Reliability Prediction Using Bayesian Updating of On-Orbit Performance

Reliability Prediction Using Bayesian Updating of On-Orbit Performance

Agenda

• Historical Perspective
  – Prediction Data
  – PRACA Data
  – Configuration Data
  – Analysis Techniques

• Improvement Initiative
  – Goals & Requirements
  – Development of FIAT & Status
  – FIAT Prototype Demo

• Continued Improvement
  – Expansion of FIAT
  – Interconnection of data
  – Output Sharing
Reliability and Risk Assessment at GSFC:

• Assists GSFC missions/organizations in implementing effective Reliability & Maintainability (R&M), Risk Management, Risk Analysis, and Lean Six Sigma (LSS) programs in order to identify, analyze, mitigate, and/or eliminate potential problems/barriers to mission and/or organizational success.

• Currently GSFC relies largely on outdated military handbooks (e.g., Mil-HDBK-217) without the benefit of utilizing actual spaceflight experience from GSFC, NASA, and industry to assess performance risk/reliability by executing project system, subsystem, and component risk assessments, reliability, and/or availability analyses (e.g., Probabilistic Risk Assessment (PRA); Fault Tree Analysis (FTA); Failure Modes and Effects Analysis (FMEA) and Critical Items Lists (CIL); Worst Case Analysis (WCA); Parts Stress Analysis (PSA); etc.)

Whereas NPD 8720.1 requires that GSFC “Share R&M data and experience for use as heritage data in support of current, follow-on, and new programs or projects.”
Historical Perspective

Prediction Data used by GSFC:

- Mil-HDBK-217 — uses constant failure rates and is not current with current spaceflight systems.
  - Constant failure rate was chosen for ease of computation without computers and was a reasonable approximation in 1970’s when 217 was first issued
  - Many components have time based wear mode and are better modeled with Weibull distribution whereas as others may over emphasize temperature stresses but not cycling stresses
- Mil-HDBK-217Plus with RiAC/Growth rate from vendors — which are still not orbital experience adjusted values but rather failure rates for operating periods, non-operating periods and cycling.

Prediction Data also available:

- RADC-TR-85-91, Reliability Toolkit, ALCATEL, BELLCORE, BRITISH TELECOM
- CNET, Telcordia, IEC, GPRD, FIDES, UTE, Siemens, etc.

Current data as used, no matter the source, is causing the large variations between prediction and on-orbit reliability/performance and reducing the value/believability of predictions.
Issues with MIL-HDBK-217:

- Data for latest versions at least 15 years out of date with no valid models for modern integrated circuits, detectors, lasers, etc.
- Per 217F Notice 2: "This Handbook is for Guidance Only - Do not Cite this Document as a Requirement."
- Per memo dated February 15, 1996 by Gilbert F. Decker, Assistant Secretary of the Army (Research, Development and Acquisition)
  - The best RFP's will directly specify performance-based reliability requirements and avoid citing any specification, standard or handbook.
  - In particular, MIL HDBK 217, Reliability Prediction of Electronic Equipment, is not to appear in an RFP as it has been shown to be unreliable and its use can lead to erroneous and misleading reliability predictions.

MIL-HDBK-217 provides little accuracy for predicting Reliability of electronic hardware, especially spacecraft hardware.
Problem Reporting, Anomaly, and Correction Action (PRACA) Data at GSFC:

- Data pre-flight is housed in the Problem Reporting/Problem Failure Reporting (PR/PFR) system – which is designed to document testing faults and corrective actions;
- Data gathered during flight is housed in the Spacecraft Orbital Anomaly Report System (SOARS) – which is designed to document flight and ground anomalies and corrective actions;
- Vendor/Industry Data when available in EIDPs and/or reporting cycles.

Historically the issue with factoring experiential data into the analysis process has been identifying explicitly the failure and success context and translating textual reports of experiences into useable statistical analysis inputs.
Analysis Techniques for failure rate updating used by GSFC:

• Weibull Analysis for failure forecasts with extremely small test data sets & Weibayes Analysis for Weibull failure forecasts only one test parameter.

• Bayesian Estimation for non-repairable systems using:
  - R-DAT a Bayesian data collection and analysis package designed specifically for risk analysts and reliability engineers who frequently need to develop and update system-specific reliability parameter estimates via:

  System-Specific Bayesian Updating
  - Use Poisson and Binomial likelihood models for time-based and demand-based data.
  - Use lognormal and normal error models for expert judgment.
  - Select your prior distribution from a wide variety of parametric distribution models, including Beta, Gamma, Lognormal, and Loguniform.
  - Update posteriors obtained in previous Bayesian updates, or generic distributions.
  - View prior and posterior distributions in graphical and tabular forms.

  Generic Distribution Development
  - Develop generic distributions based on combinations of data and expert judgments.
  - Select from lognormal, Gamma, and Beta variability distribution models.
  - Avoid specification or tuning of discrete prior grids by using R-DAT’s continuous priors.
  - View variability model parameter distributions, as well as population variability c.d.f. and p.d.f.
  - View the uncertainty bounds of the resulting distribution.
Can current SOARS/on-orbit anomaly data be used for Bayesian updating to get more NASA -based failure rates?

- Multiple feasibility studies were conducted by UMD to explore the benefits of Bayesian methods in analyzing SOARS data and estimating failures.
- These studies involved engineering analysis and aggregation of information from different data sources to gather the necessary “success” and “failure” data.
- Applied a number of simple and complex Bayesian methods depending on the nature of the data and type of parameters being estimated. Cases included:
  - Constant failures rate estimation with Poisson and Binomial data models
  - Weibull time to failure distribution estimation
  - Treatment of Uncertain Data, using Weighted Likelihood and Weighted Posterior Methods
  - Treatment of Certain Data, using Beta-Binomial distributions
- These analyses were conducted with RDAT Software.
Estimate the probability of MOC/MMOC operator error for the ACE mission using the events recorded in SOARS.

- Historically, NASA Goddard has assumed that the Multi Mission Operation Center (MMOC) / Mission Operation Center (MOC) operators are perfect i.e. probability of failure = 0; This being very optimistic because it is estimated that human contribution to risk is ~ 60 -85%.
- Hence the need to more accurately estimate human error by using available data collected from NASA missions to estimate the probability of failure (success) of the MMOC/MOC operator

\[
\pi(\rho|E) = \frac{L(E|\rho) \pi_0(\rho)}{\int L(E|\rho) \pi_0(\rho) d\rho}
\]

Where
- \(E\) = evidence (data from ACE mission)
- \(\pi(\rho|E)\) = posterior probability estimate of the MOC operator’s probability of failure
- \(L(E|\rho)\) = likelihood of the data obtained from the ACE mission
- \(\pi_0(\rho)\) = prior estimate of the MOC operator’s probability of failure
PRIOR DATA

Assume MOC/MMOC operator’s probability of failure (p) ≈ 0

- Prior Distribution = Beta (α, β)
  - \( \alpha (\alpha) \approx \# \text{ of failures in the prior dist.} \approx 1 \) (note that if \( \alpha = 0 \), then improper dist.)
  - \( \beta (\beta) \approx \text{Total \# of demands over which the failures occur} \)
    - prior \( \alpha (\alpha) = 5630 - 1 - 5629 \)
## BAYESIAN RESULTS

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*FP = Failure Probability
*SP = Success Probability
TBD Bayesian Example: AIM’s Mission Control Operator Errors

BAYESIAN RESULTS

Failure Probability

Prior distribution

Posterior distribution

Success Probability

Posterior distribution

Prior distribution
## VALIDATION

### Failure Probability

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<th>Posterior Parameters (WINBUGS)</th>
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### Success Probability

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<td>Beta</td>
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<td>Standard deviation</td>
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<tr>
<td>0.95</td>
<td>0.9985</td>
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CO

CONTEXT from Ali Mosleh, PhD - UMD

• Spacecraft: Aqua (launched 5/4/2002)
  – Dual Thruster Module (DTM): DTM-1, DTM-2, DTM-3, DTM-4
• Spacecraft: Aura (launched 7/15/2004)
  – Dual Thruster Module (DTM): DTM-1, DTM-2, DTM-3, DTM-4

4 DTMs on Aqua’s Observatory
DATA

• SOAR # S-AQUA-0052 (E-7690)
  - On September 8, 2007, the prime heater and the redundant heater on DTM-2 changed their nominal temperature profiles.

• History failure data for Aqua and Aura
  - Aqua: Between May, 2004, and December, 2005, DTM-1 thermistor data flopped back and forth. After December, DTM-1’s prime temperature curve and redundant temperature curve had swapped permanently.
  - Aqua: DTM-2 may have experienced a "Stuck On" heater on September 16, 2004 and a Heater/Thermostat failure on July 30, 2005.

<table>
<thead>
<tr>
<th></th>
<th>Aqua</th>
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<tr>
<td>DTM #1</td>
<td>1 failure</td>
<td>0 failure</td>
</tr>
<tr>
<td>DTM #2</td>
<td>3 failures</td>
<td>0 failure</td>
</tr>
<tr>
<td>DTM #3</td>
<td>0 failure</td>
<td>1 failure</td>
</tr>
<tr>
<td>DTM #4</td>
<td>0 failure</td>
<td>0 failure</td>
</tr>
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</table>
ASSUMPTIONS FOR WEIGHTED LIKELIHOODS

- Failures
  - DTM #1 for Aqua: temperatures switched back and forth but considered as 1 failure
  - DTM #3 for Aura: temperatures switched → considered as 1 failure
  - 2 additional failures for DTM #2 for Aqua ("Stuck On" heater and Heater/Thermostat failure)
- Mission time: between launch date and 9/15/2010
- Prior Lognormal distribution
  - 5th and 95th confidence interval of $10^{-8}$ and $10^{-3}$
- Weights of 0.8 and 0.2

In R-DAT:

\[ k = 4 \times 0.8 + 1 \times 0.2 = 3.4 \text{ failures} \]

\[ T = 4 \times 73,312 \times 0.8 + 4 \times 57,786 \times 0.2 = 278,427.2 \text{ hours} \]
BAYESIAN INFERENCE

- UOI: Failure rate of Aqua's DTM
- Prior: Lognormal distribution with a 5th and 95th confidence interval of $10^{-8}$ and $10^{-3}$
- Likelihood: Use of combined evidence on 2 spacecrafts

Time of operation from launch date to 9/15/2010

$T_{Aqua} = 8\text{ years, 4 months, 11 days} = 73,312\text{ hours}$

$T_{Aura} = 6\text{ years, 3 months} = 54,786\text{ hours}$

<table>
<thead>
<tr>
<th></th>
<th>Aqua</th>
<th>Aura</th>
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<tbody>
<tr>
<td>Number of failures</td>
<td>4 failures</td>
<td>1 failure</td>
</tr>
<tr>
<td>Total number of hours of operation at the date of 9/15/2010</td>
<td>$4*73,312\text{ hours}$</td>
<td>$4*54,786\text{ hours}$</td>
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<tr>
<td>Weight</td>
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</table>

(4 DTM per spacecraft)
Weighted Likelihoods Bayesian Example: Aqua's Dual Thruster Modules Failures

BAYESIAN Results

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<tr>
<th>Distribution</th>
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<th>Posterior</th>
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<td>1.187E-5</td>
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<tr>
<td>Tau</td>
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<tr>
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<td>0.99</td>
<td>0.0109</td>
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</tbody>
</table>

Legend: Prior, Posterior
Can current SOARS/on-orbit anomaly data be used for Bayesian updating to get more NASA-based failure rates?

YES!!
Need integrated tools/capabilities to develop via Bayesian methods more accurate prediction data/risk assessments based on experience for use as heritage data in support of current, follow-on, and new programs or projects.

- Create an application to capture the configuration data that is needed by the RDAT Bayesian Tool
- Build an interface to upload Anomaly/Failure data from generated SOARS Excel reports and allow the user to select specific failures for analysis
- Enhance the RDAT tool to run on a Web server and allow inputs from the FIAT Application
- Define and develop an interface between FIAT and RDAT Tool so that FIAT can pass configuration parameters and Anomaly/Failure data to RDAT for analysis and return results to the FIAT Application
- Graph the statistical output data from the RDAT Tool
- Provide a print function for the output graph and configuration parameters
- Archive/Share results
Mission Configuration Demo

a perpetual archive of Mission Configurations to give context to experience data and Bayesian analysis.
https://gsfcmissionconfiguration.gsfc.nasa.gov
Need integrated tools/capabilities to develop via Bayesian methods more accurate prediction data/risk assessments based on experience for use as heritage data in support of current, follow-on, and new programs or projects.

- Create an application to capture the configuration data that is needed by the RDAT Bayesian Tool --- Now being maintained/updated with more missions by GSFC SMA.
- Build an interface to upload Anomaly/Failure data from generated SOARS Excel reports and allow the user to select specific failures for analysis.
- Enhance the RDAT tool to run on a Web server and allow inputs from the FIAT Application.
- Define and develop an interface between FIAT and RDAT Tool so that FIAT can pass configuration parameters and Anomaly/Failure data to RDAT for analysis and return results to the FIAT Application.
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- Provide a print function for the output graph and configuration parameters.
- Archive/Share results.
FIAT Development Process:

- Discussions with RDAT/UMD teams to explain Mission Configuration capabilities
- Developed Storyboards to define page layouts to capture mission configuration, failure and success data
- Developed FIAT database to store user input analysis data
- Discussion with RDAT & Code 322 team about interface and Bayesian Analysis
- Reviewed and analyzed SOARS data
- Reviewed Feasibility Study
- Created SOARS input format/formatter
- Developed graph to plot RDAT Results
- Validate results and path forward
- Interface with the RDAT through DLL (Dynamic Link Library)
  - FIAT passes analysis parameters to RDAT
  - RDAT passes results to FIAT
FIAT Prototype Demo

a web-based orbital data Bayesian failure analysis tool for NASA missions
Step 1: Login

1. Enter a username and password
2. To obtain a username and password please contact feng@blinex.com
3. Future: Enhance system to use NDC username and Password
1. Select a Mission and the following fields will be automatically populated from the Mission Configuration application:
   a. Launch Date;  b. Still Operational
2. Current Date is automatically populated by the system
3. Enter in a Start and End date for analysis
4. Select subsystem, component, part or sub part from the pull down list for the item that is going to be analyzed. This data is pulled from Mission Configuration Application.
5. Select Failure Mode
6. Enter in the planned total operating time of the item during the mission
7. Select if you know the operating time or want the system to calculate it for you
8. If you want the system to calculate, enter yes or no if there are identical items
9. If there are identical items, enter in the redundancy information
Step 3: Redundancy Configuration

For each Redundancy Group Tab:
1. Define redundancy Rules by entering in the redundancy in the form of XX of XX
2. Select if Active Standby, Inactive Standby or Active
3. Enter in planned total operating time of the redundant group
4. Enter in how many times or was it planned for the redundancy state to change during the mission
Step 4: Upload Data File and Select Failures

1. Select Browse and select the FIAT/RDAT Template Excel Spreadsheet that has been populated with SOARS data and the Macro executed
2. The uploaded data from the Excel Spreadsheet will be filtered by the Analysis Start and End date and be filtered by subsystem, component, part and subpart that was entered in during the first configuration step
3. Select which SOARS items to be included in the analysis
Step 5: Enter Prior and Likelihood

1. Select Prior Type
2. Enter in Prior 5th and 95th Percentile values
3. Select Posterior Type
4. Enter in Event and Time values
Step 6: Analysis Output Report

1. The Analysis Report includes graphs and a dataset
2. Toggle between Linear and Logarithmic graphs
3. Select the camera icon and save a snapshot of the report to include in analysis reports
Step 6: Analysis Output Report

CDF output using logarithmic scaling

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Step 6: Analysis Output Report
Step 6: Analysis Output Report

PDF output using logarithmic scaling

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Need integrated tools/capabilities to develop via Bayesian methods more accurate prediction data/risk assessments based on experience for use as heritage data in support of current, follow-on, and new programs or projects.

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- Provide a print function for the output graph and configuration parameters
  - Archive/Share results
Future Analysis Enhancements

- Add additional Bayesian analysis capabilities from RDAT including (beyond Lognormal)
- Additional options for prior and likelihood distributions
- Homogenous and non-homogenous data analysis or Beta, Gamma, Normal, Truncated Lognormal, Uniform, & Log-Uniform distributions.
- Add additional capability to calculate success data (for example for cycled equipment or mix use)
- Add common cause failure parameter estimation module
Future Application Enhancements

- Add a function to export the output dataset to Excel
- Manage and store Prior values from:
  - FIAT Analysis
  - Predictions Databases
  - MIL Standard Documents
- Add a function to allow users to select Prior Values that are stored
- Automate the interconnection to SOARS data and its formatting
- Add a function to allow users to save and share data analysis
- Add Weibull Analysis capability (not in RDAT)
- Go Live
Feedback? & Questions?