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AN EXPERT SYSTEM FOR DIAGNOSING ENVIRONMENTALLY INDUCED SPACECRAFT ANOMALIES

by

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ABSTRACT

We are designing a new rule-based, machine independent analytical tool for diagnosing spacecraft anomalies using an expert system. Expert systems provide an effective method for saving knowledge, allow computers to sift through large amounts of data pinpointing significant parts, and most importantly, use heuristics in addition to algorithms, which allow approximate reasoning and inference and the ability to attack problems not rigidly defined.

The knowledge base consists of over two-hundred (200) rules and provides links to historical and environmental databases. The 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 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 algorithmic programs, but 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).

BACKGROUND

This joint project to develop an expert system for diagnosing environmentally induced spacecraft anomalies owes its origin to the observation by the Air Force that spacecraft anomalies were often environmentally induced. It was a common occurrence then to receive calls on problems with satellite anomalies. The expert system was initiated as a research project that could be used by program offices and contractors to eliminate the flood of calls which were becoming a nuisance. The objective was to develop a classic diagnostic tool for trying to determine, once an anomaly has occurred, whether it was caused by the environment. Hopefully this information will be useful to the design of spacecraft, so that in the future, systems will be built having increased immunity to the hostile space environment.

Historically, the Air Force has supported NASA's EnviroNET (1), so its on-line feature was considered a "natural" as a communication tool for educating its users about this innovative venture. In addition, an opportunity existed for users to feed back information that might 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. A special session on environmentally induced spacecraft anomalies chaired jointly by the Air Force and NASA at the 1990 AIAA meeting in Reno (2) brought to focus the issues of concern.

INITIAL WORK: METHODOLOGY

This research tool was originally developed by the Aerospace Corporation for a PC using a Texas Instrument commercial expert shell (3). It was then handed off to EnviroNET to develop a program to port the system to the EnviroNET central computer, which is accessible through most of the popular networks. The inference engine used is NASA's C Language Integrated Production System: CLIPS (4). 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.

Initially, recognized experts in the field were queried on how to diagnose anomalies; these "rules of thumb" were formatted into logical rules. The expert system rules involve four main types of environmental anomalies: bulk charging, surface charging, single event upsets (SEU), and total radiation dose. It should be recognized that the expert system as a tool can be expanded to include other causes of anomalies, even non-environmentally induced anomalies.

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. By applying various rules in its knowledge base, the system accesses databases, queries the user as appropriate, and arrives at a conclusion. The system output was verified by referring to historical case studies and historical data.

EXPERT RULES

The EnviroNET expert system knowledge base currently contains over two hundred (200) rules. The system goes through a varying "decision tree" based on these rules and user input in order to arrive at the likely cause of an anomaly. The rule base includes the expert system rules in a defined "if-then" format that will be "fired" under the control of the inference engine. 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 needs to be assimilated with previous anomalies data and environmental conditions, while addressing the specific circumstances of individual users.

Seldom are the environmental problems encountered by scientists rigidly defined, and thus they lack clear mathematical solutions. Under such circumstances, algorithmic programs are too limited by their sequential logic, becoming too cumbersome when trying to consider a wide range of variables of varying degrees of certainty.

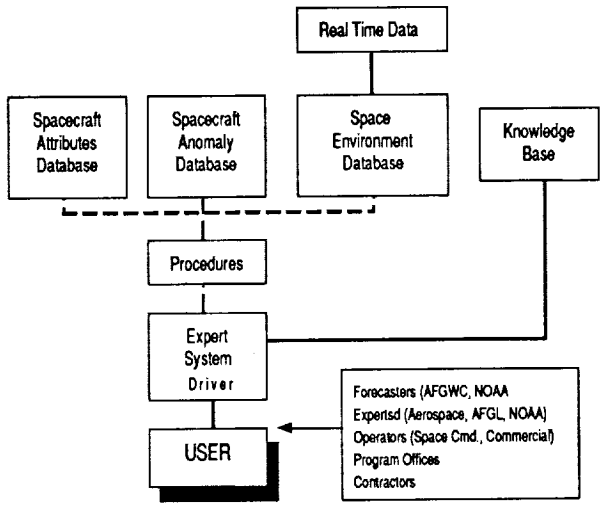

Figure 1. Expert System Configuration

EnviroNET's Expert System is being developed as an Artificial Intelligence (AI) technique to cope with this voluminous data and fluidity associated with spacecraft/environment causality models.

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), 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 1 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 can be said to "ponder the possibilities" presented by a compendium of data and knowledge 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.

```
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 2. Rule Format

```
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 3. Variable Format

The rule format used in the expert system is shown in Figure 2. 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 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.

Another advantage of using a rule-based system is that it allows direct access to and easy comprehension of the knowledge and expertise used to diagnose the anomalies as opposed to the very complicated, and sometimes esoteric coding of most normal programs. Not only does this provide a way of storing the knowledge, it also allows the system to be easily and quickly updated. These updates are accomplished by simply adding, deleting or modifying rules to which the system then automatically adjusts.

VARIABLES

The EnviroNET expert system's 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 3 shows examples of variable formats.

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 entered values for that variable. Finally, if the CFR is '*full,*' the user can input degrees of confidence from -100 to 100, which means a range from

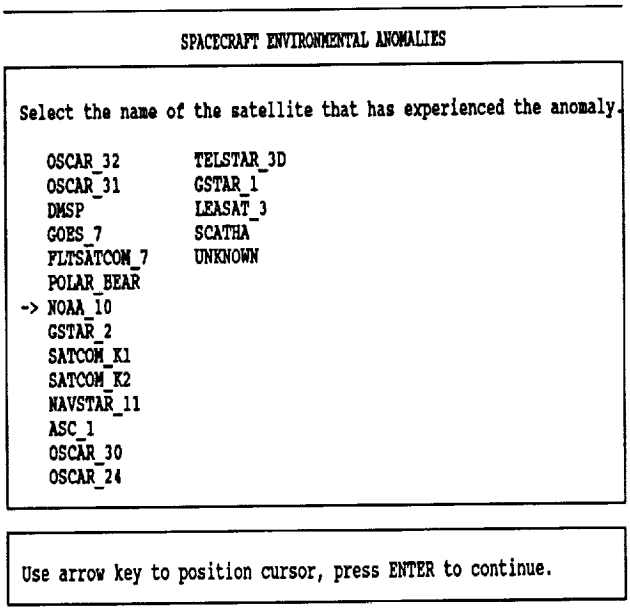

Figure 4. Satellite Selection

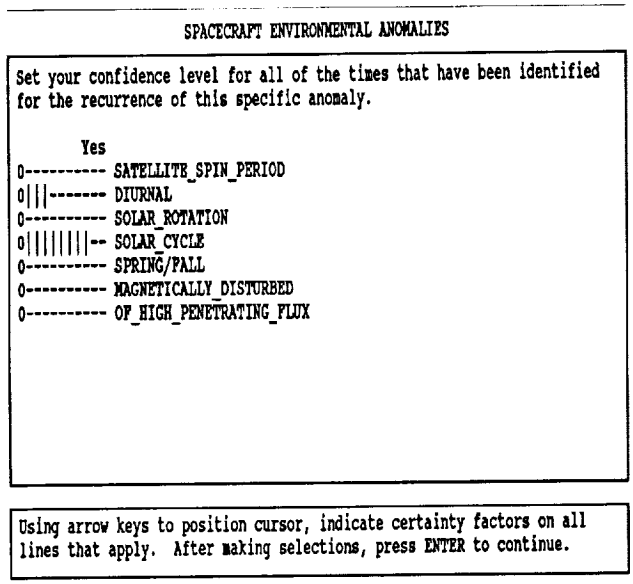

Figure 5. Multi-valued input with confidence

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 4 shows an input screen for a single-valued

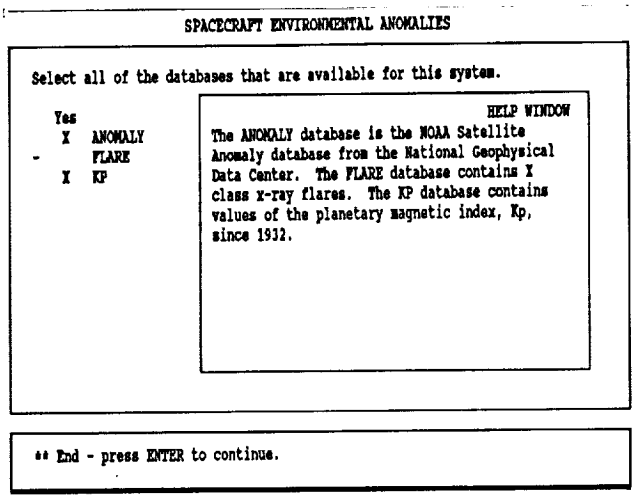

Figure 6. Database selection screen

variable which assumes 100% confidence and a CFR of '*unknown*.' Formats like this figure are examples of the user friendly interface that was designed and are intended to portray a snapshot image of what the user sees.

Figure 5 is an example of the input screen for a multi-valued variable with a '*positive*' CFR. Notice how the variable in Figure 5 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 integral 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 screen is shown in Figure 6, 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, 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.

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 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 been determined by any rules nor 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.

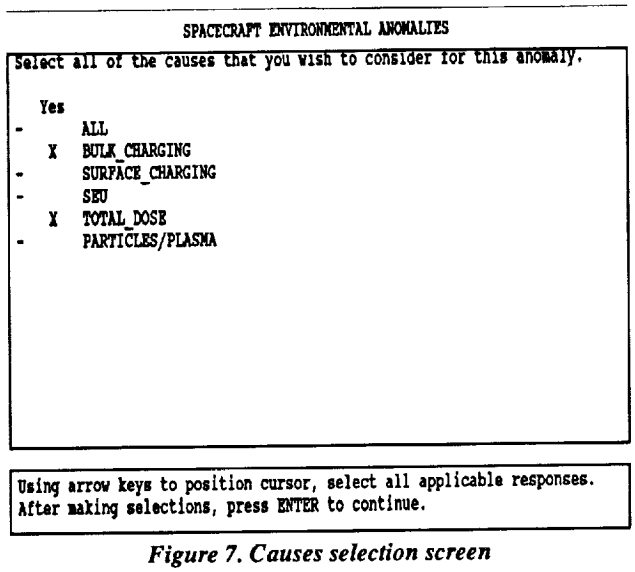

Figure 7. Causes selection screen

The user is also given the option of selecting which causes are to be considered. (See Figure 7.) 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.

UNIQUE FEATURES

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 when demonstrating the capabilities of the EnviroNET expert system and its advantages over the usual, strictly mathematical programming techniques.

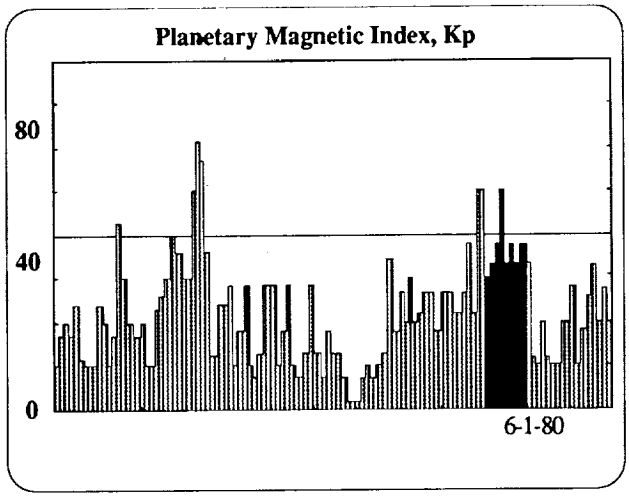

Figure 8. Kp Graph

SPACECRAFT ENVIRONMENTAL ANOMALIES

```
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 9. Trace example

The user interface 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 8 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.

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 runtime stack and determined, and searches of the databases (see Figure 9).

This allows the user to understand what is happening at any step and see the knowledge that is being used, thus giving the user confidence in the system. This type of capability is obviously not available in 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.

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 10. Backward reasoning

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 11. Backward reasoning (con't.)

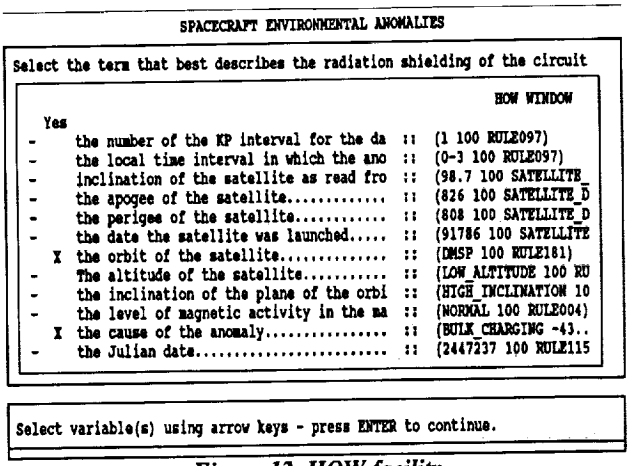

Figure 12. HOW facility

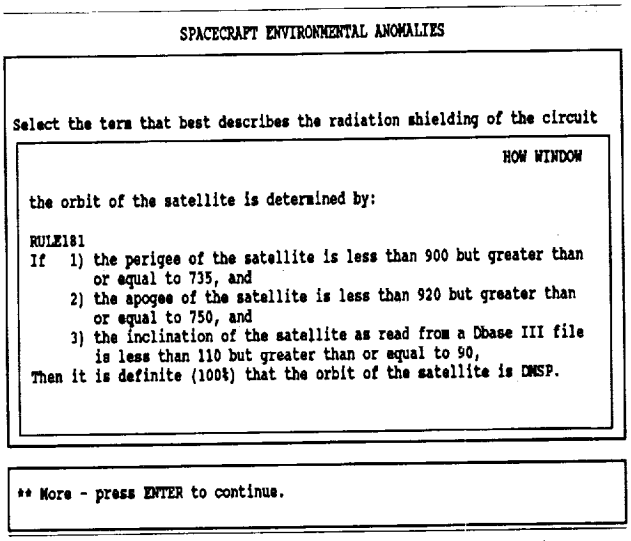

Figure 13. HOW facility (con't.)

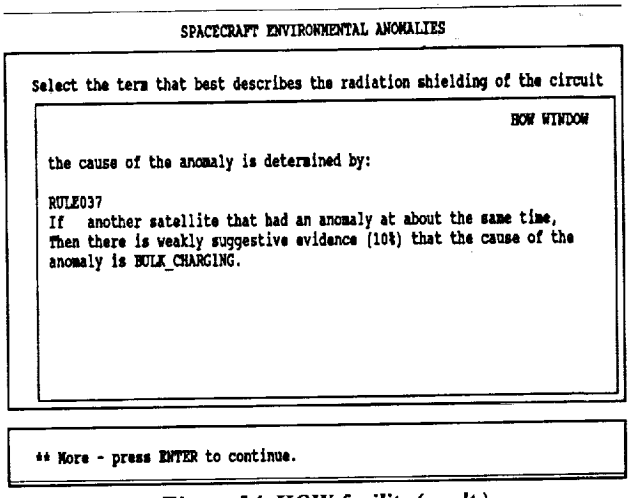

Figure 14. HOW facility (con't.)

A feature which demonstrates a definite advantage of the rule-based expert system is 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 10 and 11 show an example of this. This is not only vital to understanding and having confidence in the system, but it is also 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 determined by means other than user input, their values, and which rules (or databases) were used to determine them. Figures 12 through14 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 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 15 (see next page).

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

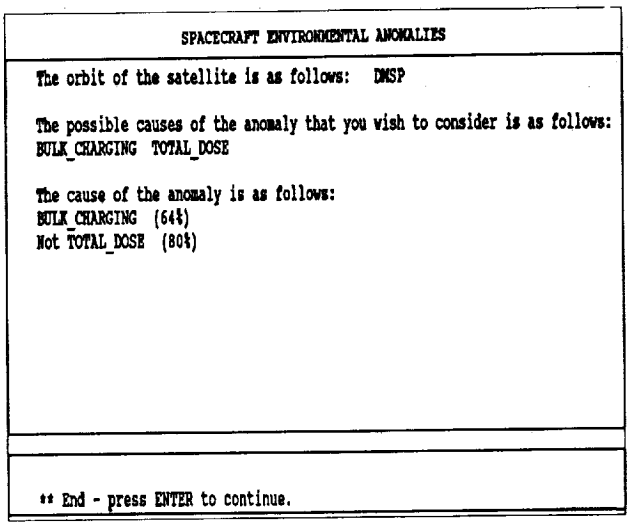

Figure 15. Results screen

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 become 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.

FUTURE WORK

We are improving our EnviroNET network with the addition of an IBM RS/6000. Because the inference engine is machine independent and the remaining code is written almost entirely in C, the porting of the system to this UNIX machine will be quite simple. 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:

The EnviroNET expert system 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 our ability to predict the environment before meaningful work can be done in forecasting satellite anomalies.

ACKNOWLEDGMENTS

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