STOPPING LAUNCH PAD DELAYS, LAUNCH FAILURES, SATELLITE INFANT MORTALITIES AND ON ORBIT SATELLITE FAILURES USING TELEMETRY PROGNOSTIC TECHNOLOGY

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ABSTRACT

Telemetry Prognostics is Failure Prediction™ using telemetry for launch vehicle and satellite space flight equipment to stop launch failures, launch pad delays, satellite infant mortalities and satellite on orbit failures. This technology characterizes telemetry behaviors that are latent, transient, and go undetected by the most experienced engineering personnel and software diagnostic tools during integration and test, launch operations and on orbit activities stopping launch pad delays, launch failures, infant mortalities and on orbit failures. Telemetry prognostics yield a technology with state-of-the-art innovative techniques for determining critical on-board equipment remaining useful life taking into account system states, attitude reorientations, equipment usage patterns, failure modes and piece part failure characteristics to increase the reliability, usability, serviceability, availability and safety of our nation's space systems.

Key Words

Satellite, Launch Vehicle, Telemetry Prognostics, Failure Prediction, Failure Analysis, Telemetry, Diagnostics, Rocket Failures, Rocket Explosions, Failure Analysis

INTRODUCTION

Aerospace telemetry started in January, 1930 with the radiosonde, a device that automatically measured temperature, barometric pressure and humidity from a balloon high in space, and sent the data back to Earth using a radio signal. The radiosonde dates back to when Pavel A. Molchanov, a Russian meteorologist, made a successful radio sounding into the stratosphere. His goal was an inexpensive and expendable means of sounding the atmosphere for temperature, moisture and wind data.

In-flight instrumentation systems were used more and more after World War II, and missile behavior as well as environmental conditions during the entire flight phase and observed through radio links. The technology of telemetry coverage opened a new area for missile design engineers to obtain valuable data for further study programs. Theoretical data could be hardened by actual data, and values could be obtained for the anticipated new missile programs. The telemetry measuring program expanded from between 30 and 40 diagnostic measurements to between 500 and 600 measurements per flight. All these measuring circuits had to be incorporated into the overall system in such a way as to not interfere with the standard system necessary for proper flight performance. The telemetry records gave perfect coverage and usually a quick explanation to system behavior.

LAUNCH VEHICLE DEVELOPMENT

In July 1955, the White House announced plans to launch an Earth-orbiting satellite for the international geophysical year (IGY) and solicited proposals from various government research agencies to undertake development. In September 1955, the Naval Research Laboratory's Vanguard proposal was chosen to represent the U.S. during the IGY. History changed on October 4, 1957, when the Soviet Union successfully launched the world’s first satellite, Sputnik I. The world's first artificial satellite was about the size of a basketball, weighed only 183 pounds, and took about 98 minutes to orbit the Earth on its elliptical path. That launch ushered in new political, military, technological, and scientific developments. While the Sputnik launch was a single event, it marked the start of the space age and the U.S.-U.S.S.R space race.

As new missiles were fielded by the Russians and Americans, rather than discard older technology missiles, NASA, DOD and the Air Force studied a strategy for expanding launch vehicle availability in 1959 using retired missiles. In 1961, they recommended that low reliable and dangerous retired Titan missiles be modified for use as military unmanned launch vehicles. Titans were hypergolic fueled rockets with fuel that ignited on contact and were dangerous when stored in missile silos. Several Titan missiles had exploded in their silos killing all who were in side. Using Titan missiles as a launch vehicle didn’t require storing them in silos. With over 300 retired and soon to be retired Titan missiles, the Air Force adopted the Titan missile as their only space launch vehicle and Martin Company, the builder of the Titan, as a sole source supplier. Titan was also upgraded for manned space launch on the NASA Gemini program.

With almost 360 Atlas retired missiles available for launch, in the 1970’s, retired Atlas missiles began to be used as Air Force unmanned launch vehicles as well. At the start of the program, Atlas launch failure rate was as high as 15%. The development of Titan and Atlas missiles resulted in the less capable Thor missile being retired from military service in 1963. However, some of the retired Thor missiles found use with NASA as the Delta launch vehicle and were modified and used extensively for space research, either as a single-stage booster or in combination with various types of upper stages for such projects as the TIROS, TELSTAR, Pioneer, and Discoverer programs. Delta payload capacity grew. Until the early 1980s, Delta served as NASA's primary launch vehicle for boosting communications, weather, science and planetary exploration satellites into orbit acquiring a launch failure rate as low as of 1 in 20 launches.

The practices used by the missile industry in test included passive monitoring of system performance with a minimum of instrumentation. Engineers would be directed to minimize the instrumentation of the missiles under test to avoid complexity and cost. Proper instrumentation impacted reliability, complexity and cost significantly due to more complex circuit design and wiring needs but testing could be completed sooner. Since reliability was successfully countered by increases in quantity of missiles purchased, adequate telemetry instrumentation of missiles could not be justified by the missile designers. Missile suppliers were rewarded with larger production contracts for lower reliable systems.

SATELLITE TELEMETRY DEVELOPMENT

Telemetry for satellites began on the Soviet satellite Sputnik, launched in 1957. Sputnik used a dual frequency telemetry downlink. In 1960, the interrogation-reply principle so popular today was developed. This is a highly automated arrangement used today in which the transmitter at the measuring location automatically transmits needed data only after being signaled. The interrogation-reply principle is now used in such fields as nuclear power generating reactors, oil-pipeline monitor-control systems and oceanography.

Satellites began to grow in size and complexity as the launch vehicle lift capability increased. Launch reliability improved slightly. Old missiles added strap on motors and upper stages for increasing lift capability but did not upgrade their telemetry systems. In the 1960's, NASA and the Air Force planned parallel manned space programs and designed high capacity telemetry systems. In 1968, Congress decided that NASA would be responsible for manned space flight. The Air Force converted their manned space assets over to unmanned.

FIGURE 1 - AIR FORCE SATELLITE TEST CENTER SUNNYVALE, CA WHERE TELEMETRY PROGNOSTICS WAS CREATED

The Air Force opened the Air Force Satellite Control Network (AFSCN) in 1969, comprising of many independently designed telemetry processing stations located around the world and a central mission control complex in Sunnyvale, California originally designed to support the Air Force soldier in space. The Aerospace Corporation emerged as the technical arm of the Air Force and standardized military satellite communications providing continuity on space programs where the military program officers were forced to relocate every 4 years. Telemetry systems capacity increased as user demands increased. Telemetry diagnostics techniques for telemetry were taken directly from missile and space launch vehicle ground testing for satellites and use was used universally. Passive monitoring was used in test to evaluate system performance and it found a place in satellite diagnostics.

With the creation of the Space Shuttle in the mid-1970s, a requirement for a higher performance space-based telemetry system arose. At the end of the Apollo program, NASA realized that MSFN and STADAN had evolved to have similar capabilities and decided to merge the two networks to create the Space flight Tracking and Data Network (STDN). In 1976, Telemetry was standardized in the IRIG 106 Telemetry Standard, generated and maintained by the Range Commander Council, US Army. IRIG 106 is used by many industries around the world.

WHAT IS TELEMETRY PROGNOSTICS?

Telemetry Prognostics is the prediction of flight equipment failures using telemetry behaving well within normal operating characteristics as well as behavior which is obviously anomalous. It allows for stopping and postponing space flight equipment failures before they occur, extending remaining usable life for equipment that remains operational though starting to fail, predicting the day the equipment will fail and isolating the cause for flight equipment failures to the component level. These translate directly in stopping launch pad delays, launch failures, on orbit infant mortalities, on orbit failures and not meeting mission life durations.

Telemetry Prognostics requires major change in analysis. Prognosticians actively monitors data to provide knowledge of whether a failure has occurred, is occurring or when a failure is likely to occur. It can stop actions when events occur. Prognosticians don't watch passively as all events are considered failure precursors until ruled out – analyst doesn't stand by and watch failures occur but reacts to telemetry events with active monitoring and action plans. A fault propagation model extends to encompass parametric data related to acceptable operating ranges, behavior and identification of degradation of functions over time. Failure Prediction™ requires high skilled personnel and in-depth knowledge of what is being actively monitored. It requires flight equipment circuit design, DC circuit analysis, circuit trouble shooting, telemetry circuit design, telemetry analysis, mechanical engineering and mission operations experience.

HISTORY OF TELEMETRY PROGNOSTICS

To reduce the risk of poor performance during the first Phase 1 testing, in 1978 the GPS Air Force program office contracted with Rockwell International, the builders of the first 12 GPS satellites for an engineering staff that would analyze all GPS satellite CDMA spread spectrum payload and SGLS TT&C downlink data and determine the reliability of the operating satellite equipment. Figure 1 is the GPS Block I satellite that Failure Analysis' Failure Prediction™ technology was developed for. The Air Force made an investment in engineering resources to secure the success of a very important program. Between 1978 and 1984 this high fidelity analysis conducted by the Rockwell satellite subsystem engineering team yielding the knowledge of the status of every aspect of the in orbit satellite hardware and the downlink payload performance, a correlation with TT&C measurement behavior and downlink navigational solution accuracy. In addition, because the Air Force needed to know what the performance of the satellites payloads were going to be in the weeks and months ahead for critical future system testing, the capability to identify satellite measurement behavior indicating an upcoming failure was imminent was successfully developed by the Rockwell engineering team based on the example of the GPS Kalman filter technology used at the GPS Master Upload Station at Vandenberg Air Force Station for predicting future frequency standard clock stability performance. The GPS Master Control Upload Station used a Kalman filter, to predict future navigation message variables and generate upload message predictions of navigation message variables accurate for up to 6 months.

The active satellite missions critical to the U.S. national defense, received the majority of remote tracking station use. GPS was in a test and concept validation phase and received very low priority for use of the remote tracking stations and was initially not allowed to use remote tracking station resources to collect engineering data. In a 24 hour period, GPS Phase I mission control personnel received only 40 minutes per satellite of real-time telemetry to determine the state of the equipment on board

Using the maximum (40 minutes/day) amount of telemetry available for each orbiting satellite, mathematical models were created using a new technique for predicting normal telemetry behavior using very little telemetry. Super-impositioning and harmonic/Fourier analysis that modeled each source of influence on measurement behavior and generated future expected behavior for comparison with actual telemetry behavior. However, because of the normal satellite maintenance activities cycling electrical power which influenced satellite measurements across the entire satellite, RFI induced TT&C equipment cycling, upload station activating the TT&C equipment, lack of telemetry on heaters, minimum temperatures were often controlled by thermostatically controlled heaters, unavailable high frequency response from the regulated bus power (28VDC) and DC/DC power supplies used on most equipment, LC and RC circuit time constants were not observable in the coarse 8-bit word resolution and the narrow data bandwidth (KHz) of GPS telemetry. All this caused the reliability of the predicted telemetry behavior comparison to actual telemetry behavior to be poor. Improvement to the modeling was needed.

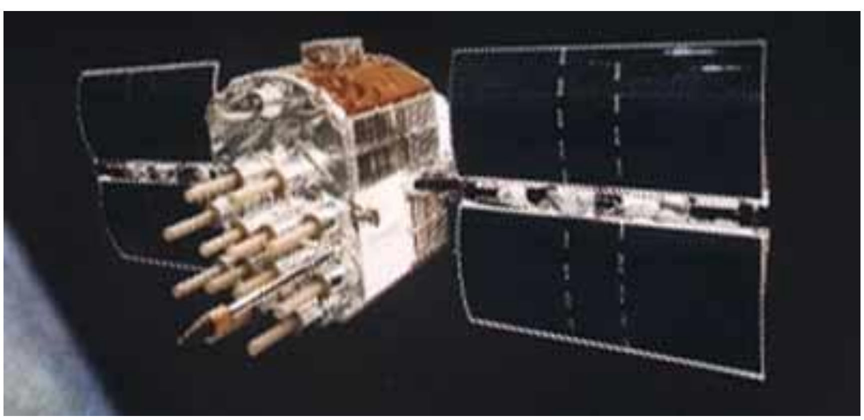

FIGURE 1 – PHASE I GPS SATELLITE WAS THE FIRST SATELLITE FAILURE PREDICTION™ TECHNOLOGY WAS DEVELOPED FOR

Normal occurring variations in telemetry behavior were ignorable but required many hours to disappear in telemetry, leaving many hours, and sometimes days, when the Prognostics were not in use leaving the satellite equipment vulnerable to failures without detection relying on traditional telemetry diagnostic techniques. Mathematical was used to model normal telemetry behavior. Because of the many years of long term, intense problem solving to provide high fidelity analysis on each telemetry measurement across all GPS satellites, and the Prognostic solutions developed, the engineering staff uncovered and identified unusual telemetry behavior well within the normal operating behavior on some satellite equipment measurements which later failed catastrophically.

BENEFITS OF TELEMETRY PROGNOSTICS TO THE GPS PROGRAM

The successful Failure Prediction^{tm} technology was used by the Air Force GPS program management to maximize the success of GPS system testing which yielded tremendous performance advantages over existing space based navigational systems such as TRANSIT and TIMATION and motivated the Air Force in 1980 to fund the complete program. The success of the Telemetry Prognostics on the tri-service flight tests allowed the Air Force to shrink the GPS program and downscale it into just 2 phases, reducing the total number of satellites needed over a 10 year period by 12, resulting in billions of program dollars saved and a shortening of the schedule for full operational constellation implementation by over 10 years. The use of Telemetry Prognostics technology on GPS satellites resulted in the successful funding of the program by the US military to the operational constellation of 24 satellites, advancements in the design of the on board frequency standards, improvements in the next generation GPS satellites renamed Block II from the Phase 1 and performance improvements across satellite payload and subsystem hardware and software resulting in increase performance, reliability and serviceability.

Table 1 provides a history of the satellites that the author used Failure Prediction™ technology on. Table 2 provides the launch vehicles Failure Prediction™ technology has been used on.

TABLE 1 - SUMMARY OF SATELLITE TELEMETRY PROGNOSTICS EXPERIENCE

Satellite Telemetry Prognostics Used On	# of Failures Predicted/ Occurred	Final Orbit Shape	Final Orbit Inclination	Final Orbit Period	On Orbit Attitude Control	Location Telemetry Prognostics Completed
Air Force GPS Satellites: NAVSTAR 1 NAVSTAR 2 NAVSTAR 3 NAVSTAR 4 NAVSTAR 5 NAVSTAR 6	 5/5 7/7 8/8 8/8 5/5 5/5	Circular (MEO)	63°	12 hrs	Spin Stabilized 3-Axis Stabilized	Launch Pad Early Orbit On Orbit
NASA EUVE	7/7	Circular (LEO)	28°	1.5 hrs	3-Axis Stabilized	On Orbit
NASA GOES I	0/0	Circular (GEO)	0°	24 hrs	3-Axis Stabilized	Factory
SCC	1/1	Circular	0°	24 hrs	3-Axis	Launch Pad

SUPERBIRD		(GEO)			Stabilized	On Orbit
INTELSAT 7&7A	0/0	Circular (GEO)	0°	24 hrs	3-Axis Stabilized	Factory

TABLE 2 - LAUNCH VEHICLES TELEMETRY PROGNOSTICS EXPERIENCE

LAUNCH VEHICLE	INJECTION ORBIT	LOCATION
TITAN 34C	LEO Circular Orbit	LV Factory
TITAN 34D	LEO Circular Orbit	LV Factory
TITAN III	LEO Circular Orbit	LV Factory
TITAN IV	LEO Circular Orbit	LV Factory
ATLAS D	LEO Circular Orbit	Launch Site
ATLAS E	LEO Circular Orbit	Launch Site
ATLAS F	LEO Circular Orbit	Launch Site
ARIANE 44L	GEO Transfer Orbit	Satellite Factory

ADVANTAGES OF FAILURE PREDICTION™

To the Satellite System Owner - Lowers risk of mission failure, lowers insurance premiums.
To the Satellite System Insurance Company – Lowers risk of mission failure.
To the Flight Equipment Supplier - Reduces shipping faulty equipment, reduces infant mortalities, increases equipment reliability, reduces equipment returns.
During LV or Satellite Factory I & T - Reduces shipping of faulty equipment to the launch pad, reduces delivery delays to launch pad, decreases launch pad delays, increases equipment reliability, identifies infant mortality candidates, increases equipment reliability.
During Satellite & LV Integration - Identifies infant mortality candidates, reduces launch delays, reduces launching faulty equipment, increases equipment returns, increases equipment reliability.
During Launch Readiness - Identifies infant mortality candidates, predicts launch failures, reduces launch failures, reduces launch delays, reduces launching faulty equipment, increases equipment reliability.
During On Orbit Mission Operations – Stops on orbit failures, identifies infant mortality candidates, predicts future equipment failures, extends equipment mission life, reduces service downtime, increases system availability, increases equipment serviceability, lowers cost, increases equipment reliability.

BENEFITS OF TELEMETRY PROGNOSTICS

Telemetry Prognostics can be used on existing satellites and launch vehicles using existing telemetry systems capabilities and accuracy. It eliminates on orbit infant mortalities and stops the launching of faulty equipment. It stops on-orbit failures before they occur, reduces launch pad delays, reduces launch vehicle failures, extends usable remaining equipment life on faulty equipment. Telemetry Prognostics identifies flight equipment that is going to fail, predicts day of equipment failure, extends on orbit mission life, increases satellite services availability reducing payload downtime, increases satellite and launch vehicle reliability and allows time to generate recovery plans before failure and is flight proven.

FEATURES OF TELEMETRY PROGNOSTICS

Telemetry Prognosticians accentuates latent, transient information that predicts future flight equipment failure in normal appearing telemetry. A prognostician detects future failures in high stressed operational environment such as launch. Results allow observing individual component or circuit failure as it is occurring. It is insensitive to quantity of telemetry available for analysis, sample rate and needs very little information to be conclusive. It is insensitive to (quality) noisy or unreliable telemetry, insensitive to least significant bit resolution. It is flight proven, platform independent and developed for use on existing missile, satellite, computer, electrical power reactor, automotive, commercial aircraft, aircraft development, helicopters, medical and launch vehicle telemetry systems.

FAILURE PREDICTION™ TECHNOLOGIES FOR STOPPING LAUNCH PAD DELAYS, LAUNCH FAILURES, INFANT MORTALITIES AND ON ORBIT SATELLITE FAILURES AVAILABLE FOR LICENSING FROM FAILURE ANALYSIS

The following technologies are available singly or in bundles. Their need is based on the capability that which already exists at the satellite, launch vehicle builder's factory and the mission control center. Each technology may not be needed at each area. Failure Analysis recommends completing failure prediction at the flight equipment supplier's factory after acceptance testing is completed, the satellite factory after satellite level acceptance testing, at the launch pad after LV and satellite integration is completed, after early orbit operations are complete and at 3 month intervals on orbit.

Technology	Purpose
Telemetry Authentication	This is used to remove noise and make the telemetry error free before super impositioning to eliminate false positives.
Super impositioning	Used to create baseline telemetry behavior from very little telemetry. Allows for the creation of mathematical formulas that generate virtual telemetry.
Rate Change Analysis	High rate changes for measurements indicate active telemetry behavior requiring research as to the cause.
Super Precision	Super precision decreases noisy data and clutter and eliminate false positives.

Mathematical Modeling	Used to create virtual telemetry.
Virtual Telemetry	Used to predict normal telemetry behavior when only insufficient telemetry is available.
Database Development	Used to create new high reliable, small size database for processing with Prognostics when access to telemetry database is not available.
SFI, SDI, NFI, NDI sampling	Used to reduce amount of telemetry for processing while not loosing accuracy.
Data Mining	Used to access large telemetry databases to generate end product results**.**
Digital Processing	Used to enhance resolution of graphics.
Active Diagnostics	Used to react to failure precursors and determine actions to take and eliminate false positives.
Active Reasoning	Used to determine failure in process.
State Based Analysis	Used to isolate unexpected equipment configuration and focus Telemetry Prognostic analysis.
Discrimination Analysis	Used to isolate failure precursor telemetry from virtual telemetry and eliminate false positives.
Change Analysis	Used to separate failure precursor telemetry from virtual telemetry and eliminate false positives.
Baseline Analysis	Used to determine what telemetry to be investigated for failure in process
Failure Precursor Pattern Recognition	Used to recognize anomalous behavior in normal appearing telemetry and eliminate false positives.
Root Cause Failure Analysis	Used to determine what piece part component is failing in circuit and how much longer equipment will operate.
Remaining Usable Life	Based on proprietary historical piece part component failure performance data.
Predicting Day of Failure	Determined by proprietary historical piece part component failure performance data.

Table 3 identifies the location that each technology used in Failure Prediction™ is recommended to be used by Failure Analysis.

TABLE 3 – WHAT TECHNOLOGY IS NEEDED AT EACH LOCATION OF SPACE FLIGHT HARDWARE DEVELOPMENT, TEST AND INTEGRATION

Failure Prediction™ Technology	**Equipment Supplier Factory**	**Satellite Factory**	**Launch Vehicle Factory**	**Launch Site**	**Mission Control Center**
Active Reasoning	X	X	X	X	X
Baseline Analysis	X	X	X	X	X
Change Analysis		X	X	X	X
Data Mining		X	X	X	X
Digital Processing					X
Discrimination Analysis	X	X	X	X	X
Failure Precursor Pattern Recognition	X	X	X	X	X

Data Base Creation					X
Mathematical Modeling	X	X	X	X	X
Predicting Day of Failure	X	X	X	X	X
Proactive Diagnostics	X	X	X	X	X
Rate Change Analysis		X	X	X	X
Remaining Usable Life	X	X	X	X	X
Root Cause Failure Analysis	X	X	X	X	X
SFI, SDI, NFI, NDI sampling		X	X	X	X
State Change Analysis		X	X	X	X
Super Impositioning					X
Super Precision					X
Telemetry Authentication					X
Virtual Telemetry	X	X	X	X	X

CONCLUSION

Telemetry Prognostics is a revolution in the use of Telemetry systems on satellites and launch vehicles. Its technology is ground tested and flight proven for both satellite and launch vehicles and decreases system risk for satellite owners and increases satellite and launch vehicle reliability for space system suppliers. Telemetry Prognostics offers a leap in technology over existing diagnostic techniques that do not allow for determining future system states. Telemetry Prognostics return on investment is high, offering to save satellite owners, space insurance companies and American tax payers hundreds of billions of dollars in failed space missions. Failure Prediction™ technology can also be used in other industries that rely on telemetry to determine equipment operations and performance such as nuclear power, automotive, medical, computer and consumer electronic products.

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