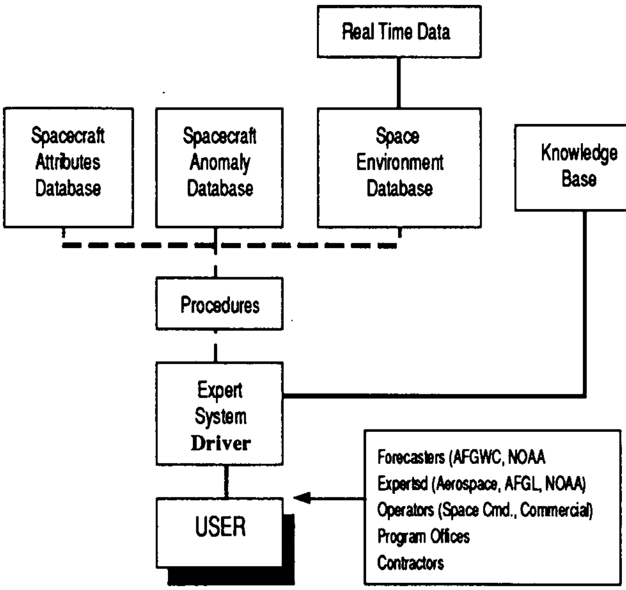

Figure 2. Expert System Configuration

can be said to "ponder the possibilities" presented by the databases and current knowledge which are too extensive to be readily assimilated by any single person. Rather than being limited to conclusions that must satisfy a set of tightly ordered mathematical statements, the system is free to offer suggestions, considerations, and likelihoods.

The rule format used in the expert system is shown in Figure 3. Each rule has a subject associated with it (in this case one of the four causes considered), a description of the rule, and then the actual rule itself. The rules also have what is termed a 'confidence factor' associated with the right hand side of each rule. Algorithms, which normal programs are limited to using, have a

```
    RULE201
    =======
      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_FLUX AND
               (ACCUM_FLUEN = HIGH OR ACCUM_FLUEN = VERY_HIGH ) )
      THEN :: (CAUSE = BULK_CHARGING CF 60)


    RULE110
    =======
      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 3. Rule Format

100% certainty to them, and are a subset of the general heuristic rules which the expert system uses.

This aspect of the rule-based expert system is very important in diagnosing anomalous behavior since much of the knowledge, rules and experience required to diagnose these anomalies have confidence factors associated with them. The use of such confidence factors in the expert system introduces the concept of 'risk assessment' to the diagnostic procedure and the inclusion of knowledge which otherwise would be lost, since it is, at the very least, extremely difficult to represent such knowledge using mathematical formulae.

VARIABLES

SEAES' use of variables is another area which makes this system unique, allowing it to handle non-algorithmic, equivocal problems. A variable in this system can take on one of three settings. It can be 'unset', meaning that it has not been input by the user and that no rule has been able to determine a value for it; it can be 'unknown' which means the user was prompted for the variable but did not know it; or it can have one or more 'values'. The unique aspects of the system are that not only can the expert system continue to execute when variables are unknown, but when variables do have values, each value has a confidence factor associated with it. Figure 4 shows examples of variable formats.

```
INCLINATION
===========
TRANSLATION :: (the inclination of the plane of the orbit with respect
                to the earth's equatorial plane )
PROMPT :: (Select the inclination of the satellite with respect to the
           earth's equatorial plane. )
TYPE :: SINGLEVALUED
EXPECT :: (EQUATORIAL LOW_INCLINATION HIGH_INCLINATION POLAR OTHER)
UPDATED-BY :: (RULE041 RULE133 RULE134 RULE135 RULE136 RULE132 RULE138
               RULE139 RULE140 RULE141 RULE142 RULE137 )
ANTECEDENT-BY :: (RULE026 RULE030)
USED-BY :: (RULE017 RULE016 RULE091 RULE089)
HELP :: ("Low inclination orbits are below 30 deg.  High
         inclination orbits are above 60 deg.  Polar orbits
         are above 80 deg.  Interplanetary orbits are undefined." )
CERTAINTY-FACTOR-RANGE :: UNKNOWN


LT_RECUR
========
TRANSLATION :: (the recurrence of an anomaly in a specific local-time
                sector. )
PROMPT :: ("Indicate the degree of certainty that you have that this
           type of anomaly has a strong tendency to recur in one local
           time sector, for example the nightside or the dayside of the
           earth?" )
TYPE :: YES/NO
USED-BY :: (RULE019 RULE020 RULE110 RULE054 RULE188 RULE189 RULE190
            RULE191 RULE192 RULE193 RULE194 RULE043 )
HELP :: (The anomaly should have occurred a few times (i.e. six or more)
        before you have confidence that the recurrence is related to a
        specific local-time sector.  Generally we are asking if the
        anomaly has a very strong tendency to occur within a 12 hour range
        in local time. )
CERTAINTY-FACTOR-RANGE :: POSITIVE
```

Figure 4. Variable Format

In the variable format, the translation and prompt string are self-explanatory. Each variable also has a type associated with it, either 'single-valued', 'multi-valued', or 'yes/no'. The 'expect' field is a list of the possible values for that variable which the user can select when and if he/she is prompted for that variable. The 'updated_by' field is a list of rules which are able to determine values for that variable, while the 'used_by' field contains rules which require this variable in order to fire. (It is possible that in order for a rule to fire, a variable must be 'unknown'). The 'help' field is the information displayed when the user presses the help key, requesting more information on the variable being prompted for. The 'certainty-factor-range' (CFR) is particular to this system, and can have a value of 'unknown', 'positive', or 'full'. The CFR being 'unknown' means that this is a possible input for that variable. If the CFR is 'positive', the user can input degrees of confidence from 0 to 100 for each of the inputted values for that variable. Finally, if the CFR is 'full' the user can input degrees of confidence from -100 to 100 which mean a range from being 100% certain the variable is not a specific value to being 100% certain that the variable is a specific value.

The confidence factors relay the confidence the user has in a certain value of the variable. This is very important since there is most likely information of which the user is not 100% sure. Such information is lost in normal programs. The combination of the confidence factors of variables and those of the rules propagates the confidence factors to other variables which are determined by these rules and ultimately to the cause of the anomaly.

Figure 5 shows an input screen for a single-valued variable (which assumes 100% confidence), and a CFR of 'unknown'. Figure 6 is an example of the input screen for a multi-valued variable with a 'positive' CFR. Notice how the variable in figure 6 can have more than one value, and each value has its own confidence factor associated with it.

FACT BASE

The fact base, a collection of informative sources related to the topic of interest, is the second basic part of an expert system. It can consist of as many separate data bases as may be deemed pertinent to solving the problem at hand. In the case of spacecraft anomalies, a fact base might contain information on the hardware currently in use, other active and past satellite systems, and historical data for orbital environments.

The database selection screen is shown in Figure 7, which shows the databases available for this system along with an example of the expert system help facility which is available for any variable. An important advantage obtained in using the expert system is that once it has been established which databases are available, the rules determine which information is pertinent, access the database for the relevant information and apply this information, (all of which is transparent to the user). Also, the database accessing is modular and easily expandable, thus if more databases need to be added,

```
SPACECRAFT ENVIRONMENTAL ANOMALIES

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

Use arrow key to position cursor, press ENTER to continue.
```

Figure 5. Satellite Selection

```
SPACECRAFT ENVIRONMENTAL ANOMALIES

Set your confidence level for all of the times that have been identified
for the recurrence of this specific anomaly.

        Yes
0---------- SATELLITE_SPIN_PERIOD
0|||------- DIURNAL
0---------- SOLAR_ROTATION
0||||||||-- SOLAR_CYCLE
0---------- SPRING/FALL
0---------- MAGNETICALLY_DISTURBED
0---------- OF_HIGH_PENETRATING_FLUX

Using arrow keys to position cursor, indicate certainty factors on all
lines that apply.  After making selections, press ENTER to continue.
```

Figure 6. Multi-valued input with confidence

only the selection screen needs to be changed, and the new rules added to the knowledge base. These capabilities free the user from sifting through large amounts of data and ensure that only pertinent information and all pertinent information is used in the diagnosis.

```
SPACECRAFT ENVIRONMENTAL ANOMALIES

Select all of the databases that are available for this system.

Yes                             HELP WINDOW
 X  ANOMALY    The ANOMALY database is the NOAA Satellite
 -  FLARE      Anomaly database from the National Geophysical
 X  KP         Data Center.  The FLARE database contains X
               class x-ray flares.  The KP database contains
               values of the planetary magnetic index, Kp,
               since 1932.

** End - press ENTER to continue.
```

Figure 7. Database selection screen

INTERFACE

The interface is one of the aspects which makes all expert systems different from one another. Since the expert shell, databases and knowledge base are independent and modular, the main purpose of the interface is to create a coordinating system which is not only user friendly, but also provides the necessary features to assist the user in understanding the system and the results.

The system's current interface driver translates forward chaining rules into a backward chaining sequence, prompting the user for information pertinent to the causes he/she wishes to consider. The main purpose of the driver is to maintain information regarding the variables which are being determined, the rules which can determine these variables, the status of the variables, and which rules can be fired.

Some variables are designated as initial variables or goal variables. The system first prompts the user for the initial variables. The driver then stacks the goal variables on the run time stack and searches the knowledge base for rules which determine (or 'update') these variables, and then puts them on the stack as well. The system focuses on those possibilities of high confidence and then assists the user by directing him/her to areas of consideration that directly affect the particular problem.

The goal (variable) in our system is the CAUSE of the anomaly, a multi-valued field variable with a 'full' CFR, since it can take on any number of the four possible causes where each cause has its own confidence factor associated with it ranging from -100 to 100.

If a variable on the left hand side of a stacked rule is unset, this variable becomes the current goal variable and is put on the stack, and the process continues. If a variable is on the stack and has not determined by any rules, or by the available database, and it has a prompt string, the user is prompted for it. This can be thought of as a transformation of the forward chaining rules in the knowledge base into a backward chaining variable sequence. Once a variable has a value, it is removed from the stack and the rules which use this variable are fired, discarded, or require the driver to put the next variable on that rule's left hand side onto the stack. The chaining process continues until the stack is empty.

Any rule on the stack that can be fired does so transparently to the user, where the confidence factors of the individual variables on its left hand side (LHS) are used for determining the confidence or validity of the entire LHS. When a rule fires, it executes the right hand side (RHS), and the confidence factor associated with its LHS is used in conjunction with the confidence factor of the rule to propagate the confidence to the RHS. This RHS execution can entail the setting of variables, the use of mathematical calculations, or the accessing of databases.

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. (See figure 8) 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.

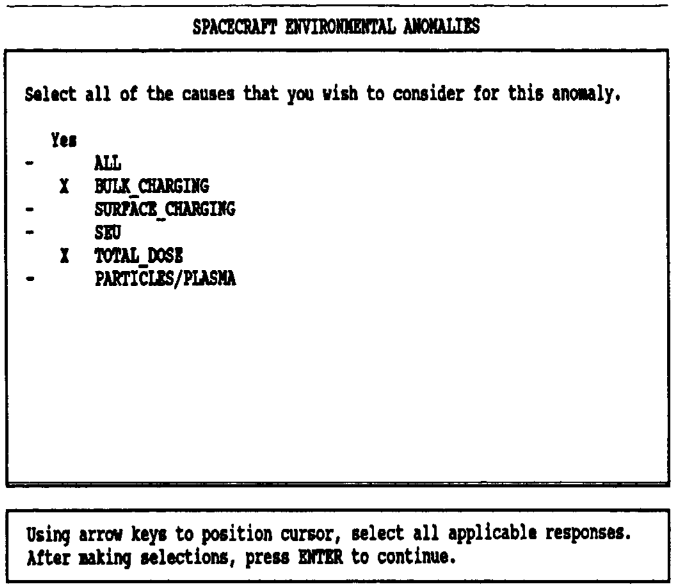

Figure 8. Causes selection screen

The ability to add intricate features and options is primarily due to the modularity of the system which the expert shell and expert system knowledge base concept itself provide. These features are the most impressive in demonstrating the capabilities of the EnviroNET expert system and its advantages over the usual, strictly mathematical, programming techniques.

The user interface also provides for accessing graphics. For example, if the user inputs that one of the databases available is Kp, the system will ask if he/she wishes to see the Kp historical graph for the time around which the anomaly occurred. If the input is 'yes', then a graph similar to the one shown in figure 9 will be displayed. (If ,however, the date is 'unset', then the system will first ask for it, and if the date is 'unknown' the system will ignore this line of questioning altogether.) This gives the user a much needed overall view of environmental information and conditions around the date in question.

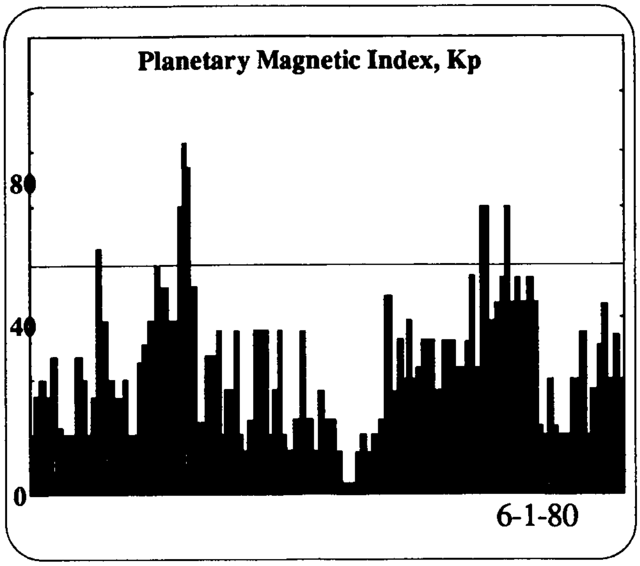

Figure 9. Kp Graph

UNIQUE FEATURES

Another feature which makes the expert system unique is its trace capability. The user can turn on the trace and send it to the screen or a file. The trace shows the rules as they are tested, variables as they are pushed onto the run time stack and determined, and searches of the databases. (See figure 10) This allows the user to understand what is happening at any step and see the

```
Setting  TOTAL_DOSE_TECHNOLOGY  =  AMORPHOUS_TTL  cf  100
Testing  RULE119
RULE119  FAILS
Testing  RULE128
RULE128  FAILS
Testing  RULE129
RULE129  FAILS
Testing  RULE131
Applying  RULE131
Setting  TOTAL_DOSE_THRESHOLD  =  1000000  cf  100
Testing  RULE120
Applying  RULE120
Setting  CAUSE  =  TOTAL_DOSE  cf  -86
old cf  -30
Mark_antec_rules_for  CAUSE  RULE027
Try_marked_antec_rules
Testing  RULE027

** More - press ENTER to continue.
```

Figure 10. Trace example

knowledge that is being used, thus giving the user confidence in the system. This type of capability is obviously not available in the purely algorithmic programs. Due to the amount of information the user could be prompted for and depending on the particular session, the user may want to review his/her inputs. This capability is available in the 'REVIEW' facility. This option also provides the user with a simple way of comparing different inputs of different sessions.

A feature which demonstrates a definite advantage of the rule-based expert system is what is called the 'WHY' option. Any time the system prompts the user for a variable, the user can ask the expert system why the system needs this variable. The system then uses its run time stack (a backward chaining stack) to follow and show the reasoning backward to the goal; that is, the cause of the anomaly. Figures 11-12 show an example of this. This is not only vital to understanding and

```
SPACECRAFT ENVIRONMENTAL ANOMALIES

Enter a value between 0 and 400 for the maximum value of the planetary

                                                          WHY WINDOW

the three hour planetary index Ap is needed to determine the level of
magnetic activity in the magnetosphere

RULE094
If   the three hour planetary index Ap is greater than 30,
Then it is definite (100%) that the level of magnetic activity in the
magnetosphere is DISTURBED.

** More - press ENTER to continue.
```

Figure 11. Backward reasoning

having confidence in the system, but it also is an important part of the expert system's use as a learning tool.

A final feature which sets the expert system apart is the 'HOW' command. As with all programs, the expert system is constantly determining variables by means other than the user inputting them, whether by the heuristics and algorithms in the rules or by extracting values from the databases. This command allows the users to, at any time, see what variables have been

```
SPACECRAFT ENVIRONMENTAL ANOMALIES

Enter a value between 0 and 400 for the maximum value of the planetary

                                                        WHY WINDOW

the level of magnetic activity in the magnetosphere is needed to
determine the cause of the anomaly

RULE021
If   the level of magnetic activity in the magnetosphere is QUIET,
Then there is suggestive evidence (50%) that the cause of the anomaly
is not BULK_CHARGING.

** More - press ENTER to continue.
```

Figure 12. Backward reasoning (con't.)

determined by means other than user input, their values, and which rules (or databases) were used to determine them. Figures 13-15 show an example of this feature. The user first selects which variables he/she wants to look at and then the system proceeds to show which rules determined them. Notice how it is possible for variables to be determined (or updated) by more than one rule. The user of course can choose any number of variables, though for this example only one variable, the cause of the anomaly, was selected. This feature not only gives the user complete control over the system, but allows him/her to see all the facts and knowledge that can be inferred from the inputs they have given, the available databases, and the expertise in the rules. As a final option, the user is also allowed, at any point, to exit from the program or begin a new session without ever leaving the program's window screen.

RESULTS

The diagnostic results are in the form of confidence factors derived from both the confidence assigned to rules by the experts and also the confidence of variables

```
SPACECRAFT ENVIRONMENTAL ANOMALIES
Select the term that best describes the radiation shielding of the circuit

                                                        HOW WINDOW
  Yes
 -   the number of the KP interval for the da  ::  (1 100 RULE097)
 -   the local time interval in which the ano  ::  (0-3 100 RULE097)
 -   inclination of the satellite as read fro  ::  (98.7 100 SATELLITE_
 -   the apogee of the satellite.............  ::  (826 100 SATELLITE_D
 -   the perigee of the satellite............  ::  (808 100 SATELLITE_D
 -   the date the satellite was launched.....  ::  (91786 100 SATELLITE
 X   the orbit of the satellite..............  ::  (DMSP 100 RULE181)
 -   The altitude of the satellite...........  ::  (LOW_ALTITUDE 100 RU
 -   the inclination of the plane of the orbi  ::  (HIGH_INCLINATION 10
 -   the level of magnetic activity in the ma  ::  (NORMAL 100 RULE004)
 X   the cause of the anomaly................  ::  (BULK_CHARGING -43..
 -   the Julian date.........................  ::  (2447237 100 RULE115

Select variable(s) using arrow keys - press ENTER to continue.
```

Figure 13. HOW facility

```
SPACECRAFT ENVIRONMENTAL ANOMALIES
Select the term that best describes the radiation shielding of the circuit
                                                        HOW WINDOW

*** also determined by:

RULE005
If   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.

** More - press ENTER to continue.
```

Figure 14. HOW facility (con't.)

```
SPACECRAFT ENVIRONMENTAL ANOMALIES

Select the term that best describes the radiation shielding of the circuit
                                                        HOW WINDOW

the orbit of the satellite is determined by:

RULE181
If   1) the perigee of the satellite is less than 900 but greater than
        or equal to 735, and
     2) the apogee of the satellite is less than 920 but greater than
        or equal to 750, and
     3) the inclination of the satellite as read from a Dbase III file
        is less than 110 but greater than or equal to 90,
Then it is definite (100%) that the orbit of the satellite is DMSP.

** More - press ENTER to continue.
```

Figure 15. HOW facility (con't.)

input by the user. Both the confidence in the rules/heuristics and the input of certainty factors by the user are needed to diagnose anomalies as they contain vital knowledge which can only be represented as such. The results window is shown in Figure 16.

The results window in our system includes, in addition to the cause(s) of the anomaly, the orbit of the satellite, whether input by the user or determined by rules, and a list of the causes considered in the diagnostics. The window can easily be modified to display any other information which is considered important. In the example, the cause of the anomaly was determined to be bulk charging with a confidence of 64%, and determined not to be total radiation dose with a confidence of 80%. The knowledge base does, of course, contain rules and formulae which can determine the cause of the anomaly with 100% confidence, or completely rule out a particular cause. For these situations the system will simply say that the cause, for example, is bulk charging or is not total dose.

The main concern with the system is the actual confidence and validity of the rules themselves. Since experts in any field are likely to disagree over certain areas, there may be rules to which other experts would apply slightly higher or lower degrees of confidence. This is certainly a consideration when using such a system, though it must be remembered that it is due to such a confidence/certainty question in the field that this type of expert system is needed. In general, as more quantitative environmental data becomes available in the immediate area of a spacecraft, we can apply the higher confidences to all of the system's rules. In addition, the features provided by the interface allow the user to see exactly what rules are being used so there is complete awareness and understanding of the formulae and knowledge being used.

An advantage of this particular system is that its interface is completely generic. Not only can the system run on many machines, the interface can be used in any field since the rules and knowledge base are completely independent of it. By substituting rules from another field, the system becomes an expert system for that field able to diagnose or solve problems towards which its tailored rules converge. In this sense the software is completely reusable.

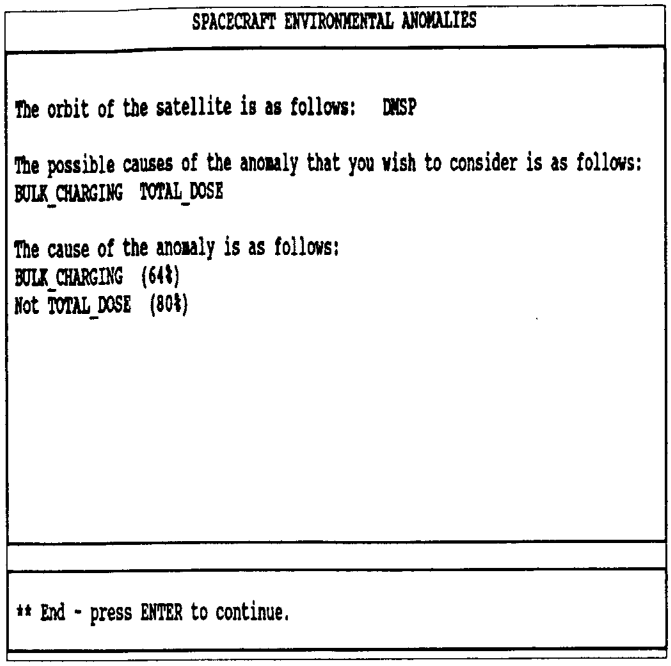

Figure 16. Results screen

FUTURE WORK

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.

For example, with X Windows the user could have one query window which prompts him/her for information, another separate window that displays which rules are being tested and fired, which variables are being searched for, and another window for graphics. With these multiple windows the user can see the entire system working at once and be freed from having to change windows to see system information.

CONCLUSION

SEAES 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 the conclusion 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 our ability to predict the environment before meaningful work can be done in forecasting satellite anomalies.

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