Operational Availability – Extended Mission Operations

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Motivation

- Each mission team is routinely asked to submit a proposal for mission extension that includes their ability to continue to produce "core" mission data products as well as solicited "enhanced" mission data products. So that:
  - *Continued funding can be allocated for operations and operational teams.*
  - *Science Community Expectations can be compared to availability/viability of expected instruments.*
  - *It can be determined if continued operations will eliminate the capability of the mission to be decommissioned and removed from the constellation successfully while not causing a safety risk.*

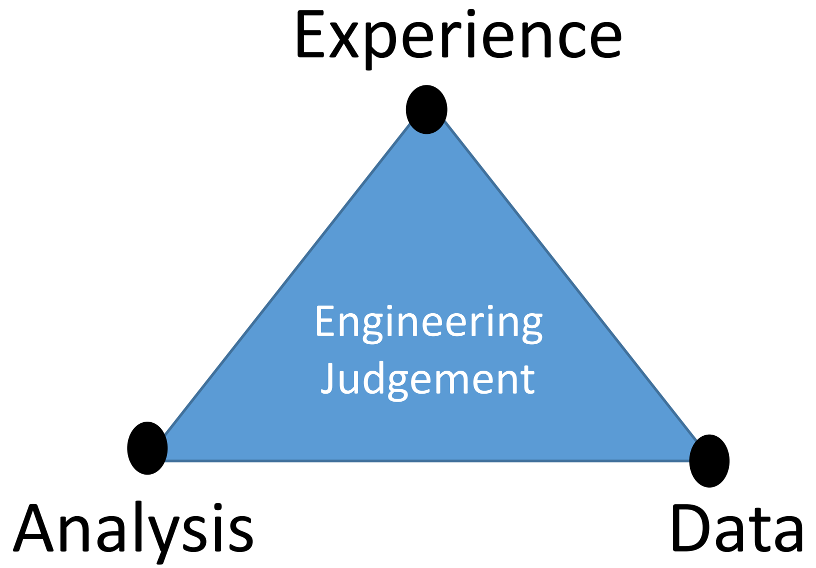
An Extended Mission Analysis is performed to support this review which infers operational availability with mission viability based on reliability.

Extended Mission Analysis

- Metrics Used to Determine Extended Availability
  - Estimated likelihood that the spacecraft will continue to provide full to minimal mission capabilities.
  - Estimated likelihood that the spacecraft will successfully de-orbit at the end of the operational mission.
  - Forecast consumable limits (with operations team).
- Results must indicate an acceptable likelihood of meeting required life.
- Results must indicate decommissioning prediction is compliant with requirement.

Analysis Methodology

- Update of the reliability model for wear/consumable susceptibilities, on-orbit failures/anomalies, and the successful deployment of all systems.



Likelihood Modeling Methods

- Four Failure Rate Modeling Methods Used
  - Good as New
  - Increased Wear
  - Weibull
  - Bayesian Updating

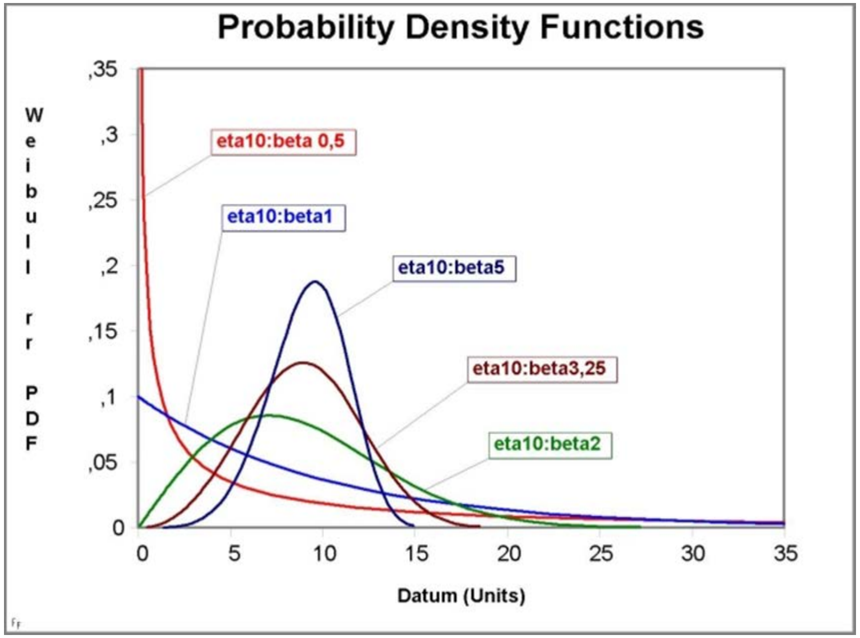
Good as New and Increased Wear Modeling

- Good as New: For non-wear items such as electronic components, original failure rates are used.

- Increased Wear: For wear related items modelled with constant failure rates, such as batteries and solar cells, a factor is applied to the original failure rate to impute unseen degradation due to time on orbit. Examples:
  - 1.5X (for ≥5yrs & <10 yrs)
  - 2X (for ≥10yrs of operations)

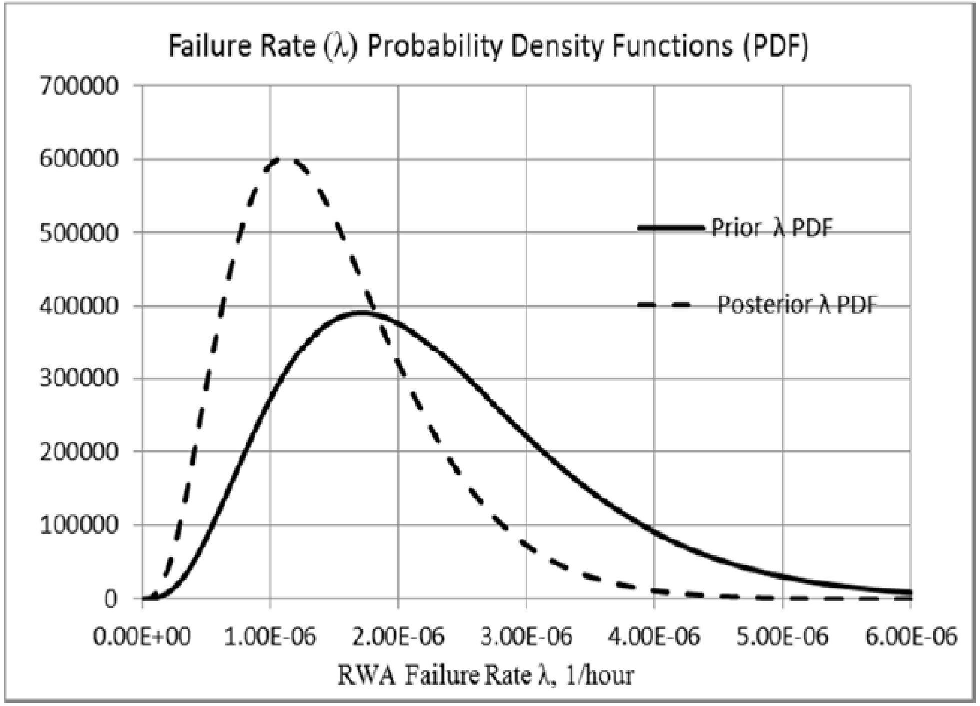
Observed Performance Failures Rate Updating - Weibull

- Weibull: When there are sufficient on-orbit data available demonstrating an increasing failure probability, this presents a case for the increased probability of new failures due to aging.
- A new experiential model for components not as good as new can be modelled based on the failure data.
- The reliability is calculated using observed failure rate updating to create a new failure model.



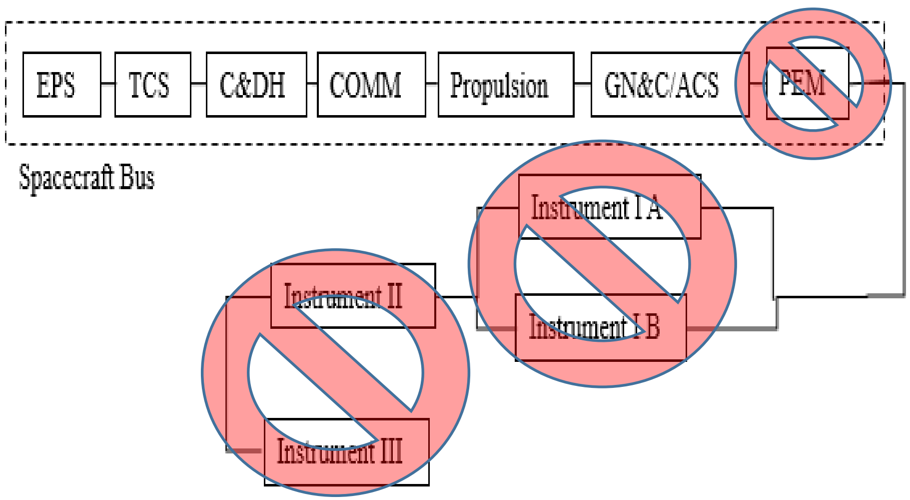
Observed Performance Failures Rate Updating - Bayesian

- Bayesian Updating: When there are components for which the on-orbit data are insufficient to calculate a new failure rate; however, there are enough on-orbit data to consider updating the existing failure rate.
- Used to create a new model from the original failure rate and on-orbit data.
- The original failure rate (the "prior") is updated with the on-orbit data to calculate a "posterior" distribution.



Decommissioning

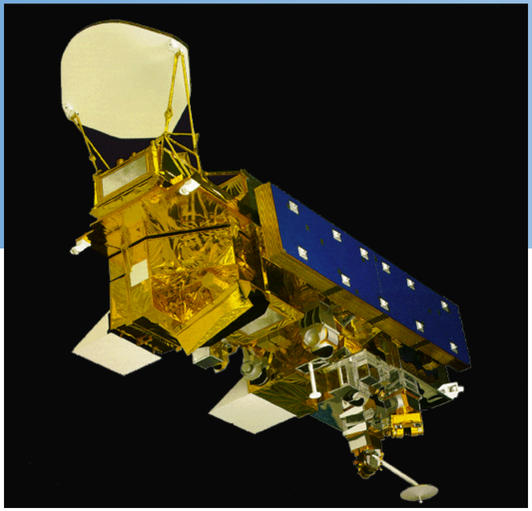
- A decommissioning analysis was performed to determine the estimated reliability of a spacecraft to survive with sufficient operational capability to accomplish deorbit maneuver successfully on a certain date or dates. The desired reliability is normally 0.90.
- Deorbit does not require the entire spacecraft to be operational, e.g., the payloads are not needed. The following hardware is generally required to be operational to accomplish the deorbit maneuver:
  - Avionics – C&DH and Propulsion Control
  - Communications
  - GN&C (or some subset)
  - Power generation and storage (some degradation is likely allowable)
  - Propulsion



CASE STUDY

EOS Aqua Extended Mission Availability Forecast

Case Study: Aqua



- Part of the Earth Observing System (EOS).
- Launched May 4, 2002.
- Analysis considers status as of 12/31/2018.
- Named for the large amount of information that the mission is collecting about the Earth's water cycle.
- Spacecraft bus and remaining instruments were functioning with no failed systems present (all A-side operations).
- **16 of 132 solar array strings lost; 66 are required based on mission power needs and generation efficiencies.**
- 2 of 6 instruments have failed.
- Multiple instrument configurations were analyzed to forecast science data availability.

Aqua Wear and Consumables

- Weibull Update
  - Solar Arrays

- Increased Wear (2x Failure Rate)
  - Battery
  - Solar Array Drive System
  - Drive Mechanisms
  - Photon Sensors

- Consumables
  - Fuel (Sufficient for life analyzed)

Aqua Solar Array Failure Data

- 16 Failures

Failures	Date	Hours
1	9/23/2009	64824
1	9/3/2010	73104
1	11/7/2010	74664
1	6/28/2011	80256
1	10/20/2011	82992
1	2/4/2012	85560
1	7/19/2012	89544
1	3/1/2013	94944
2	7/18/2013	98280
1	2/2/2014	103056
1	4/26/2015	113808
1	5/3/2016	122760
1	12/27/2017	137232
1	2/22/2018	138600
1	11/21/2018	145128

AQUA - GSFC												
ARE	1A	1C	2A	2C	3A	3C	4A	4C	5A	5C	6A	6C
ARM	1	2	3	4	5	6	7	8	9	10	11	12
String 1	Jun-11	Nov-10			Feb-12		Oct-04	Apr-15	Dec-17	May-16	Jul-12	Sep-10
String 2							Sep-09	Feb-18	Nov-18	Jun-16		Oct-11
String 3							Jul-13					Mar-13
String 4							Jul-13					Feb-14
String 5												
String 6												
String 7												
String 8												
String 9												
String 10												
String 11												
PANEL	3	4	5	6	7	8	9	10	11	12	13	14

16 Lost

Lost String

Unconfirmed

Recovered String

* Displays signs of cracked cell

0 Questionable

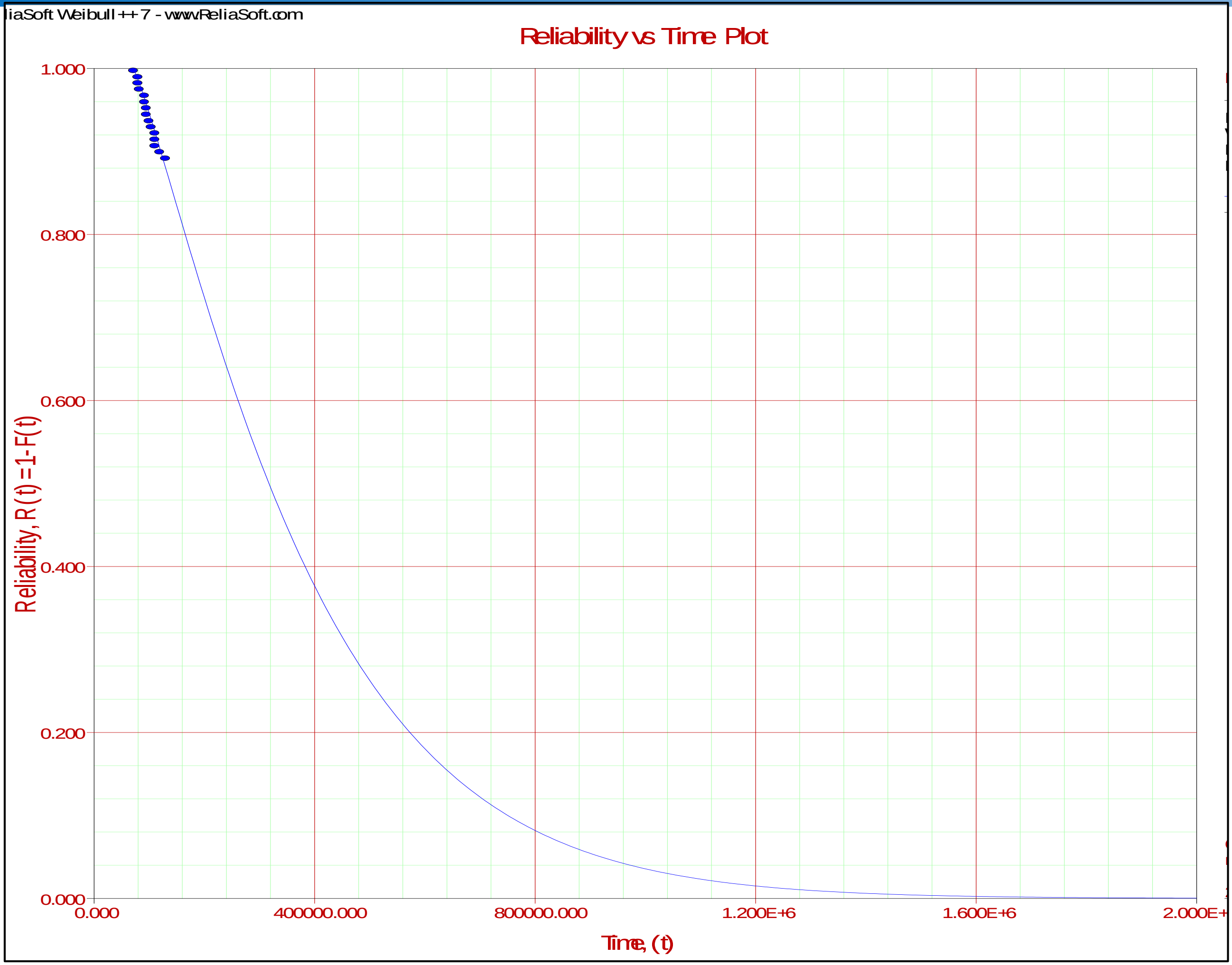
116 Operational

132 Total Strings

- Working (Suspended)

116 9/21/2017 146040

Aqua Solar String Weibull Reliability



characteristic life (η)

456,520 hours

52.1 years

shape (β)

1.116

failure free life (γ)

60,710 hours

6.9 years

Aqua Solar String Reliability

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

characteristic life (η)
456,520 hours

shape (β)
1.1157

failure free life (γ)
60,710 hours

Year	P(s) [Weibull]
2019	0.845
2020	0.830
2021	0.815
2022	0.800
2023	0.786
2024	0.771
2025	0.757
2026	0.743
2027	0.729

Aqua Solar Array Predictions

Probability of Success (Binomial Distribution)

$$F(k;n,p) = \Pr(X \le k) = \sum_{i=0}^{\lfloor k \rfloor} \binom{n}{i} p^i (1-p)^{n-i}$$

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027
Reliability (66 of 132)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.999999993

Required Strings (k):
66

Working Strings (n):
116

String Reliability (p):
From Weibull

Expected Strings Available (Conditional Probability)

$$P(A_B) = \frac{P(A \cap B)}{P(B)} \quad * 116$$

Year	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2046
Ps	0.875	0.860	0.845	0.830	0.815	0.800	0.786	0.771	0.757	0.743	0.499
Ps (Given 2018)	1.00	0.98	0.97	0.95	0.93	0.91	0.90	0.88	0.86	0.85	0.429
Expected Strings	116.0	114.0	112.0	110.0	108.0	106.1	104.1	102.2	100.3	98.5	66.2

Probability of SA Success through 12/2018: P(B)
0.875

Probability of SA Success Going Forward: P(A)

Likelihood Aqua will be Available for Extended Mission

Sub-System	End of Calendar Year									
	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
COMM SUBSYSTEM	1.0000	0.9987	0.9973	0.9960	0.9947	0.9933	0.9920	0.9907	0.9893	0.9880
TCS SUBSYSTEM	1.0000	0.9999	0.9998	0.9998	0.9997	0.9996	0.9995	0.9994	0.9994	0.9993
PROPULSION SUBSYSTEM	1.0000	0.9970	0.9940	0.9910	0.9881	0.9851	0.9821	0.9792	0.9763	0.9733
S&MS SUBSYSTEM	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999
GN&C SUBSYSTEM	1.0000	0.9977	0.9954	0.9931	0.9908	0.9885	0.9862	0.9839	0.9816	0.9793
EPS SUBSYSTEM	1.0000	0.9981	0.9962	0.9943	0.9924	0.9905	0.9886	0.9867	0.9848	0.9830
EDS SUBSYSTEM	1.0000	0.9995	0.9990	0.9985	0.9980	0.9975	0.9970	0.9965	0.9960	0.9955
C&DH SUBSYSTEM	1.0000	0.9986	0.9971	0.9957	0.9942	0.9928	0.9913	0.9899	0.9885	0.9870
S/C Bus	1.0000	0.9895	0.9790	0.9687	0.9585	0.9484	0.9384	0.9285	0.9187	0.9090
AIRS INSTRUMENT	1.0000	0.9890	0.9781	0.9673	0.9566	0.9461	0.9356	0.9253	0.9151	0.9050
AMSU - A1 INSTRUMENT	1.0000	0.9211	0.8485	0.7816	0.7199	0.6631	0.6108	0.5627	0.5183	0.4774
CERES INSTRUMENT	1.0000	0.9969	0.9883	0.9751	0.9582	0.9381	0.9156	0.8911	0.8651	0.8380
MODIS INSTRUMENT	1.0000	0.9810	0.9624	0.9441	0.9262	0.9086	0.8913	0.8744	0.8578	0.8415
S/C Bus+AIRS;CERES;MODIS	1.0000	0.9570	0.9107	0.8626	0.8137	0.7647	0.7165	0.6694	0.6239	0.5801
S/C Bus+AIRS;AMSU A-1;CERES;MODI	1.0000	0.8815	0.7728	0.6742	0.5858	0.5071	0.4377	0.3767	0.3233	0.2770
S/C Bus+MODIS	1.0000	0.9707	0.9422	0.9145	0.8877	0.8617	0.8364	0.8118	0.7880	0.7649
S/C Bus+CERES;MODIS	1.0000	0.9677	0.9312	0.8918	0.8506	0.8083	0.7658	0.7234	0.6817	0.6410
S/C Bus+AIRS;MODIS	1.0000	0.9600	0.9215	0.8846	0.8492	0.8152	0.7825	0.7512	0.7211	0.6923
S/C Bus+AIRS;CERES	1.0000	0.9755	0.9464	0.9137	0.8785	0.8417	0.8038	0.7656	0.7273	0.6894
AQUA less AMSR-E & AMSU-A2	1.0000	0.8815	0.7728	0.6742	0.5858	0.5071	0.4377	0.3767	0.3233	0.2770

Lessons Learned

- Using multiple modeling methods seems to work well for mission extension studies.
- Without increased wear or degradation trends, a mission's calculation could be same as it was at launch.
- The subsystem that is degrading may not be the weakest link, e.g., the solar arrays.
- We are highly dependent on updated configuration requirements for operations, e.g., power budgets and concept of operations.
- Confidence in all reported probability estimates is limited by the total number of test and on-orbit hours of relevant spacecraft and instrument data collected.

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