Presents

An Introduction to Telemetry Prognostic Technology

by Len Losik

For

SPACE SYSTEMS LORAL
Failure Analysis
Engineering Services

Topics

- Reason for visit
- Company Information
- Telemetry Information
- Failure Prediction™ Description
- Benefits
- Features
- Advantages
- History of Telemetry Prognostics
- Flight History
- End Products
- Failure Prediction™ Performance
- Impact on SS/L
- Other Applications
- Conclusion

1/13/2014
Reason for visit to SS/L

- Introduce SS/L to Telemetry Prognostics and Failure Prediction™ technology
- Recommend SS/L incorporate Failure Analysis’ Failure Prediction™ Telemetry Prognostics technology for upgrading equipment and spacecraft design, manufacturing, I&T and mission operations activities
- For SS/L to identify existing telemetry database formats and accessibility used in I&T, mission operations and what formats might be used in the future
Company Information

- Founded in October, 2006 to market Telemetry Prognostic technology to industries that use telemetry
- Located in Salinas California, 70 miles south of NASA Ames Research Center, at the Creek Bridge Commercial Office Complex, near Silicon Valley
- Small Business
  - 8 Employees and volunteers
  - 1500 ft² office
- Company founder pioneered telemetry prognostics over 25 years ago
Failure Analysis
Engineering Services

Company Services

Engineering Services
- Vehicle Design
- C&DH/TT&C/TC&R Subsystem Design
- Communications System Design
  - WIFI, WIMAX & Bluetooth
- Ground Station Design
- Mission Control Center Design

Technology Licensing
- Failure Prediction™ technology

Insurance
- For catastrophic equipment failure liability
Failure Analysis

Engineering Services

- Telemetry Prognostics Technology Licensing
  - Space Flight Equipment Suppliers
  - Satellite Builders
  - Launch Vehicle Builders
  - On-Orbit Satellite Owners & Operators
- Have available necessary technical resources
  - Commercially available software tools
  - Training materials
  - User manual
  - Reference books
  - Training personnel
Failure Analysis
Engineering Services

- **Insurance Services**
  - For launch vehicles, satellites and equipment that has failed
    - Research historical telemetry from factory/on-orbit to identify liable company
      - Failure precursors occur many months even years before catastrophic failure occurs allowing equipment to be repaired/replaced before launch
  - For on orbit equipment that hasn’t failed
    - Analyze telemetry database and find failure precursors to identify remaining usable life and day of failure
Failure Analysis
Engineering Services

- Failure Analysis’ Telemetry Prognostics Industry Applications
  - Satellite
  - Launch Vehicle
  - Missile
  - Aircraft
  - Helicopters
  - High Rel Computers
  - Automotive
    - Indy
    - NASCAR
  - Medical
  - Nuclear Power

SUN High Reliability Server Family
Failure Analysis
Engineering Services

**Experience**

- Failure Analysis serves commercial, military, government and civilian customers worldwide
- 30+ years in Satellite, Launch Vehicle, Missile and Aircraft Telemetry & Command and Communications Subsystem and System Design & Test
- 5 years high-rel computer server design, manufacture, test used in telecommunications industry
- Over 29 years in Telemetry Prognostics research, development and use

Atlas V Launch Vehicle
### Launch Vehicles
- Arianne
- Atlas
- Titan
- Delta
- EELV
- Sea Launch
- Space Shuttle
- Orbital Sciences

### Customers
- NASA GSFC
- NASA HQ
- NASA Ames
- DOD
- US Air Force
- NASA
- DOD
- US Air Force
- NASA GSFC
- NASA HQ
- NASA Ames
- DOD
- US Air Force
- NASA GSFC
- NASA HQ
- NASA Ames
- DOD
- US Air Force
- NASA GSFC
- NASA HQ
- NASA Ames
- DOD
- US Air Force
- NASA GSFC
- NASA HQ
- NASA Ames
- DOD
- US Air Force

### Satellites
- GPS I, II, IIA
- DMSP
- DSCS
- DSP
- MILSTAR
- GOES Next
- EUVE
- HUBBLE
- Lunar Prospector
- Cold sat
- TDRSS
- SUPER BIRD
- ANIK E
- INTELSAT
- HESSI
- NSTAR
- GMS
- Space Station
- KOMPSAT
- A2100
- FS 1300
- BS 601
- BS 702

### Factories
- Boeing Commercial
- Boeing Military
- Lockheed Martin
- Commercial
- Lockheed Martin
- Military
- Space Systems/Loral
- Ball Aerospace
- Orbital Sciences
- Fairchild Aerospace

### Ground Stations
- AFSCN
- TDRSS
- TMGS
- M³
- SMGS
- ICO
- PANAMSAT
- GLOBALSTAR
- DSN
- JPL
- GPS
- DMSP
- Svalbard
- INTELSAT
- SCC
- IONDS
- TELESAT
- KOMPSAT

### Mission Control
- NASA GSFC
- SUPERBIRD
- AFSCN
- CSOC
- Space Sciences Laboratory

### Telemetry Diagnostics & Prognostics
- GPS Block I
- GPS Block II
- EUVE
- GOES Next
- Super bird
- INTELSAT 7
- INTELSAT 7A

### High Rel Computer Server Design
- Force, Sun, HP,
Failure Analysis
Engineering Services

- Areas FA Experienced in Telemetry Prognostics Technology Applications
Failure Analysis
Engineering Services
Failure Analysis
Engineering Services

- Telemetry Prognostics Technology
  - Through the application in all areas of vehicle manufacturing & test
    - Solving 4 major problems in Satellite and Launch Vehicle industries:
      - Launch pad delays
      - Launch failures
        - The only technology that could have prevented the NASA Space Shuttle Challenger Accident
      - Early orbit infant mortalities
      - On orbit failures
    - Improving satellite and launch vehicle equipment reliability
    - Increasing on orbit equipment life
    - Lower costs to manufacture & test
    - Shortening production schedules

NASA Space Shuttle Challenger, 1986
Failure Analysis
Engineering Services

- **Failure Prediction™ Telemetry Prognostic** uses normal vehicle Telemetry to identify flight equipment that has failed, is failing and is going to fail
  - Can be extended to Software
- Created for use in a high signal noise environment, with little telemetry available
- **Telemetry Prognostics NT** is the prediction of the which measurements will exhibit future failure predictors
Failure Analysis
Engineering Services

- **Increases the contribution of equipment and vehicle design directly to the customer payload services revenue generation process**
  - **Higher equipment reliability means**
    - Longer satellite equipment mission life
      - Increase expendables
        - More income
  - **Higher reliable/trouble free equipment operations means**
    - Higher payload services availability
      - Premium prices for payload services
        - More income
Failure Analysis
Engineering Services

- Upgrades the on orbit mission operations activities from overhead/housekeeping to an integral source of revenue for owner/operator
  - By predicting when equipment will fail that interrupt communications/payload services and circumventing the failure, payload channel availability is increased allowing for charging customers premium prices
  - By using Telemetry Prognostics to increase satellite on orbit lifetimes, increases revenue for owner/operator
History of Telemetry Prognostics

- Created and used on the Air Force Global Positioning System between 1978-1984, results were documented in contract CDRL item A004
- Air Force funded the GPS Block I satellite contractor in 1978 to provide an engineering team to determine peak payload performance times to conduct critical multi-service system testing to get the highest navigation subsystem performance possible to obtain future program funding
  - No budget limits
  - No limit on technical or administration resources needed
- After GPS program was fully funded, Telemetry Prognostic technology was abandoned in 1984
**Significant Events in Telemetry Prognostics Technology**

- **1977 - 1978**: As electromechanical test engineer, used Telemetry to analyze Titan launch vehicle Thrust Vector Control Subsystem performance during valve assembly and booster I&T.
- **1978 – 1984**: Created Telemetry Prognostics and used it on GPS Block I satellites per request of GPS JPO officers, also used it successfully on GPS launch vehicle, Atlas, and to upgrade the satellite design for GPS Block II & IIA instrumentation subsystems.
- **1986**: Instrumented SUPERBIRD commercial geostationary communications satellites.
- **1988**: Used Telemetry Prognostics to instrument INTELSAT 7 & 7A satellites.
- **1990**: Used Telemetry Prognostics on SUPERBIRD launch and early orbit activities while on Ariane launch vehicle.
- **1994**: Used Telemetry Prognostics on GOES I spacecraft during factory I&T.
- **1994**: Used telemetry prognostics to predict NASA EUVE on orbit satellite Bus failures.
- **1995**: Lockheed Martin approved funding to validate Telemetry Prognostics technology for Trident Fleet Ballistic Missile applications.
- **1995**: Lockheed Martin used Recognize pattern recognition software to validate failure precursor identification capability from telemetry.
- **1995**: While at UC Berkeley, published white paper to GSFC Space Sciences Group documenting results of using telemetry prognostics on NASA EUVE on orbit LEO telescope satellite.
- **1995**: Prognostics technology accepted as NASA innovation research development and began to receive funding by NASA AMES.
1995 – Briefed the Director of Kirkland Air Force Base, New Mexico, Space Vehicle Design on the ability to predict failures on orbiting satellites

1995 – Offered to patent telemetry prognostic technology for UC Berkeley

1995 – Published paper on Telemetry Prognostics results on EUVE satellite at ITC 1996 while at Lockheed Martin

1996 – Published paper on Telemetry Prognostics results on EUVE satellite at Small Satellite Conference while at Lockheed Martin

1997 – Published paper on Telemetry Prognostics results on EUVE satellite at ITC 1997 While at Lockheed Martin

1997 – Submitted patent application to USPTO for predicting failures in fixed power DC circuits

2001 – Began incorporating prognostic technology into high-end Sun, HP and Force PC computer servers while at Force Computers


2006 – Founded Failure Analysis to market Telemetry Prognostic technology

2006 – US Navy announces desire to fund Telemetry Prognostic technology for aircraft application

2007 – Created Failure Prediction™ technology for licensing telemetry prognostics to telemetry using industries

2007 – Submitted trademarked application for Failure Prediction™ name
2007 – Submitted patent application to USPTO for predicting failures using telemetry in high reliable aerospace equipment
2007 – NASA Ames announces desire to fund telemetry prognostic technology development for NASA space missions
2007 – NRO announces desire to fund low probability of success telemetry prognostic technology projects for use on NRO satellites and launch vehicles
2007 – Submitted 2 articles in SATMAG magazine regarding Telemetry Prognostics
2007 – Submitted article to Signal magazine regarding telemetry prognostics
2007 – Submitted article to Popular Science magazine regarding telemetry prognostic technology
2007 – Monterey Herald newspaper featured Failure Analysis in its business section as top technology company in area
2007 - Naval Post Graduate School in Monterey invited Failure Analysis to lecture on telemetry prognostics
2007 – Failure Analysis contacted by Dr. Michael Griffin, head administrator at NASA HQ and requested FA to submit an unsolicited proposal for licensing Telemetry Prognostics technology
2007 – Submitted unsolicited proposal to Dr. Griffin, NASA Administrator
2007 – Failure Analysis contacted by US Navy Trident Missile program, Washington DC
## Failure Analysis

### Engineering Services

### Telemetry Prognostic Summary

<table>
<thead>
<tr>
<th>Type of Vehicle</th>
<th>Area</th>
<th>Application</th>
<th>Level of Difficulty</th>
<th>Has Prognostics Been Used?</th>
<th>Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>SATELLITE</td>
<td>Design</td>
<td>GEO</td>
<td>Low</td>
<td>Yes</td>
<td>INTELSAT 7 &amp; 7A, GPS Block II, IIA</td>
</tr>
<tr>
<td></td>
<td>Equipment Manufacturing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Factory I&amp;T</td>
<td></td>
<td>Low</td>
<td>Yes</td>
<td>GPS Block I, II, GOES I</td>
</tr>
<tr>
<td></td>
<td>Launch Pad Integration</td>
<td></td>
<td>Low</td>
<td>Yes</td>
<td>GPS Block I</td>
</tr>
<tr>
<td></td>
<td>Launch</td>
<td></td>
<td>Not done</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>On Orbit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Early Orbit</td>
<td>Medium</td>
<td>Yes</td>
<td></td>
<td>GPS Block I, SUPERBIRD</td>
</tr>
<tr>
<td></td>
<td>Final Orbit</td>
<td></td>
<td>Low</td>
<td>Yes</td>
<td>GPS Block I, EUVE, SUPERBIRD</td>
</tr>
<tr>
<td></td>
<td>LEO</td>
<td>High</td>
<td>Yes</td>
<td></td>
<td>EUVE, GPS Block I, SUPERBIRD</td>
</tr>
<tr>
<td></td>
<td>MEO</td>
<td></td>
<td>Low</td>
<td>Yes</td>
<td>GPS Block I</td>
</tr>
<tr>
<td></td>
<td>MTO</td>
<td></td>
<td>Low</td>
<td>Yes</td>
<td>GPS Block I</td>
</tr>
</tbody>
</table>

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## Failure Analysis

### Engineering Services

#### Telemetry Prognostic Use Summary

<table>
<thead>
<tr>
<th>Type of Vehicle</th>
<th>Area</th>
<th>Orbit</th>
<th>Level of Difficulty</th>
<th>Has Prognostics Been Used?</th>
<th>Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>SATELLITE</td>
<td>On Orbit</td>
<td>GEO</td>
<td>Low</td>
<td>Yes</td>
<td>SUPERBIRD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GTO</td>
<td>Low</td>
<td>Yes</td>
<td>SUPERBIRD</td>
</tr>
<tr>
<td></td>
<td>Interplanetary</td>
<td>Low</td>
<td>No</td>
<td></td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Space Probes</td>
<td>Low</td>
<td>No</td>
<td></td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Deep Space</td>
<td>Low</td>
<td>No</td>
<td></td>
<td>None</td>
</tr>
<tr>
<td>LAUNCH VEHICLE</td>
<td>Equipment Manufacturing</td>
<td>Low</td>
<td>Yes</td>
<td>TITAN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Factory I&amp;T</td>
<td>Low</td>
<td>Yes</td>
<td>TITAN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Launch Pad Integration</td>
<td>Low</td>
<td>Yes</td>
<td>ATLAS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Launch Readiness</td>
<td>Low</td>
<td>Yes</td>
<td>ATLAS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Launch</td>
<td>Not Done</td>
<td>No</td>
<td>Telemetry Not Available</td>
<td></td>
</tr>
<tr>
<td>MISSILE</td>
<td>Design, Manufacturing, Test, Launch, Submarine, Silo Storage</td>
<td>Ballistic Trajectory</td>
<td>Low</td>
<td>Yes</td>
<td>TRIDENT D4</td>
</tr>
</tbody>
</table>
Failure Analysis
Engineering Services

Why Use Failure Analysis’ Failure Prediction™ Telemetry Prognostic technology?

- FA knows what to look for
  - No two failures look alike in telemetry
- FA knows when to look for it
  - In large data bases, failure signatures are (almost) impossible to find
- FA knows where to look for it
- FA knows how to look for it
- FA knows why it works
- Failure Prediction™ has been 100% accurate to date with remaining usable life predictions
- Flight proven
**Failure Analysis**

**Engineering Services**

- Contributions in reducing vehicle production costs & schedule using Telemetry Prognostics for satellites and launch vehicles

**Equipment Manufacturing**

Up to 10%

**Satellite I&T**

Up to 40%

**Missile/Launch Vehicle I&T**

Up to 40%

**Launch Pad Integration**

Up to 10%
Failure Analysis
Engineering Services

- Contribution to increasing equipment/vehicle reliability using Telemetry Prognostics

- Equipment Manufacturing
  - Up to 20%

- Satellite I&T
  - Up to 20%

- Missile/Launch Vehicle I&T
  - Up to 20%

- Launch Pad Integration
  - Up to 20%

- On Orbit Operations
  - Up to 40%

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**Failure Analysis**

Engineering Services

- Payback to space equipment suppliers (SS/L)
  - Lower the cost to build equipment
  - Shorten the time to test equipment
  - Charge higher price for equipment
  - Offer customers reduce risk, more reliable, longer life, trouble free equipment on orbit without design changes
  - Offer customers a more technologically advanced product
    - Equipment built using Telemetry Prognostics is superior
    - Stops equipment being shipped that’s going to suffer from infant mortality
  - Stop shipping unreliable equipment to the launch pad
Failure Analysis
Engineering Services

- Increases chances at winning future business opportunities
  - Offer customers a source selection discriminator over competition
- Improve technical depth of test personnel
  - Failure Prediction training includes
    - Data mining – Algorithm development
    - Data filtering – Data processing
    - Data corruption recovery – Image enhancement
    - Image processing and enhancement
    - Linear and non linear DC circuit analysis
    - Mathematical modeling – High order modeling
    - Advanced statistical analysis – Database reduction algorithms
    - Advanced imaging analysis – Analysis and presentation
Failure Analysis
Engineering Services

- Payback to satellite builders
  - Build & test spacecraft for a lower cost
  - Build & test spacecraft with a shorter schedule
  - Charge a higher price for using Failure Prediction™ technology
  - Offer customers reduce risk, more reliable, longer life, trouble free equipment
  - Offer customers increases in satellite on orbit earnings
  - Offer customers a more technologically advanced satellite
  - Increase the technical expertise of satellite I&T personnel allowing faster and more reliable testing results
  - Stop shipping unreliable equipment for launch
  - Increase customer confidence in your product
Payback for On Orbit Mission Operations

- Lower on orbit operations cost
  - Reduce staff
    - Schedule engineers in only when necessary based on results of telemetry prognostics analysis
    - Prognostics replaces continuous trending, monitoring with limits.
  - Switch to day shift only or lights out operations with 24/7 anomaly alert response capability through software alerts using pagers

- Increase communications channel revenue
  - Higher availability channels at a premium price
Increase satellite equipment reliability, operability, payload services availability, serviceability, maintainability

- Decreases payload services down time
  - Stop unreliable equipment from failing, interrupting payload services
  - Particularly important for revenue generating services and high value mission critical payload services
  - Switch to redundant unit during quiescent period, minimizing impact to payload services
    - Satellite engineers can execute preplanned equipment contingency/recovery procedures in unstressed environment ahead of time
Lowers risk of mission failure

- Identify unreliable equipment long before failure occurs
  - Change thermal environment, extend remaining usable life
  - Power off unreliable equipment off/power on redundant unit and avoid surprise failures
  - Develop contingency procedures ahead of need in the event of equipment failure for identified unreliable equipment
  - Recommend powering on all redundant equipment after launch to verify equipment reliability

Extend equipment on-orbit lifetime

- By identifying which equipment is unreliable, operators can change the thermal environment of unreliable equipment and extend remaining usable life
Failure Analysis
Engineering Services

- Predict satellite operating equipment failures many months before they occur, lower risk of compounding failure with inadvertent mission loss action
- Be able to determine remaining usable life of unreliable equipment
  - Determine actual on orbit mission life (weeks, months)
- Be able to provide a day of failure for unreliable equipment for planning purposes
# Failure Analysis

Engineering Services

<table>
<thead>
<tr>
<th>Examples of Types of Equipment Failures for Telemetry Prognostics to Predict</th>
<th>Does Telemetry Prognostics Work?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit</td>
<td>Yes</td>
</tr>
<tr>
<td>Short circuit</td>
<td>Yes</td>
</tr>
<tr>
<td>Piece-part component wear out</td>
<td>Yes</td>
</tr>
<tr>
<td>Piece-part failure</td>
<td>Yes</td>
</tr>
<tr>
<td>Piece part degradation</td>
<td>Yes</td>
</tr>
<tr>
<td>Over-temperature</td>
<td>Yes</td>
</tr>
<tr>
<td>Under-temperature</td>
<td>Yes</td>
</tr>
<tr>
<td>Propellant/oxidizer/pressurant leaks</td>
<td>Yes</td>
</tr>
<tr>
<td>Electrostatic discharge</td>
<td>No</td>
</tr>
<tr>
<td>Single event upsets</td>
<td>No</td>
</tr>
<tr>
<td>Lubricant dry up</td>
<td>Yes</td>
</tr>
<tr>
<td>Bearing wear out</td>
<td>Yes</td>
</tr>
<tr>
<td>Switch failure</td>
<td>Yes</td>
</tr>
<tr>
<td>Contact wear out</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Failure Analysis
Engineering Services

Features of Failure Prediction™ Telemetry Prognostics

- Generic techniques
- Detects future failure in normal appearing telemetry
- Detects future failures in high stressed operational environment
- Observe individual component/circuit failure as it is occurring
- Insensitive to quantity of telemetry
- Insensitive to (quality) noisy or unreliable telemetry
- Insensitive to amount of telemetry available for analysis
- Insensitive to LSB resolution
- Flight proven
- Data processing platform independent
- Developed for use on existing Satellite and Launch Vehicle telemetry systems
- Vehicle independent
# Failure Analysis

## Engineering Services

### Advantages of Failure Prediction™ Telemetry Prognostics

<table>
<thead>
<tr>
<th>To the Satellite Owner (pre-launch)</th>
<th>To the Insurance Company</th>
<th>To the Flight Equipment Supplier</th>
<th>To the Satellite Builder</th>
<th>To the LV Builder</th>
<th>To the Satellite Owner/Operator (after launch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowers risk of mission failure</td>
<td>Lowers risk of mission failure</td>
<td>Stops shipping faulty equipment to the satellite manufacturer</td>
<td>Charge higher price for satellite</td>
<td>Charge higher price for launch vehicle</td>
<td>Earn more revenue</td>
</tr>
<tr>
<td>Lows cost of insurance premium</td>
<td>Stops infant mortalities</td>
<td>Increases equipment reliability</td>
<td>Reduces equipment returns</td>
<td>Predicts future equipment failures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increase equipment reliability</td>
<td>Stops infant mortality failures</td>
<td>Predicts future equipment failures</td>
<td>Predicts future equipment failures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increases test personnel expertise</td>
<td>Increases equipment reliability</td>
<td>Predicts future equipment failures</td>
<td>Predicts future equipment failures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shorter delivery schedule</td>
<td>Shortens satellite delivery schedule</td>
<td>Increases equipment reliability</td>
<td>Increases equipment serviceability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduces cost</td>
<td>Lows cost to test satellite</td>
<td>Reduces service downtime-increases system availability</td>
<td>Reduces service downtime-increases system availability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increases test personnel expertise</td>
<td>Increases equipment reliability</td>
<td>Increases equipment serviceability</td>
<td>Increases equipment serviceability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increases equipment maintainability</td>
<td>Increases equipment serviceability</td>
<td>Increases equipment serviceability</td>
<td>Increases equipment serviceability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increases operations personnel expertise</td>
<td>Increases equipment serviceability</td>
<td>Increases equipment serviceability</td>
<td>Increases equipment serviceability</td>
<td></td>
</tr>
</tbody>
</table>
Failure Analysis
Engineering Services

*Failure Prediction™ Telemetry Prognostics Disadvantages*

<table>
<thead>
<tr>
<th>To the Satellite Owner (pre-launch)</th>
<th>To the Insurance Company (pre-launch)</th>
<th>To the Flight Equipment Supplier</th>
<th>To the Satellite Manufacturer</th>
<th>To the LV Manufacturer</th>
<th>To the Satellite Owner/Operator (On Orbit)</th>
<th>To the Insurance Company (On Orbit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher cost for satellite &amp; launch vehicle</td>
<td>Requires personnel Training</td>
<td>Requires personnel training</td>
<td>Requires personnel training</td>
<td>Requires personnel training</td>
<td>Requires personnel training</td>
<td>Requires personnel training</td>
</tr>
</tbody>
</table>

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Failure Analysis
Engineering Services

- Redefines the failure rate of a system
- Traditional bathtub curve for complex electrical systems
Improves Payload Services Availability (100% duty cycle)
Failure Analysis
Engineering Services

- **Failure Prediction™ Telemetry Prognostics technology is superior to traditional acceptance testing**
  - Prognostics technology
    - Identifies equipment that has failed
    - Identifies flight equipment that is failing
    - Identifies flight equipment that will fail
  - Traditional acceptance testing
    - Identifies equipment that has failed
Failure Analysis
Engineering Services

Telemetry
# Failure Analysis
## Engineering Services

### Telemetry Technology Evolution

<table>
<thead>
<tr>
<th>Data Collection</th>
<th>Monitoring During Test/Diagnostics</th>
<th>Prognostics</th>
<th>Prognostic NT?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schilling 1812</td>
<td>Missle Technology 1946</td>
<td>Digital Telemetry 1957</td>
<td>PANAMSAT Commercial Space 1985</td>
</tr>
<tr>
<td>Olland 1874</td>
<td>Atlas Missile 1954</td>
<td>Titan Rocket 1961</td>
<td></td>
</tr>
<tr>
<td>Seismic Recording 1906</td>
<td>Thor/Delta Missile 1955</td>
<td>Delta Rocket 1962</td>
<td></td>
</tr>
<tr>
<td>Marconi Wireless Communications 1907</td>
<td>Titan Missile 1955</td>
<td>INTELSAT/COMSAT 1964</td>
<td></td>
</tr>
<tr>
<td>Radiosonde 1930</td>
<td></td>
<td>AFCSN 1969</td>
<td></td>
</tr>
</tbody>
</table>

1/13/2014
Telemetry for commercial satellites is considered overhead, included as a cost of doing business.

- Needed for equipment AT, I&T AT, launch readiness, early orbit & on-orbit equipment configuration control, orbit maintenance activities, equipment failure detection and recovery activities.

- NASA & Air Force use telemetry to improve follow-on satellite functionality and performance.
Failure Analysis

Engineering Services

Number of Analog Telemetry Measurements for Commercial, NASA, Military and Quasi-Governmental Satellites

- Quasi Government Satellites
- Commercial Satellites
- NASA Satellites
- Air Force Satellites
TELEMETRY PROGNOSTICS DESCRIPTION
Failure Analysis
Engineering Services

- Identification of incipient faults
- Prognostics integrates proactive diagnostics with active reasoning
- The value in monitoring the future health and status of space assets has been realized by the military to be critical for system readiness.
- Various component/parts related prognostic techniques have been developed in laboratories, universities and industry
- Failure Prediction™ is a generic, tailorible tool that integrates embedded test and sensor data into prognostic information.
Failure Analysis
Engineering Services

1/13/2014

Identification of Failure Precursors in Telemetry Process Page 1

A

B
Was There A Change In Equipment Configuration That Is Responsible For The Change in Data Behavior?

Yes

No

Is The Data Behavior Unrealistic?

Yes

Assume Data Behavior Is Due To Failed Sensor

No

Assume Data Behavior Is A Failure Precursor

Determine Remaining Usable Life and Day of Failure For Equipment Failure Precursor Data Is From

Is The Collection Of Data From Electronic Equipment Complete?

Yes

Stop

No

Continue To Collect Data From Electrical Devices, Ignore Data From Failed Sensors
Telemetry Prognostics Technical Approaches

1. Piece-part suppliers integrate prognostic technology for self-prognosis and makes the information available to telemetry
   1. FPGA’s
   2. Microprocessors
   3. Systems on a chip

2. Box/unit level suppliers provide the information to telemetry
   1. Self-prognosis
   2. Fixed lifetimes notify time is up

3. Failure Analysis’ Failure Prediction™ technology vehicle level telemetry prognostics
   1. Identifies latent, intermittent information well within normal that identifies upcoming failure
Telemetry Prognostics

- Requires major change in analysis attitude
- Prognostician actively monitors data to provide knowledge of whether a failure has occurred, is occurring or when a failure is likely to occur
- All events are considered failure precursors until ruled out by research – analyst doesn’t stand by and watch failures occur
- A fault propagation model extends to encompass parametric data related to acceptable operating ranges, behavior and identification of degradation of functions over time.
- Requires high skilled personnel
- In-depth knowledge of what is being actively monitored is required

Telemetry Diagnostics

- Developed from ground test environment
- Used for passively monitoring information
- Record the data and look at it later
  - After the fact response
- Events are recognized but no action is taken
  - If error messages are used diagnostician waits for error message before taking action
- Lack of event alarms
- Doesn’t require in-depth understanding of what’s being monitored
- Analysis is accomplished post event
- Allows lower skilled personnel
- Most common approach throughout many industries
- Inadequate for today’s customer expectations
IMPACT ON PIECE-PART RELIABILITY
Failure Analysis

Improves Piece Part Lot Wear Out Failure Rate

How Well Failure Prediction™ Improves Reliability

- Number of Failures Without Failure Prediction™ technology
- Number of Failures with Failure Prediction™ technology
Failure Analysis
Engineering Services

- Increasing Flight Equipment Life

Piece-part Time-to-Failure vs Temperature

- Stress Ratio = Applied Stress / Rated Stress (e.g., voltage, power)
- Stress Ratio = .6
- Stress Ratio = .8
- Stress Ratio = 1
**Failure Analysis**

**Engineering Services**

- **Piece Part Component Wear Out**
  - Worst-case circuit analysis (WCCA) examines the effects on electronic circuits caused by variations of piece-parts beyond their initial tolerance.
    - The variations can be the result of aging or environmental influences, which can cause circuit outputs to drift out of specification.
    - WCCA also determines the mathematical sensitivity of circuit performance to these variations and provides both statistical and non-statistical methods for handling the variables that affect circuit performance.
  - Electronic piece-parts fail in two distinct modes
    - Catastrophic, which is dramatic and abrupt
    - Piece-part's parameters varying beyond both its nominal and initial (purchase) tolerance limits whereby the circuit continues to function but with degraded performance, ultimately exceeding the circuit's required operating limits.
  - To eliminate piece-part catastrophic failures, the worst-case electrical stress and derating analysis ensures that all parts are properly derated.
    - The analysis of variables allows designers to predict whether the circuit will stay within its specified performance limits under all of the combinations.
Class S Piece Parts

- Electronic piece part lot testing of components are expected to operate under varying temperatures depicted by their application in a piece of hardware.
  - Test temperatures range from -55 °C to maximum of 125 °C.
  - Documenting device responses from electrical test conditions are a requirement for Class S level verification.
- Samples of electronic devices undergo life testing to reveal two basic failure modes, infant mortality and wear out.
- Infant mortality depicts those devices that fail early in their operating life for reasons unrelated to normal designed parameters.
- The conditions for a life test include; accelerated temperature (100-190 °C) for test duration of (30 hrs. to 7500 hrs.).
  - These conditions will depend mainly on the temperature designed for the test. A rule of thumb is that "the shorter the test, the higher the temperature" needed in order to equate the proper stress conditions to the length of the test.
Failure Analysis
Engineering Services

- Reliability Predictions per MIL-HDBK-217

- Reliability Predictions are used in the development of products and systems to compare alternative design approaches and to assess progress toward reliability design goals. They're often criticized as not being accurate forecasts of field reliability performance because they don't usually account for all the factors that cause field failures. Nevertheless, predictions are a valuable form of analysis that also provide insight into safety, maintenance and warranty costs and other product considerations.

- Does not consider prognostics technology
Reliability Predictions per MIL-HDBK-217

MIL-HDBK-217 has been the mainstay of reliability predictions for about 40 years but it has not been updated since 1995, and there are no plans by the military to update it in the future. The handbook includes a series of empirical failure rate models developed using historical piece part failure data for a wide array of component types. There are models for virtually all electrical/electronic parts and a number of electromechanical parts as well. All models predict reliability in terms of failures per million operating hours and assume an exponential distribution (constant failure rate), which allows the addition of failure rates to determine higher assembly reliability. The handbook contains two prediction approaches: the parts stress technique and the parts count technique and covers 14 separate operational environments, such as ground fixed, airborne inhabited, etc. As the names imply, the parts stress technique requires knowledge of the stress levels on each part to determine its failure rate, while the parts count technique assumes average stress levels as a means of providing an early design estimate of the failure rate. Typical factors used in determining a part's failure rate include a temperature factor ($\pi_T$), power factor ($\pi_P$), power stress factor ($\pi_S$), quality factor ($\pi_Q$) and environmental factor ($\pi_E$) in addition to the base failure rate ($l_b$). For example, the model for a resistor is as follows:

$$l_{\text{Resistor}} = l_b \pi_T \pi_P \pi_S \pi_Q \pi_E$$
Failure Analysis
Engineering Services

• **Failure Prediction™** redefines reliability prediction analysis
  
  • **Increased Mean Time Between Failures**
    
    • $MTBF = \text{Average Life/Number of Failures}$
    
    • Number of failures approaches 0, $MTBF$ gets very large
    
    • Expects replacement of parts

  • **Increases Mean Time To Failure**
    
    • $MTTF = \text{Is the amount of time the product should last}$

  • **Decreases Mean Time To Repair**
    
    • $MTTR = \text{Is the average time to repair equipment back to acceptable operating conditions. Once the equipment breaks down, the actual time spent on detecting a failure has occurred, arranging spares, resources, planning and executing the tasks and then bringing it back to operating condition.}$
Failure Analysis
Engineering Services

- **Reliability Predictions per RDF 2000**
  - RDF 2000 is the new version of the CNET UTEC80810 reliability prediction standard that covers most of the same components as MIL-HDBK-217. The models take into account power on/off cycling as well as temperature cycling and are very complex with predictions for integrated circuits requiring information on equipment outside ambient and print circuit ambient temperatures, type of technology, number of transistors, year of manufacture, junction temperature, working time ratio, storage time ratio, thermal expansion characteristics, number of thermal cycles, thermal amplitude of variation, application of the device, as well as per transistor, technology related and package related base failure rates. As this standard becomes more widely used it could become the international successor to the US MIL-HDBK-217.
FAILURE PREDICTION™ TECHNOLOGY
Failure Analysis
Engineering Services

Telemetry Prognostics training includes

- Signal conditioning
  - Filtering
  - Amplification
- Linear & non linear DC circuit analysis
  - Circuit design
  - Troubleshooting
- Satellite communications
  - Satellite communications design
  - RF Communications
  - Digital communications
- Digital signal processing
- Telemetry & Command systems design & test
- Mechanical design
  - Thermal control design
- Telemetry software design, development & test
- Command software design
  - Validation & verification
- Statistical analysis
  - Deterministic
  - Bayesian
  - Stochastic
- Mathematical modeling
  - Harmonic/Fourier Analysis
    - Fourier transforms
    - FFT
  - Kalman filtering
  - Neural networks
  - Regression analysis
Failure Analysis
Engineering Services

● **Failure Prediction™** consists of:
  
  ● *Technology for compensating for unreliable telemetry*
    ● Eliminate false positives
  
  ● *Technology for minimizing telemetry database size for processing*
    ● On orbit database sizes can be immense
      ▪ Reduction of 99.999% in size is achievable
    ● Some are too large to access data for processing
  
  ● *Technology for compensating for insufficient amount of telemetry*

  ● *Technologies for creating normal telemetry*

  ● *Technology for identifying failure precursors in normal telemetry*

  ● *Technology for discriminating between normal telemetry and anomalous normal telemetry*

  ● *Technology for processing and displaying data*

  ● *Capability to determine remaining usable life and day of failure*
Telemetry measurement behavior is inconsistent between the same measurements from the same circuits, on the same equipment, many different tools and technologies are needed to eliminate false positives

Variety in piece part performance in circuit guarantees different behavior
Failure Analysis
Engineering Services

- **Prognostics is accomplished by a prognostician**

  - **Prognostician**
    - An engineer that uses an array of imaging technologies to diagnose latent, intermittent electrical/mechanical component/circuit failure behavior
    - Requires 4 year technical degree in electronics
    - Must understand and be experienced with linear and non linear DC circuit design, DC circuit troubleshooting, worse case circuit analysis, aerospace acceptance testing, electrical and mechanical layouts, thermal analysis, piece-part failure analysis and behavior under test, data analysis, imaging analysis, telemetry system design,

- **X-Ray Radiologist**
  - A physician that uses an array of imaging technologies (such as ultrasound, computed tomography (CT, X-rays) and magnetic resonance imaging (MRI) to diagnose or treat disease.
   - Requires 4 year medical degree and 5 years post graduate training.
   - Must understand and be experienced in nuclear medicine, physics of medical imaging, diagnostic imaging technology
# Failure Analysis

## Engineering Services

## Telemetry Prognostics Content Summary

<table>
<thead>
<tr>
<th>Technology</th>
<th>Purpose/Objective</th>
<th>In Software</th>
<th>Will be in Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Reasoning</td>
<td>Takes passively monitored symptoms and returns fault diagnosis</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Telemetry Authentication</td>
<td>To remove/replace unreliable telemetry</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Rate Change Analysis</td>
<td>To identifies suspect telemetry for further analysis</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>State Change Analysis</td>
<td>To identify telemetry for further analysis</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Multi-variant Limit Analysis</td>
<td>To identify suspect telemetry behavior</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Statistical Sampling</td>
<td>To reduce size of telemetry database to analyze</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Super Impositioning</td>
<td>To create virtual telemetry behavior</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Mathematical Modeling</td>
<td>To generate predictive modeling functions</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Digital Processing</td>
<td>To improve image resolution</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Super Precision</td>
<td>To improve image resolution</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
# Failure Analysis

## Engineering Services

## Telemetry Prognostics Content Summary

<table>
<thead>
<tr>
<th>Technology</th>
<th>Purpose/Objective</th>
<th>In Software</th>
<th>Will be in Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Mining</td>
<td>To identify suspect telemetry behavior in large databases of telemetry</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Database Generation</td>
<td>To reduce the amount of telemetry to analyze</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Baseline Analysis</td>
<td>To determine normal telemetry behavior</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Change Analysis</td>
<td>To identify deviations from normal telemetry behavior</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Discrimination Analysis</td>
<td>To be able to discriminate normal from failure precursors</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Root Cause Analysis</td>
<td>To identify circuit/component failing</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Remaining Usable Life</td>
<td>To determine remaining usable life of equipment</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Day of Failure Analysis</td>
<td>To determine day of failure of unreliable equipment</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Where/When To Do Telemetry Prognostics

- Prefer to maximize the stress to equipment first to induce piece part failure
  - At the box supplier factory after acceptance testing is complete
  - Before and after spacecraft level acceptance testing is complete to reduce testing schedule
  - After satellite is exposed to launch environment and payload turn on/checkout on orbit
  - At least every 3-6 months on orbit
## Failure Analysis

### Engineering Services

**Suggested Location of Failure Prediction™ Implementation**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Box Supplier</th>
<th>Satellite Factory</th>
<th>LV Factory</th>
<th>Launch Site</th>
<th>Mission Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telemetry Authentication</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Rate Change Analysis</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>State Change Analysis</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Super Impositioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Mathematical Modeling</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Virtual Telemetry</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Super Precision</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>SFI, SDI, NFI, NDI sampling</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Data Mining</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Digital Processing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Proactive Diagnostics</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Active Reasoning</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Change Analysis</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Baseline Analysis</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Discrimination Analysis</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Failure Pattern Recognition</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Root Cause Failure Analysis</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Determining Remaining Usable Life</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Predicting Day of Failure</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Multi-variant Limit Analysis</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Failure Analysis
Engineering Services

Failure Prediction™ History/Flight History
US Air Force GPS officers indicated that they would like to have the ability to predict future navigation payload performance weeks/months ahead for scheduling critical system wide multi-service program field tests.

The Rockwell subsystem engineering staff responded by developing Telemetry Prognostics to predict future equipment failures between 1978 and 1984.

The Telemetry Prognostics results were then used by the Air Force to schedule real-time future multi-service GPS flight tests made by all arms of the military that were critical to receiving program funding.

To maximize the success of the programs flight tests, the Air Force decided critical program testing would only be accomplished with stable satellite navigation payload equipment as determined by Telemetry Prognostics.

Due to the success of Telemetry Prognostics which allowed field tests to be done with peak payload performance, the GPS program was fully funded.

Rockwell then used Telemetry Prognostics technology to improve the design of Block II and Block IIA satellites.
Results of Telemetry Prognostics on satellite and launch vehicle telemetry, included the discovery that equipment that failed on orbit had unexplainable telemetry behavior during factory test well within behavior considered normal and the same equipment would later fail on orbit.

Based on the success of Failure Analysis’ Telemetry Prognostics to identify failures in normal appearing telemetry for on orbit flight equipment, investigation into the source of unexplainable telemetry behavior in normal appearing telemetry at the factory was conducted by the GPS subsystem engineering team.
Results uncovered that flight equipment suppliers are shipping equipment with latent failures that cannot be detected through traditional acceptance testing resulting in infant mortalities.

Satellite and Launch Vehicle suppliers during I&T are schedule and cost driven, and do not have the opportunity to research unusual normal appearing telemetry behavior from equipment.

Satellite and Launch Vehicle suppliers are shipping and launching equipment with latent failure precursors present resulting in infant mortalities and launch failures.
Liability concerns

When does equipment fail?
- With the availability of failure precursors?
  - In the past the knowledge and identification of failure precursors was not available
- When catastrophic failures?
  - Historically, failure analysis has been done with only the immediate telemetry to identify the failure

Failure Prediction™ technology now allows the identification of a impending failure months ahead of time, prior to launch
## Failure Analysis

### Engineering Services

- **Telemetry Prognostics Flight History**

<table>
<thead>
<tr>
<th>Satellite Telemetry Prognostics Used On</th>
<th>Final Orbit Shape</th>
<th>Final Orbit Altitude (nmi)</th>
<th>Final Orbit Inclin.</th>
<th>Final Orbit Period (hours)</th>
<th>Sun to Orbit Plane Angle (Beta) Range</th>
<th>On Orbit Attitude Control</th>
<th>Location Telemetry Prognostics Completed</th>
<th>Amount of Telemetry Analyzed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Force GPS</strong></td>
<td>Circular (MEO)</td>
<td>10,900</td>
<td>63</td>
<td>12</td>
<td>-86 -0 +86 -78 0 +78 -86 0 +86 -86 0 +86 -78 0 +78</td>
<td>•Spin Stabilized •3-Axis Stabilized</td>
<td>•Launch Pad •Early Orbit •Final Orbit</td>
<td>6 years 6 years 5 years 5 years 3 years 2 years</td>
</tr>
<tr>
<td>1</td>
<td>Elliptical (MTO)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Circular (MEO)</td>
<td>10,900</td>
<td>63</td>
<td>12</td>
<td>-86 -0 +86 -78 0 +78 -86 0 +86 -86 0 +86 -78 0 +78</td>
<td>•Spin Stabilized •3-Axis Stabilized</td>
<td>•Launch Pad •Early Orbit •Final Orbit</td>
<td>6 years 6 years 5 years 5 years 3 years 2 years</td>
</tr>
<tr>
<td>3</td>
<td>Elliptical (MTO)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Circular (MEO)</td>
<td>10,900</td>
<td>63</td>
<td>12</td>
<td>-86 -0 +86 -78 0 +78 -86 0 +86 -86 0 +86 -78 0 +78</td>
<td>•Spin Stabilized •3-Axis Stabilized</td>
<td>•Launch Pad •Early Orbit •Final Orbit</td>
<td>6 years 6 years 5 years 5 years 3 years 2 years</td>
</tr>
<tr>
<td>5</td>
<td>Elliptical (MTO)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Circular (MEO)</td>
<td>10,900</td>
<td>63</td>
<td>12</td>
<td>-86 -0 +86 -78 0 +78 -86 0 +86 -86 0 +86 -78 0 +78</td>
<td>•Spin Stabilized •3-Axis Stabilized</td>
<td>•Launch Pad •Early Orbit •Final Orbit</td>
<td>6 years 6 years 5 years 5 years 3 years 2 years</td>
</tr>
<tr>
<td><strong>NASA EUVE</strong></td>
<td>Circular (LEO)</td>
<td>375</td>
<td>28</td>
<td>1.5</td>
<td>-51 -0 -51</td>
<td>3-Axis Stabilized</td>
<td>•Final Orbit</td>
<td>45 years</td>
</tr>
<tr>
<td><strong>NASA GOES I</strong></td>
<td>Circular (GEO)</td>
<td>19,000</td>
<td>0</td>
<td>24</td>
<td>-23 -0 +23</td>
<td>3-Axis Stabilized</td>
<td>•Factory</td>
<td>3 months</td>
</tr>
<tr>
<td><strong>SCC SUPERBIRD</strong></td>
<td>Circular (GEO)</td>
<td>19,000</td>
<td>0</td>
<td>24</td>
<td>-23 -0 +23</td>
<td>3-Axis Stabilized</td>
<td>•Launch Pad •Final Orbit</td>
<td>6 weeks</td>
</tr>
<tr>
<td></td>
<td>Elliptical (GTO)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>INTELSAT 7&amp;7A</strong></td>
<td>Circular (GEO)</td>
<td>19,000</td>
<td>0</td>
<td>24</td>
<td>-23 -0 +23</td>
<td>3-Axis Stabilized</td>
<td>•Factory</td>
<td>none</td>
</tr>
</tbody>
</table>
### Telemetry Prognostics Launch Vehicle Flight History

<table>
<thead>
<tr>
<th>Launch Vehicle</th>
<th>Injection Orbit</th>
<th>Location</th>
<th>Amount of Telemetry Analyzed</th>
<th>Were Any Failure Predicted/Occurred</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITAN 34C</td>
<td>LEO Circular Orbit</td>
<td>LV Factory</td>
<td>1 year</td>
<td>No</td>
</tr>
<tr>
<td>TITAN 34D</td>
<td>LEO Circular Orbit</td>
<td>LV Factory</td>
<td>1 year</td>
<td>No</td>
</tr>
<tr>
<td>TITAN III</td>
<td>LEO Circular Orbit</td>
<td>LV Factory</td>
<td>1 year</td>
<td>No</td>
</tr>
<tr>
<td>TITAN IV</td>
<td>LEO Circular Orbit</td>
<td>LV Factory</td>
<td>1 year</td>
<td>No</td>
</tr>
<tr>
<td>ATLAS D</td>
<td>LEO Circular Orbit</td>
<td>Launch Site</td>
<td>2 weeks</td>
<td>No</td>
</tr>
<tr>
<td>ATLAS E</td>
<td>LEO Circular Orbit</td>
<td>Launch Site</td>
<td>2 weeks</td>
<td>No</td>
</tr>
<tr>
<td>ATLAS F</td>
<td>LEO Circular Orbit</td>
<td>Launch Site</td>
<td>2 weeks</td>
<td>No</td>
</tr>
</tbody>
</table>

1/13/2014
Failure Analysis
Engineering Services

TELEMETRY PROGNOSTICS END PRODUCTS
Failure Analysis
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- Telemetry Prognostics Products

Start

Finish

Minor Frames
Predicting Day of Failure

- Based on Failure Analysis’ database of flight hardware failures past actual remaining of usable life
  - Probability of occurring and actual day of failure
    - 90% at 3 months, 75% at 6 months etc.

- Failure Analysis updates database of failure durations on a continuous basis when data is available
  - Failures are considered proprietary information and is not disseminated outside the companies
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● *Failure Prediction™ Performance*

Comparison Between Failure Prediction™ RUL, Actual RUL and Average Actual RUL

- Failure Prediction™ Predicted Remaining Life (months)
- Actual Remaining Life of Flight Equipment (months)
- Average Actual Remaining Life (months)

Number of Failures

Months of Remaining Usable Life

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Probability of Reaching A Duration of Remaining Life (%) VS Months of Remaining Usable Life
Elimination Of False Positives

- Failure Prediction™ developed for applications in which there are enormous penalties associated with false alarms
  - Reduces the reliability of technology
    - Ignore alerts
- Commercial Nuclear Industry
  - False alarms result in plant shutdowns, which cost $1M per day. EPRI studies have shown that 25% of nuclear plant trips are false alarms from degrading sensors (many sensors have much shorter MTBFs than the assets they are monitoring).
    - Result: After a rigorous 2 year evaluation, the US NRC formally approved the use of MSET for continuous calibration validation of all safety-critical and life critical sensors in all US nuclear plants.
**Failure Analysis**

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- **NASA Space Shuttle:**
  - Although many shuttle countdowns have been aborted prior to liftoff, one shuttle mission was aborted 2 seconds after liftoff in 1985. The cost of this incident was $50M to NASA. Failure analysis showed that 2 redundant vibration sensors had malfunctioned simultaneously, falsely indicating an anomalous surge in engine vibration. There was no engine problem.
  - NASA awarded $700K in contracts to adapt MSET for continuous surveillance of sensors and components on space shuttle main launch vehicles.

- After 72 years of telemetry analyzed, no false positives, no false negatives have occurred
How Does Telemetry Prognostics Impact SS/L?
Failure Analysis
Engineering Services

- No changes to current vehicle designs needed
  - To increase the amount of equipment used with, increasing the equipment instrumented can be done
- Add education and training in Telemetry Prognostics for use in AT
- Be prepared to return more flight equipment to suppliers and manufacturing
  - Turn around time may impact vehicle integration
    - This may delay AT
- Be prepared to convince equipment suppliers they are shipping unreliable equipment
- Be prepared to require Telemetry Prognostics use during equipment AT just like SS/L, in procurement specifications
Failure Analysis
Engineering Services

● Changes during satellite I&T
  ● Prior to starting AT
    ▪ Operate all satellite equipment, analyze all vehicle telemetry using telemetry prognostics, identifying equipment that will fail in AT
      ▪ Remove, repair or replace equipment identified as unreliable
  ● During AT
    ▪ Analyze all satellite telemetry using telemetry prognostics
      ▪ Remove, repair or replace equipment identified as unreliable
      ▪ Should be no equipment needing repair or replacement
      ▪ AT will be completed quickly
  ● After AT is completed
    ▪ Operate all satellite equipment, analyze telemetry from all equipment while operating
      ▪ Remove, repair or replace equipment identified as unreliable
Areas that can be improved for Failure Prediction™
- More vehicle equipment needs to be instrumented
  - Circuit/unit voltage and/or current and/or temperature
- Not real-time, but can be
  - Real time data must be put in context with previously stored telemetry
    - Need to have available telemetry to create baseline behavior
  - If used real-time, performance is degraded,
    - More false positives
- LSB resolution could be improved
FAILURE ANALYSIS

OTHER TELEMETRY PROGNOSTIC RELATED PROGRAMS
Failure Analysis
Engineering Services

- NASA’s Current Funding of Telemetry Prognostics
  - Multi year, multi million dollar projects headed by NASA Ames
  - 2006 Small Business Innovation Research (SBIR) projects
    - Aeronautical systems - Aviation Safety
      - Integrated Vehicle Health Management
      - Prognosis technology for predicting aircraft failures
    - Space Exploration systems – Future spacecraft & launch vehicles
      - Integrated Vehicle Health Management
      - Prognostic technology for predicting vehicle failures
  - NASA Space Shuttle
    - Funded Argonne National Laboratory with a $700,000 contract for use of SPRT on main engines analysis on launch pad
# Failure Analysis

## Engineering Services

- **Funded NASA SBIR Telemetry Prognostics Technology Development Projects for 2006**

<table>
<thead>
<tr>
<th>NASA Subtopic</th>
<th>NASA Proposal Title</th>
<th>Research Firm</th>
<th>NASA Proposal #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Vehicle Health Management</td>
<td>Diagnostics and <strong>Prognostics</strong> for Space Applications</td>
<td>Global Technology Connection Inc</td>
<td>06-I A1.07-8707</td>
</tr>
<tr>
<td>Integrated Vehicle Health Management</td>
<td>Aircraft Electrical Power System Diagnostics and Health Management</td>
<td>Techno-Sciences, Inc.</td>
<td>06-I A1.07-8798</td>
</tr>
<tr>
<td>Integrated Systems Health Management</td>
<td>Automated Fault Diagnostics, Prognostics, and Recovery in Spacecraft Power Systems</td>
<td>Qualtech Systems, Inc.</td>
<td>06-I X2.01-8204</td>
</tr>
<tr>
<td>Integrated Systems Health Management</td>
<td>Integrated Health Management for Space Flight Digital Systems</td>
<td>Ridgetop Group, Inc.</td>
<td>06-I X2.01-9421</td>
</tr>
</tbody>
</table>
Government agencies currently evaluating Failure Prediction™ technology include:

- **NRO**
  - Satellites
  - Launch Vehicles
- **NASA**
  - Satellites
    - Space Station
  - Launch Vehicles
  - Lunar mission
  - Mars mission
- **Air Force**
  - Satellites
  - Launch Vehicles
- **Air Force**
  - Aircraft jet engines
  - Vehicle testing
- **Navy**
  - Gas Turbine Engine testing
  - Fleet Ballistic Missile Program
- **Missile Defense Agency**
Air Force & Navy Funding Prognostics Programs

- Requiring equipment suppliers to add data at the box level in telemetry that predicts upcoming failures
  - Equipment suppliers know their equipment the best
    - Select the parameters that indicate equipment failures
- Telemetry Prognostics replaces expensive, complex preventive maintenance programs
  - Only repair & replace as required to failed equipment
  - Lowers operational costs
  - Increases equipment reliability
  - Increases equipment maintainability
  - Increases equipment serviceability
Failure Analysis
Engineering Services

- Use of Telemetry Prognostics in Other Industries
  - Nuclear Power
    - Argonne National Laboratory
      - SPRT - Sequential Probability Ratio Test for static time varying sequences
      - MSET – Multi-variante State Estimation Technique for dynamic time series data
  - Computer Servers
    - High-Reliability (>99.999%) Computer Servers
      - Sun Microsystems
        - Added thousands of sensors with lifetimes ½ of servers
        - Uses SPRT and MSET for Prognostics
      - Force High Rel PC servers
        - Proprietary techniques
Failure Analysis
Engineering Services

- **Sequential Probability Ratio Test (SPRT)**
  - Pattern recognition technique for high sensitivity, high reliability sensor and equipment operability surveillance.
    - Define patterns a priori

- **Multi-variate State Estimation Technique (MSET)**
  - Online model-based fault detection and identification
    - Define model a priori
  - Predicts what each process should be based on predefined behavior
  - Incorporates the SPRT to monitor the residuals between the actual observations and the predefined behavior
Failure Analysis
Engineering Services

**Failures Identified Using MSET & SPRT**
# Failure Analysis

Engineering Services

- **Comparison Between Failure Prediction™ & MSET**

<table>
<thead>
<tr>
<th>Performance</th>
<th>Failure Prediction™</th>
<th>MSET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is there experience in Satellite, Launch Vehicle &amp; Missiles?</td>
<td>Yes</td>
<td>No, space shuttle only</td>
</tr>
<tr>
<td>Is there a need to redefine normal behavior for every measurement?</td>
<td>No</td>
<td>Yes, each measurement behavior must be predefined by experts</td>
</tr>
<tr>
<td>Does it compensate for equipment cycling?</td>
<td>Yes</td>
<td>No, need steady state equipment operations</td>
</tr>
<tr>
<td>Can it predict failure precursors?</td>
<td>Yes</td>
<td>No, only uses limits to generate alarms</td>
</tr>
<tr>
<td>Compensate for measurement/circuit aging characteristics?</td>
<td>Yes, without predefinition</td>
<td>Only with predefined behavior from experts for every measurement</td>
</tr>
<tr>
<td>Does it use Virtual Telemetry?</td>
<td>Yes to generate baseline behavior and predict normal behavior</td>
<td>Yes, to input into prognostic software to stop limit alarms</td>
</tr>
<tr>
<td>Can it identify failed transducer circuit?</td>
<td>Yes</td>
<td>Yes, only if normal behavior is predefined, input into prognostic software cannot be turned off, cannot identify the difference between failed sensor and failure precursor</td>
</tr>
</tbody>
</table>
## Failure Analysis
### Engineering Services

<table>
<thead>
<tr>
<th>Performance</th>
<th>Failure Prediction™</th>
<th>MSET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can it turn off input into prognostic software?</td>
<td>Yes</td>
<td>No, virtual normal telemetry behavior must be created and continuously fed into prognostic software to stop limit alarms even after transducer failure</td>
</tr>
<tr>
<td>Is there limit analysis?</td>
<td>up to 5 sets</td>
<td>1 set</td>
</tr>
<tr>
<td>Is pattern recognition technology used?</td>
<td>No</td>
<td>Patterns need to redefine for every measurement for recognition by experts</td>
</tr>
<tr>
<td>Does modeling of normal behavior occur?</td>
<td>Yes</td>
<td>No, must be predefined by experts</td>
</tr>
<tr>
<td>Is there simultaneous measurement analysis?</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Does it use proactive diagnostics?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Does it use active reasoning?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Is there a Prognostician?</td>
<td>Yes</td>
<td>No, there is only software limit alarms and predefined behavior</td>
</tr>
</tbody>
</table>
Failure Analysis
Engineering Services

- **Documents/publications made available for SS/L**
  - Failure Analysis data sheets
  - Telemetry Prognostics Technology presentation, 9/2007, by Len Losik
  - Predicting Failures and Estimating Duration of Remaining Service Life from Satellite Telemetry paper, 10/1995
  - Lockheed Martin Trident Fleet Ballistic Missile Program Telemetry Prognostics 6 month/$500K IR&D Results, 11/1995
Telemetry Prognostics

- Lowers Vehicle Program Costs
- Shortens Testing Schedule
- Can use it as Discriminator
- Determines Remaining Usable Life
- Determines Day Of Failure
- Increases Equipment Reliability
- Increases Equipment Serviceability
- Increases Equipment Availability
- Increases Equipment Usable Remaining Life
- Stops On Orbit Infant Mortalities
- Stops On Orbit Failures
- Extends Equipment On Orbit Life
- Uses Flight Proven Techniques
- Highly Reliable
- Available Today
Failure Analysis
Engineering Services

**Next Step for SS/L**
- Evaluate information left by FA for credibility and suitability for
  - Equipment manufacturing
  - Factory I&T
  - Mission control
- Analyze flight equipment manufacturing and satellite I&T failures/rework costs, schedule impacts on past satellite programs to determine validity of FA claims

**Next Step for FA**
- Wait for information to be developed by SS/L to quantify costs savings and schedule reductions on SS/L satellite programs
- Request another visit to SS/L to discuss use of Failure Prediction™ technology with existing satellite programs
- Resolve any questions

1/13/2014
Results of our meeting

- Educate SS/L on Failure Prediction™ technology?
- Request SS/L use Failure Prediction™ technology?
- FA Receive information on SS/L telemetry database formats?