Predicting Failures and Estimating Duration of Service Life from Satellite Telemetry

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Abstract. This paper addresses research completed for predicting hardware failures and estimating remaining duration of service life for satellite components using a Failure Prediction Process (FPP) as envisioned by the University of California Berkeley, Center for Extreme Ultraviolet Astrophysics (CEA). It is a joint paper, presenting initial work completed at the CEA using telemetry from the EUV EXPLORER (EUVE) satellite and statistical computation analysis completed by Lockheed Martin. This work was used in identifying suspect "failure precursors" and is followed by a Lockheed Martin exploration into the application of statistical pattern recognition methods to identify FPP events observed visually by the human expert. Both visual and statistical methods were successful in detecting suspect failure precursors. From experience, an estimate for remaining service life for each unit was developed and compared with the actual time the equipment remained operable.

We assumed that telemetered data from electrical and electro-mechanical components have unique signatures for normal operational behavior. Changes, however brief, in that normal behavior could be interpreted as indicators (precursors) of degradation, which could, in some predictable time span, lead to component failure. The indicators of interest in this research occurred within normal operating behavior and are not detectable by limit-checking schemes. The long-term objective of this research is to develop a resident software module which can provide information on FPP events automatically, economically, and with high reliability for long-term management of spacecraft and ground equipment. Based on the detection of an FPP event, an estimate of remaining service life for the unit can be calculated and used as a basis to manage the failure.

Part 1 by L. Losik, L-3 Communications Telemetry & Instrumentation

EUVE Science Payload

The U.C. Berkeley Center for EUVE Astrophysics is responsible for operating NASA's EUVE science payload. EUVE telemetry is received by Tracking and Data Relay System (TDRS) satellites and is forwarded to the CEA in Berkeley using NASA communications systems. The EUVE satellite was launched successfully on June 7, 1992 on a DELTA II launch vehicle. The EUVE primary mission was completed in 1994, at which time the EUVE scientific and engineering community proposed ideas to extend the mission.

One idea proposed to utilize the EUVE satellite as a testbed for providing critical flight experience to technologies that would lower satellite mission costs. Members of NASA's science team approved and participated in this activity and named the project the EUVE Testbed program[1]. The CEA collaborated with the NASA Ames Research Center, the Jet Propulsion Laboratory, and Goddard Space Flight Center (GSFC) in selecting projects that would have low investment costs and significant project cost reductions. It was hoped that successful projects developed on EUVE could be used on other NASA, military, and commercial space programs.

Another project proposed to validate suspect failure precursors occurring prior to a hardware failure. The EUVE satellite was experiencing failures that threatened to end the extended mission. If a failure precursor could be identified for single thread hardware, it was hoped that an impending failure could be "managed" to prolong the mission instead of bringing the mission to an end.

Introduction to the "Failure Prediction Process"

The engineering staff began using telemetry analysis techniques developed and used on the Air Force GPS Block I program[2]. Author Losik had participated in Air Force satellite system telemetry behavior and payload performance comparison activities and studies on GPS Block I between 1978 and 1984. It was his intent to augment many of the same analysis techniques used there, modify them, and add to them his experience with unit- and spacecraft-level test for identifying suspect failure precursors in EUVE telemetry. Table 1 is a comparison between GPS and EUVE factors related to the failure precursor study. The comparison is provided to identify the similarities and differences between GPS satellites and the EUVE satellite on which this work is based.

Table 1. Comparison Between GPS and EUVE Factors Related to the FPP

Parameter	Air Force (GPS Block I)	NASA's EUVE/EP
Orbit Altitude	10,900 nmi	275 nmi
Orbit Period	12 hours	1.5 hours
Orbit Inclination	63 degrees	28.5 degrees
Orbit Shape	circular	circular
Nodal Regression	0.03 deg./day	6.6 deg./day
Telemetry Collected	10 min. in 6 hrs.	99.9%
BB Modulation Type	PCM	PCM
Power Bus Voltage	28V, regulated	28V, regulated
Monitors per Satellite	3600	370
Satellite Weight[1]	1744 lb	4,000 lb
Satellite Power	500 watts	3,000 watts
Mission Life	4 years	10 years

Two significant characteristics of the EUVE satellite and mission made it an excellent platform to validate the existence of failure precursors: 1.) almost 100% of all EUVE telemetry is received and archived, and 2.) the Explorer Platform was designed so that redundant units remain powered along with the primary unit. These characteristics provided two and sometimes four independent telemetry streams for analysis. Examples of redundant equipment that operate simultaneously with the primary unit include two telemetry transmitters, three rate gyros, four reaction wheels, two star trackers, three batteries, and two tape recorders with four independent transporter units used in series. The flight hardware failures included in this paper[4] relate to equipment from these groups.

A partial history of the EUVE satellite hardware failures relevant to this paper consists of: 1.) Gyro B current monitor fluctuations beginning on January 29, 1992 and a corresponding gyro erratic rate output reported by GSFC Flight Dynamics Facility personnel approximately four months later, 2.) Transmitter B failure on April 2, 1994, and 3.) tape recorder B malfunction on June 26, 1994.

The recorder malfunction was cleared temporarily and the unit was operated without incident until September 1994 when transporter unit #1 failed completely. Three months later, in December 1994, the redundant tape recorder unit A, transporter unit #1, failed also.

The Failure Prediction Process

Software was created at the CEA that automated EUVE telemetry decommutation and extraction of monitor values at the desired quantity and location around the EUVE satellite orbit. This data was sent to separate files for importing to a commercial plotting tool called MATLAB used to identify suspect failure precursors. MATLAB displayed the processed telemetry in a format suitable for visually detecting suspect failure precursors.

The process of selecting specific data samples, measuring the duration between samples, extracting data, identifying specific data display requirements, and evaluating data is known as the Failure Prediction Process (FPP). Anomalous patterns are identified as suspect failure precursors and are known as FPP events. Telemetry that has been converted into engineering units and then displayed with MATLAB has proven far more effective in identifying FPP events than analyzing unconverted telemetry data.

Background

Satellite equipment goes through extensive testing[3] during design, manufacturing, integration, and test activities to ensure that, when in orbit, the satellite will meet performance and lifetime operating requirements. Telemetry monitors are provided so that equipment operational performance and on/off status can be easily determined during factory test and on-orbit operations. Additional monitors and their information are often used during factory test to provide design engineers with information for determining proper equipment design and performance. Often, these special test monitors are disconnected or not included, are not available from the telemetry system on orbit, and are not provided in the telemetry for control centers. Specific monitors may also not be used when information from other existing monitors can be combined. Some key measurements needed in control centers are made by combining provided monitors. Examples include spacecraft angular momentum, electrical spacecraft load power being consumed, and remaining battery capacity.

The Explorer Platform was designed to operate for ten years. NASA's plan for EUVE was to have on-board equipment removed and replaced by astronauts several times over the mission life. The GPS Block I satellite used as a basis for comparing with EUVE was to be discarded after test data validated navigation system performance. Table 2 is a comparison of EUVE and GPS Block I satellite hardware failures per subsystem for the EUVE and one GPS satellite, and 2,500 other satellite failures occurring between 1962 and 1983. GPS Block I satellite, FSV-7, was selected from nine other Block I satellites for comparison because of the number of hardware failures it sustained and the different subsystems the equipment failures occurred on.

Table 2. Comparison of On-Orbit Failures per Mission

Satellite Subsystem	(Hecht, 1985)[3] %	EUVE[4] %	GPS (FSV-7)[2] %
TT&C	25	20	25
Guidance and Navigation	14	20	50
Electrical Power	13	0	0
Data Systems	9	20	N/A
Thermal Control	6	0	0
Propulsion	4	N/A	0
Structures	4	0	0
Spacecraft Bus Subtotal	**75**	**60**	**75**
Visual/IR Sensors	13	0	0
Communications Payload	5	0	0
Special Payloads	4	40	0
Navigations Payload	3	0	25
Payload Subtotal	**25**	**40**	**25**

Benefits to Predicting Hardware Failures

Popular methods of identifying hardware problems include using "limits" for analog monitors, configuring confirmation of status indicators, and confirming/determining the functional performance of the equipment. Limits for analog monitors tend to be extremely broad and developed from equipment acceptance (AT) and qualification (QT) factory testing taken from design and procurement specifications. "Normal" operating range limits can be used to track trends, but predicting future peak-to-peak behavior is unreliable. "Status" checking is done on discrete measurements (looking for improper bit values — examples include on/off, hi/low, A/B, normal/straight-through). Status is also determined functionally in the event status indicators are not provided (example: if the RF signal is being received by the ground station, then the transmitter is operating).

It can be demonstrated that suspect failure precursors occur well within the normal operating range of analog measurements. The ability to identify these hardware failure precursors in analog measurements offers the following key advantages:

- Reduction and possible elimination of flight hardware ground test
- Visibility into future failures during ground test
- Prediction of "infant mortality" failures before launch so that the units can be exchanged out on the ground
- Reduction or elimination of the number of personnel and facility resources necessary to resolve problems/anomalies in control centers
- Lower skilled personnel to monitor and control equipment while increasing system reliability
- Managing failures (possibly eliminating some) and extending the useful life of remaining equipment
- High level of reliability to man-intensive activities and elimination of expert personnel
- Reduction of redundant on-board equipment
- Filtering unnecessary telemetry for analysis and archiving

Estimating Remaining Service Life

Remaining service life estimates were provided based on past failure analysis activities that Mr. Losik participated in. The estimates were made after the first or initial suspect failure precursor was identified. From the author Losik's experience, once a small or large change in telemetry behavior is identified, no more than six months of operational life is expected to remain on the unit (a failure being defined as an out-of-spec condition). If it is not known whether the very first suspect failure precursor has been "caught," then the six-month duration is shortened. However, the estimate for remaining life would not be greater than six months.

The six-month duration can be refined by compiling large numbers of failures. Flight hardware vendors keep their equipment failure history proprietary, and so compiling large data sets consisting of any one supplier's equipment failure history is not feasible. The results of the U.C. Berkeley research included one failure that the remaining-service-life estimate was longer than predicted. The estimate was for six months, but the unit operated for nine months (see summary Table 3).

Results Using the FPP on EUVE Platform Failed Hardware

Both Transmitter A and B telemetry was analyzed. Transmitter A telemetry showed no suspect failure precursors. Transmitter B FPP-processed telemetry showed a suspect failure precursor present in early December 1993. This was approximately four months prior to complete Transmitter B failure. The duration over which the suspect failure precursor can be observed in the MATLAB output was approximately 20 days. The suspect failure precursor was observable in the Forward RF Power monitor only; however, the unit's temperature monitors recorded values of 50°C for almost ten consecutive days during the suspect failure precursor event.

After results were obtained by the FPP at the CEA on Transmitter B, the Engineering Statistical Analysis Group at the Lockheed Martin Advanced Technology Center in Palo Alto, California, was contacted to discuss the results and determine their interest and capability in developing software that could replicate the FPP visual evaluation of suspect failure precursors. Lockheed Martin agreed to analyze Transmitter B telemetry using standard industry statistical techniques and proprietary statistical pattern recognition analysis tools. Their results demonstrated that suspect failure precursors behaved very differently from normal telemetry, and that FPP events could be isolated and identified using their approach.

Figure 1 contains a set of FPP graphics for Transmitter B Forward RF Power, which illustrates suspect failure precursor events in the data stream. Transmitter A shows no failure precursors.

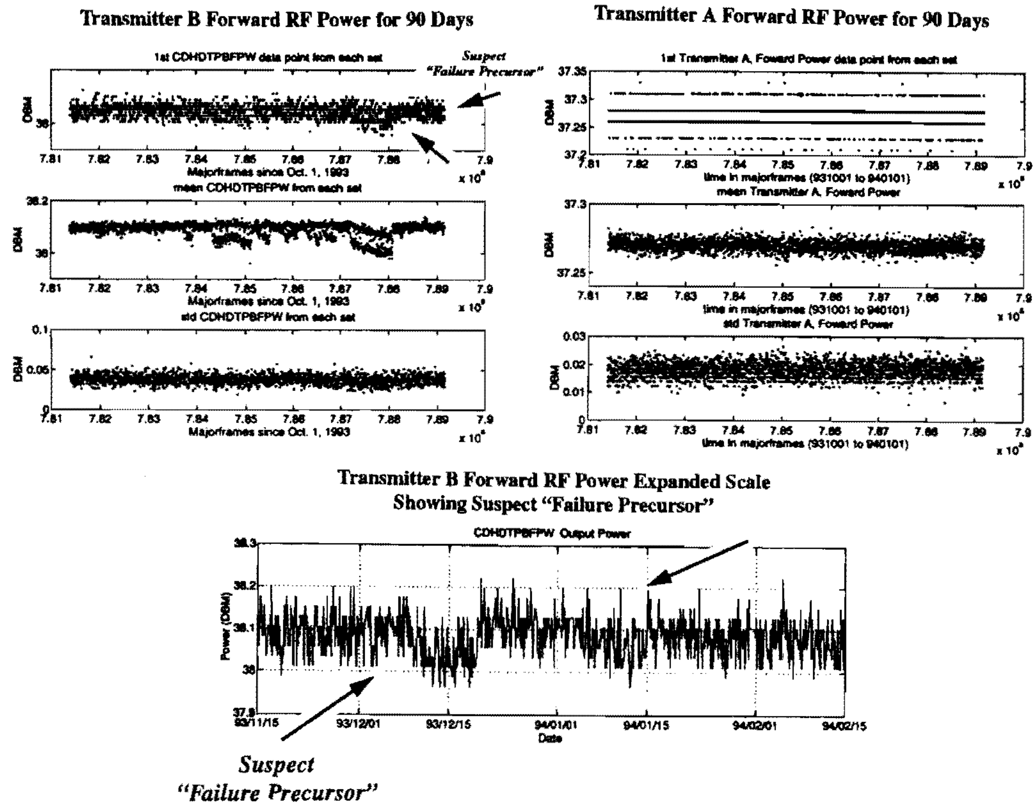

Figure 1. EUVE Transmitter A and B Forward RF Power FPP Plots

Table 3 shows the EUVE hardware and telemetry analyzed by the FPP and the results for failed Explorer hardware. Lockheed Martin analysis applied only to Transmitter B. The analysis using the FPP uncovered a surprise gyro anomaly that was under investigation by another satellite mission. Gyro C performance data was in use, and the EUVE satellite integrator was duly advised.

Table 3. **Summary of All Results from FPP Analysis on Failed Explorer Platform Hardware**

EUVE Failures Analyzed with FPP	FPP Event Expected?	FPP Event Shown?	Date of FPP Event	Date of Hardware Failure	Time Between Suspect Failure Precursor and Failure	Estimate for Remaining Service Life	FPP % Accuracy to Date
Xmtr. A	No	No	None	None	None	> 6 months	100%
Xmtr. B	Yes	Yes	12/93	4/94	4.5 months	< 6 months	100%
GYRO A	No	No	N/A	N/A	N/A	> 6 months	100%
GYRO B	Yes	Yes	1/93	Unknown	Unknown	< 6 months	100%
GYRO C	No	Yes	6/92	----------	-------------	> 6 months	100%
T/R A	Yes	Yes	3/94	12/94	9 months	< 6 months	100%
T/R B	Yes	Yes	4/94	9/94	5 months	< 6 months	100%

Part 2 by S. Wahl and L. Owen, Lockheed Martin Advanced Technology Center

Introduction

After reviewing the research by the U.C. Berkeley, CEA on the Failure Prediction Process (FPP), the Lockheed Martin Advanced Technology Center authors proposed to explore a unique methodology for detecting FPP events using statistical pattern recognition analysis. Their intent was to determine if the statistical approach could detect the FPP events found visually by the author Losik. For the data provided, the statistical analysis not only detected the FPP events identified by the CEA approach, but also isolated additional behavior patterns, which when reviewed by author Losik, were also determined to be suspect failure precursors. Following are the methodology and results of that exploration.

Statistical Approach

Standard univariate descriptive statistics were employed to determine the characteristics of the five variables in the data sample. Extreme outliers, high and low, were identified. Each variable was plotted versus time, using an expanded X-axis scale from the high-density plots produced by the CEA for detailed visual examination and pattern detection. This exercise was done to familiarize the Lockheed Martin team with the nature of the data and to understand the nature of the patterns identified as FPP events by author Losik. A subset of the data, containing both normal operating conditions and outliers, was then examined using Lockheed Martin-developed software known as RECOGNIZE.

RECOGNIZE is a statistical pattern recognition analysis program that was developed to support aerospace engineering and manufacturing problem investigations. The program is a collection of statistical tools that includes Fisher Linear Discriminant Analysis, non-linear mapping, 2-D plotting, Nearest Neighbor identification, and a 2-class frequency histogram.

The primary use of RECOGNIZE is to create a 2-class multivariate statistical model for use in identifying and quantifying contributors to a problem. The model isolates those variables that are the distinctions between acceptable and non-acceptable performance in a tested population (learning set), and then classifies untested objects in terms of probability of success. Another application is to create zero-time models based on product manufacturing variables for the purpose of a baseline in product service-life studies. RECOGNIZE was used to create multivariate "windows-in-time" for the FPP project. It is the first application of the program to telemetry analysis.

Windows-in-Time Vectors

Statistical pattern recognition vectors, composed of spacecraft component status variables measured from the telemetry stream, were computed for selected time segments. Figure 2 shows a typical telemetry stream for a set of payload transmitter variables similar to the variables data available on EUVE Transmitter B. These vectors provide windows-in-time that represent the state of health of spacecraft components.

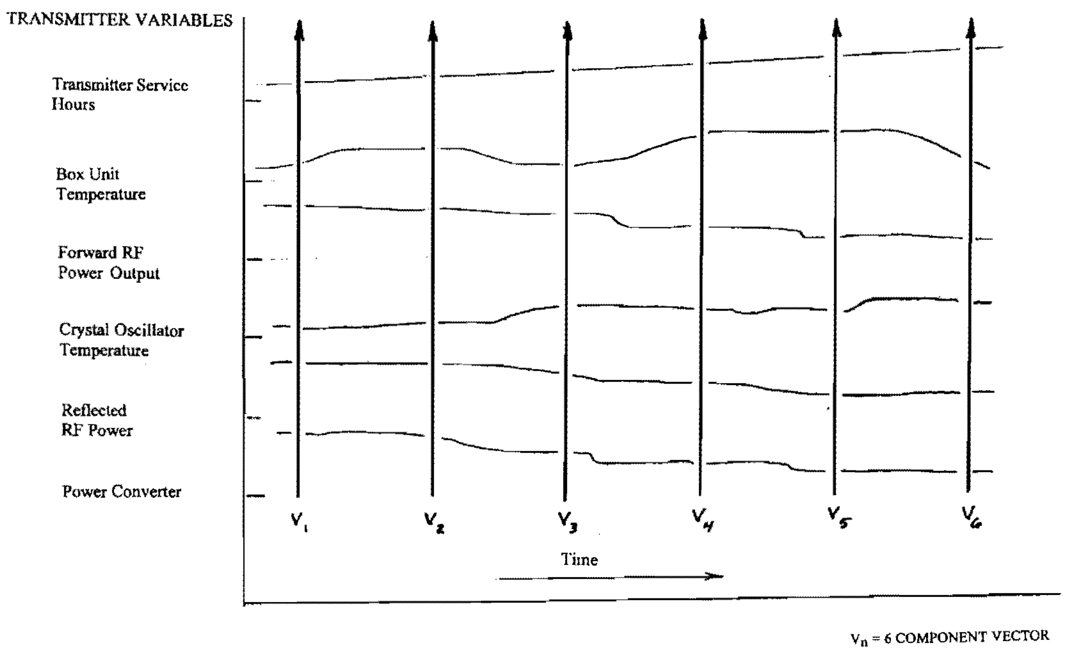

Figure 2. Concept of Windows-in-Time for Spacecraft Component State-of-Health Status

The computer vectors are projected into higher-dimensional space, and subsequently projected to a 2-dimensional plot for visual analysis. Six vectors project to 6-dimensional space. When plotted on a nonlinear map, the location of the computed vectors establishes regions of normal component behavior and regions of probable component failure. From this analysis, the time course to probable component failure is understood. Figure 3 is a conceptual nonlinear map showing plotted vectors related to transmitter operation. The vector points are periodically plotted and represent a state-of-health index for the transmitter.

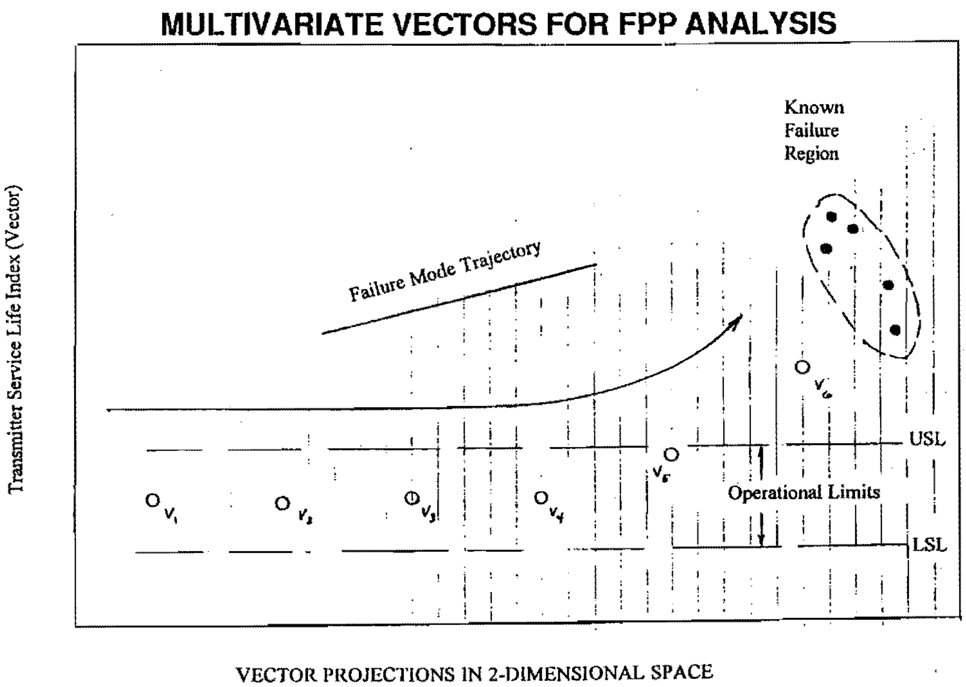

Figure 3. Conceptual Nonlinear Map: Normal Transmitter Vectors Degrading to Failure

"Operational limits" refers to a predetermined operational band that represents the vector limits for normal operation. The operational limits and the vectors for known operational failures need to be established for actual spacecraft components. Evaluation of similar components from multiple spacecraft are required to determine if there are common normal operational limits for specific components from the same vendor used on similar spacecraft.

Transmitter B Analysis

Data was sampled from the EUVE satellite from September 1993 to April 1994, when Transmitter B failed. The CEA data, shown in Figure 1, is based on the first data point from each major frame in the selected data set. Data used in the Lockheed Martin Advanced Technology Center exploration was the mean and standard deviation of each major frame from the same data set. (A major frame is defined as the data from a 45-minute sample; Reference 5 further defines the sampling method used.)

Figure 4, containing a set of univariate plots from the same sample time period, shows an example of a suspect FPP event, as identified by author Losik. This event, not detected on the original CEA plots, shows an upward mean shift for an isolated period of time. This pattern occurred within the specified operating parameters and would not have been flagged by conventional specification limits monitoring.

For ease of viewing, a subset of the means data sample from EUVE Transmitter B was created spanning the entire data period. As shown in Figure 5, extreme outliers were included and vectors were generated using four of the five variables available. Two of the variables in the data set were highly correlated; only one was selected for the windows-in-time vector.

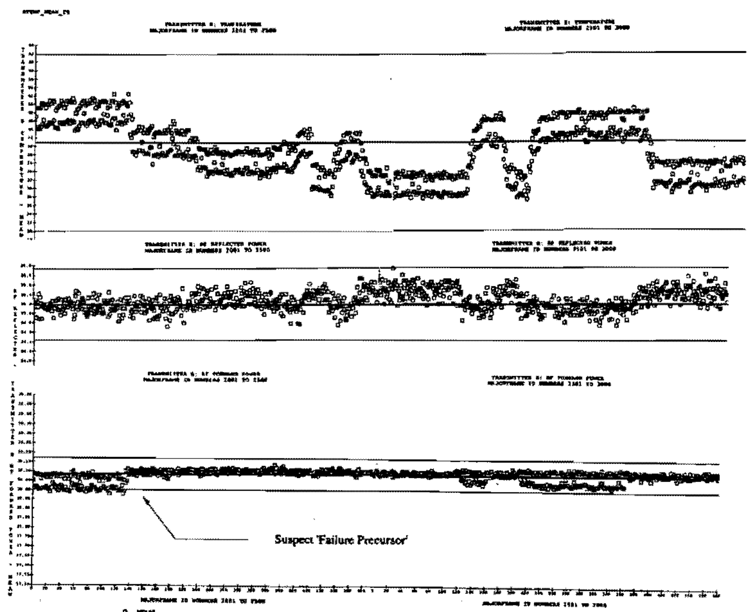

Figure 4. EUVE Transmitter B Variables Showing a Pattern Identified as an FPP Event

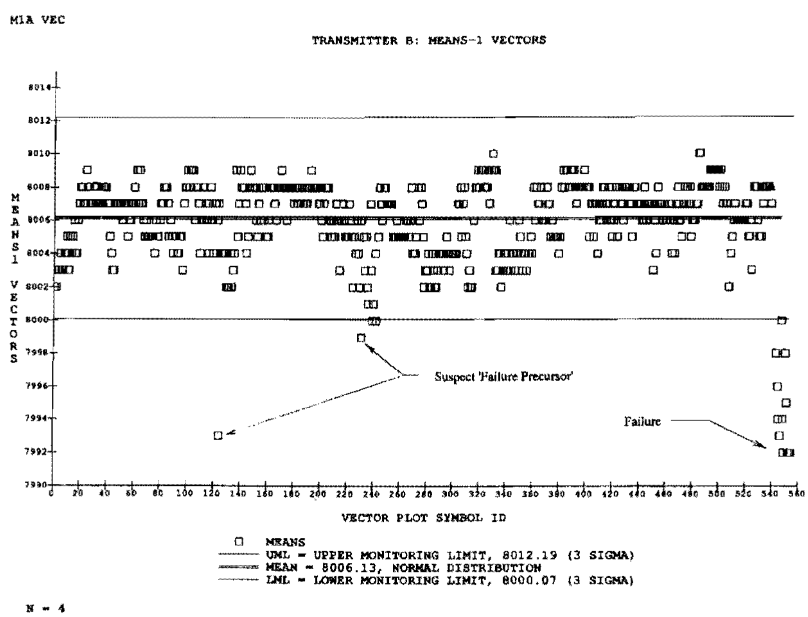

Figure 5. Statistical Pattern Recognition Vectors for EUVE Transmitter B

Trending down to failure, rather than up, as shown in the concept drawing, multiple FPP events (defined as vector points outside a 'normal' 3-sigma band) are visible.

Summary

As an exploratory data analysis effort, a vector profile based on sample EUVE Transmitter B telemetry was mapped on a 2-dimensional plot. The vector components were selected transmitter variables. The resulting vector profile established a region in hyperspace that represented probable transmitter failure. The failure region correlated to the precursors detected by the human expert. Several FPP events not seen by the expert in prior evaluations were also detected.

It therefore appears that a pattern recognition analysis approach, using the RECOGNIZE program, could provide an effective method for establishing time courses to component failure. Data from additional satellites will be required to determine if the FPP events observed prior to component failures on EUVE occur similarly on other systems. Assuming such similarities are found and allowing for minor variations due to payload, mission, and spacecraft bus configurations, it would appear probable that a generic software package can be developed to automate the research methodology. Used at a ground station, such a system would provide early warning of component degradation, providing informed decisions on component management. Loaded on board a spacecraft, an FPP software module could provide automated responses to known situations, thus freeing ground station operators for other essential tasks.

It is the author Losik's belief that the FPP sampling frequency and quantity used allows engineers to identify suspect failure precursors independent of unit operations, spacecraft attitude, attitude change rates, orbit shape, period, or any other characteristic that affects the internal spacecraft environment. The FPP allows the visual analysis of large quantities (3 to 5 months worth) of telemetry on a single display. It is because of the sampling frequency, size of samples, location of samples, and display characteristics that the FPP can be used on any orbiting spacecraft as well as with ground-based equipment. A white paper[5] is available that includes a complete description of the work completed at the U.C. Berkeley, CEA and Lockheed Martin.

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Biography

Len Losik has worked in RF engineering design, advanced development, and marketing in commercial, NASA, and military space since 1985 during his employment at Space Systems/Loral and McDonnell Douglas. Mr. Losik worked in project management at the Space Sciences Laboratories at U.C. Berkeley, and in commercial space marketing for L-3 Communications Telemetry & Instrumentation.