

Reliability Prediction Using Bayesian Updating of On-Orbit Performance



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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



Historical Perspective



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- Currently GSFC relies largely on outdated military handbooks (e.g., Mil-HDBK-217) without the benefit of utilizing actual spaceflight experience from GSFC, NASA, and industry to assess performance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.





Historical Perspective



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



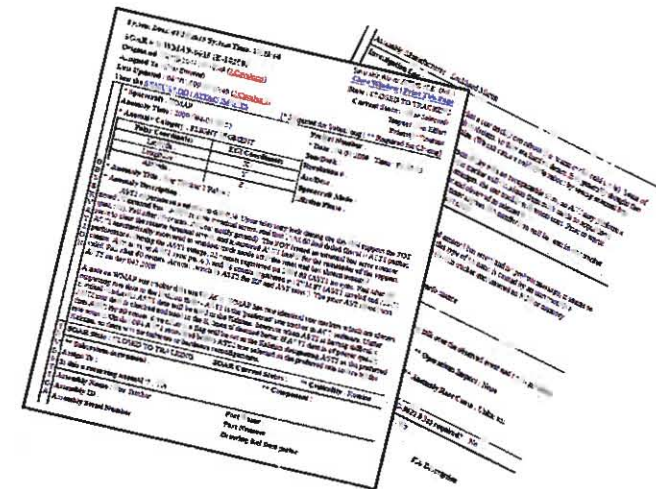
Historical Perspective



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.





Historical Perspective



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.



Historical Perspective



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 Weighed Posterior Methods
 - Treatment of Certain Data, using Beta-Binomial distributions
- These analyses were conducted with RDAT Software

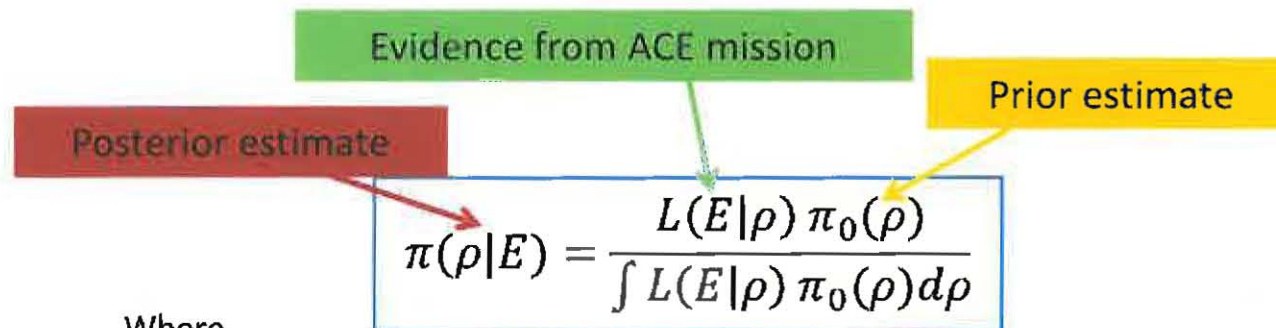


TBD Bayesian Example: AIM's Mission Control Operator Errors



CONTEXT from Nsimah J. Ekanem, NASA/UMD

- 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



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



TBD Bayesian Example: AIM's Mission Control Operator Errors



PRIOR DATA

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

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



TBD Bayesian Example: AIM's Mission Control Operator Errors



BAYESIAN RESULTS

Distribution Parameters	Prior Estimates (*FP)	Prior Estimates (*SP)	Posterior Estimates (*FP)	Posterior Estimates (*SP)
distribution	Beta	Beta	Beta	Beta
alpha	1	5629	25	11240
beta	5629	1	11240	25
mean	0.0001776	0.9998	0.00222	0.9978
var	3.154E-08	3.15E-08	1.967E-07	1.97E-07
0.01	0.000001785	0.9992	0.00132	0.9966
0.05	0.000009112	0.9995	0.001544	0.997
0.1	0.00001872	0.9996	0.001674	0.9972
0.5	0.0001231	0.9999	0.002191	0.9978
0.9	0.000409	1	0.002804	0.9983
0.95	0.0005321	1	0.002997	0.9985
0.99	0.0008178	1	0.00338	0.9987

*FP = Failure Probability

*SP = Success Probability

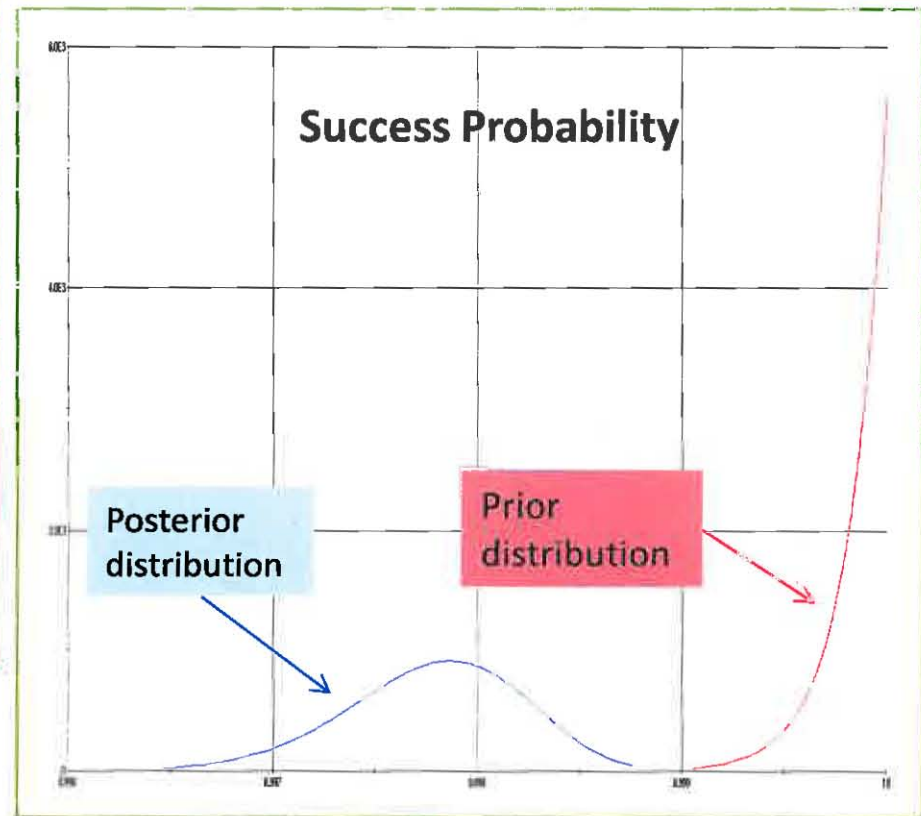
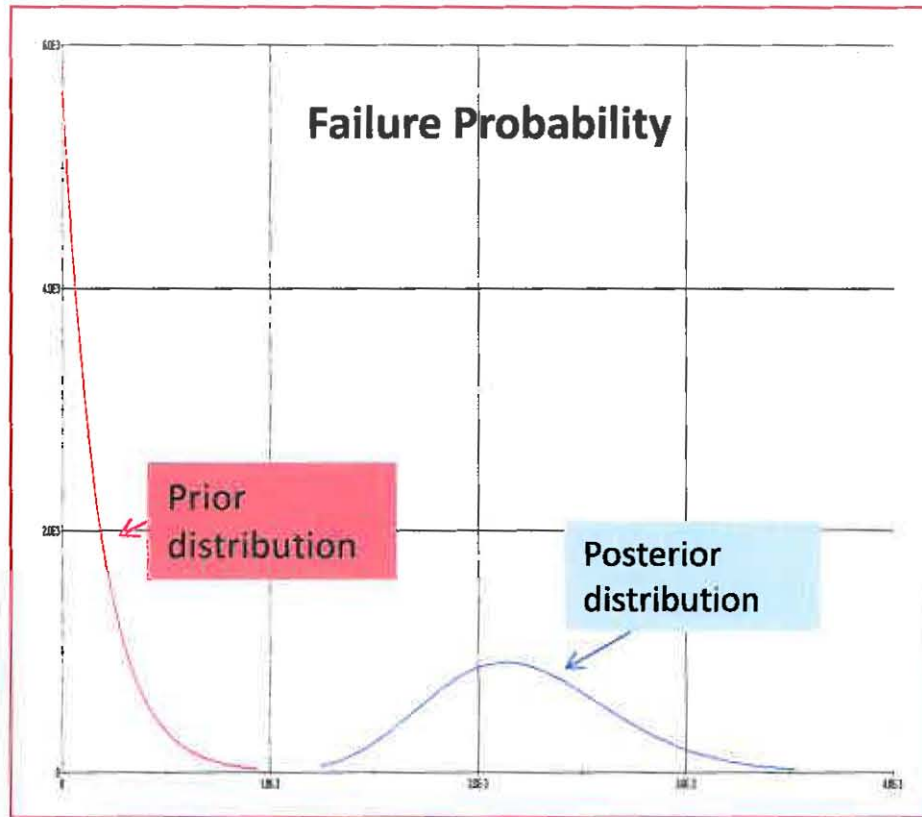




TBD Bayesian Example: AIM's Mission Control Operator Errors



BAYESIAN RESULTS





TBD Bayesian Example: AIM's Mission Control Operator Errors



VALIDATION

Failure Probability

Distribution Parameters	Posterior Parameters (RDAT)	Posterior Parameters (WINBUGS)
Distribution	Beta	Beta
Mean (p)	0.00222	0.002223
Standard deviation	0.0004435	0.0004459
Var	1.967E-07	1.988E-07
0.05	0.001544	0.001541
0.5	0.002191	0.002191
0.95	0.002997	0.003015

Success Probability

Distribution Parameters	Posterior Parameters (RDAT)	Posterior Parameters (WINBUGS)
Distribution	Beta	Beta
Mean (p)	0.9978	0.9978
Standard deviation	0.000444	0.0004473
Var	1.97E-07	2.00077E-7
0.05	0.997	0.997
0.5	0.9978	0.9978
0.95	0.9985	0.9985

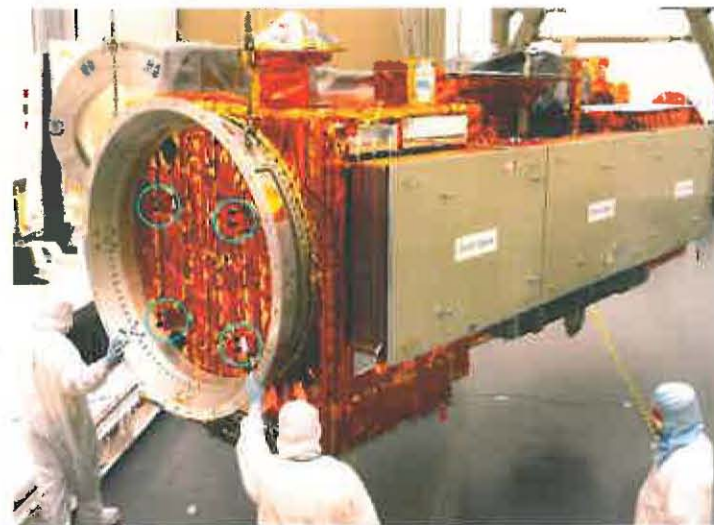


Weighted Likelihoods Bayesian Example: Aqua's Dual Thruster Modules Failures



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



Weighted Likelihoods Bayesian Example: Aqua's Dual Thruster Modules Failures



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
 - Aura: On August 16, 2005, Aura's DTM-3 prime and redundant thruster temperature profiles switched

	Aqua	Aura
DTM #1	1 failure	0 failure
DTM #2	3 failures	0 failure
DTM #3	0 failure	1 failure
DTM #4	0 failure	0 failure



Weighted Likelihoods Bayesian Example: Aqua's Dual Thruster Modules Failures



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:

$$k = 4*0.8 + 1*0.2 = 3.4 \text{ failures}$$

$$T = 4*73,312*0.8 + 4*57,786*0.2 = 278,427.2 \text{ hours}$$



Weighted Likelihoods Bayesian Example: Aqua's Dual Thruster Modules Failures



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

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

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

	Aqua	Aura
Number of failures	4 failures	1 failure
Total number of hours of operation at the date of 9/15/2010	4*73,312 hours	4*54,786 hours
Weight	0.8	0.2

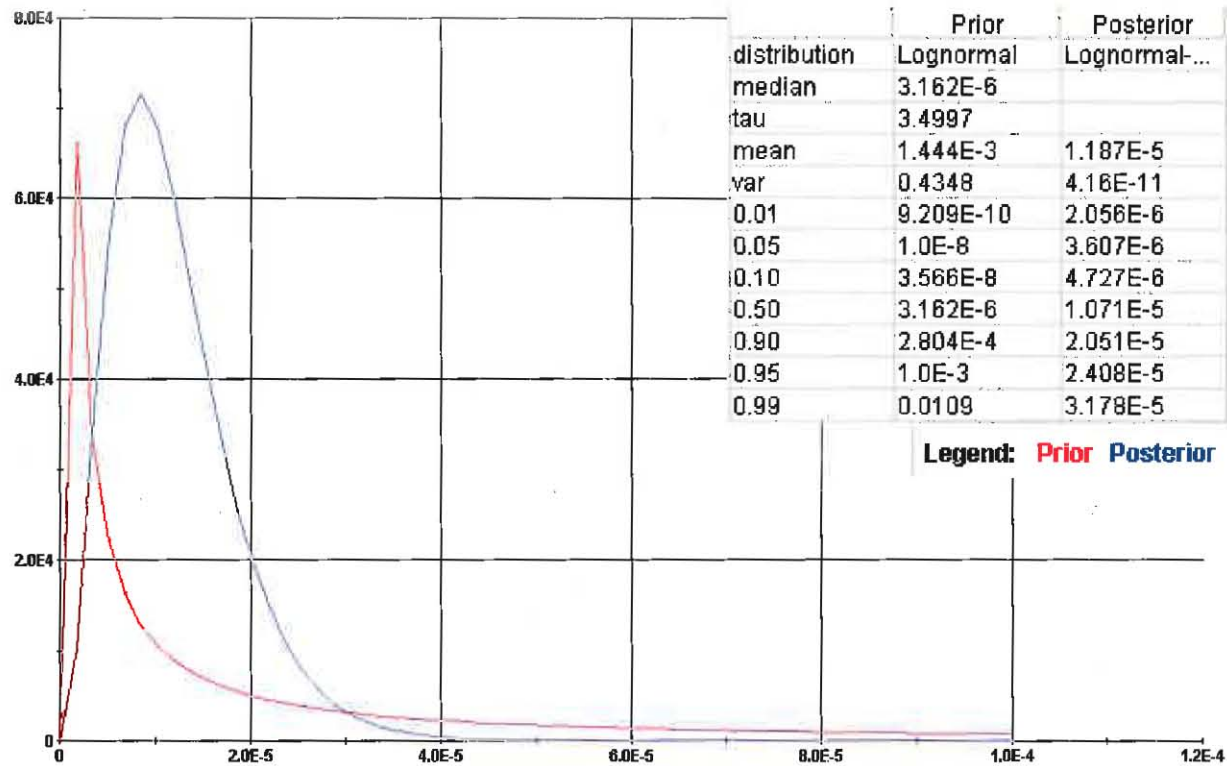
(4 DTMs per spacecraft)



Weighted Likelihoods Bayesian Example: Aqua's Dual Thruster Modules Failures



BAYESIAN Results





Historical Perspective



Can current SOARS/on-orbit anomaly data be used for Bayesian updating to get more NASA –based failure rates?

YES!!



Improvement Initiative



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.

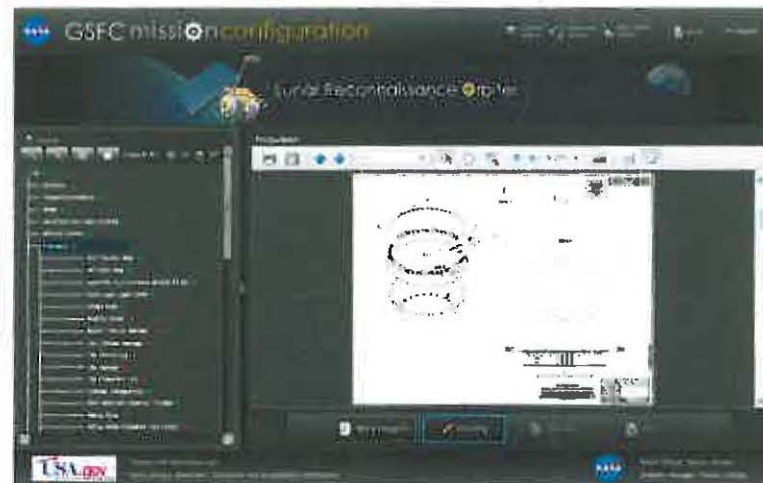
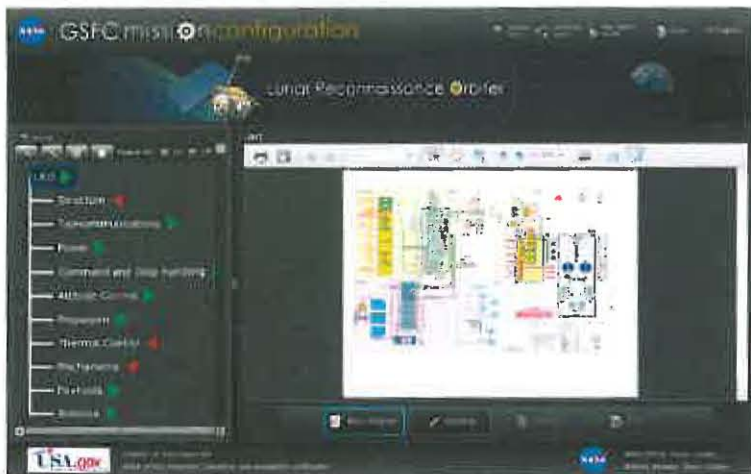




mission configuration

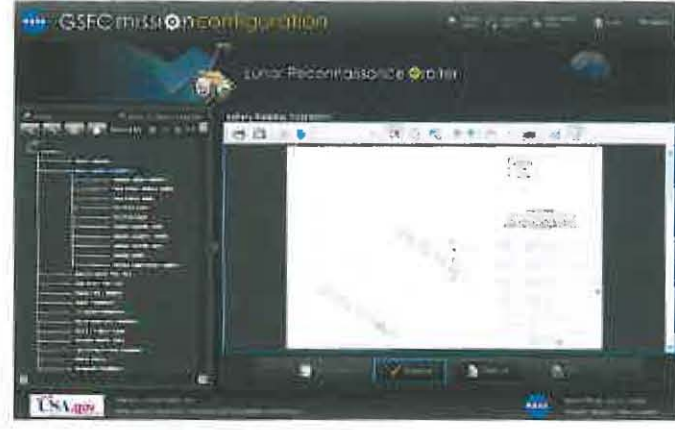
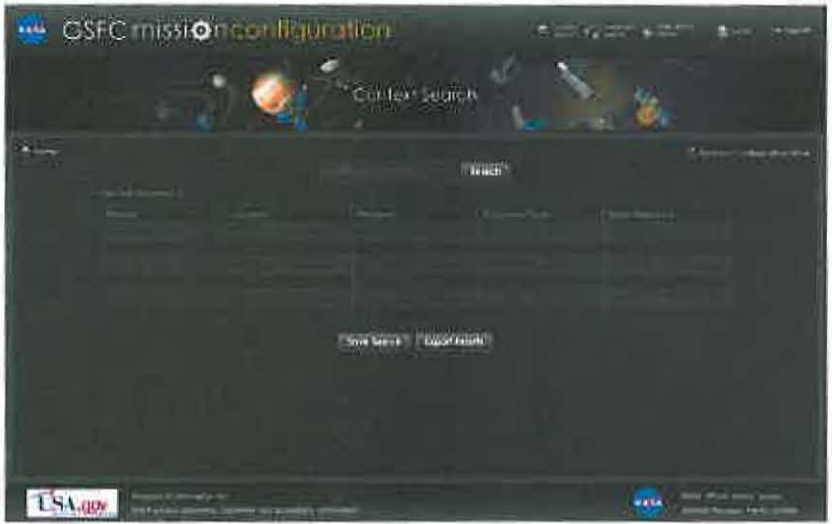



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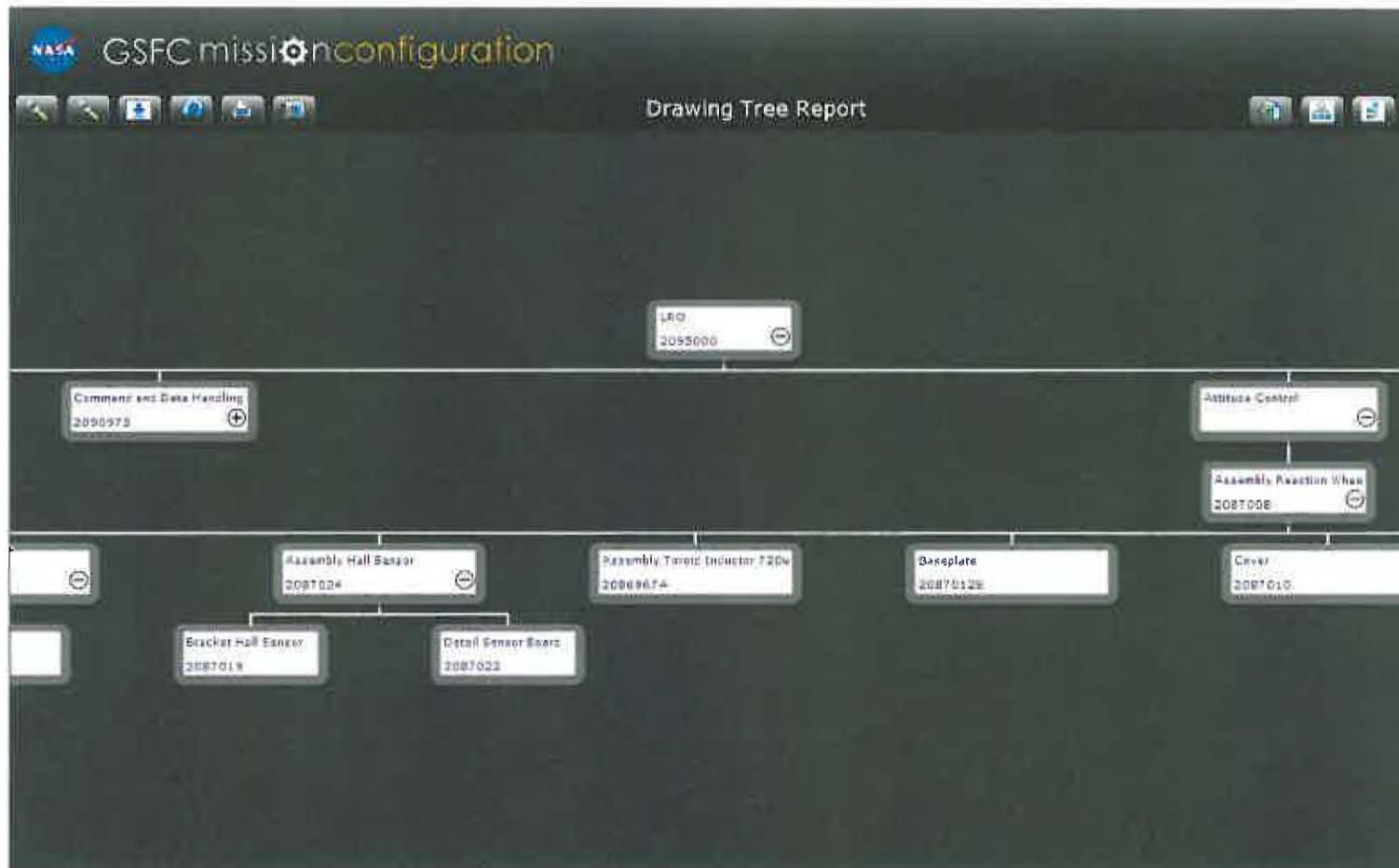


mission configuration



mission configuration





Improvement Initiative



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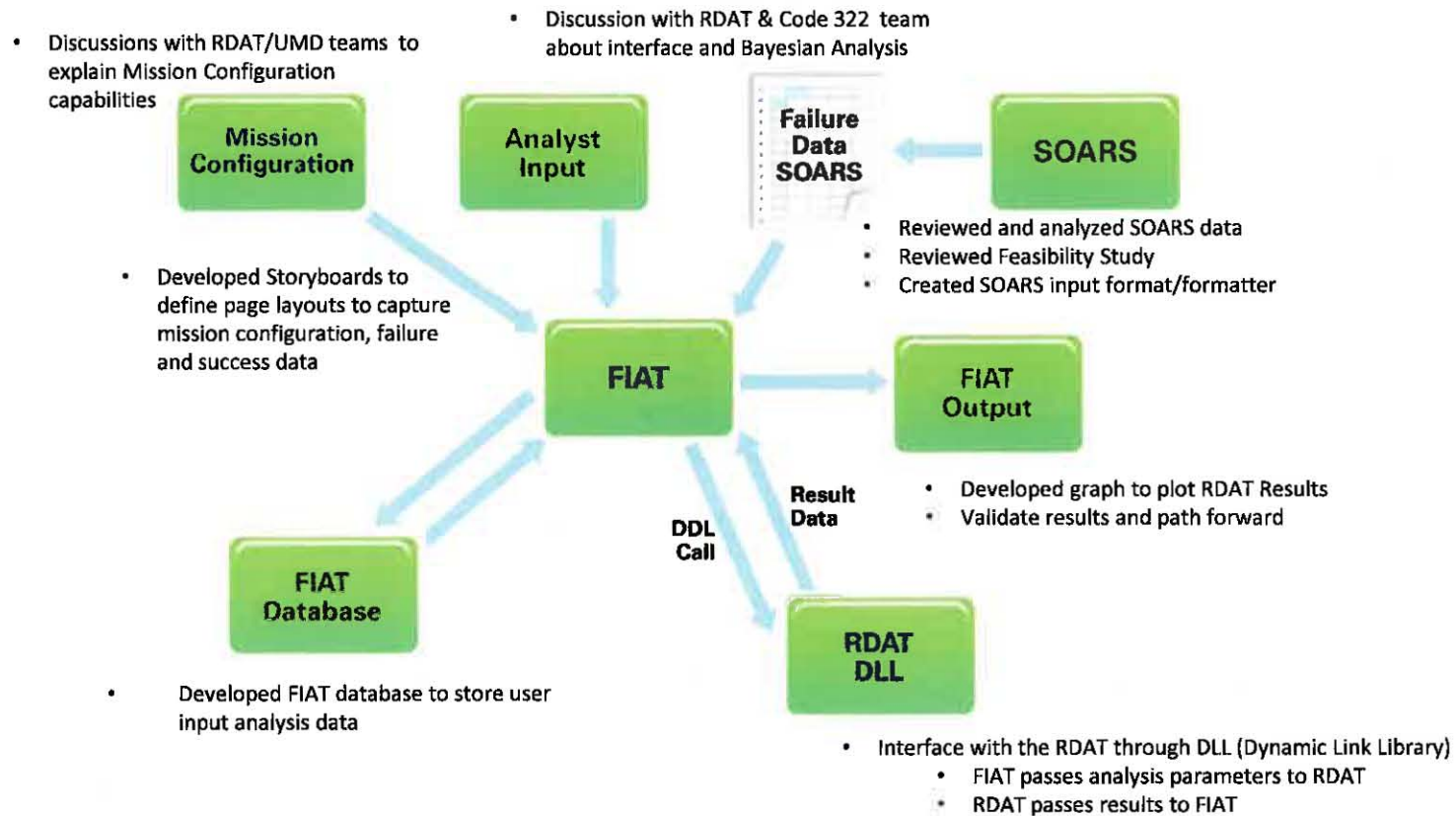
- ✓ Create an application to capture the configuration data that is needed by the RDAT Bayesian Tool --- *Now being maintained/updated with more missions by GSFC SMA.*
- Build an interface to upload Anomaly/Failure data from generated SOARS Excel reports and allow the user to select specific failures for analysis
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Improvement Initiative



FIAT Development Process:





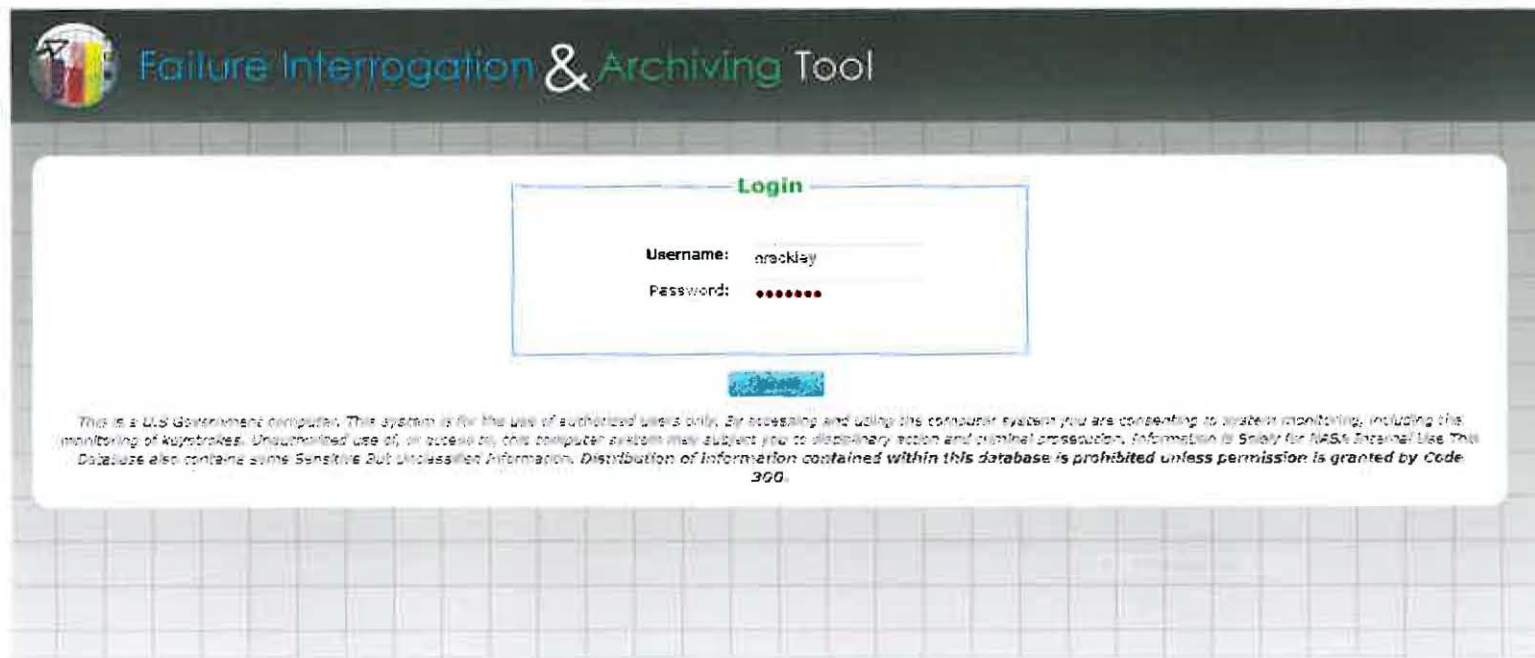
FIAT Prototype Demo

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



Step 2: Configuration Setup

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.





Failure Interrogation & Archiving Tool

Step 2: Configuration Setup (cont.)

Mission: LRO Launch: 10/11/2009
Still Operational? Yes No Current Date: 09/29/2012
Start Date (Analysis): 02/01/2008 End Date (Analysis): 10/31/2009
Select an item for which reliability data needs to be analyzed:
Payloadcode -- Select a Component -- No part available No support available
Failure Mode: Failure During Operation
What is the planned total operating time of the item during the mission? (i.e. What % of the mission time is the item powered ON) 100 %
Do you know the total operating hours for the class of components, or you want the system to calculate the total operating hour?
 I know the total operating hours Let the system calculate it
Are there other items in the Mission that are identical to the item selected? Yes No
How many? 6
Are there any redundancy formations? Yes No
How many? 2

Back Next

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

Failure Interrogation & Archiving Tool

Redundancy Group 1 Redundancy Group 2

Define Redundancy Rules:

Redundancy is in the form of 1 of 3 needed for the mission.

Active Standby - parallel operating Inactive Standby - Standby Active - Series

What is the planned total operating time of the redundant group during the mission? (i.e. what % of the mission time is the redundant group powered ON) 100 %

How many times did it is it planned for the redundancy state to change during the mission?

Previous Next

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



Failure Interrogation & Archiving Tool



Step 4: Upload Data File and Select Failures

Anomaly Data Excel File: Browse

Mission: LR0

Subsystem: Payloads Component: N/A Part: N/A Subpart: N/A

Start Date: 09/01/2009 End Date: 10/31/2009

Anomaly Date	Anomaly Title	Is Failure
07/07/2009	WAC file corruption	<input type="checkbox"/>
07/11/2009	LR0C Init Filename Invalid Length	<input checked="" type="checkbox"/>
07/20/2009	LR0C Imaging error during Mini-RF Activation	<input checked="" type="checkbox"/>
07/27/2009	LR0C WAC File Corruption	<input checked="" type="checkbox"/>
08/01/2009	LR0C WAC current drop	<input type="checkbox"/>
08/14/2009	LR0C Power Cycle (RTS #96) Again	<input type="checkbox"/>
08/18/2009	LRLOADFILE Command on an LR0C Initialization File Containing SCS Bootstrap Code	<input type="checkbox"/>
08/18/2009	RTS#98 power-cycled LR0C	<input type="checkbox"/>
10/09/2009	Unable to process WAC Image through DMS	<input checked="" type="checkbox"/>

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



Failure Interrogation & Archiving Tool

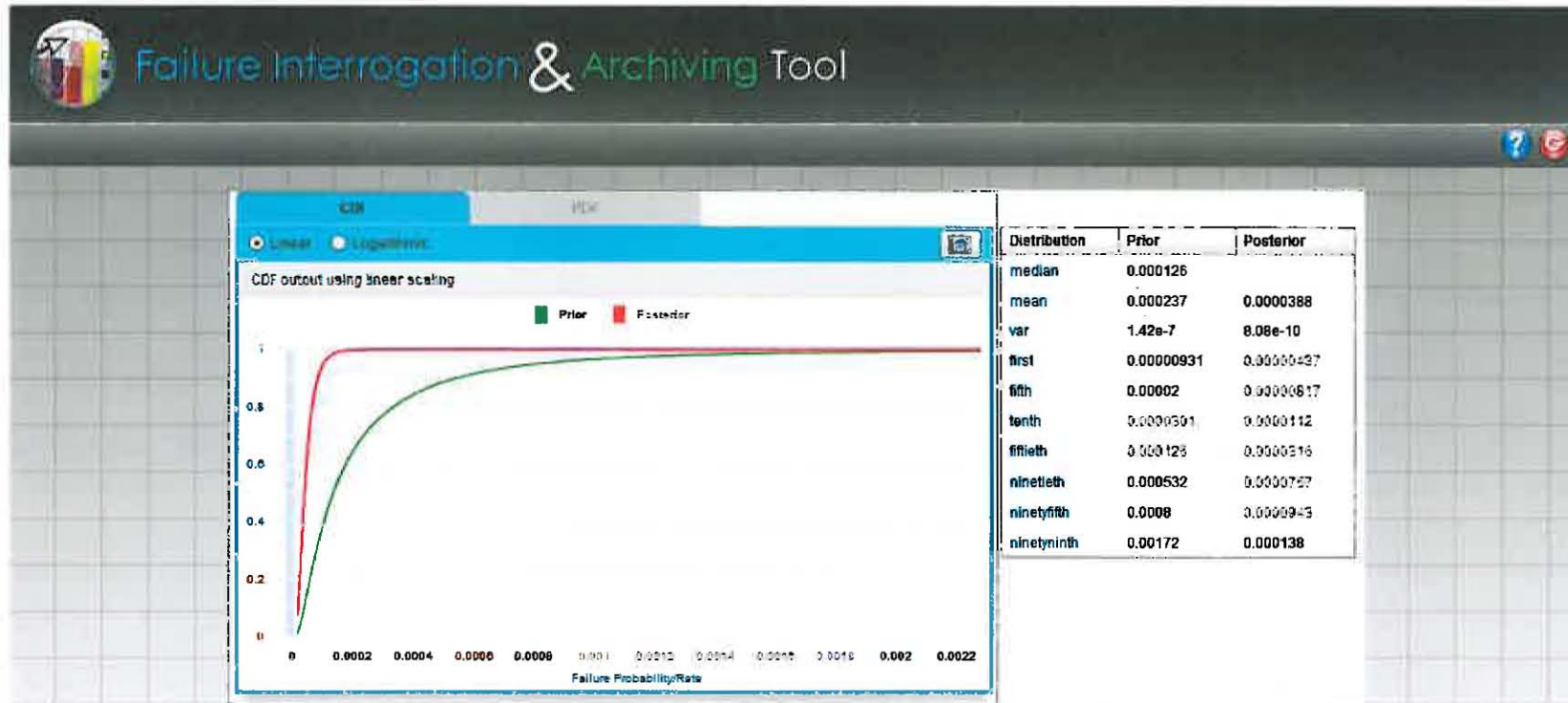
Step 5: Enter Prior and Likelihood

The screenshot shows the 'Failure Interrogation & Archiving Tool' interface. The 'Prior' section includes a 'Model: 5th/95th' label, a 'Prior Type: Lognormal' dropdown menu, and input fields for '5th: 0.00002' and '95th: 0.0008'. The 'Likelihood' section includes a 'Posterior Type: Poisson' dropdown menu, an 'Event: 4' input field, and a 'Time: 20400 hrs.' input field. There are two blue buttons at the bottom of the form area.

1. Select Prior Type
2. Enter in Prior 5th and 95th Percentile values
3. Select Posterior Type
4. Enter in Event and Time values



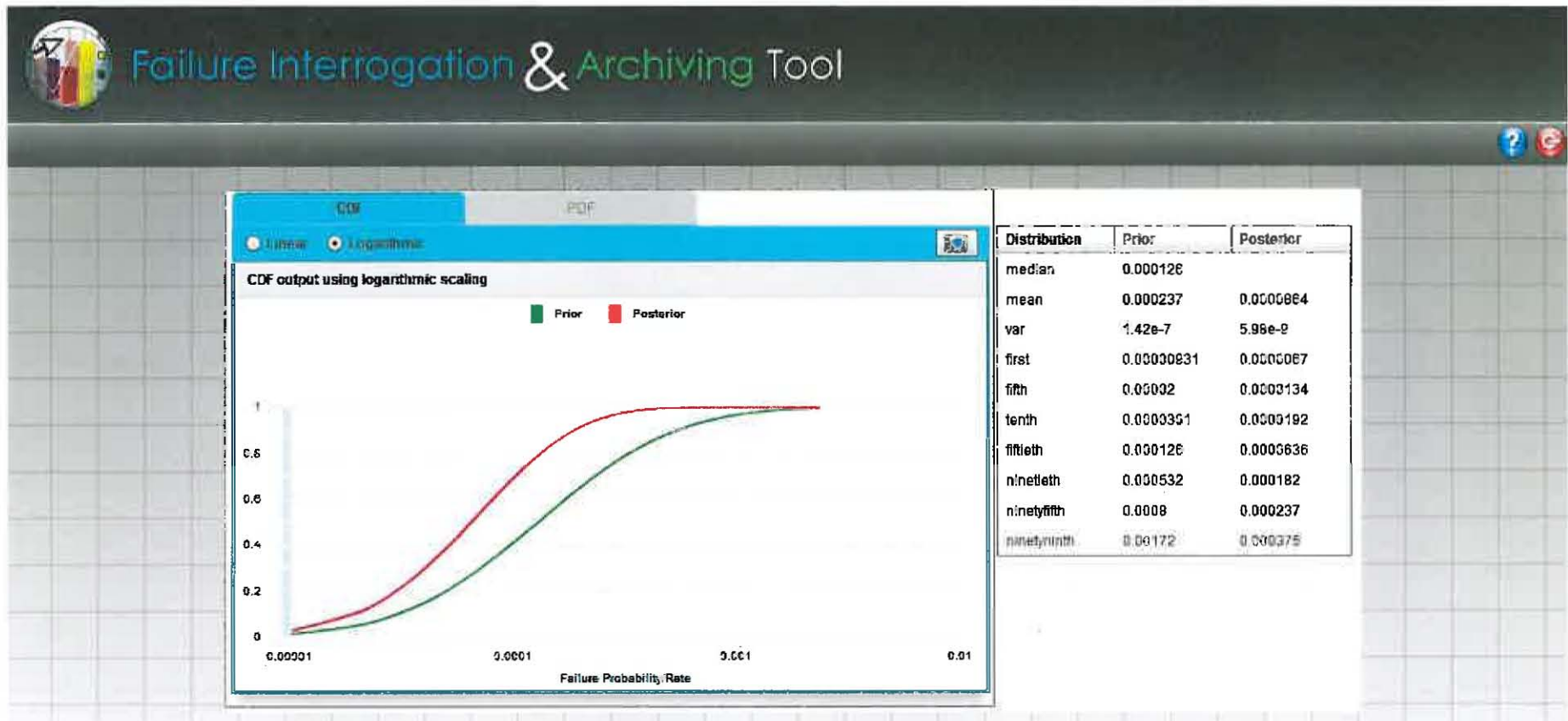
Step 6: Analysis Output Report



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

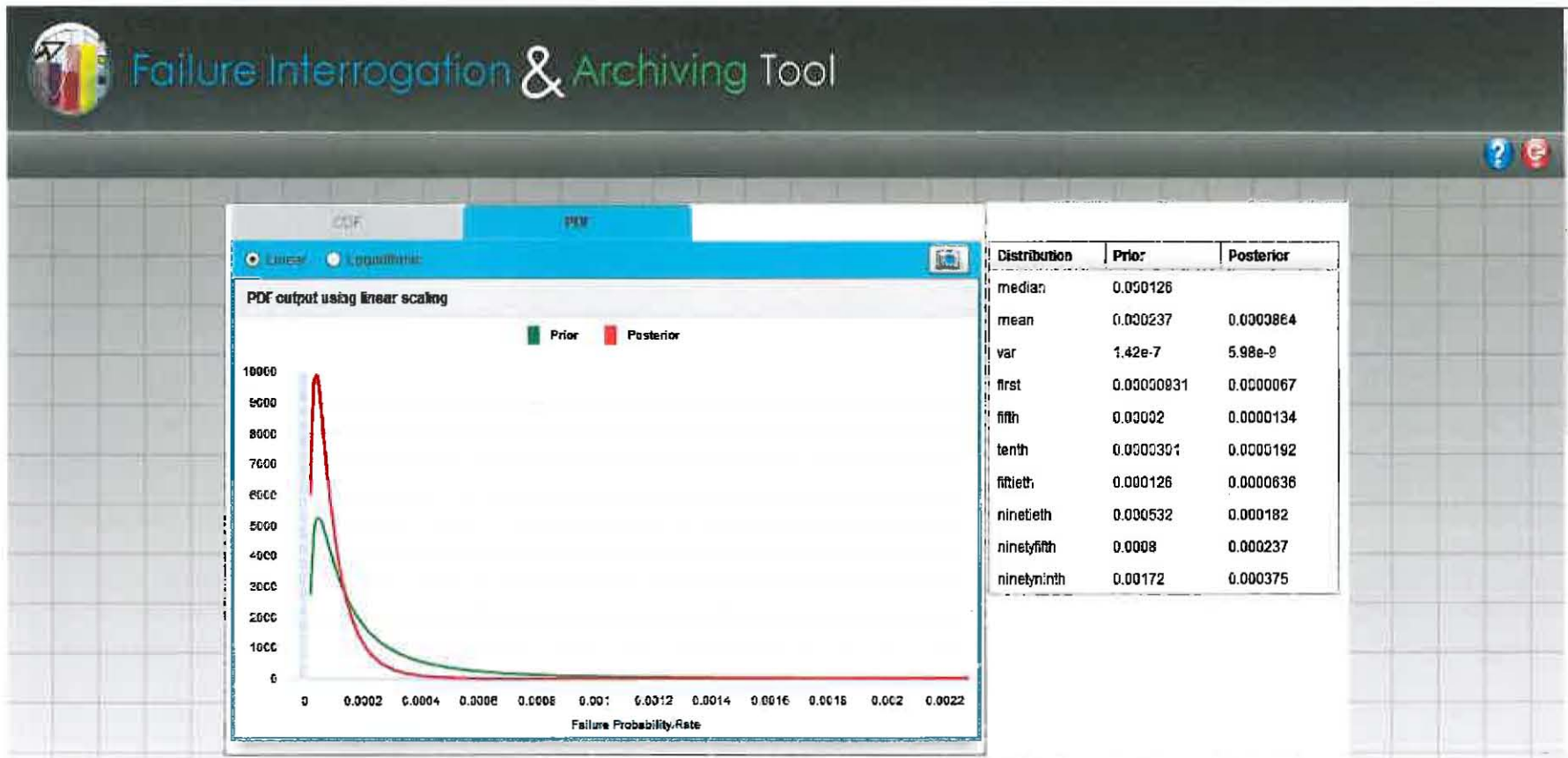


Step 6: Analysis Output Report



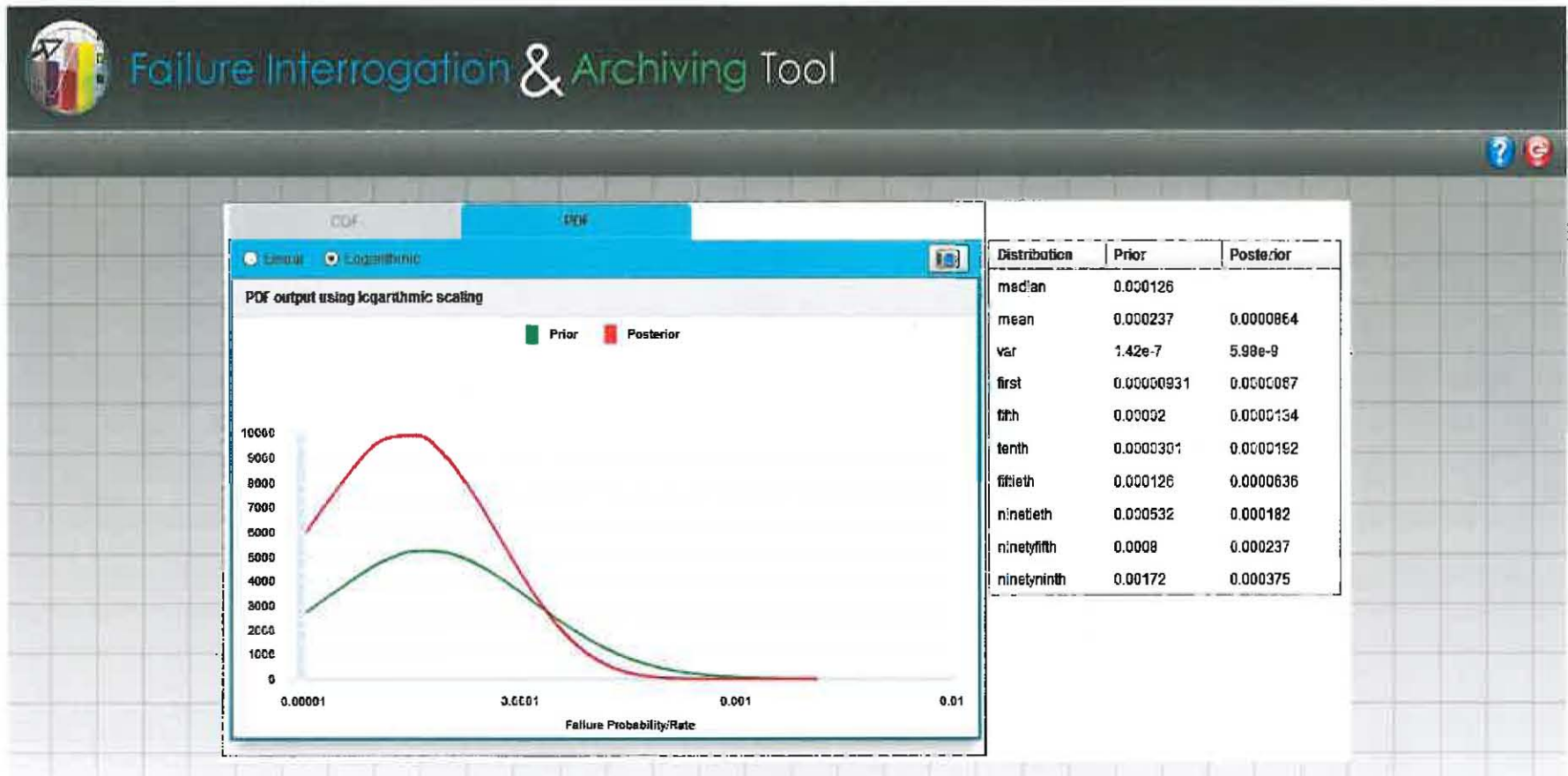


Step 6: Analysis Output Report





Step 6: Analysis Output Report





Improvement Initiative



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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?



4 DTMs on Aqua's Observatory

