# Making Commercial Space Safe by Measuring Spacecraft Equipment Remaining Usable Life Before and After Launch

Len Losik, Ph.D [1]
*Failure Analysis*

**Abstract**

**An outcome of the ICBM, cold-war era was using probability reliability analysis to calculate equipment usable life/reliability using stochastic equations. Commercial and military procurement specifications for space vehicles still include the requirement for the space vehicle builder to calculate the probability of success ($P_s$) using the stochastic equations dictated in the contract. Using stochastic equations in a probability reliability analysis to quantify launch vehicle and spacecraft equipment reliability and confirming spacecraft equipment performance in a factory acceptance-testing program produces space systems whose usable life is dominated by premature failures that will cause a quick end to a commercial space tourism industry. The suppliers of electrical and mechanical parts promise that some will fail prematurely and yet no physical measurement of part or equipment usable life is contractually required before launch. Procurement contracts for space vehicles only require the builder to measure and confirm equipment performance and since there is no relationship between equipment performance and usable life, space vehicle equipment fails prematurely without financial penalty – a hold-over from the cold war. Using predictive algorithms in a prognostic and health management (PHM) program will measure space vehicle equipment usable life to identify the equipment that will fail prematurely for replacement. Commercial satellites that fail prematurely regularly are usually insured against premature failures, but the launching of tourists to space requires the game changing reliability centered, prognostic technology, which employs intelligent, self-prognostic equipment to stop surprise equipment failures that lead to catastrophic failures and loss of life. Using a PHM in the manufacture of space systems increase the safety obtained from using the NASA man-rating requirements. In a PHM, a prognostic analysis converts common equipment analog telemetry used during factory test to measure and confirm contractual equipment performance to a measurement of equipment usable life by demodulating telemetry behavior in time, amplitude, frequency and phase. Just as the police detective was replaced with the scientifically trained, forensic scientist; the medical doctor replaced by the scientifically trained radiologist to read medical images, the aerospace engineer needs to be replaced by the prognostician trained in completing a scientific analysis of equipment performance data to ensure space tourist safety. This paper includes the results from the prognostic analysis completed on commercial, military and NASA satellites, missiles and launch vehicles that identified the presence of accelerated aging in equipment analog telemetry test data from electrical and mechanical parts that were suffering from accelerated aging, missed by the engineering analysis completed by the equipment vendors, that failed prematurely. The results demonstrate that an engineering analysis and factory testing does not identify the equipment with parts suffering from accelerated aging that pass factory testing but will fail prematurely increasing of a catastrophic failure during the launching of tourist to space.**

## 1. Introduction

The commercial space industry does not rely on government contracts to remain in business. Commercial space missions are completely self-sufficient, earning revenue by selling the services that the commercial satellites provide to a wide variety of government and non-government customers. When government agency funding is involved for

[1]President and Chief Technical Officer, 501 Plum Street, Suite 48, Capitola CA, Senior Member

business survival, the mission is not a fully commercial mission. Today, as in 1960, the procurement contracts for commercial, military and NASA launch vehicles and spacecraft only include financial penalties for a late delivery to the launch pad that cause delays by missing the brief, launch window forcing financial penalties over $1,000,000.00/day. No financial penalty is levied on the space vehicle builder when any space vehicle equipment fails prematurely. This may motivate some space vehicle management and test personnel to overlook surprise behavior in test data that identifies the equipment that will fail prematurely and misdiagnose it as systemic noise and ignore it because the testing schedule is slowed increasing risk of missing the delivery date when every “glitch” in the test data is investigated . Due to the high rate of premature failure of equipment on NASA procured satellites, NASA GSFC has adopted on-orbit delivery with a guarantee of a free satellite in the event of a premature failure and the FAA Office of Commercial Space Transportation (OST) is rewriting its permit and licensing requirements to reflect on-orbit delivery.

Table 1 illustrates the rate of premature product/equipment failures in a variety of industries including the commercial, military and NASA space industries. The premature failure rate for space vehicles is exceeded only by the number that occurs on aircraft. Thus, the safety of the space tourist must be the primary driver that will allow the space tourism industry to be successful. [16]

**Table 1. The Equipment/Product Premature Failure Rates for Many Industries Illustrating Aircraft Equipment Fails Premature more often than Satellite and Launch Vehicle Equipment (Failure Analysis).**

| INDUSTRY | PREMATURE PRODUCT/EQUIPMENT FAILURE RATE | DYNAMIC ENVIRONMENTAL FACTORY ACCEPTANCE TEST PROGRAM USED? |
|---:|:---:|:---:|
| **Aircraft** | 25% | Yes |
| **Satellite & Launch Vehicle** | 24% | Yes |
| **CD’s** | 20% | No |
| **Consumer electronics** | 20% | No |
| **Software** | 20% | No |
| **Computer** | 15% | No |
| **Semi-Conductor Chips** | 15% | No |
| **Video Recorders** | 10% | No |
| **Office Equipment** | 6% | No |
| **Cameras** | 4% | No |
| **Food** | 0.5% | No |


**Figure 1. The Damaged Virgin Galactic Commercial, Manned SpaceShip1 without Intelligent, Self-Prognostic Equipment Returning for Landing after Reaching Suborbital Altitude in 2009 Winning the $10M Ansari X-Prize with Damage to the Bottom Rear Fuselage Clearly Visible from the Detachment of the Solid Rocket Motor during Suborbital Injection Preventable by using a PHM. [17]**

Removing the space tourism industry from the NASA manned and unmanned space mission paradigm that is cost-limited is possible today by using a prognostic and health management (PHM) program, which invasively measures all equipment usable life using predictive algorithms and common equipment analog telemetry before launch and while the equipment is operating in space.

Figure 1 identifies the damaged fuselage on the commercial SpaceShip1 that occurred from the premature failure of the on-board solid rocket motor manufactured by SpaceDev used to achieve suborbital altitude. The explosion and subsequent damage was heard by the crew when the detachment of the solid rocket motor occurred during suborbital injection but was not mentioned to the press.[17] The same solid rocket motor attachment mechanism will be used on the much larger SpaceShip2 planned to start launching tourists to suborbital altitude in 2013. The failure would have been prevented if Scaled Composites had employed a PHM in the manufacturing and test of the SpaceShip1. Many technical decisions are different to prevent a failure from occurring rather than react to a failure after a failure occurs in a PHM.

The NASA space missions including manned launches are cost-limited due to the constrained budget from Congress and as result, NASA's astronauts must accept the well-defined risk calculated by NASA and supplied to the launch pad while space tourists do not need to. Many technical compromises are made in the design of manned space vehicles by NASA technical and management personnel that increase risk to the astronaut safety due NASA's manned space programs being cost-limited and NASA planning to react to a failure after a failure occurs rather than adopt a program to prevent failures from occurring.

**Table 2. Results from an Aerospace Corporation Study Included 60 Satellites Purchased by the Air Force Proved that Equipment without Self-Prognostic, Intelligence that are Subjected to Dynamic Environmental Factory Acceptance Testing Results in Equipment with Reliability is Dominated by Premature Failures.**

**Average Number of Mission Degrading Equipment Failures Occurring in Vehicle Level ATP After Equipment-Level ATP for 60 Air Force Satellite**

| Program | No. of satellites tested | Test failures/satellite | | | | | | No. of satellites flown | Flight failures/ satellite |
|---|---|---|---|---|---|---|---|---|---|
| | | Acoustic | TC | Acoustic | TV | TC | Acoustic | | Early flight (first 45 days) |
| E2 | 4 | – | 5.5 | – | 2.8 | – | 0.5 | 4 | 0.5 |
| D1* | 3 | 0.3 | – | – | 1.7 | – | – | 3 | 2.0 |
| D2* | 1 | 0 | 2.0 | – | 2.0 | – | – | 1 | 1.0 |
| D3* | 9 | 0.9 | 1.4 | – | 1.6 | – | – | 7 | 0.6 |
| D4/D5* | 2 | 0.5 | 1.5 | – | 0 | – | – | 1 | 0 |
| B | 16 | 0.6 | – | – | 1.2 | – | – | 11 | 0.6 |
| G | 4 | 1.0 | – | – | 3.8 | – | – | 3 | 2.0 |
| F1 | 5 | – | 1.0 | 0.4 | 0.4 | – | – | 4 | 0.3 |
| F2 | 3 | – | 4.3** | 0.7 | 1.3 | – | – | 1 | 0 |
| H1 | 2 | 0.5 | – | – | 5.5 | – | – | 2 | 1.0 |
| H2a | 1 | 2.0 | – | – | 2.0 | 6.0 | – | 1 | 1.0 |
| H2b | 2 | 0.5 | – | – | 3.0 | 9.0 | – | 2 | 0.5 |
| C | 8 | 1.1 | – | – | 3.0 | – | – | 7 | 0.4 |
| Total: 60 | | | | | | | | Total: 47 | |
| Weighted averages | | | | 4.0 | | | | | 0.7 |

*Spacecraft only.
**Pre-environmental functional part of TC.

A cost savings decision was made by Space Shuttle management early in the design that all the Space Shuttle wing telemetry was to be stored on-board for downloading later. This decision led the Columbia Program Manager to believe that the Space Shuttle Columbia wing had not been damaged during ascent because the wing telemetry was not available for real-time analysis.

The commercial space industry is poised to start launching tourists using a variety of space vehicles including reusable; aircraft-launched rocket-powered vehicles pioneered by NASA and Orbital in 1990. The NASA/Orbital unmanned winged Pegasus launch vehicle is flown to 40,000 ft and released for automatic ignition to achieve an orbital velocity of 17,000 miles/hour using the on-board solid rocket motors. The NASA/Orbital Taurus XL rocket suffered from three catastrophic failures in nine launches. It was suspended for use by NASA as result.

Today, the aerospace companies that produce commercial launch vehicles and satellites receive full payment for rockets and satellites that fail prematurely thus minimizing any motivation to stop producing spacecraft that fail prematurely. This occurs because the procurement contract requires the use of probability reliability analysis (PRA) engineering that specifies that some equipment can fail prematurely without penalty. Today, aerospace and defense companies are not contractually obligated to deliver space systems that will not fail prematurely and so the space vehicle procurement contracts must include requiring all equipment that will fail prematurely to be identified and replaced before launch.

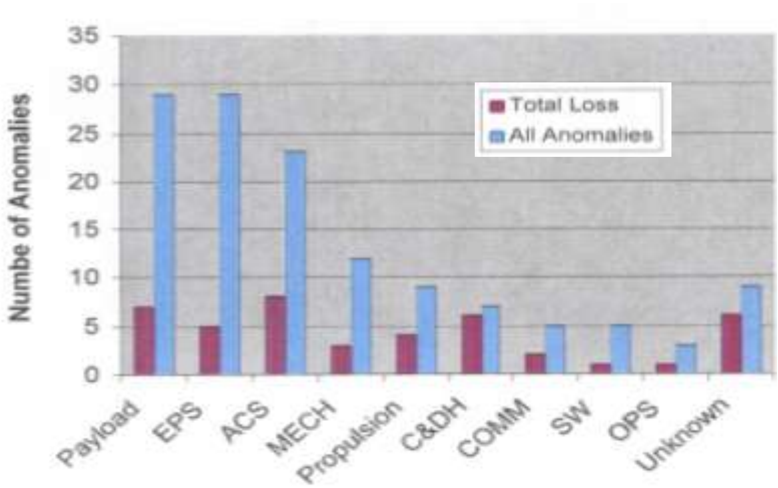



**Figure 2. Results from a NASA GSFC Study Completed to Quantify the Number of Premature Spacecraft Subsystem Equipment Failures that Occurred on NASA GSFC-Procured Satellites without Intelligent, Self-Prognostic Equipment from 1990 to 2001.**

[5] Launch vehicle and spacecraft premature equipment failures occur frequently due to company's not measuring equipment usable life to identify the equipment that will fail prematurely for replacement. The usable life of equipment is calculated contractually requiring probability reliability analysis (PRA) be completed using stochastic (meaningless) equations provided in the procurement contracts and contract references to quantify rocket and satellite equipment reliability, a holdover from the cold war in the 1960's.

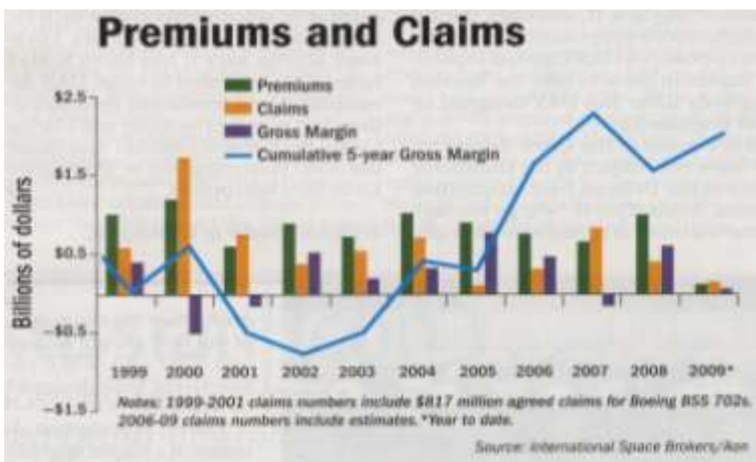



**Figure 3. The Loss and Profitability of the Commercial Launch Insurance Underwriters, Illustrating the High Number of Commercial Satellites without Intelligent Equipment that Fail Prematurely Every Year. Each Commercial Launch is Insured from between $15M to $90M.**

To summarize, stochastic equations use past, random information from like-equipment to arrive at conclusive results that is just conjecture. Stochastic equations are used when the time and expense is not available to accurately quantify or define the desired behavior. Stochastic equations are used to begin the quantification of unknown behavior and are not the actual quantification of behavior as is believed by many that are trained to use stochastic equations in the aerospace and defense industries.

## II. The Future in Commercial Space

After the rush to design, test and field Unites States ICBMs in the 1950's and 1960's was over, no one went back to re-evaluate the use of PRA and stochastic (conjecture) equations to quantify equipment usable life and so the use of PRA to quantify the reliability of rockets and spacecraft remains contractually required for most commercial launch vehicles. NASA does not rely on the results from PRA to quantify reliability, but NASA still must supply the PRA calculations to the launch pad personnel for NASA contracted launches. PRA dictates that equipment failures are instantaneous and random (Markov property) and thus cannot be prevented and most of the aerospace and defense community believes this.

**Figure 4. The Commercial, Virgin Galactic's White Knight Carrying the much Larger SpaceShip2 for Launching Tourists to Suborbital Altitude in 2013 without Intelligent, Self-Prognostic Equipment using a the Solid Rocket Motor Attachment Mechanism that Failed Previously on SpaceShip1.**

Starting in 1990, the NASA/Orbital Pegasus commercial, unmanned rocket was used to launch small payloads to space suffered 5 failures out of 35 launches and all 5 failures occurred within the first 15 launches. This premature failure rate is consistent with almost all other rockets and spacecraft. Three of the five failures were catastrophic failures with destruction of the rocket occurring in flight, while 2 Pegasus failures experienced lower performance than needed to get the payload to the correct altitude.

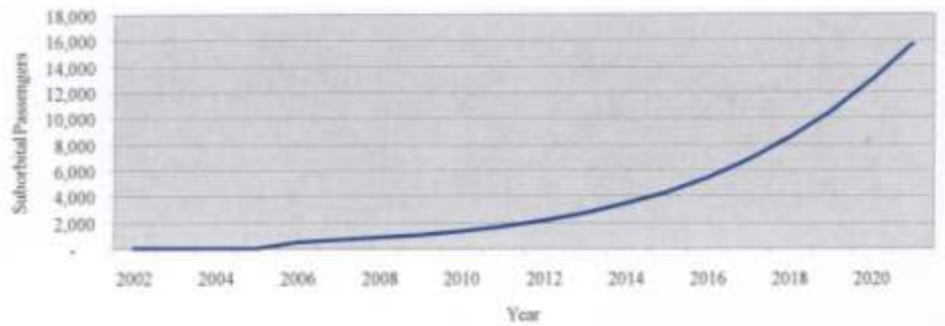



**Figure 5. The Predicted Growth in Commercial Suborbital Flights in the Space Tourism Industry Assuming no Catastrophic Failures Occur During Flight causing Loss of Life to Diminish Customer Interest.** [14]

When using an aircraft to launch a rocket, the aircraft serves as a reusable booster. It increases launch vehicle payload capability and reduces the cost of each launch. At 40,000 feet, the Pegasus release altitude, the Pegasus winged rocket is only about 10% of the minimum altitude needed for a stable orbit in space, which is 4% of a generally stable low earth orbit. The airliner is designed for approximately Mach 0.8, which is only about 3% of orbital velocity necessary. The largest cause of delay for a launch using a launch pad is unstable weather. Carrying the launch vehicle to 40,000 feet takes the Pegasus above the troposphere, into the stratosphere, thus an aircraft launched rocket is largely immune to weather-induced delays, and their associated cost. (Bad weather is still a factor during takeoff, ascent and the transit to the staging point though for the aircraft.

In response to private enterprise initiating a space tourism industry, NASA is considering sanctioning stays by private space tourists on the International Space Station (ISS). If the interest in space tourism is implemented, it will represent a significant change in NASA's attitude toward space from space exploration and space science to space tourism. NASA sponsored space tourism would take advantage of commercial spacecraft being developed with government subsidies under the NASA commercial crew program.

Figure 4 is the Virgin Galactic White Knight Aircraft carrying the SpaceShip2 with a solid rocket powered space tourist spaceship. The SpaceShip1 won the $10,000,000 X-prize in 2009 that will be used to launch tourists to suborbital altitude.

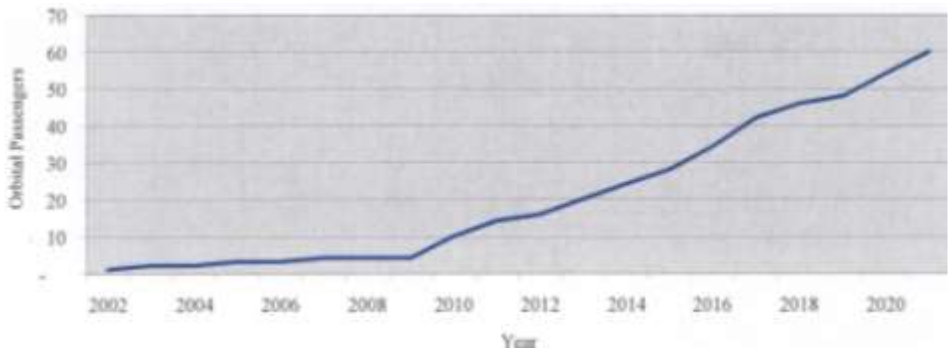



**Figure 6. The Predicted Growth in Commercial Orbital Rocket Flights in the Space Tourism Industry Assuming No Catastrophic Failures Occurring Causing Loss of Life during Flight to Diminish Customer Interest.** [14]

Other ISS space tourists have included Mark Shuttleworth, an Internet entrepreneur; Greg Olsen, Anousheh Ansari, an Iranian-American businessperson; Richard Garriott, a computer game designer and son of NASA astronaut Owen Garriott; Charles Simonyi; and Guy Laliberte.

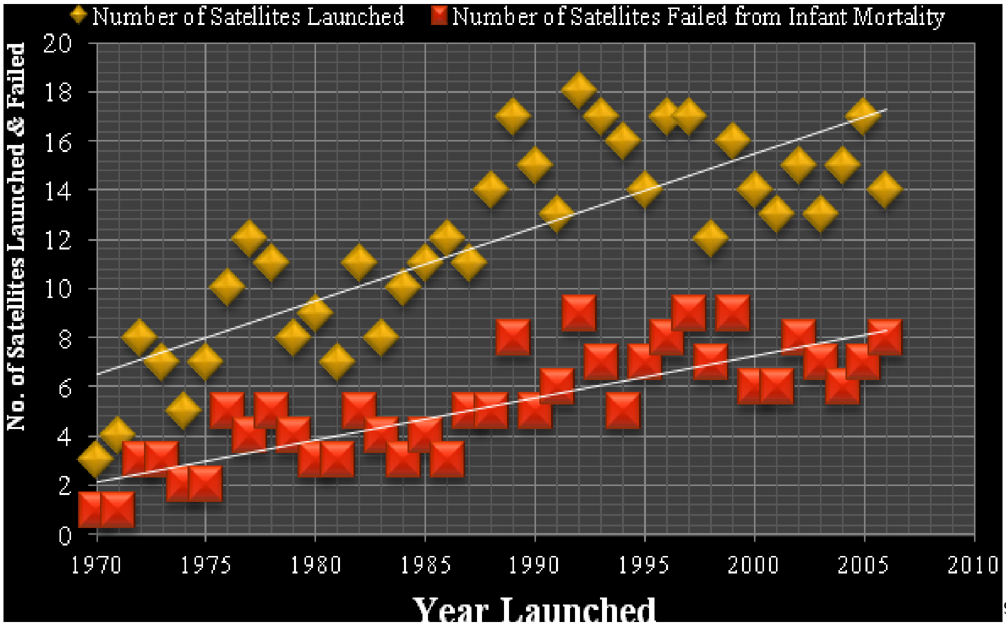
Each private space traveler paid approximately $30 million to fly into space and to stay on the ISS. NASA has opposed space tourist visits to the International Space Station. When Dennis Tito first took his trip to the ISS, he came under sharp criticism from then NASA Administrator Dan Goldin believed space tourist visits to the ISS were inappropriate and placed an undue strain on NASA personnel on the station.

## II. What is the Cause of Premature Equipment Failures on Rockets and Spacecraft?

[5] The suppliers of electrical and mechanical parts used in spacecraft and launch vehicles promise customers that purchase their parts that a few will fail prematurely. This information is available to space vehicle builders in the form of proprietary normal and cumulative distribution curves and this information is used in the stochastic equations in the contractually required reliability analysis. The dynamic environmental acceptance testing program (ATP) which is used to measure and confirm contractual equipment performance requirements was added to the manufacturing process of launch vehicles and spacecraft specifically to increase the likelihood that the parts that were promised to fail prematurely by the suppliers would fail prematurely would fail during ATP. [1] Studies completed by Aerospace Corporation and others have proved that equipment that passes factory testing will fail prematurely during launch and after the spacecraft arrives in space making space a dangerous place to work.

Launch vehicle and spacecraft equipment that is designed to function within contractual performance specifications fail prematurely when at least one electrical or mechanical part suffers from accelerated aging. [8] In the past, the non-repeatable transient events (NRTE) causes from the premature aging of parts that identify the equipment with parts suffering from accelerated aging were misdiagnosed as experiencing systemic noise and the transient events were ignored. With the computer processing speed in GHz and the telemetry bandwidth remaining in Hz or KHz, any NRTE that occurs in the test data is from the equipment and not from other sources.

The mission life of spacecraft and launch vehicles is determined contractually by using predefined stochastic (conjecture) equations in a probability reliability analysis (PRA) from references such as Mil STD 217. Once the U.S. government adopted probability reliability analysis (PRA) in 1960 to quantify equipment and vehicle reliability in probabilistic terms, the government contractors simply stopped looking for the causes of premature equipment failures and developed production processes that matched with the failure rates that the government stated was contractually acceptable. [2,3,6]




[9]

**Figure 7. The Premature Failure Rate of Geostationary Commercial Satellites Based on Insurance Claims Filed by the Owners for Financial Losses from 1970 through 2005 (Frost & Sullivan) [6]**

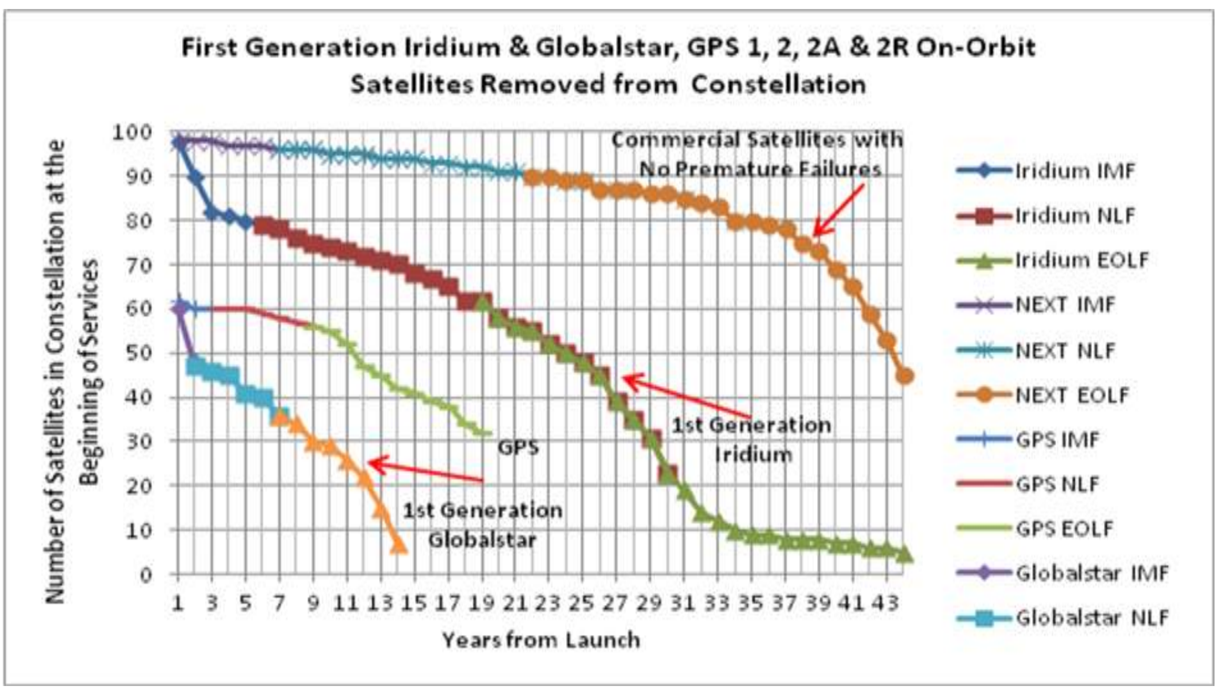



**Figure 8. The Commercial Single String and Quadruple Redundant GPS Satellites without Intelligent, Self-Prognostic Equipment Removed from Service after Failing Prematurely from the Iridium and GLOBALSTAR Telecommunications Satellites from the Start of the Constellation Filling.**

According to Aerospace Corporation NASA, commercial and military spacecraft all continue to suffer from infant mortality failures at rates up to a 70% within the 45 days of launch [1].

Figure 7 illustrates the yearly premature failure rates most commercial satellites starting in 1970. The rate rarely varies indicating that the cause is a systemic one and not related to personnel. To ensure safety on commercial space vehicles, the requirement to measure equipment usable life after ATP is completed needs to be added to the procurement contracts just as procurement contracts require equipment performance to be measured and confirmed during ATP.

Figure 8 illustrates the major increase in single-string satellite life that occurs when satellite subsystem equipment do not fail prematurely. The space vehicle procurement contract requires companies to measure and confirm equipment performance, and for many decades it was believed that equipment that passes factory performance testing are more likely to meet mission/usable life requirements even though there is no relationship between equipment that passes performance testing and usable life.

**Figure 9. The Sierra Nevada Reusable Dream Chaser for Launching Up to Seven People to Earth Orbit and the ISS, Winning $125M from NASA's CCDev Funding Designed without Intelligent, Self-Prognostic Equipment. First Launch Could Occur as Early as 2016.**

[16] The goal a prognostic and health management (PHM) program is to eliminate premature failures of electronic parts using a prognostic analysis. It will replace the diagnostic analysis that employs the engineering analysis and probability reliability analysis (PRA). Using PRA to quantify equipment reliability, the cost to raise the reliability increases much faster than the gain in reliability. The rate eventually forces the program cost to overwhelm the program funding available while never achieving 100% reliability.

The premature failure rates of space vehicle equipment from parts that fail prematurely are proprietary information and are not generally available to the public because it is "competitive-sensitive" information. Only a few organizations such as The Aerospace Corporation accumulate the failures rates of military and NASA space vehicle equipment and publish the contractor-proprietary information infrequently.

The Falcon 9 launch vehicle was funded by private sources for less than $900M to design, test and manufacture by SpaceX, headquartered in Hawthorne, California using both senior personnel from the industry and a large group of personnel with little or no experience in the space industry. Existing launch vehicles developed by the Air Force or NASA cost over $9B to develop and so the Falcon 9 demonstrated that the process used by the U.S. government agencies is overly expensive and unnecessary. Originally planned to be a reusable launch vehicle to lower the cost of each launch, its reusability will not be exercised for several years. The cost to launch to either LEO or GEO is $50M and is much cheaper than most other launch vehicle services. The inexpensive Falcon 9 has a long waiting list of customers, which should cause the price to increase after several successful launches.

The Falcon 9 does include using up triple redundancy but does not measure avionics and propulsion subsystem equipment usable life before launch and so during the development program, 4 premature failures occurred proving that the Falcon 9 will duplicate the reliability/learning curve experienced by all other launch vehicles and should experience a long-term reliability of less than 90%. The Falcon 9 and Dragon upper stage combination won a Commercial Resupply Services (CRS) contract from NASA to resupply the International Space Station under the Commercial Orbital Transportation Services (COTS) program and so is no longer a 100% commercial program because it is relying on government contracts for funding.

### III. What is Telemetry and Why can Telemetry be Critical to the Space Tourist Safety?

[5] An analog telemetry interface is embedded in circuits and mechanisms and so the information from a telemetry circuit is equipment performance related information. Performance information is information about how well equipment is functioning only. For equipment that passes performance testing, how well equipment is operating is unrelated to how long the equipment will operate because performance is unrelated to usable life.

Telemetry is access to the internal functioning of electrical and mechanical equipment and the information (i.e. voltage, current, temperature etc.) is available external to the unit for routing to remote locations for analysis. used during factory testing by test personnel, which include both engineering staff and test technicians to measure and confirm equipment performance. It is also used when the spacecraft is launched and on-orbit to determine equipment performance, configuration and status. Telemetry was developed by the jet aircraft flight-test community to measure jet-aircraft avionics equipment performance during aircraft flight-testing at Edwards AFB in the event the pilot was killed before debriefing the flight test engineers could occur. Telemetry systems were added to spacecraft and launch vehicle equipment in the early 1960's for a variety of applications. Telemetry was back-fitted to ICBMs already fielded.

[5] Telemetry is used by factory test personnel to measure and confirm space-vehicle equipment performance during factory testing, before launch, during launch and in space. It was not added to quantify equipment usable life as most technical personnel believes in the space industry.

[15] Equipment that passes performance testing (ATP) will often fail prematurely because stable equipment performance is unrelated to equipment usable life.  To measure equipment usable life, proprietary predictive algorithms demodulate the telemetry behavior to convert the equipment performance data, including equipment telemetry data, to a measurement of usable life.

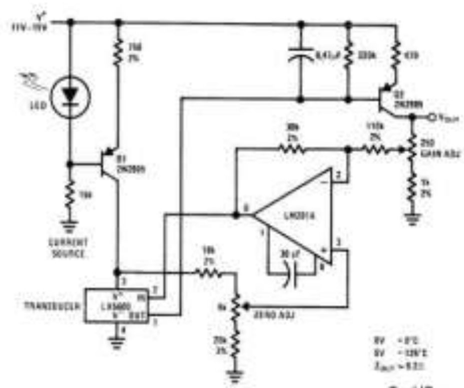



**Figure 10. An Example of an Electrical Circuit Providing Analog Telemetry outside the Circuit from a Test Point for Measuring Circuit Performance during ATP and Measuring Usable Life in Intelligent, Self-Prognostic Equipment.**

[2] Because spacecraft manufacturers do not measure and confirm spacecraft equipment usable life before launch, spacecraft reliability is dominated by infant mortality failures. Premature equipment failures occur after the spacecraft equipment has been exhaustively and comprehensively performance tested twice in factory equipment-level and vehicle-level acceptance-testing programs (ATP) demonstrating that performance testing of equipment is inadequate for producing equipment that won’t fail prematurely.

[7] Spacecraft equipment remaining usable life is measured by using the equipment analog telemetry (equipment performance data) generated during factory ATP and used to measure and confirm contractual equipment performance. The measurement of equipment usable life is done by using proprietary predictive algorithms to process the equipment analog telemetry behavior.

Proprietary predictive algorithms demodulate telemetry behavior and illustrate the presence of accelerated aging that may be present in normal appearing telemetry from fully functional equipment. Accelerated aging in equipment test data is caused from at least one piece-part (electrical or mechanical) aging in performance must faster than all other parts in a circuit or mechanism. Equipment with accelerated aging in its performance test data will fail prematurely with 100% certainty.

Telemetry is required on launch vehicles and spacecraft because telemetry provides access to internal circuit or mechanism behavior, which is performance information. Telemetry (e.g. voltage, current, temperature, RPM, PSIA, etc.) has become so important to mission success that the Air Force offers dedicated careers in spacecraft telemetry, promising personnel the opportunity to work with the most advanced technology known to man. Telemetry was considered an overhead cost by company management, but its use by proprietary predictive algorithms to measure equipment usable life now associates telemetry with mission success. NASA does not offer the courses.

## IV. The Game Changing Technology using Proprietary Predictive Algorithms used on NASA, Air Force and Commercial Satellites, Missiles and Launch Vehicles

A predictive algorithm includes a series of actions, resulting in a scientific analysis, made by personnel trained to identify the presence of accelerated aging that is related to equipment end-of-life. Using predictive algorithms as part of a prognostic and health management program will prevent surprise failures from occurring. The technical decisions made to prevent surprise failures are different from the decisions for reacting after a surprise failure occurs. Using diagnostic technology, personnel are trained to react with an engineering analysis after a failure occurs. An engineering analysis allows speculation and conjecture when insufficient engineering data is available, thus often associating the failure with the wrong cause.

Predictive diagnostics identify the equipment that will fail prematurely using a scientific analysis for replacement thus preventing a failure from occurring. Changing the paradigm from one of reaction to prevention requires training in completing a scientific analysis. The academic and on the job experience necessary to complete the scientific analysis is acquired with special training. Proprietary predictive algorithms simply relate past equipment, non-repeatable transient events that is identifiable in equipment engineering test data with equipment end of life. The relationship of time series-data (telemetry), prognostics (predictive diagnostics) and prednostics (determining remaining usable life) is as follows:

§ = Analyze operator

| Start with Time Series Data: | | Used to: |
|---|---|---|
| § Time Series Data | = Diagnostic Data | Identify equipment failures |
| § Diagnostic Data | = Prognostic Data | Illustrates the information for prognosticians to predict a future equipment failure |
| § Prognostic Data | = Prednostic data | Determine the day of failure and remaining usable life |

The analyze operator illustrates the relationship between diagnostic, time-series data such as equipment telemetry and equipment remaining usable life or equipment end of life is defined by predictive algorithms. In predictive diagnostics, the analysis of diagnostic data /analog telemetry results in a diagnostic analysis (current technology). The analysis of the results from a diagnostic analysis is prognostic data. The analysis of the prognostic data results is prednostic data, which is the prediction of the equipment remaining usable life. In a prognostic or scientific analysis, the “analysis” operator is accomplished by the predictive algorithms thus making telemetry critical to mission success instead of an overhead cost.

**Table 3. An Example of a List of Proprietary Dynamic, Data-Driven Predictive Algorithms for Measuring Spacecraft Equipment Usable Life Accomplished Manually.** [13]

| 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 from noise improving image accuracy and resolution |
| **Discrimination Analysis** | Identifies behavior that has changed from normal behavior |
| **Mathematical Modeling** | Generates normal behavior from an inadequate amount of data |
| **Multi-Variant Limit Analysis** | Simultaneous analysis across several measurements/channels of data |
| **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 suitable for prognostic analysis |
| **Dataset Generation** | Creates data set manually when access is not available |

## V. The First Commercial Spacecraft Designed to use Predictive Algorithms to Measure Subsystem Equipment Usable Life at the factory before Launch.

In 1988, INTELSAT released a request for a proposal (RFP) for nine INTELSAT VII, geostationary communications satellites. In the RFP, INTELSAT requested that bidders to instrument INTELSAT VII satellite subsystem equipment with more than usual amount of telemetry. This statement was made because INTELSAT owned and operated their own satellites and grew to value the information from INTELSAT satellite telemetry to diagnose and troubleshoot satellite equipment anomalies. In addition, telemetry was used to help complete a failure analysis in the event equipment failed to function as expected. Equipment telemetry is valued highly by engineers but distained by program management who seldom have had to responsibility to complete a failure analysis on the spacecraft they were responsible.

**Figure 11. An Artist's Concept of the 1st Satellite Designed using Prognostic Technology, the INTELSAT VII C and Ku-Band Geostationary Communications Satellite by the Author.. Only Eight of Nine INTELSAT VII Satellites made it to Geostationary Orbit Due to a Premature Failure on a Long March Launch Vehicle in 1996.**

[19] A stuck south solar array panel on the Intelsat 19 (Figure 12) broadcasting satellite that dislodged itself in mid-June 2012 as the sun to panel angles changed.  The reason the panel stuck is not known definitively nor will it ever be known. The builder is not contractually required to produce equipment that will not fail prematurely but could be if the contract was upgraded by Intelsat requiring Intelsat satellite suppliers to be fined when equipment fails prematurely. In 2011, the U.S. Air Force fined Lockheed Martin $15M for the premature failure of the AEHF-1 satellite's apogee engine after we suggested it to General Sheridan, AFSMC Commander. Lockheed martin's management had stated that they were not contractually obligated to deliver satellites with equipment that will not fail prematurely.

The Intelsat 19 satellite's south solar array stayed folded against the spacecraft following satellite deployment from a Sea Launch, Zenit 3SL rocket June 1, 2012. Intelsat announced that the solar panel unfurled on its own on June 12, soon after Intelsat 19 reached geostationary orbit about 22,300 miles over the equator. Telemetry from the satellite indicated the solar array had deployed on its own indicating that the stuck array deployment mechanism was influenced by the sun angle in which the solar array panel was automatically commanded to deploy. The same solar panel deployment mechanism was used on several other satellites that have been delayed for launch until the failure can be agreed to.

The Intelsat 19 satellite was manufactured by Space Systems/Loral of Palo Alto, Calif. Intelsat 19 was intended to distribute video and television services across the Asia-Pacific region.

Solar array and antenna deployment mechanisms such as those used on the Intelsat 19 satellite are generally exercised before launch at the satellite factory using benign thermal conditions that do not reflect the actual sun angles experienced in space causing unpredictable panel distortions that hinder deployment during and thus are most susceptible to failure. SSL has experienced many solar array and antenna deployment mechanisms that did not perform when expected and has not upgraded their deployment procedures. Commercial satellite builders such as SSL are not contractually required to identify the equipment that will fail prematurely after passing factory acceptance testing for replacement before launch and so not do so.

The major commercial satellite builders such as Space Systems LORAL, Boeing and Lockheed Martin have been aware that the on-board equipment that will fail prematurely can be identified after factory testing for replacement, but choose not to do so. Space Systems LORAL engineering has stated to the author that SSL is not interested in learning how build equipment that will not fail prematurely.

Figure 13 illustrates how complex commercial satellite solar array panels are exercised at the commercial satellite factory test before being stowed for launch. The panels are deployed in a benign thermal environment that does not occur during deployment on-orbit when the panels are commanded to deploy in space. Satellite builders that practice preventing catastrophic failures from occurring rather than reacting to one after one occurs will restrict the sun angles that antenna and solar array panels deployments are made to prevent antennas and panels from becoming physically distorted from unpredictable sun/shade conditions causing that cause stuck deployments.

**Figure 12. The $150M Intelsat 19 Geostationary, Commercial Communications Satellite being Rotated Looking for Dropped Tools and Physical Debris at the Completion of Integration & Test, Designed without Intelligent, Self-Prognostic Equipment. An Intelsat 19 Satellite Failed Prematurely on June 1, 2012 when the South Solar Array Deployment Mechanism Failed to Deploy the Solar Panel and Threatened a Complete Financial Loss for INTELSAT. Several Weeks Later, the South Panel Deployed Spontaneously as the sun angles Changed to a Favorable Thermal Condition.**

As long as “standard” (old) industry practices are used and the satellite procurement contracts do not specify the builder to identify the equipment that will fail prematurely for replacement, no penalties can be levied on the builder. Any financial losses from the failure of equipment will be paid by the insurance underwriter, also further discouraging satellite builders to identify the equipment that will fail prematurely for replacement.

**Figure 13. An Example of how Commercial Satellite Builders Exercise Complex Solar Array Deployments using Benign Thermal Conditions that do not Reflect Actual On-Orbit Sun Angles Experienced by the Panels that Cause Severe Solar Panel Distortions Resulting in Stuck Panel and Stuck Antenna Deployments.**

.

## VI. Results From The Prognostic Analysis Completed On 12 U.S. Air Force GPS Block I Test & Evaluation Satellites [5]

A prognostic analysis was completed routinely on the telemetry from all six of the U.S. Air Force Global Positioning System (GPS) Block I on-orbit satellites. This occurred between 1978 and 1988 by the author who was the Boeing GPS Space and Ground Segment Manager at the Air Force Satellite Test Center (STC) located at the Sunnyvale Air Force station in Sunnyvale CA. The development of the prognostic analysis using the satellite telemetry was necessary because of internal conflicts within the Air Force at the STC and the AFSMSC would not allow the engineering staff the spacecraft telemetry desired but only 40 minutes of telemetry a day. We had access to 10 minutes of GPS satellite telemetry, every 6 hours.

.

**Figure 14. The $55M Boeing GPS NAVSTAR 1 Satellites Procured by the Air Force in 1974 in Factory Integration & Test was Expected to Fail Prematurely without Intelligent Equipment On-Board.**

The Air Force STC used a conglomeration of antiquated remote tracking stations that were built for several different military space and aircraft missions and so were not the same in capability and performance. Unlike the NASA communications systems for routing telemetry to remote locations, the Air Force remote tracking stations used a wide variety of commercially available space and ground secure and non-secure communications systems to get the satellite telemetry to the STC. Commercial communications links had a 1 x $10^{-6}$ BER and so was often a source of noise in the telemetry.

With 40 minutes of telemetry per day, per satellite we scientifically analyzed it hoping to identify any prognostic markers that indicated that equipment was suffering from accelerated aging and would fail in the near future. Six additional GPS Block I satellites were in different stages of manufacture at the satellite factory and the test data from their equipment was used to complete the prognostic analysis of the six on-orbit GPS satellites.

The test data from the six GPS Block 1 satellites at the factory was searched for the presence of transient behavior, which was often found. The venders of the GPS subsystem equipment with transient behavior were contacted and asked to explain the source of the transient behavior in the test data. The vender personnel stated that transient behavior was caused from systemic noise and was to be ignored.

At the time, it was not considered possible to predict equipment failures because reliability analysis engineering requires failures to be instantaneous and random (the Markov property) and many technical support personnel believed it. The on-orbit GPS NAVSTAR 1 through NAVSTAR 6 satellites suffered from a variety of premature subsystem equipment failures. Including total satellite and launch vehicle failures. A failure analysis was always completed for each of the equipment that failed prematurely because the Air Force was planning to purchase over 100 additional GPS satellites and wanted to ensure that all performance and systemic design problems were corrected before the purchase.

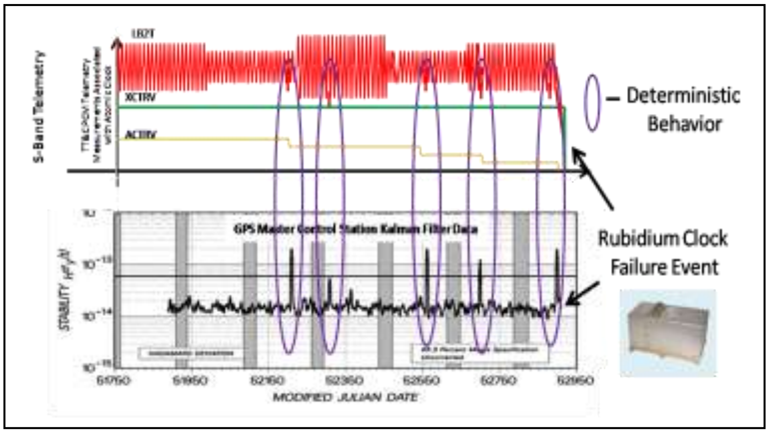



**Figure 15. Post-Processing Results from the Prognostic Analysis Completed on the Air Force/Boeing GPS NAVSTAR 1 Rubidium Atomic Clock Telemetry and GPS Master Control Station Kalman Filter Data Illustrating the Presence of Accelerated Aging that was Missed by the Failure Analysis Completed by the Vendor.**

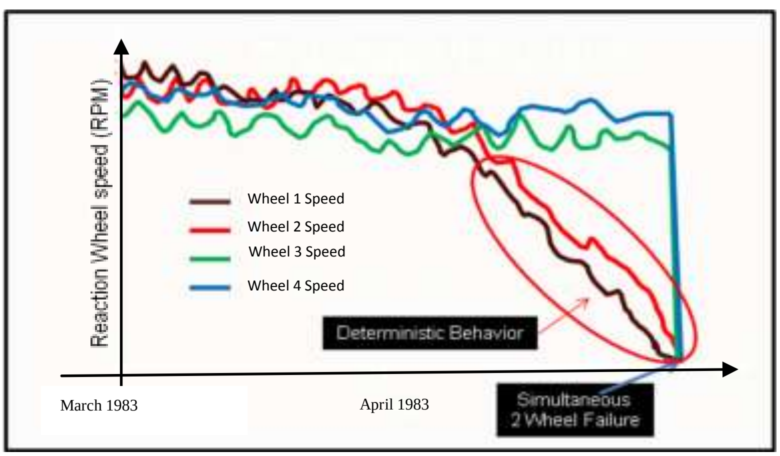



**Figure 16. Post-Processing Results from the Prognostic Analysis Completed on the Telemetry from the GPS NAVSTAR 5 Teldix Reaction Wheel Assembly Illustrating Transient Behavior (inside the red oval) Preceding Simultaneous Dual Reaction Wheel Failure that was Missed by the Engineering Analysis Completed by the Vendor.**

In March 1983, 2 of the 4 reaction wheels on NAVSTAR 5 (SV-7) were experienced an NRTE in wheel speed telemetry. This behavior indicated that two of the four reaction wheels were increasing in stiction and that both reaction wheels would lock up causing full loss of satellite attitude control. The behavior of the telemetry allowed the failure of both reaction wheels to be predicted with certainty. Two weeks later, both NAVSTAR 5 reaction wheels froze and a subsequent loss of satellite attitude control and a $75,000,000.00 financial loss occurred.

**Figure 17. An Artist Concept of the Boeing $83M GPS Block II Satellite Designed using Results from the Prognostic Analysis completed on the 12 Boeing Block I GPS Satellites.**

Prognostic analysis were completed beginning in 1978 identified the presence of NRTEs (accelerated aging) in the telemetry from the many on-board NiCd batteries that were essential for electrical power during earth and lunar eclipses and atomic frequency standards used to generate GPS timing. An NRTE was also identified in the GPS Kalman filter data generated from the GPS satellite atomic clocks and other satellite equipment that failed prematurely. The NRTE were misdiagnosed as systemic noise and ignored because engineering personnel believed it was not possible to measure equipment usable life and predict equipment failures.

Prior to the simultaneous failure of the NAVSTAR 5 reaction wheel 3 & 4 in 1983 (see Figure 16), the GPS NAVSTAR 5 satellite TT&C Motorola SGLS RF telemetry transmitter unit #1 failed prematurely in 1981. The back-up transmitter unit was powered on using a 100% duty cycle.

If the NAVSTAR 5 reaction wheels had been spun-up to 2000 rpm to increase the wheel assembly temperature, the lubrication would have soften and migrated into the wheels and stopped the increase in reaction wheel stiction and the loss of NAVSTAR 5 would not have occurred.

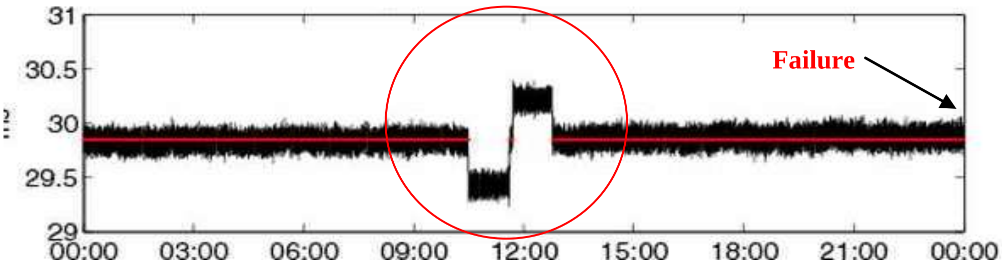



**Figure 18. Post-Processing Results from the Prognostic Analysis Completed on the GPS NAVSTAR 5 Motorola SGLS TT&C RF Transmitter Unit 1 RF Power Output Analog Telemetry Collected Prior to Failure (at time 00.00) that was Missed by the Failure Analysis Completed by the Vendor.**

Figure 18 is the results from the prognostic analysis completed on the analog telemetry from the NAVSTAR 5 Motorola TT&C SGLS RF transmitter unit 1. It revealed a non-repeatable transient event (NRTE) occurring in the RF power telemetry measurement several hours prior to the total transmitter failure. The NAVSTAR 5, Motorola failure analysis concluded that the 3rd stage of the RF 3 amplifier chain had failed due to premature aging.

The prognostic analysis in Figure 18 concluded that the transient event observed may not have been the first one and a prediction of remaining usable life was not made. The transient event did indicate that the Motorola GPS Satellite SGLS RF transmitter would be failing prematurely.

**Table 4. Summary of GPS Satellite Subsystem Equipment Premature Failures that Exhibited a Transient Event Observed (TEO) on GPS NAVSTAR 1-3 Satellites** [5, 10]

| GPS SATELLITE ON-ORBIT SUBSYSTEM EQUIPMENT FAILURE | NAVSTAR 1 (SV1) | NAVSTAR 2 (SV2) | NAVSTAR 3 (SV3) |
|---|---|---|---|
| Rb Frequency Standard 1 Primary Mode | TEO | TEO | TEO |
| Rb Frequency Standard 2 Primary Mode | TEO | TEO | TEO |
| Rb Frequency Standard 3 Primary Mode | TEO | TEO | TEO |
| Rb Frequency Standard #1 VCXO Mode | TEO | TEO | TEO |
| Rb Frequency Standard #2 VCXO Mode | TEO | TEO | TEO |
| Rb Frequency Standard #3 VCXO Mode | TEO | TEO | TEO |
| Solar Array Thermistor | TEO | N/A | TEO |
| Battery #3 Over Temperature | TEO | TEO | TEO |
| Propulsion Catalysts Bed 0.1 lbf Thruster Heater | TEO | N/A | N/A |

**N/A: Not Applicable**

The prognostic analysis that was completed on the GPS spacecraft subsystem equipment failures in Table 4 and Table 5 were completed during the GPS program's test and evaluation (T&E) phase (circa 1980). The results were used to redesign some of the GPS Block II and IIA satellite equipment, add equipment to the satellite subsystems and increase requirements in satellite subsystem equipment performance.

**Table 5. Summary of GPS Satellite Subsystem Equipment Premature Failures that Exhibited a Transient Event Observed (TEO) on GPS NAVSTAR 4-6 Satellites** [5, 10]

| GPS SATELLITE ON-ORBIT SUBSYSTEM EQUIPMENT FAILURE | NAVSTAR 4 (SV4) | NAVSTAR 5 (SV7) | NAVSTAR 6 (SV12) |
|---|---|---|---|
| Rb Frequency Standard 1 Primary Mode | TEO | TEO | N/A |
| Rb Frequency Standard 2 Primary Mode | TEO | TEO | N/A |
| Rb Frequency Standard 3 Primary Mode | TEO | N/A | N/A |
| Rb Frequency Standard 1 VCXO Mode | TEO | N/A | N/A |
| Rb Frequency Standard 2 VCXO Mode | TEO | N/A | N/A |
| Rb Frequency Standard 3 VCXO Mode | TEO | N/A | N/A |
| Cs Frequency Standard 4 | TEO | N/A | N/A |
| RF Transmitter 1 | N/A | TEO | N/A |
| Reaction Wheel 1 & 2 | N/A | TEO | N/A |
| Battery # 3 Over Temperature | TEO | N/A | N/A |
| Catalysts Bed Thruster Heater | TEO | N/A | N/A |

**N/A: Not Applicable**

Table 4 and Table 5 summarize the results from the many prognostic analysis completed on the first 12 GPS satellites by the dedicated staff of GPS satellite's subsystem engineering team that occurred from the first launch in February 1978 through 1984 on NAVSTAR 1-6. The information from the six Block 1 GPS satellites in production at the factory was used to confirm the presence of NRTEs in equipment data from the vender is included in this paper.

Some of the technology used on the GPS satellites was new to the Air Force GPS Program Office personnel such as L-Band downlinks, SGLS PRN ranging, CDMA spread spectrum modulation, atomic frequency standards and a 12 hour high inclination satellite orbit that required a "noon turn". As a result, the Air Force personnel were highly motivated to pay the builder to complete many engineering analysis so that they could learn about the equipment behavior hoping that it would lead to decisions that would improve the performance of the GPS space segment during test & evaluation (T&E).

The results from all the prognostic analysis that were completed during the T&E phase of the GPS program were used by the Air Force GPS Program Office Air Force officers to improve the design and safety of the next 40 GPS satellites purchased from the same builder. These improvements and design changes include:

- Identify that the GPS satellite thermal blankets were degrading faster than expected and thus an increase in the number of silver and gold multi-layer Mylar and Kevlar thermal blankets were added on future GPS satellites;
- A redesign of the #3 NiCd battery thermal radiators to allow the temperature to be controlled completely by the thermal heaters
- Increase the amount of adhesive used on telemetry sensors located outside the main body of the satellite;
- Using four atomic frequency standards per GPS satellite instead of three.
- Internal design changes to the GPS space-qualified rubidium and cesium atomic clocks to increase their usable life, performance and frequency and drift stability characteristics.
- Add 2 additional 0.1 lb thrusters to increase the opportunities to complete delta-V for period control.

## VII. Results From The Prognostic Analysis Completed on 4 Air Force's Atlas E And F Used To Launch GPS Block 1 Satellites To MEO

The Army-Air Force Atlas ICBM was reassigned as a launch vehicle due to failures in the silos of the thin-walled, lightweight first stage fuel tank that required fuel for rigidity. Beginning in 1978, ten Air Force GPS Block 1 satellites were launched using modified Atlas launch vehicles designated the Atlas E & Atlas F. The Atlas was chosen because they were readily available, cost $15M each and were easily modified for the many different satellites the Air Force was launching at the time.

In 1981, President Reagan ordered that all military and government satellites including the 100 proposed GPS Block II satellites be launched using the Space Shuttle. NASA had built five Space Shuttles planning to use all five to support the launch of all NASA and all military satellites and many commercial satellites.

Over the several hundred Atlas launches, the Atlas had a premature failure rate of 1 in 7 launches. This failure rate occurred on the launches of the GPS satellites as well. The Atlas F used the Star 37E as its upper stage SRM for placing each satellite into an elliptical orbit with a 12,000-mile apogee and 90-mile perigee. The GPS satellite also used the Star 37E SRM to raise perigee to 12,000 miles, making a circular orbit with an altitude of 12,000 miles.

The first Atlas F launched the first GPS satellite in February 1978. It was not until the 3rd launch that a prognostic analysis was completed on Atlas launch vehicle during launch readiness activities by the author on the data/telemetry during launch readiness at Vandenberg AFB. As the GPS Space and Ground Segment Manager, the author directed the launch of the first 7 GPS launches for the contractor including the GPS engineering team at Vandenberg AFB.

In the author's position, he directed the GPS Atlas launch team at Vandenberg AFB, SLC 3E and 3W to ensure that there was no transient behavior identified in the Atlas launch readiness data. The analysis was not completed on the SV-5 launch readiness data and the SV-5 Atlas F launch vehicle failed at lift off.

The SV-5 satellite was to be NAVSTAR 5, but the Atlas F failed at lift off during the launch of SV-5. The Boeing SV-7 satellites replaced SV-5 for NAVSTAR 5. SV-12 was the GPs Block 1 qualification vehicle. SV-1`2 was assembled and exposed to worse case environmental and operational conditions that met or exceeded what was to be experienced by each GPS satellite during launch and while on orbit. SV-12 was to be scrapped afterwards, due to the overexposure of the equipment to worse case conditions. However, SV-12 was refurbished and retrofitted with the first IONDS nuclear detonation detection subsystem and was launched and became NAVSTAR 7. SV-11 was transferred to the Air Force STP program and used to test new and different atomic clocks and other military payloads.

**Figure 19. Air Force Atlas E/F Launch Vehicle used to Launch GPS NAVSTAR 1 through 10 between 1978 and 1986, Eventually Upgraded to be the Atlas V Commercial and EELV Military Launch Vehicle. Under General Dynamics, the Atlas E & F Demonstrated a 1 in 7 Failure Rate Across Many Space Programs.**

**Table 6. The Use of the Air Force Atlas E & F Launch Vehicle History on the GPS Program**

| NAVSTAR # | Contractor Satellite Identifier | Launch Date | Atlas Launch Vehicle | Was a Prognostic Analysis Completed |
|---|---|---|---|---|
| 1 | SV-1 | 2/78 | F | No |
| 2 | SV-2 | 5/78 | F | No |
| 3 | SV-3 | 1078 | F | Yes |
| 4 | SV-4 | 12/78 | F | Yes |
| Note 1 | SV-5 | 2/80 | F | No |
| 5 | SV-7 | 4/80 | F | Yes |
| 6 | SV-6 | 12/81 | F | Yes |
| 7 | SV-12 | 7/83 | E | No |
| 8 | SV-8 | 6/84 | E | No |
| 9 | SV-9 | 9/84 | E | No |
| 10 | SV-10 | 10/85 | E | No |
| | SV-11 | none | none | No |

**Note 1: SV-5 launch failed and SV-7 became NAVSTAR 5**

## VIII. Results From The Prognostic Analysis Completed On SUPERBIRD B Commercial, Geostationary Communications Satellite In 1991

The commercial SUPERBIRD geostationary Ka and Ku-Band, 4 KW, 1.5 metric ton communications satellite was designed with a 21-year design life to meet a 12.5-year mission life. SUPERBIRD B was manufactured by SSL in Palo Alto CA for the Space Communications Corporation (SCC) in Japan.

SUPERBIRD was one of many communications satellites purchased by SCC that shared names to confuse the Japanese people in the event a failure occurred. In 1991, after the completion of the 3rd liquid apogee engine motor firing inserting SUPERBIRD B into a geosynchronous orbit, an NRTE was identified in the apogee engine temperature analog telemetry measurement by the author who was the SUPERBIRD B launch Contingency Director. The NRTE was used to predict the premature failure of the SUPERBIRD B liquid apogee engine by the SUPERBIRD B Contingency Director (author).

**Figure 20. An Artist's Concept of the $85M SCC/SSL SUPERBIRD B Satellite whose Apogee Engine Failure was Predicted in 1991 during Final Orbit Raising Activities in Geosynchronous Orbit Altitude.**

**Figure 21. SUPERBIRD Satellite 100 lb Apogee Thruster Motor for Reaching Geosynchronous Altitude**

The NRTE in the liquid apogee engine temperature telemetry data was identified by a follow-up thermal analysis by the SUPERBIRD thermal control subsystem engineer that was suggested by the author concluded that the SUPERBIRD apogee engine qualification temperature was exceeded and that the apogee engine could not be relied on for another firing and assumed no longer functional. The engine was not used again and the conclusion that the engine had failed was not verified.

The results of the prognostic analysis on the SUPERBIRD B apogee engine premature failure showed that the over-temperature condition was predicted to occur accurately. This over-temperature required the thermal control subsystem to be redesigned for the larger propulsion fuel tanks and the much longer apogee engine burns.

The prognostic analysis (search for an NRTE) also identified that the SCC SUPERBIRD B bi-propulsion subsystem thermal analysis completed for the design of the apogee engine failed to incorporate the extra long burn durations used for the much larger satellite which was the reason the apogee engine overheated. The satellite failed prematurely about one year later after an oxidizer isolation valve in the bi-propellant propulsion subsystem was left open for 3 days.

## IX. Results From Measuring The Satellite Subsystem Equipment Remaining Usable Life on the NASA/U.C. Berkeley EUVE Satellite [5, 12, 18, 20]

[18] In 1994, after the NASA/U/EUVE LEO satellite had completed its primary mission, the U.C. Berkeley program mamanagement decided to use the EUVE satellite as a test-bed to discover methods of collecting mission data while lowering the cost to opertae the Space Sciences Laboratory, Center for EUV Astrophysics (CEA) facility.[3]

The author, assigned as the CEA EUVE Engineering Manager and EUVE Program Manager at the CEA decided to search the satellite equipment telemetry to identify transient events that preceded equipment failures. These transients could be used to eliminate the need for mission operations and routine engineering analysis of the satellite data routinely.

**Figure 22. Artist's Concept of the NASA GSFC/U.C. Berkeley EUVE LEO Space Science Directorate Multi-Mission Satellite used by the Author at U.C. Berkeley Space Sciences Laboratory to Prove that Equipment Failures Could be Predicted and Prevented.**

The EUVE payload and Bus equipment analog telemetry was routed to the CEA using the NASA TDRSS space-based data relay system. NASA developed the CCSDS packetized format for data relay that increased the reliability of telemetry by eliminating the ppresence of an NRTE caused from RF and dataline noise. From eith poor S/N or Eb/No. This was important during the prognostic analysis completed on the EUVE satellite at the CEA becasue the telemetry at the CEA was noise free. All NRTEs present in telemetry were related to the equipment end-of-life.

[20] The results of the prognostic analysis successfully identified the presence of NRTEs that preceded each of the the satellite subsystem Bus equipment failures and the prediction for the remaining usable life matched with the actual remaining usable life within 5%.

The results from measuring the NASA EUVE satellite Bus and telescope payload 10 high-voltage photon detectors telemetry remaining usable life using proprietary predictive algorithms pioneered on the GPS program allowed the identification of the EUVE satellite subsystem equipment with an NRTE related to satellite equipment end-of-life (EOL).

These results were also provided to the NASA GSFC space science directorate in a white paper as well as published with personnel from Lockheed Martin Space Systems Company located in Sunnyvale California at the International Telemetry Foundation conference in Las Vegas NV in 1996 and 1997 and the AIAA Smallsat Conference in Ogden UT in 1997.

Table 7 summarizes only the EUVE Bus equipment whose telemetry had accelerated aging and the prediction for remaining usable life and the actual remaining usable life. The EUVE TDRSS TT&C Transmitter Unit A telemetry along with Transmitter B telemetry was to illustrate that there was not transient behavior in other equipment telemetry when Transmitter B telemetry exhibited accelerated aging.

Both EUVE Satellite TT&C Motorola TDRSS RF transmitters used in the prognostic analysis in Figure 23 were operated with a 100% duty cycle until TDRSS Transmitter B failed. Transmitter analog telemetry was available from both during the same periods. A comparison of the telemetry behavior from Transmitter A and Transmitter B in Figure 23 illustrates that there was no transient behavior present in the telemetry from Transmitter unit A.

**Table 7. Summary of Results from Measuring Remaining Usable Life on the NASA EUVE Satellite Subsystem Bus Equipment [18, 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 | 4.5 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 | note 1 | note 1 | > 6 Months | 100% |
| T/R A TU #1 | Yes | Yes | 3/94 | 12/94 | 9 months | < 6 months | 100% |
| T/R B TU #1 | Yes | Yes | 4/94 | 9/94 | 5 Months | < 6 months | 100% |

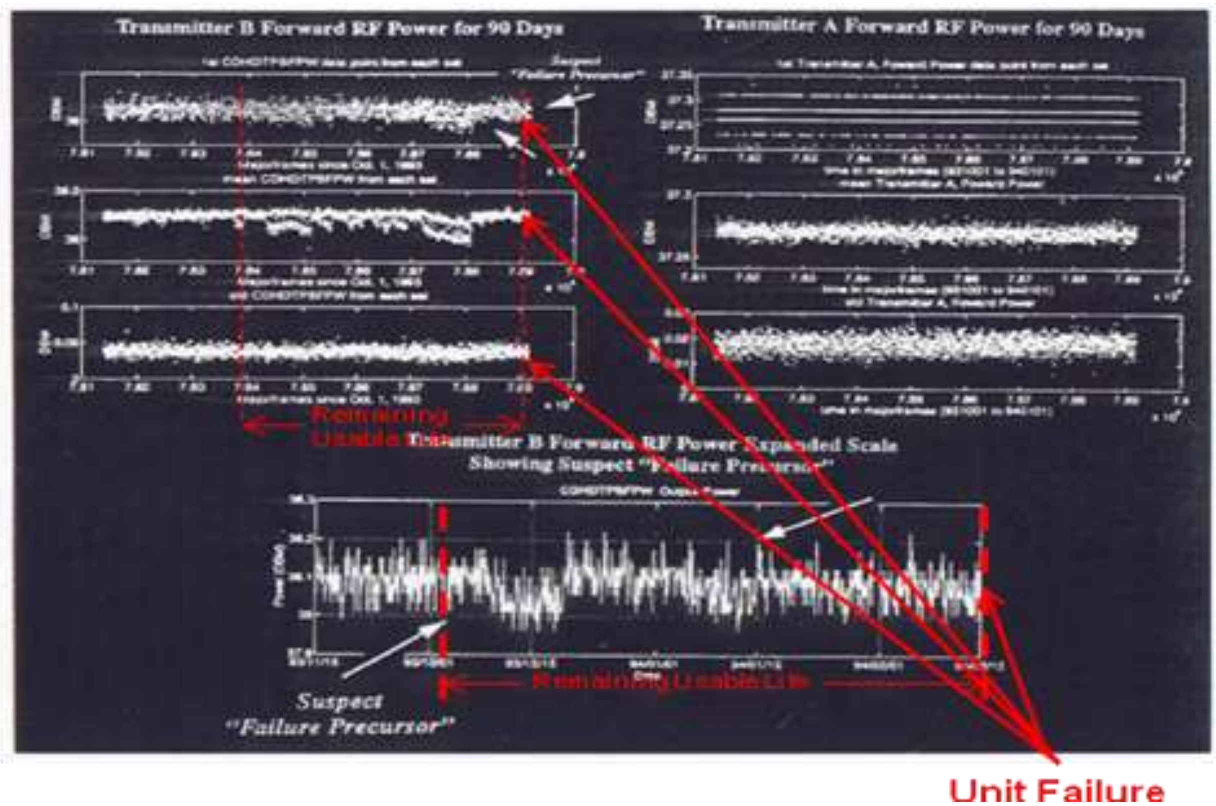



**Figure 23. Results from Measuring Remaining Usable Life of the EUVE Motorola TDRSS RF Transmitter Unit A and Unit B, Missed in the Engineering Analysis Completed by the Vendor. [18, 5]**

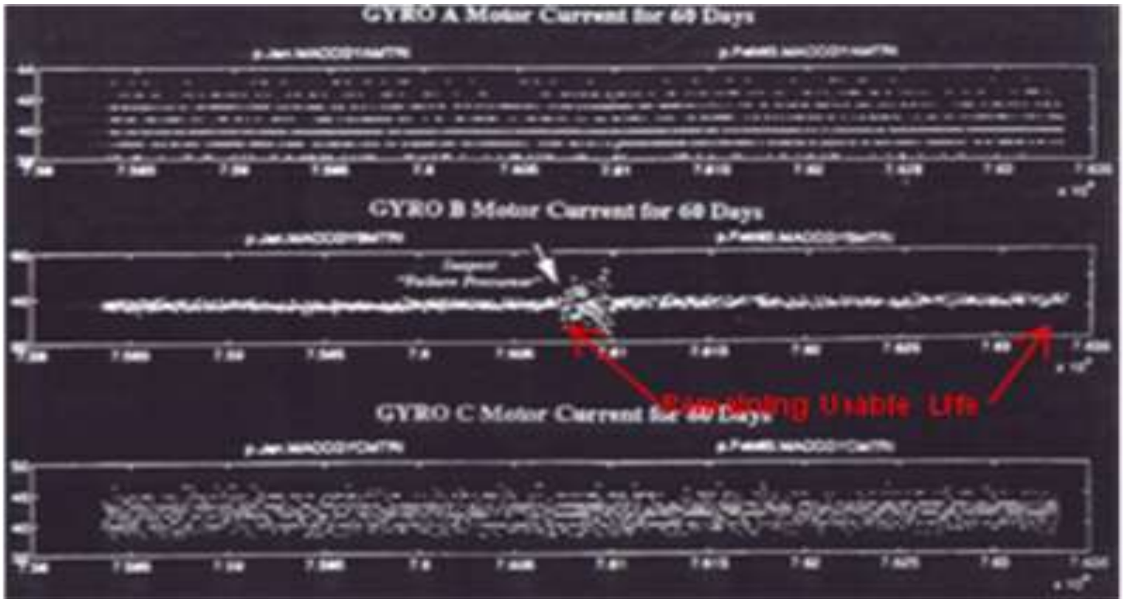



**Figure 24. Post-Processed Results Illustrating the Presence of Accelerated Aging in Gyro B Telemetry, Measuring Remaining Usable Life on the NASA EUVE Rate Gyro Unit B, missed by Engineering Analysis Completed by the Gyro Vendor. Gyro A & C Motor Current Telemetry from the same Period has no Accelerated Aging and Neither Gyro A or Gyro C Failed Prematurely** [18, 5,]

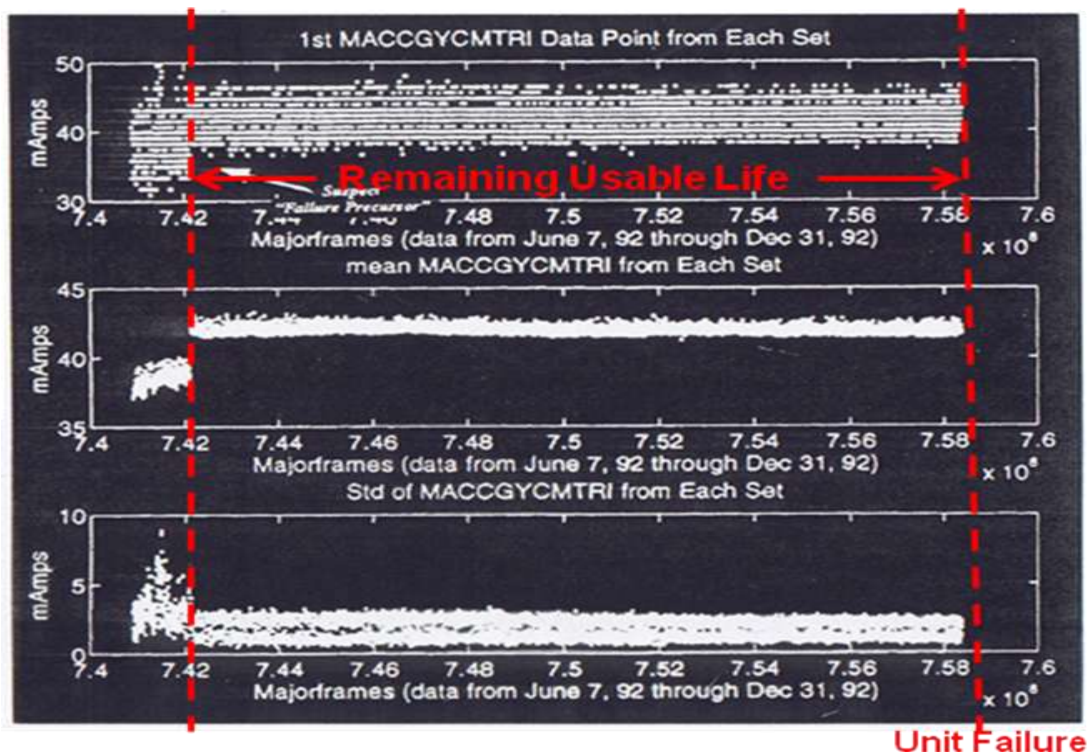



**Figure 25. Post-Processed Results Illustrating Accelerated Aging from Measuring the Remaining Usable Life on NASA EUVE Satellite Rate Gyro Unit C Motor Current Telemetry at a Late that was Missed in the Engineering Analysis Completed by the Vendor.** [18, 5]

There was no accelerated aging found in any of the 10 EUV high voltage photon detector's analog telemetry, indicating that none of the EUV photo detectors contained piece-parts that were degrading in performance prematurely. The high voltage photon detectors were predicted to function normally for at least one more year. All EUV photon detectors operated normally until the EUVE satellite burn-in over Egypt in 2002.

## X. Results from the Prognostic Analysis Completed on the NASA GOES Next-I–M Satellites

The results from the prognostic analysis completed on the GOES Next I satellite by the author who was the NASA GOES Next spacecraft manager at the builder's facility showed that there were no NRTEs in any of the GOES Next I satellite telemetry after ATP was completed.

The GOES Next I (GOES 8) satellite was the only GOES Next satellite to have a full prognostic analysis completed by the author who was the NASA spacecraft test manager, of the five GOES Next I-M satellites. As a consequence, only the GOES Next I satellite did not suffer from premature failures.

**Figure 26. The NASA/NOAA/SSL GOES I Satellite Receiving a Prognostic Analysis by the Author at the Satellite Factory Located in Palo alto CA.**

The GOES Next J-M satellite subsystem equipment sufferred from several piece-part failures during ATP and while on-orbit. The GOES Next I satellite electrical power control and distribution (PCU) unit on GOES I suffered at least 5 different failures and was finally scrapped proving that the cause of the failures were from several parts sufferring from accelerted aging. The government quality inspectors (DCMC) finally agreed that the reliability of the power control unit was in question and needed to be scrapped and DCMC personnel were not aware that the cause of the several failures during I&T was that the unit was failing and not from any specific part failing.

**Table 8. Summary of the Results from the Prognostic Analysis Completed on the 5 NASA/NOAA GOES Next I-M Satellites After ATP and before Launch**

| GOES Next Satellite | Was a Prognostic Analysis Completed Prior to Launch? | No. of Premature Equipmen Failures | Desired Mission Life (years) | Mission Life (years) Including Storage Mode | Operational Date [3] | Year Decommisioned |
|---|---|---|---|---|---|---|
| I | Yes | none | 5 | 9 | 11/94 | 5/03[3] |
| J | 80% | many | 5 | 2 | 9/95 | 1998 |
| K [1, 2] | 10% | many | 5 | 11 | 7/98 | 12/09[3] |
| L [1, 2] | 10% | many | 5 | 11 | 6/06 | 6/11[3] |
| M [1,2] | 10% | many | 5 | 7 | 4/03 | N/A |

Note 1: A full prognostic analysis was not completed. Note 2: Builder and NASA would not provide information on the number of premature failures that has occurred on GOES Next K-M satellite. Note 3: The GOES Next exceeded their mission life after their imager and/or sounder failked because of the multiple other payloads that were on-board continued to provide useful data or useful services.

Due to the poor reliability of the GOES I-M satellites from equipment that failed prematurly to function as desired and built and tested by SSL, the NASA GOES Next program management at NASA GSFC decided to take award them to another satellite builder in a competitve bid process.

After the poor reliability of the GOES I-M satellittes due to the high number of premature failures on equipment with previous flight history, NASA GSFC initiated a new contractual requirement for spacecraft builders that future satellite delivery would occur on-orbit for with payment to the builder for work completed along with a free replacement satellite in the event the satellite failed prematurely. The FAA Office of Commercial Space Transportation (OST) is updating their launch permot and licensing process for delivery on-orbit.

If NASA will require spacecraft suppliers to measure equipment usable life and replace the equipment that will fail prematurely, the requirement for space insurance can be dropped and NASA satellites will stop failing prematurely, meeting and exceeding mission life requirements and achieving mission success.


**Figure 27. A Commercially Available, Windows/Intel-Based Prognostic Analysis System using Proprietary Predictive Model-Based and Data Driven Algorithms to Convert Equipment Analog Telemetry into a Measurement of Equipment Usable Life.**

## XI. Conclusion

To produce launch vehicles and spacecraft that will provide safe transportation to space that will not fail prematurely possibly causing loss of life, the aerospace engineer needs to be trained to complete a scientific analysis on the space systems equipment test data and manufacturing process, because the engineering analysis used commonly today may use speculation and conjecture in its conclusions. The engineering analysis and the decisions that results from its conclusions used to produce space vehicle equipment has proved to be inadequate, producing the catastrophic failures of major commercial as well as military and NASA space assets including, loss of life.

The procurement contracts for rockets and spacecraft do not require contractors to identify and replace the equipment that will fail prematurely because PRA is used to determine equipment reliability. The commercial space tourist community will be negatively affected when spacecraft and launch vehicle equipment fails prematurely.

Spacecraft and launch vehicle equipment fails prematurely because builders do not and are not required to measure equipment usable life that passes factory ATP. Commercial, military and NASA spacecraft equipment analog telemetry is created by providing data from an internal circuit or mechanism (a.k.a. test points) outside the equipment for routing to remote locations. Spacecraft equipment analog telemetry is performance related data because it is information about how well the equipment is performing and equipment that passes performance-testing fails prematurely because performance data generated during testing is unrelated to equipment usable life.

Predictive algorithms demodulate telemetry behavior in time, amplitude, frequency and phase and converts analog telemetry behavior (performance data) into a measurement of equipment usable life. Measuring spacecraft equipment usable life leverages the presence of non-repeatable transient behavior. Measuring equipment usable life after ATP is completed will identify the spacecraft equipment that will fail prematurely for replacement before launch and will stop the premature failures of launch vehicles and spacecraft.

The results from a prognostic analysis of equipment telemetry behavior are superior to 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. In an engineering analysis, speculation and conjecture can be used to arrive at potential causes of a failure. A prognostic analysis is a scientific analysis that uses the same past equipment performance data used in an engineering analysis, to predict future equipment end-of-life with certainty.

The prognostic analysis completed on the NASA, Air Force and commercial satellites included in this paper was pioneered over 30 years ago on the 12 Air Force GPS Block 1 satellites. On the GPS satellites, it was demonstrated that satellite equipment with transient behavior, caused from at least one part with accelerated aging, would fail prematurely with 100% certainty.

Measuring spacecraft equipment usable life that passes ATP using a prognostic analysis will identify the on-board equipment that will fail prematurely for replacement if the prognostic analysis is completed at the equipment factory, spacecraft factory, launch pad or while the equipment is operating in space. Using telemetry to measure and confirm equipment performance (ATP) and usable life increases the importance of analog telemetry to be critical to mission success by increasing safety and mission assurance enabling the commercial space industry to initiate and sustain a successful commercial space industry and commercial space tourism industry.

## References


1. Hamberg, Otto and Tosney, William, "The Effectiveness of Satellite Dynamic Environmental Acceptance Tests" Aerospace Corporation. 1989.
2. Chang, I-Shih, Aerospace Corporation, "Launch Vehicle Reliability," Crosslink, 2001.
3. Robertson, Brent, Stoneking, Eric, "Satellite GN&C Anomaly Trends," NASA GSFC, Code 570, Greenbelt MD., paper number AAS 03-071, 2002
4. Losik, Len, "Upgrading the Space Flight Factory Acceptance Testing for Equipment and Space Vehicle Design, Manufacture, Test and Integration," AIAA Space 2009 Conference proceedings.
5. Losik, Len, "Predicting Hardware Failures and Estimating Remaining-Usable-life from Telemetry," SanLen Publishing, Sacramento, CA, 2004, ISBN 978-0-9767491-9-6
6. Frost & Sullivan, "Commercial Communications Satellite Bus Reliability Analysis," 2005.
7. Losik, Len, Wahl, Sheila, Lewis, Owen, "Predicting Hardware Failures and Estimating Remaining-Usable Life from Telemetry," Lockheed Martin Space Systems Company, Proceedings from the International Telemetry Conference, Las Vegas, NV, October, 1996
8. Cheng, Shunfeng and Pecht, Michael, "Multivariate State Estimation Technique for Remaining Usable Life Prediction of Electronic Products," Association for the Advancement of Artificial Intelligence, CALCE, 2007.
9. Losik, Len, "Stopping Launch Pad Delays and Launch Failures, Satellite Infant Mortalities and On-Orbit Satellite Failures Using Telemetry Prognostic Technology," Proceedings from the International Telemetry Conference, Las Vegas NV. October 2007.
10. Losik, Len, "GPS Quarterly Orbital Test Report," 1983, Contract 78-2543-371, CDRL Item AOO4.
11. Space Systems LORAL, GOES I-M Data Book, 2001 located at http://goes.gsfc.nasa.gov/text/goes.Databook.
12. Losik, Len, CEA EUVE Monthly Report, Center for EUV Astrophysics, U.C. Berkeley Space Sciences Laboratory, Berkeley CA. June 1995, Center for EUV Astrophysics, U.C. Berkeley.
13. Failure Analysis, "Dynamic Data-Driven Predictive Algorithms Users Guide," V2.25, Capitola CA.
14. "Space Tourism Market Study, Orbital Space Travel & Destinations with Suborbital Space Travel", 2002, Futron Corporation, Bethesda, MD.
15. "Predicting Hardware Failures & Estimating Remaining Usable Life from Telemetry," Final Report, Lockheed Martin Space Systems Company, Sunnyvale CA. 1996.
16. Pecht, Michael, "Prognostics and Health Management of Electronics," University of Maryland, Wiley & Sons Publishing, Hoboken, New Jersey, ISBN: 978-0-470-27802-4.
17. Rutan, Richard, http://www.dickrutan.com/lectures.html.
18. Losik, Len, "Results from the Prognostic Analysis Completed on the NASA EUVE Satellite," Proceedings from the 2012 IEEE Aerospace Conference, Big Sky Montana.
19. Clark, Stephan, "Spaceflight Now," http://www.spaceflightnow.com/sealaunch/is19/120619array/
20. Wahl, Sheila, Lewis, Owen, "Predicting Hardware Failures & Estimating Remaining Usable Life from Telemetry," Lockheed Martin Missiles and Space Company, Final Report, 1996.