

USING ANALOG TELEMETRY TO MEASURE EQUIPMENT MISSION LIFE AND UPGRADE FACTORY EQUIPMENT ATP

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ABSTRACT

For equipment and systems that are too expensive and too important to fail such as launch vehicles and spacecraft, the actual reliability is dominated by infant mortality failures that occur soon after dynamic environmental ATP that is used to eliminate the equipment that will fail prematurely. Premature equipment failures greatly increase risk getting to space and working in space, slowing down the growth of commercial space tourism. Premature equipment failures occur because during factory ATP, only equipment performance is measured and there is no relationship between equipment performance and equipment reliability. Accelerated aging was documented preceding GPS satellite atomic clock failures during the 10 years of the GPS Block I test and evaluation phase. Prognostic technology leverages the presence of accelerated aging to identify equipment that will fail. A prognostic analysis uses the same prognostic algorithms to convert equipment telemetry used to measure equipment performance to a time-to-failure (TTF) measurement, previously made using a probability distribution function. The equipment with accelerated aging that is present after ATP can be replaced, stopping infant mortality failures from occurring and producing equipment with 100% reliability. When all spacecraft and launch vehicle equipment that will fail prematurely are identified and replaced, satellite and launch vehicle reliability will be 100% and getting to space and working in space will be much safer.

INTRODUCTION

Today, space vehicle reliability is predicted by reliability analysis engineering, which defines reliability in probabilistic terms as a probability of success (P_s) or failure ($1-P_s$). This means that each time a reliability result is calculated; it is unrelated to any specific equipment's reliability but is a generalization for any unit that shares the same data used in the calculation. When reliability analysis was added in 1960 to the production of space vehicles, it was the best idea anyone had at the time to increase the reliability of complex systems. Many other actions were taken to increase the reliability of launch vehicles and spacecraft including powered-down redundant equipment was added for long-life systems, while powered-on standby equipment and voting schemes were added to increase the likelihood of success for launch vehicles, addition of the dynamic environmental ATP, quality improvement programs and the screening and traceability of parts was also incorporated. At almost the same time, telemetry was added to equipment from the flight test applications for retrieving aircraft test data before the test pilots were killed. After equipment failures occurred, a failure analysis was added to identify the part

that failed looking for any design flaws or process problems that could be corrected so that any future parts would not repeat the failure.

The Air Force Space and Missiles Systems Center was first informed of the presence of accelerated aging (transient behavior) preceding satellite equipment failures between 1978 and 1988 on the Air Force Global Positioning System program in contractual reports generated by Boeing GPS engineering personnel.

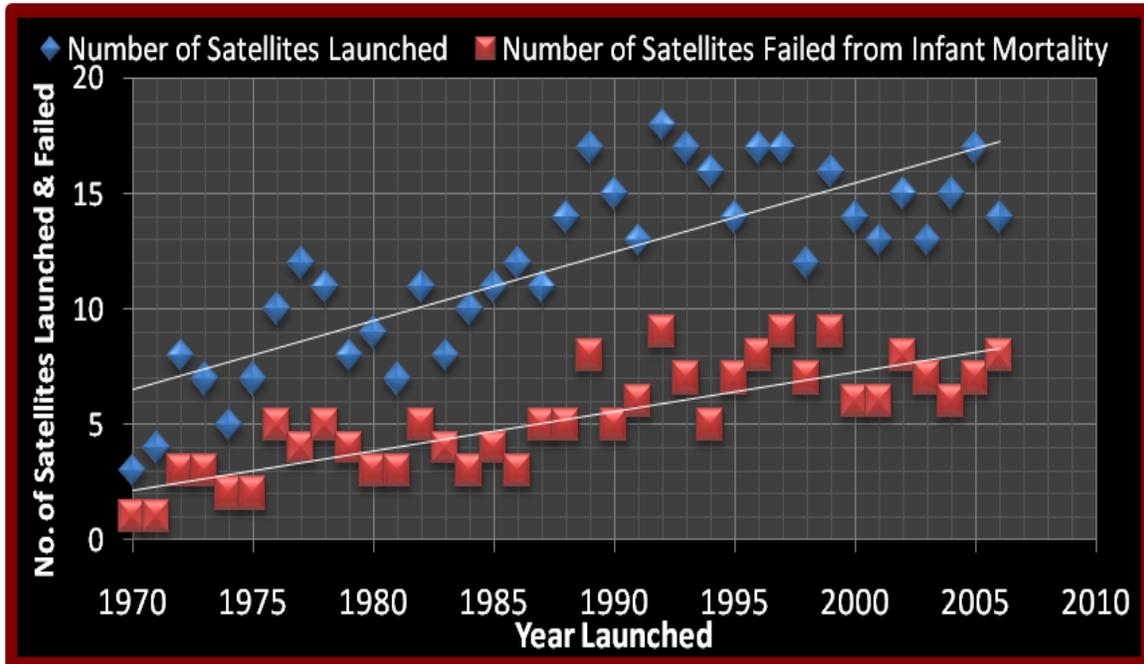


FIGURE 1 COMMERCIAL SATELLITE AND LAUNCH VEHICLE MISSIONS (BLUE) AND 25% YEARLY INFANT MORTALITY FAILURE RATES (RED) ⁷.

¹ Between 1978 and 1988, there were six GPS on-orbit satellites and six GPS satellites in production. Transient behavior was identified in the data from the six GPS satellites on-orbit atomic clocks and the same behavior was found in the GPS satellite atomic clocks on the satellites in production. The behavior was believed to be from noise and Boeing engineering personnel were instructed to ignore the behavior by the vendors. Today, prognostic technology defines the transient behavior identified on Air Force GPS satellite atomic clocks as prognostic markers that identify the equipment that will fail prematurely. Adding this one sentence to all satellite and launch vehicle contracts will move the space industry to the 100% (measured) reliability domain today. Requiring equipment to meet a measured mission life will diminish use of reliability analysis engineering that allows premature equipment failures on military space assets which is responsible many hundreds of satellites and launch vehicle losses. ² Most of today's launch vehicles meet a P_s of over 98%. Many of today's satellites meet a P_s of 90% and yet, these same space systems fail at a rate close to 25%.

² Today's satellites are expected to operate for over 15 years, many are successful and when a satellite fails prematurely within one-year, it demonstrates that the ATP required by the satellite

and launch vehicle owners for building and testing space vehicles is inadequate. In today's reliability paradigm that uses quality improvement programs, the screening and traceability of parts, testing equipment, calculating reliability and using best practices, the reliability of an ICBM/launch vehicle would be higher. To meet the P_s , contractors only have to show, using the equations in reliability analysis, that their system meets the contractual P_s reliability. Thus, the reliability calculated using reliability analysis engineering is unrelated to the reliability of any specific equipment or vehicle.

In today's reliability paradigm that uses probabilities to quantify reliability, it is technically and financially impossible to meet a P_s of 100% because the cost of increasing the likelihood of a success (P_s) increases exponentially as minor improvements may be made in P_s and 100% reliability can never be achieved using probabilities. It is premature failures failures that are eliminated using a prognostic analysis to identify the accelerated aging present in test data using prognostic technology. Since equipment reliability is dominated by infant mortality failures, eliminating the equipment with accelerated aging and thus infant mortality failures allows the production of equipment with 100% reliability.

³ In 2001, Aerospace Corporation published the results of Air Force launch vehicle reliability. This report provided the reliability of most U.S. and international launch vehicles since their inception in the 1950's. ⁴ In 2005, Aerospace Corporation published their results of their studying to explain why Air Force satellites and launch vehicles fail prematurely after exhaustive and comprehensive dynamic, environmental factory acceptance testing. The Aerospace Corporation study results blamed all contractors for a variety of (unsubstantiated) actions. We used a different strategy to understand why equipment fails prematurely after passing testing. We searched the equipment test data generated during production for the early signs of premature aging/failure (a.k.a. accelerated aging) found them and then developed prognostic algorithms that illustrate them and developed the training necessary for anyone to identify them from other normal transient behavior from fully functional equipment whose test data appears normal.

The state-of-the-art in producing satellites and launch vehicles include a 3-step testing, including flight qualification, equipment-level and vehicle-level dynamic environmental acceptance testing. The qualification test proves the equipment will operate after exposure to the worse case environmental conditions that may occur during flight. The acceptance test exposes the equipment to slightly less harmful conditions. This testing includes vibration, shock, thermal, vacuum, EMI and EMC. Each test is designed to expose the equipment to the worse case environment in a serial order and then the equipment performance is measured. This testing is used to identify the equipment that fails for repair or replacement. A failure occurs when the equipment performance is not met for any reason. Any failed equipment is repaired, replaced or salvaged. For many decades, the space industry has relied on this testing of equipment before use to produce reliable equipment possible. Space vehicle equipment is often considered highly reliable due to the extreme testing conditions used before flight. Based on the 25% failure rates of Air Force space vehicles, testing satellites is inadequate.

WHAT IS A PROGNOSTIC ANALYSIS?

A prognostic analysis is a forensic analysis that includes converting launch vehicle and satellite subsystem equipment performance data (including telemetry) generated during test, into reliability data. A prognostic analysis includes the search for latent, transient behavior, often occurring in plain sight of personnel in normal occurring test data from fully functional equipment. Often, over the decades, the presence of transient behavior and accelerated aging is ignored or misdiagnosed since is not repeatable and not associated with reliability. This behavior is often misdiagnosed and ignored. An analogy is the forensic science used at a crime scene, when for many decades the evidence used today to convict a criminal was often in plain sight of the police working the crime scene but overlooked. However, they were not trained to identify the forensic evidence and so it was ignored and many criminals were not apprehended.

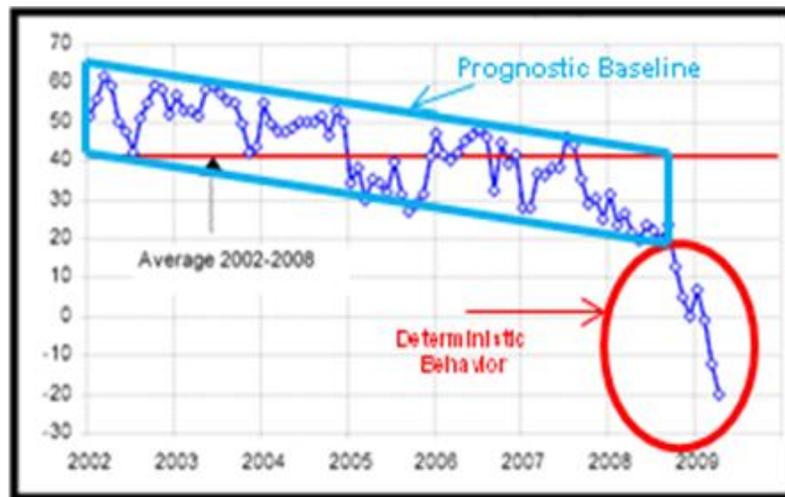


FIGURE 2 AN EXAMPLE OF A PROGNOSTIC ANALYSIS USING EQUIPMENT TELEMETRY ILLUSTRATING THE BASELINE BEHAVIOR

A prognostic analysis leverages the “analysis” of time-series data (including telemetry) to generate prognostic information. Using that same “analysis” function, we analyze the diagnostic information to generate prognostic information. We then “analyze” the prognostic (predictive) information and generate prednostic (remaining-usable-life) information. Just as a diagnostic analysis identifies past equipment behavior with great certainty, a prognostic analysis identifies future equipment behavior with great certainty. A prognostic analysis does not identify equipment that will fail prematurely from a short or open circuit from either thermal expansion or contraction and so it must be completed after ATP. Subjecting equipment to ATP will increase the likelihood that the equipment that will fail from an open or short circuit will occur during ATP.

Equipment telemetry/test points provide internal access to the behavior of equipment/products as time-series data. For industries that do not use telemetry, telemetry is developed to meet the needs of the industry and added into systems. For satellites and launch vehicles, telemetry has been the primary method for measuring the functional equipment performance. Prognostic analysis shares telemetry used to measure equipment performance to measure equipment

reliability. Engineers trained in identifying the early signs of premature aging/failure in normal appearing telemetry from fully functional equipment, search telemetry behavior for the early signs of premature aging/failure present only in telemetry from equipment that will be failing within one year of the analysis.

⁵ A prognostic analysis can be completed at any physical location using the information (telemetry) from a complex system or equipment/product. The information generated depends on when the analysis is conducted relative to a failure. When a prognostic analysis is done on equipment prior to a failure, it is an invasive measurement of the reliability of the equipment because telemetry is embedded into electrical circuits and mechanisms. A prognostic analysis can determine if the equipment/product will function normally for at least one year. Just as diagnostic activities (e.g. troubleshooting, data collection, data reduction, data display, data analysis, failure analysis etc.) allows the identification of what has caused a problem/failures, a prognostic analysis identifies the problem/failure that is going to occur in the near future (up to 1 year in advance).

Prognostic markers/deterministic behavior mimic other behavior such as such as transients from equipment cycling, sensor failure, noise and corrupted data. Our training allows the discrimination of deterministic behavior from other normal occurring behavior. Today a failure analysis is conducted to identify what failed. Further investigation can identify why the unit failed such as a flawed part. Further investigation can identify why the flawed part was flawed and how to stop flawed parts from being used. These are all actions after a failure has occurred.

In a prognostic analysis, normal baseline behavior is determined first, in the event that insufficient information is available to develop and baseline behavior, algorithms are provided to generate virtual baseline behavior from on an understanding and definition of what the baseline behavior should be. After the amount of information available for a prognostic analysis is known, the data is compiled using our data summation algorithm.

In a prognostic analysis, equipment telemetry is evaluated looking for noise, corrupted data and other behavior that may mimic deterministic behavior that can be caused by transients from normal equipment cycling, noise and sensor failure. If signal or data noise is present, our algorithms will replace/remove it with contiguous data, corrupted data will be replaced and/or removed. In the event that there is insufficient data to develop a baseline, algorithms are available to use whatever data is available and fill in where data is missing and predict future normal behavior.

The search for accelerated aging must be made after ATP because ATP will identify equipment that will fail from a short or open circuit caused from thermal expansion and ensure that sufficient design margins were used.

PREDICTING EQUIPMENT TIME-TO-FAILURE (TTF) USING PROGNOSTIC ANALYSIS

In reliability analysis, the reliability of large quantities of parts and equipment are determined. When individual performance of parts and equipment is not measured, a stochastic

process in reliability analysis provides probabilities of events occurring based on commonly acceptable distribution curves. These distribution curves model many behaviors.

⁶To predict an accurate time-to-failure (remaining-usable-life) after the early signs of failure are detected, we use the cumulative distribution curve developed from our proprietary database of aerospace/vehicle equipment failures we have analyzed over 30-years. Distribution curves model normal occurring behavior and are tools used to quantify the failure rates at a complex system such as an aircraft the beginning-of-life, normal lifetime and end-of-lifetime failure rate. In the equipment failures we analyzed, we measured the duration between the failure precursor and the actual failure to generate the cumulative distribution. We have used this cumulative distribution to predict the duration of remaining usable with 100% accuracy.

HOW TO MEASURE EQUIPMENT REMAINING USABLE USING PERFORMANCE DATA

To measure equipment reliability using performance data, we complete a prognostic analysis and search for accelerated aging in the equipment times-series operational data (telemetry). We use prognostic algorithms to illustrate the accelerated aging, which is often present in normal appearing data from fully functional equipment. The performance data that is converted into reliability data includes equipment telemetry of any type of data and engineering units including the most common telemetry available from equipment suppliers.

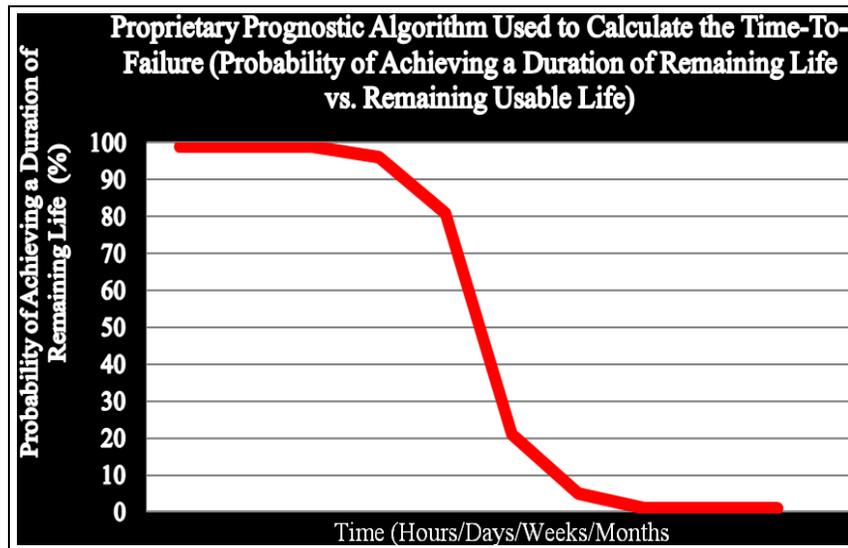


FIGURE 3 PROPRIETARY CUMULATIVE DISTRIBUTION USED TO DETERMINE THE TIME-TO-FAILURE PS FOR EQUIPMENT WITH ACCELERATED AGING

Equipment with accelerated aging will fail prematurely with 100% certainty. Just as in reliability analysis that calculates MTBF (mean-time-between-failures) which is a statistical result, our TTF is a statistical result based on the remaining usable life generated from many other equipment failures in our proprietary database of satellite and launch vehicle equipment failure we have conducted prognostic analysis.

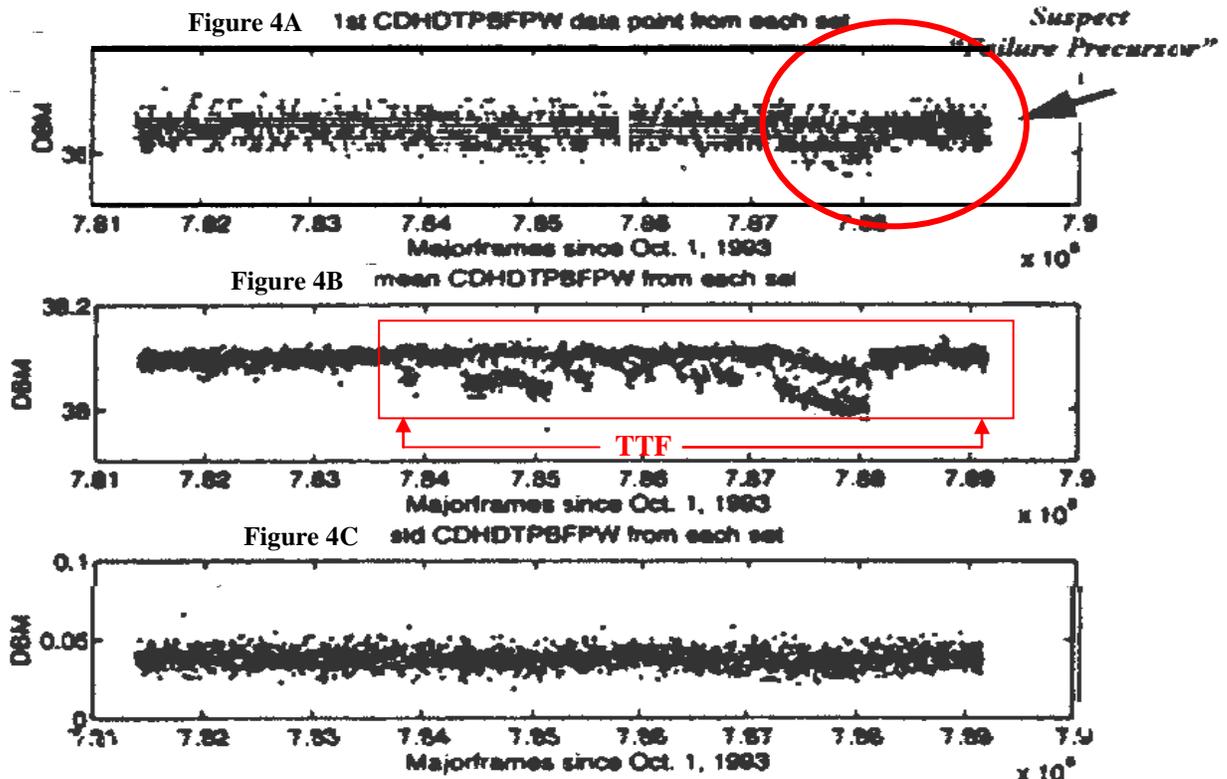


FIGURE 4 POST PROCESSING RESULTS FROM THE PROGNOSTIC ANALYSIS OF THE NASA EUVE MOTOROLA TDRSS TRANSPONDER

A prognostic analysis can use as little as one analog measurement or an unlimited number of analog measurements. We use data mining algorithms to correlate accelerated aging behavior occurring from several time series measurements. Accelerated aging is caused from the premature aging (relative to the other parts in the unit) of at least one part in either the electrical and/or mechanical circuits/assemblies and the effect of part(s) with accelerated aging has on the circuit/assembly operation as observed in unit telemetry.

³ The many difficulties of identifying accelerated aging includes it is latent, transient behavior that is never duplicated and thus the accelerated aging observed in one unit cannot be used to identify the behavior in another unit. The identification of accelerated aging in performance data may occur in one analog measurement or any number of measurements as well as the unit's functional performance data, the ability of the unit to receive and transmit information. The prognostic analysis algorithms will illustrate accelerated aging, which is often in normal appearing performance data from fully functional equipment that fail when initially used.

Accelerated aging expresses itself as latent, random appearing and unexpected transient behavior, whose entire data set is never repeated and thus pattern recognition systems cannot identify it in similar units. The unexpected (after diagnostic analysis is completed) transient behavior cannot be correlated with other normal component/assembly behavior that induces

transient behavior such as thermal heater cycling or equipment power cycling. Accelerated aging is deterministic behavior, which when deterministic behavior is in the unit's analog telemetry or functional performance, the resulting behavior of the units operational condition is fully predictable. The initiation of accelerated aging in equipment telemetry and/or functional performance from the equipment beginning of life (BOL) is random, but once accelerated aging is initiated, the end of life (EOL) of the unit is certain and the time-to-failure (remaining usable life) is predictable.

CONCLUSIONS

Space vehicle equipment, and space vehicle reliability is dominated by premature failures that occur within one year of use. These can be eliminated using a forensic (prognostic) analysis after equipment and vehicle testing is completed to identify the equipment with accelerated aging. A forensic (prognostic) analysis illustrates accelerated aging in equipment test data that will fail prematurely with 100% certainty that is present up to one year in advance of a failure. A prognostic analysis includes converting equipment performance data (including but not limited to equipment telemetry) collected during factory test into reliability by using the start of the accelerated aging and our proprietary cumulative distribution to define the equipment time-to-failure/remaining usable life. By identifying the equipment that will fail premature for replacement using a prognostic analysis, spacecraft, satellites and launch vehicles will have 100% reliability and getting to space, working and visiting space will be safe. Prognostic technology and prognostic analysis is for equipment that is too expensive and too important to fail.

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