Results from the Prognostic Analysis Completed on the NASA Extreme Ultra Violet Explorer Satellite

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Abstract **- This paper summarizes the results from the multi-year research program completed at U.C. Berkeley, Space Sciences Laboratory, Center for Extreme Ultra Violet Astrophysics (CEA) in collaboration with engineering personnel from the Advanced Analysis Department at Lockheed Martin Space Systems Company. The research used the NASA EUVE satellite subsystem and payload equipment analog telemetry from the NASA/U.C. Berkeley Extreme Ultra Violet Explorer, low earth orbiting space science satellite and predictive algorithms pioneered on the Air Force's Global Positioning System satellites to measure the EUVE satellite on-board equipment remaining usable life and predict EUVE satellite subsystem equipment failures.**

The results of the research conducted at the CEA has been repeated by other major aerospace companies and is used widely on several major aircraft programs in the new F-35 Joint Strike Fighter but is not acceptable in the manufacture and test of space vehicles.

The research was approved by the Director of the Center of EUV Astrophysics and was to demonstrate that satellite subsystem equipment usable life could be measured accurately and that equipment failures could be predicted using predictive algorithms and satellite subsystem and payload equipment telemetry. The purpose of the research was to demonstrate to NASA GSFC space science personnel that EUVE CEA mission operations team was willing to risk the health of the EUVE satellite to increase the length of the EUVE science mission by using new technologies to lower the cost of the EUVE mission operations.

Using PRA as the only tool to calculate equipment reliability, results in the belief that equipment failures cannot be predicted and so cannot be prevented. If the EUVE engineering team could prove the presence of behavior in equipment telemetry that always preceded a surprise failure, then the equipment could be identified and replaced prior to launch stopping the premature failures of NASA, Air Force and commercial satellites and launch vehicles.

After the success obtained in the research completed on the NASA EUVE program, the author continued to design space vehicles to provide telemetry for measuring equipment usable life and complete prognostic analysis on NASA spacecraft to identify any on-board equipment that was going to fail prematurely for replacement at space vehicle factories.

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1. INTRODUCTION

The procurement contractual requirements that spacecraft suppliers must meet include the on-board equipment performance, spacecraft mission life and electrical, mechanical and physical interface requirements. The spacecraft equipment performance and interface requirements are measured and verified many times during factory dynamic environmental acceptance testing (ATP). The equipment mission life is calculated using PRA. The equipment usable life is not measured and confirmed before launch and so spacecraft and launch vehicle equipment reliability is dominated by premature failures.

For spacecraft, premature failures often mean that the spacecraft will not achieve its desired mission life and this may result in the need for the purchase of another spacecraft and launch vehicle costing many millions of dollars.

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The relationship between spacecraft equipment performance, spacecraft mission life and equipment usable life is complex and varies with duration of use. If space vehicle equipment does not meet its performance requirement sometime during factory testing, it is repaired or replaced before launch.

Figure 1 U.C. Berkeley, Space Sciences Laboratory Center for EUV Astrophysics

The contractual requirements used to purchase spacecraft and launch vehicles from the government or military includes the requirement suppliers must measure and confirm equipment performance requirements as identified in performance specifications in the contract. To meet the space system's mission life requirement, reliability analysis engineers calculate spacecraft mission life using contractually defined references such as MIL HDBK 217.

Spacecraft mission life is a duration identified so that bidders can know the amount of expendable supplies to include as well as choose the parts to be used. These items greatly affect the price submitted by bidders. Parts are purchased from manufacturers with a duration of time to expect the parts to function normally under the specified environmental conditions.

[12] The quality of a part is subjective and often ditermined by the price. The parts with higher quality have a higher unit price. The parts supplier usually decides which quality level their parts receive. Part factories are audited infrequently to ensure adeqaute manufacturing standards are in place and implemented.

[13] According to the MIL HDBK-217, the quality of a part has a direct effect on the part failure rate and the quality level of a part appears in the part models as the factor π_Q. Many piece-parts used in the manufacture of space vehicles are covered by specifications that have several quality levels; hence, the part models have values of π_Q that are keyed to these quality levels. Such parts are listed with their quality designator are shown in Table 1. The detailed requirements for these levels are clearly defined in the applicable specification, except for microcircuits. Microcircuits have quality levels, which are dependent on the number of MIL-STD-883 screens (or equivalent) to which they are subjected.

The results of the calculation for a spacecraft's mission life is in probabilistic values which are unrelated to a real duration of time. Mission life includes factors for the lifetimes of the piece-parts used as published by parts suppliers. The factors used to calculate mission life chnage as the needs of the purchasing organizations chnage.

Table 1 An Excerp from MIL HDBK-217F Identifying the Different Quality Levels used in the Aerospace Industry to help Define Piece-Part Quality

Part	Quality Designator
Microcircuits	S, B, B-1, Other: quality levels to be determined by screening level
Discrete Semiconductors	JANTXV, JANTX, JAN
Capacitors, Established Reliability (ER)	D, C, S, R, B, P, M, L
Resistors, Established Reliability (ER)	S, R, P, M
Coils, Molded, Reliability (ER)	R. F., S, R, P, M
Relays, Established Reliability (ER)	R, P, M, L

Over the decades, piece-part lifetimes have increased as manufacturing processes improved and these longer lifetimes for piece-parts are reflected in the longer mission lifetimes that are calculated today for todays satellites. The failure rates of parts have improved as well, but all part suppliers still promise that some of their best parts will fail prematurely.

To ensure that spacecraft equipment will achieve the contractually required mission life, spacecraft builders will calculate the reliability on paper using stochastic equations in probability reliability analysis (PRA) from reliability standards such as MIL HDBK 217. [13] The information used in stochastic equations is somewhat random information related to similar equipment or systems that was used in the past to quantify how long other equipment of a like manner may function before failing catastrophically.

The results from the stochastic equations appear meaningful and the results are artificially high by selecting the information that will provide high results, but neither result is related to the desired knowledge of equipment mission life/useful life of the four elements.

[2] When reliability is defined as the likelihood (probability) of a failure occurring or not occurring, the reliability of a system is quantified using stochastic

equation of four elements in series, where each element has a reliability of 0.98 is:

$$R_s = R_1 \times R_2 \times R_3 \times R_4$$

or

$$R_s = 0.98 \times 0.98 \times 0.98 \times 0.98$$

therefore:

$$R_s = 0.922$$

This type analysis has been used to quantify space systems equipment mission life for many decades because PRA was the only method that could be agreed to in 1960 when PRA was adopted to quantify equipment mission life and reliability. The information added to the stochastic equations in a PRA is provided by equipment and parts suppliers and is historical information that is unrelated to the equipment under manufacturing.

Just as the likelihood of a coin landing on either side has a 50% probability, when a coin is tossed the actual number it will land on either side will be much different in a large number of coin tosses. This is because the likelihood of an event occurring is unrelated to whether the event will really happen.

PRA and stochastic equations were adopted for reliability in 1960 because no one could think of a better idea and not because PRA was the right tool to use to produce equipment that wouldn't fail prematurely. Fifty years ago, the origin of NRTEs were believed from "glitches" in digital test equipment and software aafter analog circuits were replaced with digital circuits and software and RF and land line noise from either low Eb/No or low S/No. The industry has never changed their belief as the performance and stability of digital test equipment and communications systems have greatly improved.

2. Designing Spacecraft to Allow the On-Board Equipment Remaining Usable Life to be Measured Before Launch

Figure 2 is an artist concept for the INTELSAT VII commercial, geostationary communications satellite designed in 1987 to meet the growing communications needs of international communications companies. The INTELSAT VII satellites were the very first commercial communications satellites designed by the author to have the on-board equipment remaining usable life measured using equipment analog telemetry to identify any equipment that was going to fail prematurely after passing factory ATP and arriving on-orbit. On past commercial satellite programs, the company management instructed that the number of telemetry measurements be minimized to save cost, weight and complexity.

The Space Systems LORAL INTELSAT VII and INTELSAT VIIA satellites were chosen to be the first satellite produced to have on-board equipment remaining usable life to be measured because the RFP used by INTELSAT for the procurement of the INTELSAT satellites requested an overabundance of equipment analog telemetry to be available. This statement provided an opportunity for all equipment to have available analog telemetry to measure such data as the equipment temperature, load current and load voltage. Generally only about 85% of the subsystem equipment has telemetry available when the purchaser allows the builder to decide which equipment will provide telemetry. INTELSAT gave a commondation to the company for the design of the telemetry subsection of the TC&R subsystem.

Figure 2 An Artist Concept of the INTELSAT VII & VIIA Commercial, Geostationary Communiocations Satellites

The INTELSAT VII satellites were also the first to use a microprocessor-based, centralized and distributed control system using a Mil STD 1750A processor architecture and a Mil STD 1553B data bus allowing on-orbit reprogramming of the telemetry measurement format. The programming language was considered ADA which was also the preferred language for future government satellite procurements.

There was another major reason that NRTEs were associated with noise is that each time an NRTE occurred, the time to research and identify the origin of the transient greatly slowed the testing schedule and increased the likelihood of missing the delivery date and receiving a financial penalty.

[12] The spacecraft test schedule is tightly controlled with the launch window and meeting the delivery for the launch window became an overriding requirement. The procurement contracts were written so that there were no financial penalty when equipment failed prematurely after passing testing.

The desired equipment and/or spacecraft mission life is defined by the purchaser of the spacecraft in the contract allowing spacecraft builders to optimize their design for the lowest cost hoping to win the contract to build the spacecraft. Today's long life satellites can have a design life of over 23 years to meet a mission life of 15 years. Many long life satellites do not survive past the first year and many long life satellites operate much longer than the 15 year mission life.

[10] Unlike spacecraft equipment performanace that is measured and confirmed using industry standard testing pradtices (ATP) before launch. Equipment mission life is calculated on paper using stochastic equations in a probabilityy reliability analysis.. The PRA was borrowed from merchant shipping industry and it is used in the process for determining what an insurance company may charge for an insurance premium in the merchant shipping industry.

The spacecraft equipment performance is measured and verified during dynamic environmental factory acceptance testing (ATP), and ATP may occur over several days or several weeks. Equipment performance is measured before during and after the equipment is exposed to the extreme conditions that the spacecraft may be forced to endure. The equipment performaqnce is also measured agian just before launch for one last time hoping to identify any equipment that may not survive the launch for replacement.

[4] During ATP, spacecraft equipment may also fail from a variety of other reasons than performance and be repaired or replaced before launch. After ATP is completed, the equipment that passes usable life shopuld be measured and the equipment that will fail prematyurely replaced.

The space indsutry relies soley on calculating reliability on paper using the stochaistic equations to quantify the likelihood of a failure occurring in a PRA and so specific equipment usable life is not measured before launch.

Our model-based or data-driven proprietary predictive algorithms include a series of actions that may use sofware to process and display equipment performance data. The objective of the prognostic analysis is to illsutrate the presence of a non-repeatable transient event[2] or NRTE, often present in normal appearing performance data from fully functional equipment that is misdiagnosed as noise.

[5] An NRTE in equipment test data is caused from at least one part aging in performance much faster than all the oethers causing transient events that are discerable in telemetry[6]. The presence of an NRTE is not allowed when using probability reliability analysis which is founded on the requirement that the behavior under analysis must occur instantaneously and randomly (the Markov property). This also means that there is no behavior preceding a failure that can be related to the failure. So using proprietary predictive algorithms to measure equipment usable life is a non-Markov measurement.

The NRTE that is related to equipment end-of-life can be used by engineers to determine the remaining usable life of equipment allowing the equipment to be discarded and replaced before use, stopping the premature failure of equipment on board complex aerospace equipment such as launch vehicles and satellites.

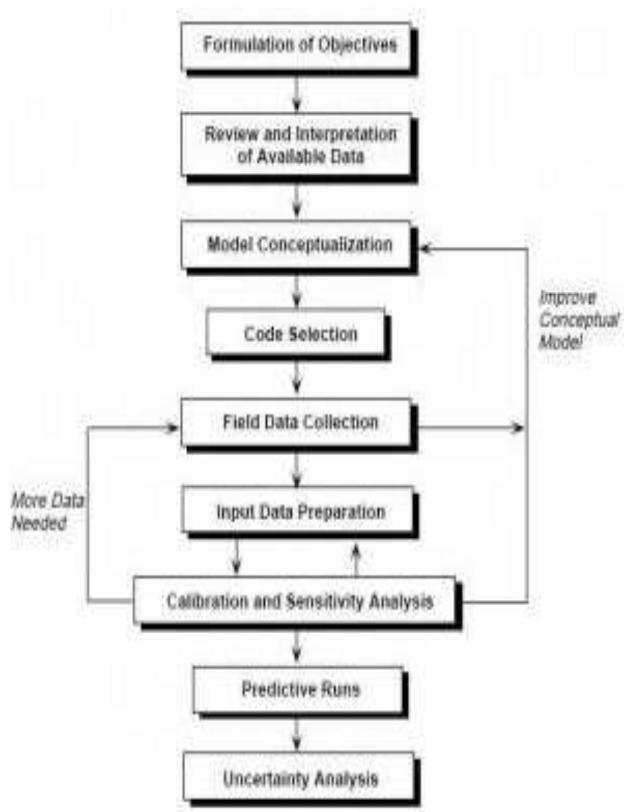


Figure 3 A Process used to Develop a Proprietary Model-Based Predictive Algorithm.

3. USING TELEMETRY TO MEASURE SPACECRAFT MISSION LIFE

The mission life of the equipment is a required duration that is specified in the purchase contract that is based on the duration of time that consumable are provided and is derived from many sources of information including piece-parts suppliers that attempt to quantify the expected duration of time that parts will function normally. When equipment mission life does not match with equipment usable life, a premature failure occurred. However, since parts suppliers promise that a few of their parts will fail prematurely, some equipment mission life will not match with the equipment usable life.

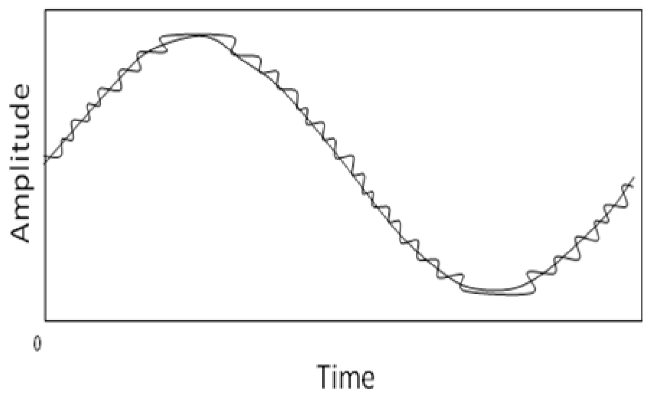


Figure 4 A Diagram Illustrating that Digital Telemetry is Sampled Analog Data

[4] Equipment telemetry and remote ground stations to collect telemetry was adopted throughout the aerospace industry in the late 1950's from the jet aircraft flight test community to measure equipment performance. During early jet aircraft flight-testing, pilots were dying before they could debrief the flight-test engineers on the performance of the equipment and so telemetry was added to all equipment and the facilities to collect and route the telemetry was developed and used. In the aircraft industry, equipment usable life is not a design driver because aircraft are serviceable and thus replaceable when they fail.

Telemetry was added to spacecraft and launch vehicle equipment in the early 1960's. It is used to measure and confirm spacecraft or launch vehicle equipment performance during each phase of the factory acceptance test program (ATP) before launch. Inadvertently out of desperation, engineers hoped that measuring and equipment performance before launch would somehow increase the likelihood that spacecraft equipment would not fail prematurely.

This did not happen and the premature failure rates of spacecraft and launch vehicle equipment combined is about 25% per year [10, 11, 12], Only NASA does not track the frequency that premature failures occur on NASA spacecraft and space missions. When spacecraft equipment fails prematurely, the builder treats the occurrence as proprietary information and competitive sensitive and does not allow the failure rates of its equipment to be in the public domain.

Due to the digitization and reconverting back to analog behavior, that is reconverted back to digital information and then reconverted back to analog information from aerospace vehicles and systems, the processing and display of telemetry has been the source of many NRTEs that have rendered the validity of telemetry questionable, minimizing program managements reliance on its behavior for critical decisions.

[4] Although the term telemetry commonly refers to wireless (RF) data transfer mechanisms (e.g. using radio, hypersonic or infrared systems), it also encompasses data transferred over other media, such as a telephone or computer network, optical link or other wired communications like a phase line carrier.

Analog telemetry provides internal access directly to electrical or mechanical circuit behavior and mechanism behavior that is otherwise not available. The information from telemetry is performance information which is unrelated to usable life.

Telemetry is used in a variety of applications to measure and confirm both performance and remaining usable life remotely and locally. Telemetry is inherently unreliable because of the RF communications and landline communcations systems it must use to arrive at its desired location.
Telemetry is reconstrcated analog data, but due to decisions made by engineers, some information is sampled at higher rates than others and so aliasing may exist which may allow the desired behavior to be missed due to its sampling rate.

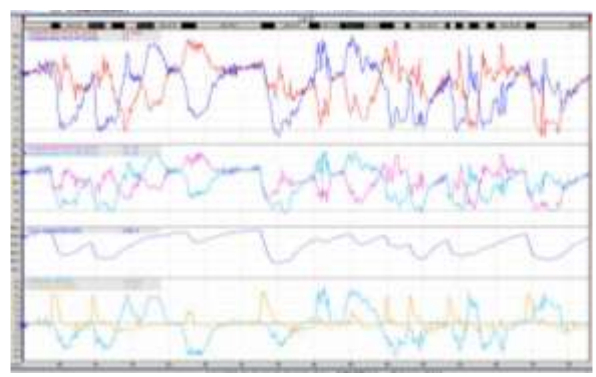


Figure 5 Seven Channels of Equipment Analog Data on a Strip Chart Recorder Software Display System

Telemetry is used throughout the aerospace industry to measure and confirm equipment performance before during and after acceptanvce testing. It is the only data that is stored for access at a later time for completing a failure analysis. The nature of telemetry is to use as little as possible because of the added cost and complexity which increases rick and slows down testing when too much data is generated for close evakuation.

For satellites, telemetry behavior exhibits harmonic behavior and so Fourier ananlysis can be used to generate normal behavior or predict future behavior from some fundamental information about the satellite.

Telemetry originated in the jet aircraft flight test community in the late 1950's to retreive aircraft equipment performance information at remote locations before the pilot died. Telemetry is sampled analog measurements and the equipment with telemetry, bit depth, sample rate and measurement accuarcy are variable. Telemetry is considered mission essential to engineers responsible for quantifying equipment behavior. To program managers who decide how much telemetry is provided, telemetry is an overhead cost and one that is to be minimized because there is no financial payback for using telemetry.

It is the procurement contracts that require companies to use telemetry, but these contracts usually allow each company to decide on what equipment provides telemetry, what the sample rate will be and the accuracy of each measurement since telemetry is not costed separately but is part of the instrumentation subsystem.

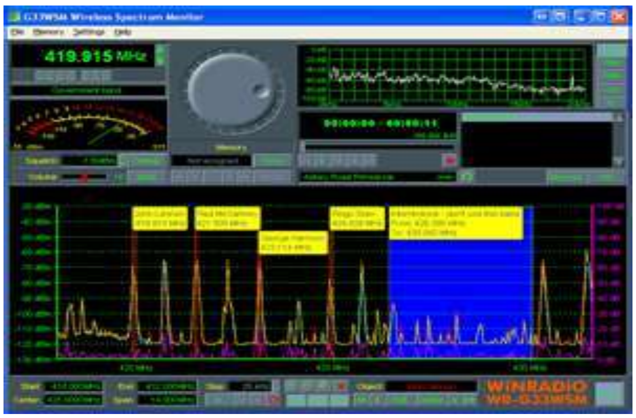


Figure 6 Example of Software-Based Telemetry Processing and Display System using Visual Images for Quicker Training and Problem Identification

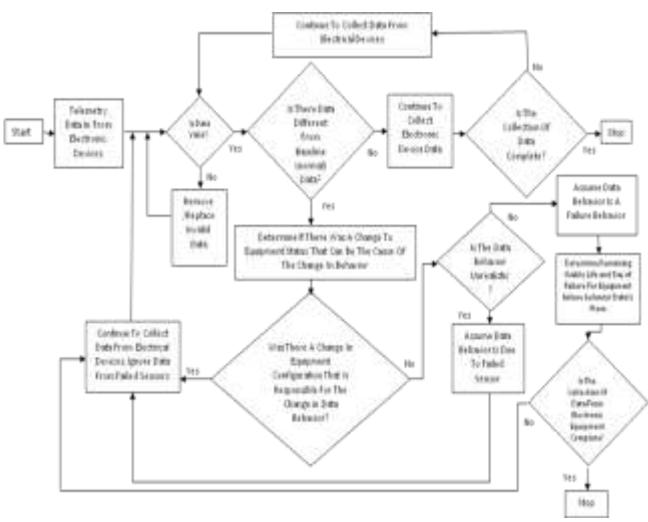


Figure 7 A Flow Diagram for Using Proprietary Predictive Algorithms to Identify Air Force Satellite Equipment with an NRTE in Analog Telemetry Behavior

Mearuring equipment usable life with telemetry will increase the value of telemetry to the program manamager becasue telemetry will allow the usable life of equipment to be known and the replacement of equipment that will fail prematurely thus ensuring an increase in the likelihood of mission success.

4. What is Prognostic Technology?

Prognostic technology includes the tools, practices and engineering philosophy needed to identify the equipment/products that is exhaustively and comprehensively performance tested but will fail prematurely.

PRA was adopted as a tool to quantify equipment reliability so that better decision making could be done for maximizing space-vehicle equipment reliability. . Prognostic technology will replace PRA that provides results as a probability of a failure occurring, with a physical and invasive measurement of equipment usable life.

Prognostic technology includes using pro-active diagnostics prior to a failure occurring to prevent a failure rather than simply react to a failure after one has occurred, active reasoning and model-based and data-driven proprietary predictive algorithms for illustrating accelerated aging. [6]

Prognostic technology includes the use of proprietary predictive algorithms for illustrating NRTEs in test data including normal appearing data from fully functional equipment that meets all performance specifications. Equipment with an NRTE in its telemetry/performance test data has at least one piece-part with accelerated aging. Equipment with piece-parts with accelerated aging will fail prematurely with 100% certainty.

Proprietary predictive algorithms contradict the belief that equipment failures are random and instantaneous and so the use of PRA which uses the Markov property can be replaced with a physical measurement of usable life rather than calculate the likelihood of a failure occurring. The Markov property is a fundamental assumption of the behavior that is quantified using reliability analysis so that stochastic processes can quantify parts, equipment, systems, processes and software reliability in probabilistic values.

Due to the complex spacecraft support networks that include remote ground and tracking stations such as those used by the U.S. Air Force and NASA, the presence of noise is a common occurrence. Noise mimics the transient behavior since noise is a non-repeatable transient event

When noise from RF or landline communications systems may be present, the algorithms for identifying and removing this noise must be available. Since electrical or RF signal noise of many types may be present at mission control centers and at launch pad in which RF communications systems are routinely employed, these noise removal algorithms must be available for use.

Prognostic technology acknowledges that electrical piece-parts and mechanical assemblies age from the instant that electrical power or mechanical stress is applied. Parts aging profiles may force them to fail prematurely and prior to their failure, the parts may initiate transient behavior that is identifiable in test data.

This premature aging profile is often misdiagnosed as systemic noise but is observable by using predictive algorithms to illustrate the behavior often found in normal appearing behavior from fully functional equipment, and do not fail instantaneously but degrade in functional performance over time. We call the unexpected degradation in parts performance, "accelerated aging."

[9] Using a prognostic analysis in the space-vehicle equipment factory and at the space vehicle factories will identify the equipment that will fail prematurely for replacement. Measuring equipment usable life after measuring equipment performance will upgrade space equipment manufacturing and testing processes.

[7] Figures 8 through Figure 12 are the achieved accuracy and data measurement sampling used in the research completed at U.C. Berkeley CEA to measure EUVE space vehicle equipment remaining usable life using the predictive algorithms that were pioneered [2] on the Air Force GPS satellites.

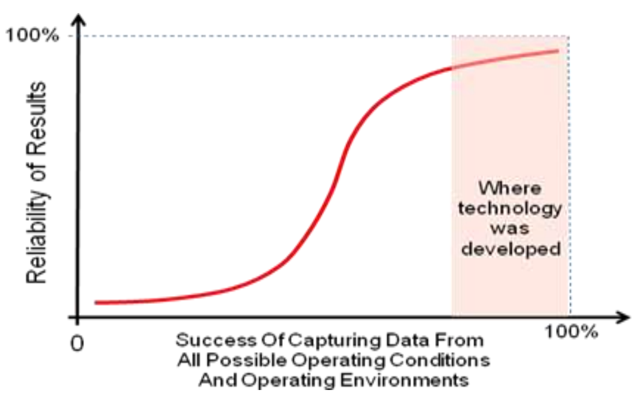


Figure 8 Achieved Accuracy vs. Operating Conditions and Environments Used for Baseline [9]

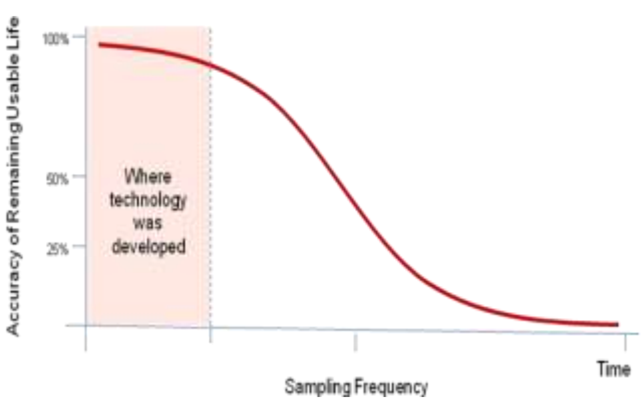


Figure 9 Achieved Accuracy of Measured RUL vs. Sample Frequency Used in Analysis [9]

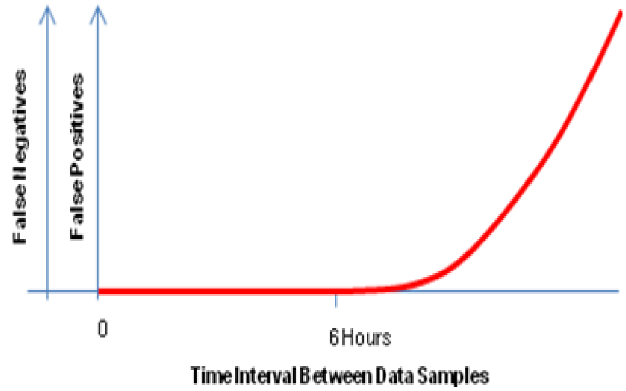


Figure 10 Achieved Numbers of False Positives and False Negatives vs. Sampling Frequency [9]

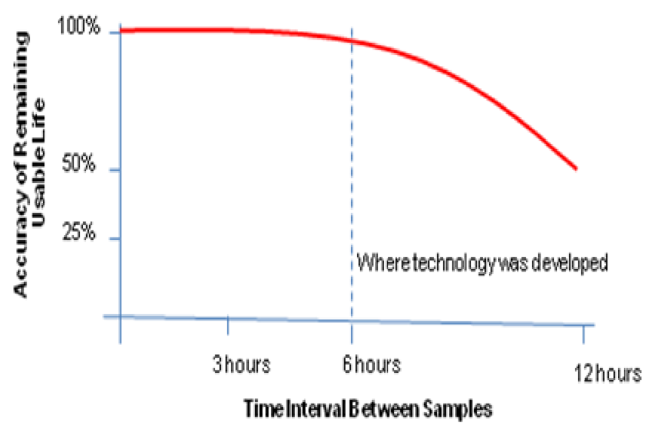


Figure 11 Achieved Accuracy of the Measured Remaining Usable Life vs. Duration between Samples of Telemetry [9]

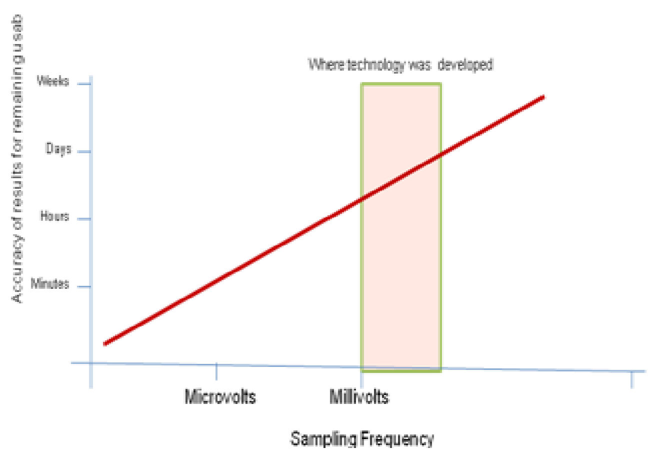


Figure 12 Achieved Accuracy of the RUL using Different Telemetry Measurement Sampling Frequency [9]

The predictive algorithms used on the GPS satellites processed telemetry from a full RF and electrical line noise environment.

The results of the accuracy from measuring satellite and launch vehicle equipment remaining usable life are not random because the results are based on actual equipment failures. The results are a probability (Ps) of achieving a RUL based on the many past equipment failures analyzed and the many real durations of remaining usable life, that occurred on real equipment.

The results from using our cumulative distribution in Figure 13 has resulted in remaining usable life predictions within 5% of the actual remaining usable life from equipment with an NRTE identified that failed prematurely.

The accuracy of the prediction for the remaining usable life of equipment with accelerating aging is far less important to the reliability, than having the capability to identify all the equipment that will fail prematurely with 100% certainty for replacement before launch.

5. Proprietary Predictive Algorithms Used on the NASA EUVE Satellite Subsystem Equipment

Prognostic technology includes pro-active diagnostics, active reasoning and model-based and data-drive prognostic algorithms for illustrating accelerated aging and the belief that equipment failures are a combination of random and deterministic behavior [6]. Prognostic technology includes the use of algorithms for illustrating the information in normal appearing data that prognosticians use to identify piece-parts and assemblies that have failed, is failing and will fail in the near future.

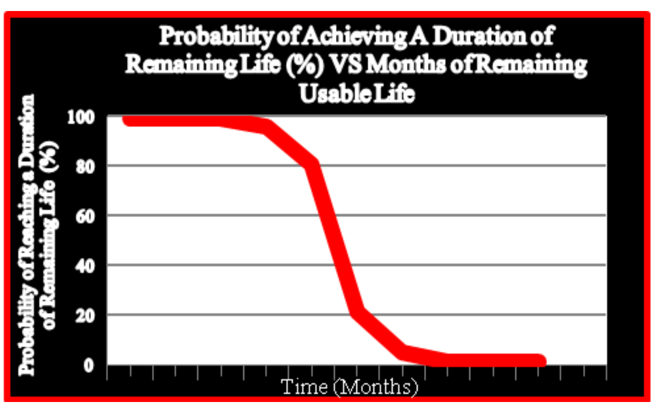


Figure 13 A Proprietary Cumulative Distribution for Determining Satellite Equipment Remaining Usable Life [9]

Model-based prognostic algorithms incorporates failure models of the system into the estimation of remaining useful life (RUL) and so are well suited for pattern recognition systems. Data-driven algorithms use existing operational data to determine normal behavior and discriminate normal from the early signs of premature aging/failure.

Table 2 A List of Proprietary Data-Driven Proprietary Predictive Algorithms used to Measure Equipment Remaining Usable Life in a Noise Environment [9]

Algorithm Name	Purpose of Algorithm
Baseline Analysis	Identifies short and long term normal data behavior
Change Analysis	Determines change from normal behavior.
Comparison Analysis	Determines when a change in normal behavior is occurring
Day of Failure	Search large data sets for common behavior during the same time
Digital Processing	Replaces outliers improving image accuracy and resolution
Discrimination Analysis	Identify behavior that has changed from normal behavior
Mathematical Modeling	Generates normal behavior from an inadequate data
Multi-Variant Limit Analysis	Simultaneous analysis across several variables
Rate Change Analysis	Identifies magnitude of change of behavior
Remaining Usable Life	Determines remaining usable life
Statistical Sampling	Reduces amount of data without eliminating desired behavior
State Change Analysis	Identifies data to be evaluated
Super Impositioning	Identifies data to be analyzed further for failure signature
Super Precision	Improves data integrity
Telemetry Authentication	Improves data integrity
Virtual Telemetry	Creates normal data behavior when none is available
Data Integration	Creates image for analysis
Dataset Generation	Creates data set manually when access is not available

In the launch vehicle environments, signal line noise may be present caused from degradation in Eb/No, RF noise from low S/No and a variety of sources as well as equipment noise that generates the data used to conduct a prognostic analysis may be present and the prognostic algorithms must be able to identify, remove/replace this data.

Prognostic technology acknowledges that electrical piece-parts and mechanical assemblies do not fail instantaneously but degrade in functional performance over time. We call the unexpected degradation in parts performance, "accelerated aging." This means that equipment failures may occur randomly but not instantaneously and so do not have the Markov property.

[8] The prognostic analysis that was completed on the NASA EUVE satellite used all available equipment telemetry. The EUVE mission shared TDRSS telemetry and command services and so most of the telemetry that was generated by the EUVE satellite from launch was available for analysis. The TDRSS network provides almost 100% covergae and when the services are paid for, TDRSS provides highly stable and reliable data to themission control centers.

The proprietary predictive algorithms in Table 2 were pioneered on the Air Force's Global Positioning System satellites and used to identify the presence of accelerated aging in equipment performance data, including equipment telemetry, when RF or signal line noise may be present, too much data is present or not enough information is available to develop baseline behavior. They have been used successfully on NASA, Air Force and commercial satellites and launch vehicles with no false positives and no false negatives.

6. Results from the Prognostic Analysis Completed on the NASA/U.C. Berkeley Extreme Ultra Violet Explorer LEO Space Science Satellite [4]

Figure 14 The $300M 4.5m Tall, 4,000 lb NASA/U.C. Berkeley EUVE Telescope and the Fairchild Multi-Mission Satellite Bus

The U.S. Army Explorer program was the United State's first attempt to launch an artificial satellite to space. It began as a U.S. Army proposal to place a scientific satellite into orbit during the International Geophysical Year in 1957; however, that proposal was rejected in favor of the U.S. Navy's Project called Vanguard. After Vanguard failed to get a satellite to space, the Explorer program was reestablished to catch up with the Soviet Union after that nation's launch of Sputnik 1 on October 4, 1957. Explorer 1 was launched January 31, 1958 just 3 months after Sputnik. Besides being the first U.S. satellite, Explorer 1 is known for discovering the Van Allen radiation belt.

The Army's Explorer program was transferred to NASA in 1958, which continued to use the name for an ongoing series of relatively small space missions, typically an artificial satellite with a science focus. Over 90 Explorer space missions have been launched from 1958 to 2011.

Over the years, NASA has launched over 90 Explorer program spacecraft carrying a wide variety of scientific investigations.

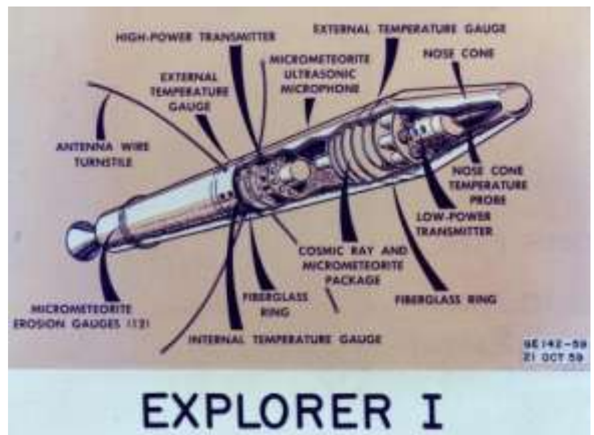


Figure 15 The U.S. Juno 1 Launch Vehicle with the Upper Half used to enclose the Explorer 1 Satellite

The Juno 1 launch vehicle carried a small satellite called Explorer 1. The Juno 1 launch vehicle was launched at 10:48 pm on January 31, 1958 and was the first U.S. satellite in space.

The Explorer Program Office at Goddard Space Flight Center in Greenbelt, Maryland, provides management of the multiple scientific exploration missions in the Explorer space flight program. Explorer missions are selected through a peer review process and the results must provide new understanding in space science. The missions are characterized by relatively moderate cost, and by small to medium sized missions that are capable of being built, tested and launched in a short time interval compared to the large observatories.

The U.C. Berkeley EUV telescope in Figure 18 and NASA's new multi-mission, modular satellite (M^3S) bus by Fairchild Space Company (now Orbital) was named the Extreme Ultra Violet Explorer (EUVE) and EUVE was the first high-energy payload flown by the new NASA GSFC space science directorate.

[14] The objectives of the NASA/U.C. Berkeley EUVE (Extreme Ultra-Violet Explorer) mission were:

(1) Produce a high-sensitivity all-sky survey in the 70- to 760-angstrom portion of the spectrum;
(2) Perform a "deep survey" of a strip of the sky along the ecliptic with extremely high sensitivity;
(3) Perform follow-up spectroscopic observations on bright extreme ultraviolet point sources;
(4) Study stellar evolution and the local stellar population;
(5) Investigate energy transport in stellar atmospheres; and
(6) Study and publish results on ionization and opacity of the interstellar medium.

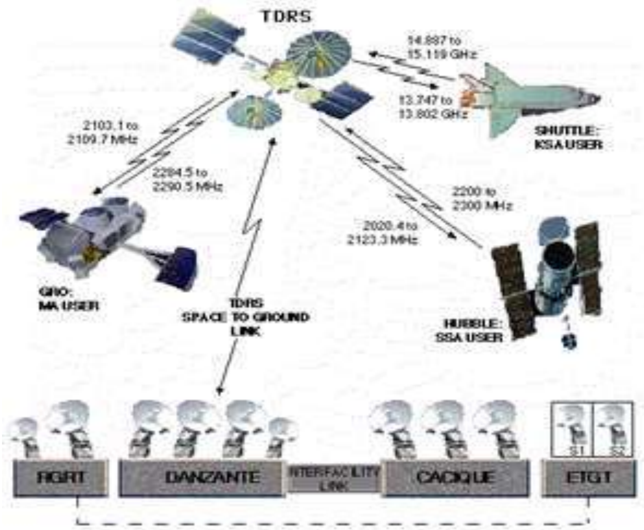


Figure 16 The NASA Space-Based Telemetry System for Routing Spacecraft Telemetry to the SSL CEA

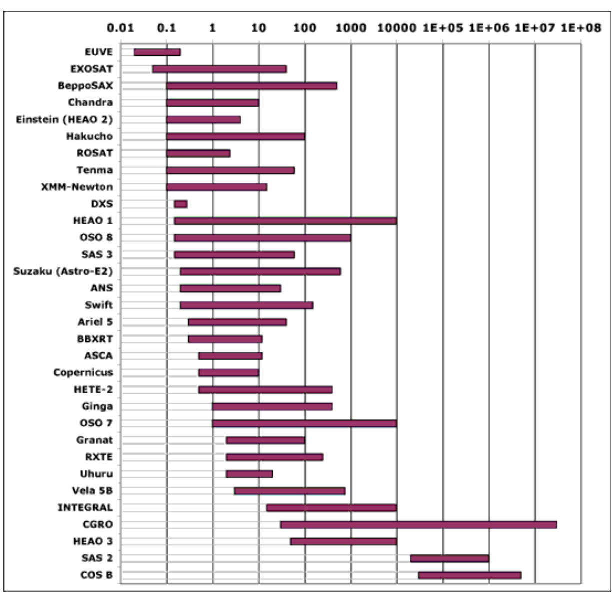


Figure 17 The U.C. Berkeley EUVE Mission was NASA's first High Energy Space Physics Explorer Mission

EUVE was designed for on-orbit servicing by the NASA Space Shuttle astronauts for a full 10-year space science mission life. The science payload included three grazing incidence UV telescopes covering 80-900 angstroms (188 kg each) and one EUV spectrometer (323 kg). The scanning telescopes compiled all-sky maps over 80-900 angstroms with positional accuracy of 0.1 deg. The spectrometer observed in the anti-Sun direction along the ecliptic, to complete a survey in two bands between 80-500 angstroms.

Figure 18 NASA/U.C. Berkeley EUV Telescope during Assembly

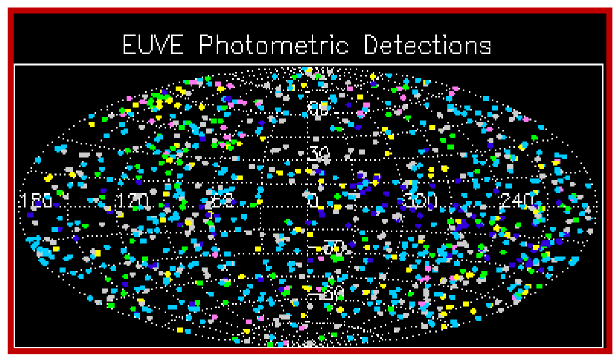


Figure 19 Results from the EUVE All sky Survey from the EUVE Satellite's Primary Mission

The initial "all-sky" survey was completed in January 1993, and a Guest Observer program was initiated in February 1993. EUVE payload telescope and science observation mission planning was one from the Center for EUV Astrophysics at the University of California, Berkeley.

[1] In 1994, after the NASA EUVE LEO space science satellite had completed its primary mission, the U.C. Berkeley program mamanagement decided to use the EUVE satellite as a test-bed to discover advanced methods of collecting mission data while lowering the cost to opertae the EUVE CEA facility (see Figure 1). [3]

The author was the EUVE Engineering Manager and EUVE Program Manager and was directed by the Director of the CEA to search the satellite equipment telemetry to identify transient events that preceded equipment failures. These transients could be used to predict the day equipment would fail and eliminate the need for full time mission operations engineering team to complete engineering analysis of the satellite data routinely.

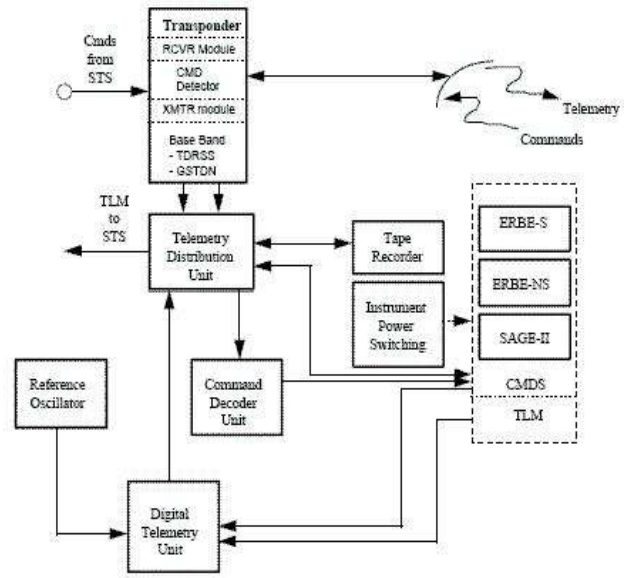


Figure 20 NASA EUVE STDN/TDRSS C&DH Subsystem Block Diagram

The mission control team and mission control center for the EUVE satellite Bus was located at NASA GSFC and the EUVE telescope payload mission control personnel and payload planning group and the EUVE guest observer program was located at the U.C. Berkeley, Center for EUV Astrophysics. The EUVE satellite Bus subsystems included GN&C, EPS, TCS and Structures. Because the EUVE Bus was to be serviced by astronauts, it had no propulsion subsystem that increased risk to astronauts and so the altitude of the EUVE could not be controlled.

The EUVE C&DH subsystem was very robust and designed compatible with both the NASA STDN distributed, ground-based remote satellite tracking stations that are located around the world and the NASA TDRSS, space-based data relay system.

The EUVE satellite telemetry was routed through TDRSS (see Figure 16) that used the NASA CCSDS packtized data format. Called CCSDS. CCSDS was a robust data transfer technology that is used today on the Internet and includes removing bit erors occurring from a variety of sources making all satellite telemetry data highly reliable. The EUVE satellite payload and Bus engineering telemetry were downlink from the EUVE satellite using the high gain steerable antenna at 512 Kbit/sec. to a TDRSS satellite.

The NASA EUVE satellite equipment telemetry was processed at the CEA using proprietary predictive algorithms pioneered on the Air Force Global Positioning System program (circa 1980). The predictive algorithms were used to predict GPS satellite equipment failures with certainty. The prognostic analysis that was completed on the EUVE satellite telemetry began in 1994. It was completed in late 1995.

The Advanced Development group at Lockheed Martin Missiles and Space Company (LMMSC) was contacted and asked to participate in the research. LMMSC manufactured many military satellites at the satellite factory located in Sunnyvale CA and had a history of producing many military satellites that failed prematurely immediately after arriving in space.

Table 3 Summary of EUVE Satellite Satellite Design and Performance Parameters included in this Paper[3]

Spacecraft Parameter	**NASA EUVE**
Orbit Altitude/Period	275 nmi/90 minutes
Orbit Inclination	28.5 degrees
Orbit Shape	Circular
Nodal Regression	6.6^0/day
Telemetry Rate	10Kb/sec
Telemetry Collected	99.9%
Basband Modulation	PCM
Bus Voltage	28V regulated
# of Analog Telemetry Measurements	3600
Satellite Weight	4,000 lbs.
Satellite EOL Power	3,000 watts
MMMS Bus Mission Life	10 years
EUV Payload Mission Life	3 years
TT&C Format	STDN, TDRSS
Frequency	14 GHz, 2.0 GHz
Encryption	None
TDRSS Antenna	High Gain Sterrable Dish
STDN Antenna	Low gain omni coverage

The results from measuring the NASA EUVE satellite Bus and telescope payload equipment remaining usable life using proprietary predictive algorithms and equipment telemetry identified all the EUVE satellite subsystem and payload equipment with an NRTE that was related to the equipment end of life.

The summary of results pertaining to the EUVE Bus equipment in Table 4 identies the results from the prognostic analysis completed on the NASA EUVE satellite We did not scrutinize the quality of the images produced by the EUVE telescope, which would have provided additional performance data. Since there were no transient behavior observed in detector voltage telemetry, there would not have been transient behavior in the telescope data.

Table 4 Summary of Results From Measuring Remaining Usable Life on the NASA EUVE Satellite Subsystem Equipment [5]

Summary of Results from FPP Analysis on Explorer Platform Monitors

EUVE Failures Analyzed with FPP	Suspect "Failure Precursor" Expected?	Suspect "Failure Precursor" Detected?	Date of Suspect "Failure Precursor"	Date of Hardware Failure	Time Between Suspect "Failure Precursor" and Failure	Estimate for Remaining Service Life*	FPP % Accuracy to Date
Transmitter A	No	No	None	None	None	> 6 months	100%
Transmitter B	Yes	Yes	12/93	4/94	4.2 months	< 5 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	note 1	note 1	> 6 Months	100%
TR A TU #1	Yes	Yes	3/94	12/94	9 months	< 6 months	100%
TR B TU #1	Yes	Yes	4/94	9/94	5 Months	< 5 months	100%

The results of the prognostic analysis in Table 4 successfully identified the presence of NRTEs in only some equipment that preceded each of the the satellite subsystem equipment failures and the remaining usable life that was predicted matched with the actual usable life within 5%.

Figure 21 EUVE Telescope Multi-Plate Channel (MPC) EUV Photon Detectors

EUVE Telescope Payload Monitors	Date Telemetry Processed	Suspect "Failure Precursor" Expected?	Suspect "Failure Precursor" Found?	Remaining Service Life Estimate	Accuracy of FPP
DET1HVLT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET2HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET3HVLT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET4HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET5HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET6HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET7HVIT	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET1HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET2HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET3HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET4HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET5HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%

Table 5 Results from Measuring Remaining Usable Life on EUVE Telescope (Figure 18) MCP Photon Detectors 1-4 High Voltage Telemetry [5]

Table 6 Results from Measuring Remaining Usable Life on EUVE Telescope (see Figure 21) MCP Photon Detectors 5-10 High-Voltage Telemetry [5]

EUVE Telescope Payload Monitors	Date Telemetry Processed	Suspect "Failure Precursor" Expected?	Suspect "Failure Precursor" Found?	Remaining Service Life Estimate	Accuracy of FPP
DET6HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET7HVPF	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET1HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET2HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET3HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET4HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET5HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET6HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET7HSUP	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET1HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET2HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET3HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET4HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET5HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET6HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%
DET7HCUR	1/1/95 - 3/1/96	No	No	> 6 Months	100%

Table 5 indicates that there was no accelerated aging found in all of the telemetry that was searched looking for the presence of accelerated aging in for 4 out 10 EUV photon detectors. The 4 detectors that received a prognostic analysis functioned normally another 7 years until the end of the mission in 2002.

Table 6 indicates that there was no accelerated aging found in all of the analog telemetry that was processed searching for photon detector 5 through photon detector 10. There was no accelerated aging found in any of the detector analog telemetry and the 5-photon detectors functioned normally until the end of the mission in 2002.

Due to space constraints, only the Bus equipment telemetry that had accelerated aging present is included. Not all the EUVE Bus equipment telemetry that received a prognostic analysis is included. The telemetry from the spacecraft equipment that accelerated aging was present in telemetry is included.

Figure 22 NASA EUVE Motorola TDRSS/STDN Compatible TT&C Transponder

Both EUVE Satellite TT&C Motorola TDRSS RF Transmitters in Figure 23 were operated with a 100% duty cycle until TDRSS Transmitter B failed.

The results in Figure 23 show that there was no transient behavior present in the telemetry from the EUVE TDRSS RF Transmitter unit A that did not fail prematurely during the same period that the transient behavior were occurring in TDRSS Transmitter B analog telemetry. The actual TDRSS Transmitter B remaining usable life of 4.5 months was within 5% of the duration predicted.

The results in Figure 26 show that only Gyro B had transient behavior present during the time the telemetry was processed using proprietary predictive algorithms. The unit failed when predicted.

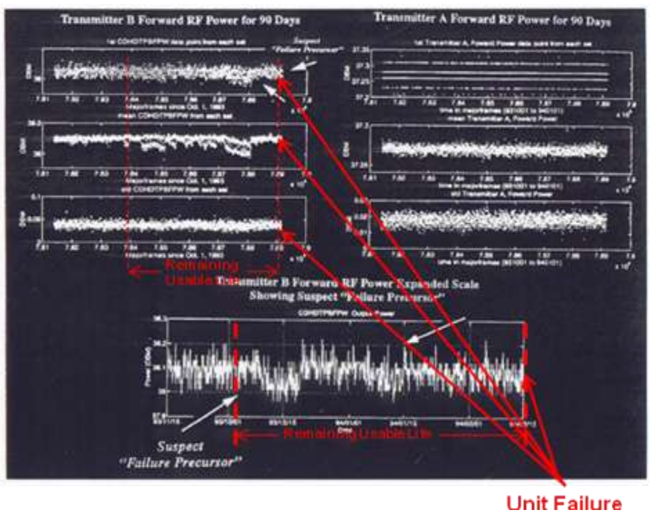


Figure 23 Processed Results from using Predictive Algorithms to Measure the Remaining Usable Life of the Motorola TDRSS/STDN RF Transmitter Unit A and Unit B [5]

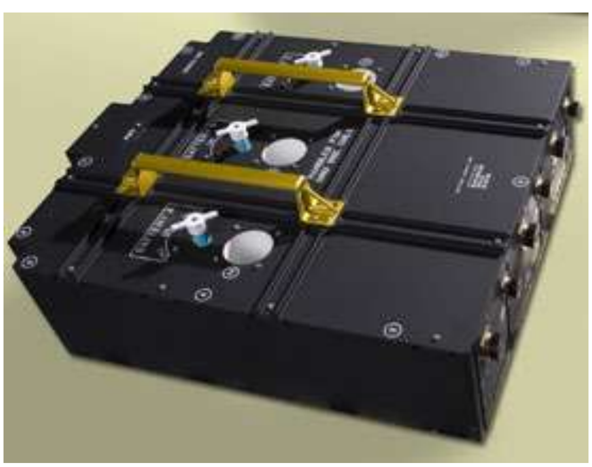


Figure 24 The Honeywell EUVE/Hubble Spacecraft Rate Gyro A, B & C Units that Failed Prematurely between 1992 and 1995.

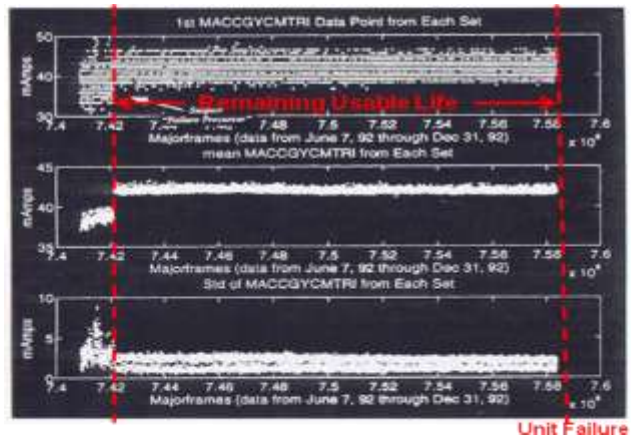


Figure 25 Post Processed Results from using Predictive Algorithms to Illustrate the Transient Behavior in EUVE Satellite's Gyro C Motor Current Telemetry

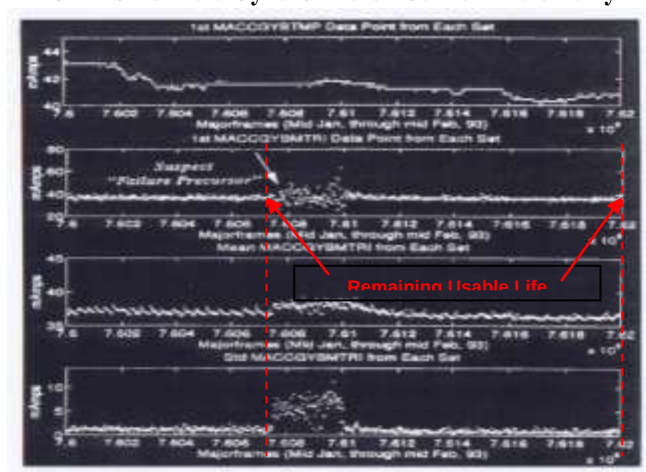
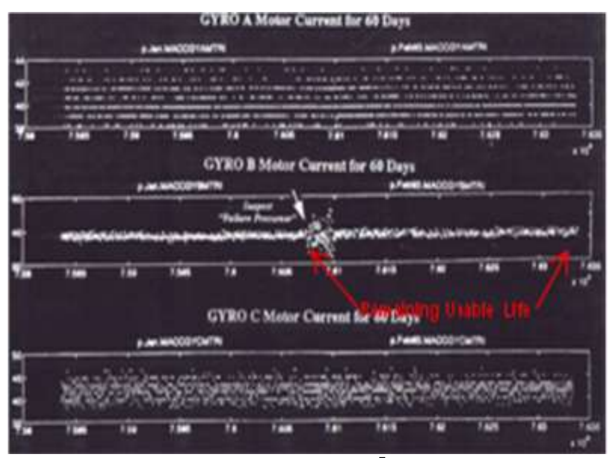


Figure 26 Processed Results from using Proprietary Predictive Algorithms to Illustrate an NRTE and Measure the Usable Life on NASA EUVE Satellite Rate



Gyro Unit B [5]

Figure 27 Post Processed Results Illustrating Accelerated Aging in EUVE satellite's Rate Gyro Unit B Motor Current Analog Telemetry for Measuring Gyro B Remaining Usable Life [5]

Figure 28 The NASA Explorer Program Solid State Tape Recorder Unit A and Unit B that Failed 7 Years Prematurelyon the NASA EUVE Satellite

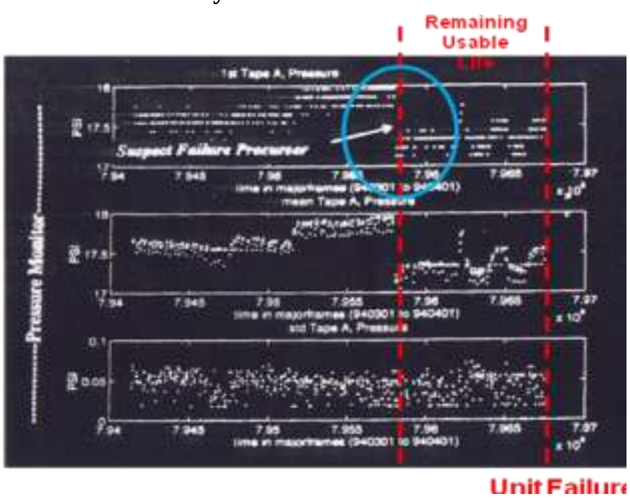


Figure 29 Post Processed Results from Measuring Remaining Usable Life on the EUVE Solid State Tape Recorder Unit A using Tape Pressure Telemetry Measuremen

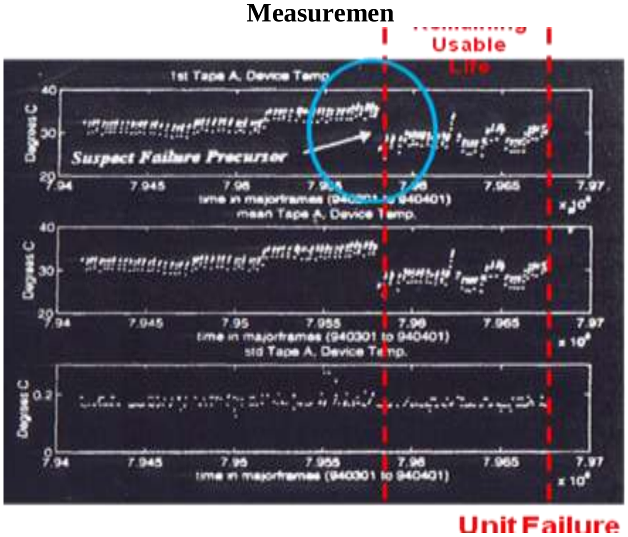


Figure 30 Post Processed Results from Measuring EUVE Solid State Tape Recorder Unit A Remaining Usable Life using Unit Temperature Telemetry Measurement

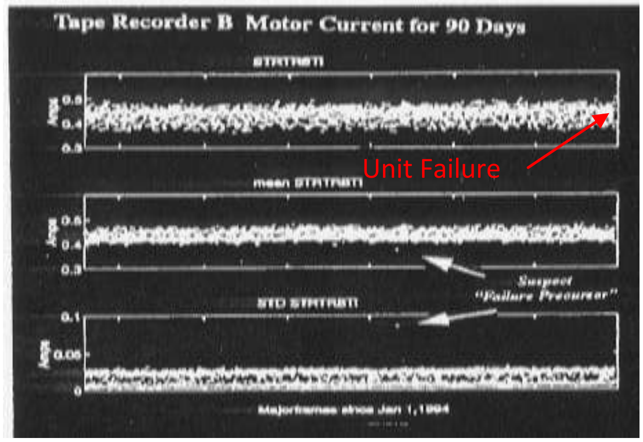


Figure 31 Post Processed Results from using Predictive Algorythms to Illustrate Transient Behavior in EUVE Tape Recorder B Motor Current Telemetry Prior to Unit Failure

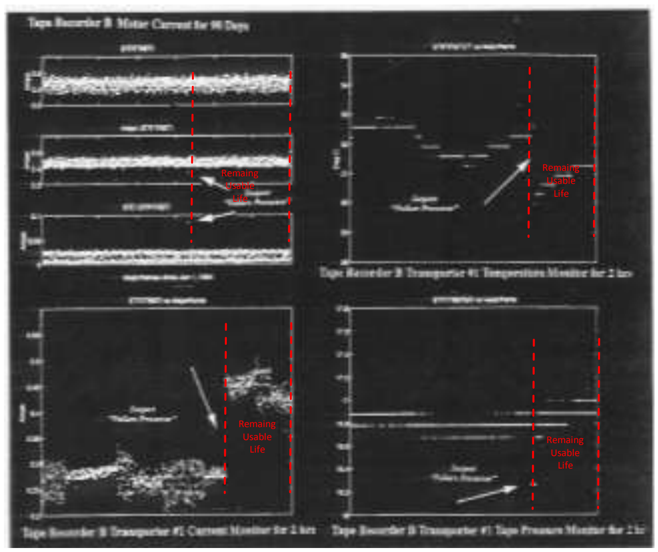


Figure 32 Composite of Post Processed Results from using Predictive Algorythms to Illustrate Transient Behavior in EUVE Tape Recorder B Analog Motor Current, Unit Temperature and Tape Pressure Telemetry

The four different graphs in Figure 32 are for the prognostic analysis that was completed on Tape Recorder B motor current, motor temperature and tape pressure are expanded views of the transient behavior identified in the post-processed Tape Recorder B motor current telemetry in Figure 31.

After the prognostic analysis was completed on the EUVE satellite in 1995, the remaining EUVE day shift science operations personnel that monitored the payload telescope telemetry in the CEA EUVE science control center was disbanded. The lights were turned off allowing the funding from science operations team to be used to lengthen the duration of the EUVE guest-observer science program from 1995 until 2001.

Figure 33 U.C. Berkeley EUVE CEA Science Center and the EUVE Science Mission Planning Team

In 1997, the EUVE Satellite Bus mission control activities were transferred from NASA GSFC to the CEA to reduce mission operations costs. Due to the reduction in mission operations costs from closing the mission control center at the CEA and the transfer of Bus operations to the CEA, the EUVE mission was extended twice, but cost and scientific merit issues led NASA to a decision to terminate the mission in 2000.

EUVE satellite flight operations ended on January 31, 2001 when the spacecraft was placed in a safe hold. The single operating TDRSS Transmitter A was commanded off on January 2, 2001. EUVE re-entered the Earth's atmosphere over central Egypt at approximately 11:15pm EST on January 30, 2002. The mission is considered a success since it accomplished all its scientific, technological, and outreach goals.

7. CONCLUSION

A prognostic analysis is a scientific analysis that converts equipment telemetry a.k.a. performance information into a measurement of equipment remaining usable life using proprietary predictive algorithms. A prognostic analysis requires equipment to have at least one analog telemetry measurement. This could result in an increase of about 5% from current telemetry used on spacecraft.

The results from a scientific analysis are superior to the results from an engineering analysis to identify the equipment that will fail prematurely. An engineering analysis uses past equipment data to quantify past equipment behavior with certainty. A prognostic analysis is a scientific analysis that uses past equipment behavior to predict end-of-life.

The prognostic analysis completed on the NASA EUVE satellite telemetry confirmed that the subsystem equipment with accelerated aging would fail prematurely with 100% certainty. The results of the research concluded that the cost of satellite on-orbit mission operations could be reduced by mission operations engineers measuring satellite equipment remaining usable life so that satellite subsystem equipment failures could be predicted and engineering support personnel be assigned only the day that the equipment failure was predicted to occur.

[15] From the prognostic analysis we submitted to NASA HQ Safety and Mission Assurance Department, NASA adopted a prognostic and health management plan as part of an integrated vehicle-health management plan for all future aircraft, manned and unmanned space missions. We submitted prognostic analysis for the NASA EUVE satellite, Orbital Taurus XL launch vehicle failures and the NASA Space Shuttle Challenger and Columbia accidents,

A prognostic analysis, as part of a PHM will identify the presence of accelerated aging in equipment analog telemetry that causes an NRTE. An NRTE is related to end-of-life in equipment that passes performance testing. Equipment with a part exhibiting accelerated aging will suffer from a premature failure with 100% certainty. Proprietary predictive algorithms illustrate NRTEs, often present in normal appearing data from fully functional equipment.

Based on the results from this research, all space vehicle manufacturers that measure space vehicle equipment usable life after factory acceptance testing is completed by processing equipment analog telemetry using predictive algorithms will stop premature failures of satellites and launch vehicles. This will begin a new era in space for producing spacecraft and launch vehicles that do not fail prematurely – a goal that has been unachievable for over 60 years.

For programs/missions that are too expensive or too important to fail, measuring equipment usable life before use provides the tools to produce systems that will not fail prematurely.

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Author Bio

Dr. Losik is the President and Chief Technical Officer of Failure Analysis. He is an award winning spacecraft designer, winning awards from the Air Force for his technical and leadership contributions that led to the funding of the GPS program and from INTELSAT for the design of the 12 Intelsat VII and VIIA communications satellites. He has over 30 years experience in the design, manufacture and test of military, NASA and commercial satellites, ground stations, missiles and launch vehicles as an RF and digital design engineer, systems engineer, Engineering Manager and Director at companies such as Boeing, Lockheed Martin, United Technologies, LORAL and L3 Communications.

As the Boeing GPS Space and Ground Segment Manager on contract to the GPS Program Office, Dr. Losik was responsible for the design, test, launch and on-orbit operations of over 52 GPS satellites. During the test & evaluation phase, Dr. Losik developed the first predictive algorithms that demodulated the GPS spacecraft equipment telemetry behavior to identify the equipment that was going to fail prematurely and predict their remaining usable life. As the NASA/NOAA GOES Next Spacecraft Manager, he was responsible for the design, manufacture and test of 10 NASA/NOAA GOES Next 3-axis stabilized, geostationary weather satellites and he completed a prognostic analysis on the first GOES Next satellite.

As the Air Force Titan 34D and Boeing IUS solid rocket motor test manager at United Technologies, he led the 5 to 7 segment upgrade on the Titan 3 SRM. As a TC&R subsystem engineer, Dr. Losik led the design of the first commercial, geostationary communications satellite designed to have its subsystem equipment usable life measured to identify the equipment that was going to fail prematurely earning a commendation from INTELSAT.

Dr. Losik also designed the first commercial Ku-band TC&R subsystem, and led the design and launch of the first Mil Std 1750A microprocessor-based, central and distributed satellite command and control system using a 1553B data bus and ADA software. He was the first to integrate the RF and digital ground station equipment into a 21-slot PC rack mount unit.

Dr. Losik also integrated predictive algorithms into the telecommunications industry, NEBS and ETSI 99.999% availability, high-reliability embedded computer servers and workstations.

Dr. Losik has written and published over 40 books, 25 magazine articles and over 35 technical papers at technical conferences across a wide variety of industries.