Designing and Managing for a Reliability of Zero!

Bill Purdy & Mike Hurley

Topics

- **Two Slides on the Naval Research Lab**
  - **Provide some Sense of Where We are Coming From**

- **The Goal**

- **A Little Philosophy**

- **What the Reliability Prediction Is and Is Not**

- **Comparing Predictions to Spacecraft Data**

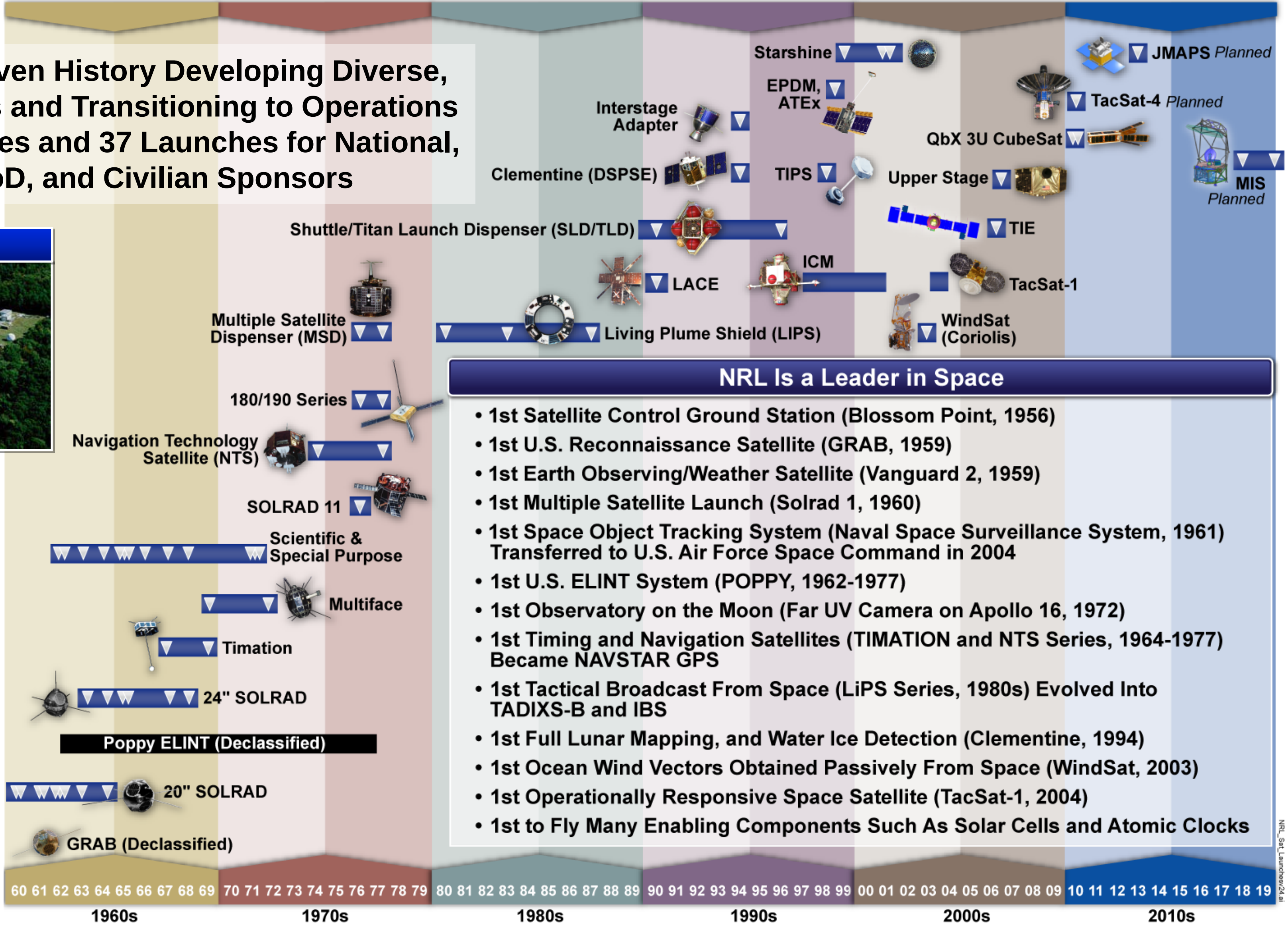
- **Considerations for True, On-Orbit Reliability**

- **Going Forward**

Naval Research Laboratory's Space History
Developing New Capabilities With Operational Impacts

- **NRL Has Proven History Developing Diverse, New Systems and Transitioning to Operations**
  - **92 Satellites and 37 Launches for National, DoD, and Civilian Sponsors**

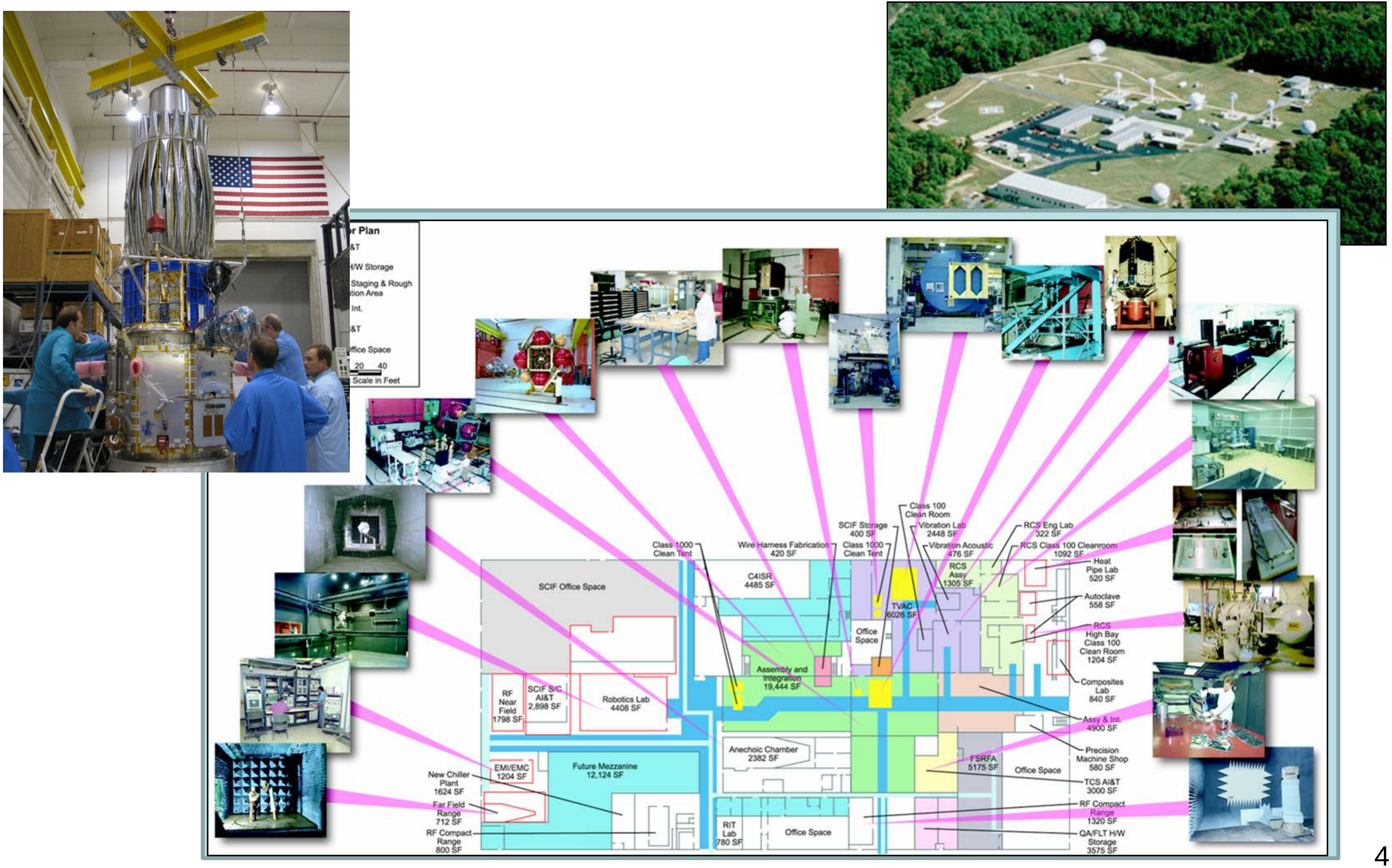
Blossom Point



NRL Is a Leader in Space

- 1st Satellite Control Ground Station (Blossom Point, 1956)
- 1st U.S. Reconnaissance Satellite (GRAB, 1959)
- 1st Earth Observing/Weather Satellite (Vanguard 2, 1959)
- 1st Multiple Satellite Launch (Solrad 1, 1960)
- 1st Space Object Tracking System (Naval Space Surveillance System, 1961) Transferred to U.S. Air Force Space Command in 2004
- 1st U.S. ELINT System (POPPY, 1962-1977)
- 1st Observatory on the Moon (Far UV Camera on Apollo 16, 1972)
- 1st Timing and Navigation Satellites (TIMATION and NTS Series, 1964-1977) Became NAVSTAR GPS
- 1st Tactical Broadcast From Space (LiPS Series, 1980s) Evolved Into TADIXS-B and IBS
- 1st Full Lunar Mapping, and Water Ice Detection (Clementine, 1994)
- 1st Ocean Wind Vectors Obtained Passively From Space (WindSat, 2003)
- 1st Operationally Responsive Space Satellite (TacSat-1, 2004)
- 1st to Fly Many Enabling Components Such As Solar Cells and Atomic Clocks

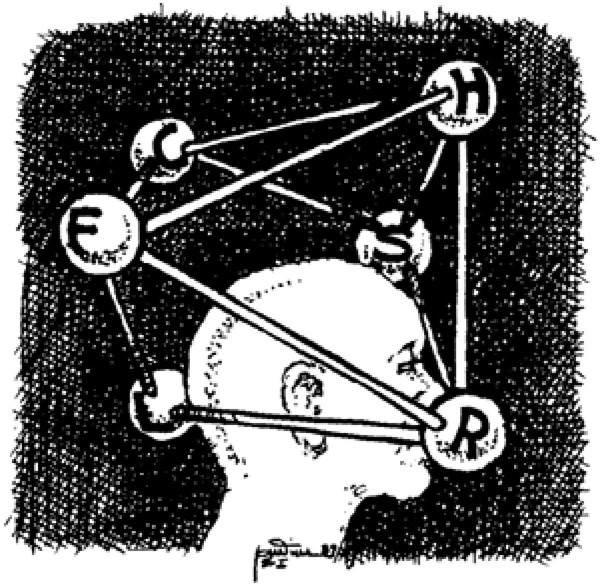
NRL – Hands-On
Design, Integration, Test, & Operations



The Goal

- To provoke the reader to reevaluate their thoughts on reliability.

- Ultimately, this paper strives to advance the industry-wide understanding necessary to better achieve reliable, available space systems for users.



A Little Philosophy

- The space industry’s philosophy and management understanding of reliability may be one of the most important drivers in space programs today.
  - Often misunderstood and misapplied on space systems
- “Reliability” is heavily influenced by the perspective of the space system program office and developers.
  - Rarely from the perspective of the end users
  - Requirement is even “met” before launch
- Ironically, efforts to achieve high reliability often prove counterproductive to schedule and cost, which are essential elements of reliability, especially from a user’s perspective.
- On-orbit reliability for users is what ultimately counts.

Late = Unreliable

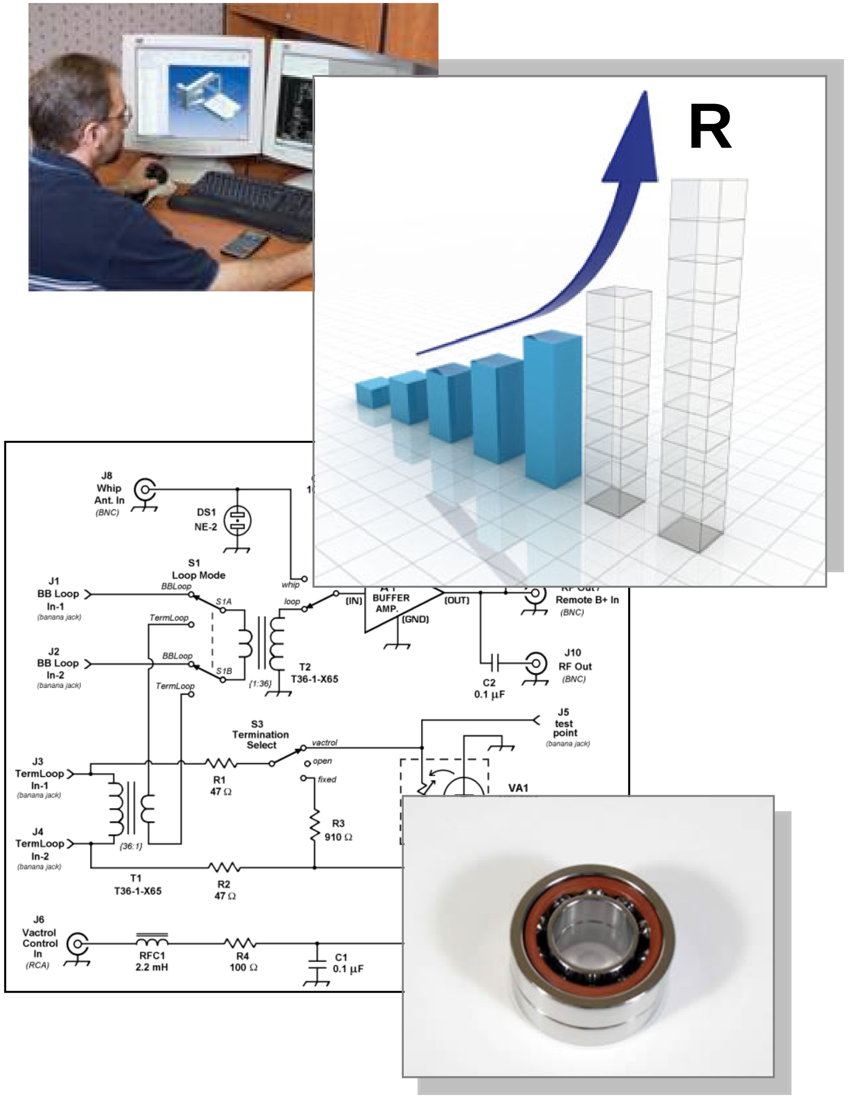
- **For example: If a program delivers late, then the true reliability is zero for every day, usually every year, it is late.**

Case	Predicted Reliability at 5 Years	Delivery Date; start of Year	Probability of Success at End of Year					Comment
			1	2	3	4	5	
1	90%	0	98%	96%	94%	92%	90%	High Reliability, deliver on time
4	90%	4	0%	0%	0%	98%	96%	High Reliability, deliver late

- **Program Office: "I have achieved 90% reliability but I was a little late."**
- **User: "You have achieved zero reliability for the first 3 years."**

What Reliability Analysis Is…A Good Tool

- **Proper reliability analysis can be one of the most economical practices for improving true spacecraft reliability.**
- **Mil-Standard-217F, Section *3.2***
  - ***"The Role of Reliability Prediction - Reliability prediction provides the quantitative baseline needed to assess progress in reliability engineering. A prediction made of a proposed design may be used in several ways. Once a design is selected, the reliability prediction may be used as a guide to improvement by showing the highest contributors to failure…"***
- **Reliability prediction analysis, along with associated analyses such as the failure modes and effects analysis (FMEA) and parts stress analysis over temperature, are excellent for identifying weak links in a design and making improvements.**



What the Reliability Analysis Prediction Does and Does NOT Include

Failure Modes Considered in Reliability Prediction	**Failure Modes NOT Considered in Reliability Prediction**
• Electronic part failure • Solder joint failure • Connector / pin failure • Mechanical moving elements e.g. bearing failure	• Design failure • Software failure • Operator error • Proper build, assembly & workmanship • Late launch (schedule impacts) • Insufficient funds

Reliability Analysis
Does NOT Predict On-Orbit Performance (1 of 4)

- **Reliability analysis is fundamentally misapplied as a predictor of spacecraft success on orbit.**

- **Both MIL-STD-217F and on-orbit data confirm this point.**

- **Mil-Standard-217F, Section *3.3***
  - ***"…Hence, a reliability prediction should never be assumed to represent the expected field reliability as measured by the user … note that none of the applications discussed above require the predicted reliability to match the field measurement."***

- **Therefore, the spacecraft community must avoid this tendency for misuse which can lead to bad decisions.**

Reliability Analysis
Does NOT Predict On-Orbit Performance (2 of 4)

- **Predicted Reliability, or Ps, does NOT predict On-Orbit reliability**

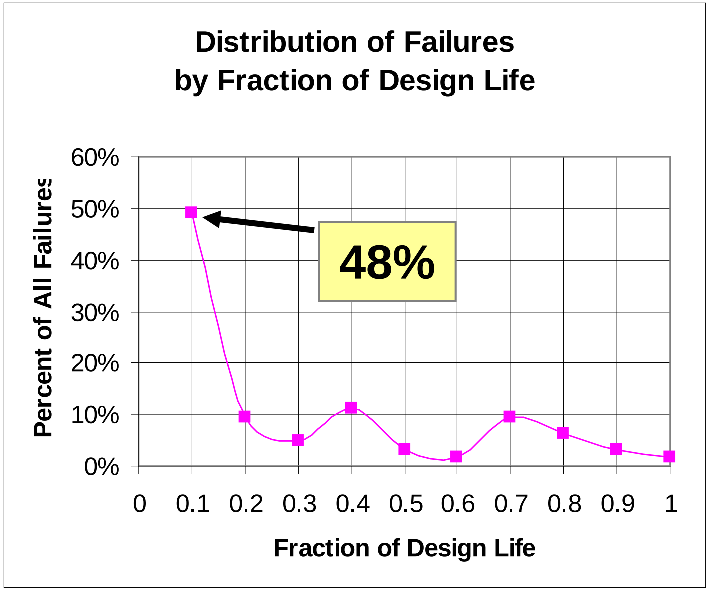
$$P_s = e^{-\lambda t} \neq On-Orbit\ P_s$$

- **1) Completely misses decades of on-orbit data confirming high failure rates within the first year on-orbit**
  - **These early failure modes are inherently not considered in the calculations**
- **2) Consistently under-estimates life of "low reliability" or "single string" spacecraft, which is often the case for small satellites**
  - **Examples on next slide**

Failure Distribution Grouped by Years On-Orbit

0 - 1	1 - 3	3 - 5	5 - 8	>8
41%	17%	20%	16%	6%

Ref: "A Study of On-orbit Spacecraft Failures" by Tafazoli [1]
Includes 156 failures on 130 of 4000 spacecraft from 1980 to 2005

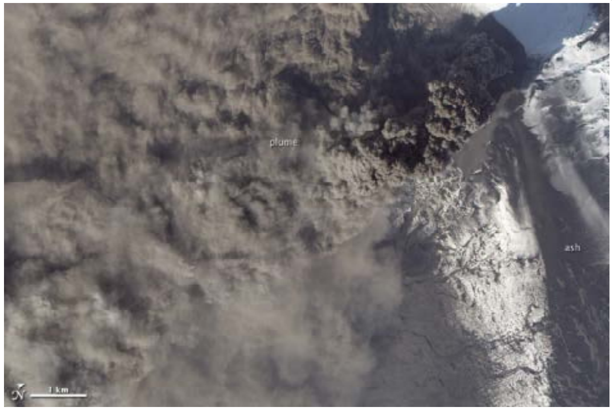


Ref: "Satellite G&C Anomaly Trends", Robertson & Stoneking [2]
Includes 63 failures with data from 750 spacecraft from 1990 to 2002

Reliability Analysis
Does NOT Predict On-Obit Performance (3 of 4)

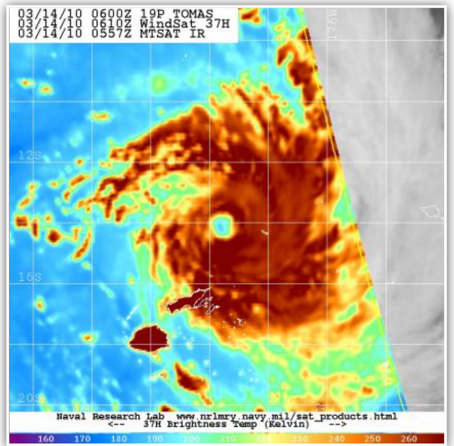
Examples: Long Life Contrary to Prediction

- **NASA's EO-1 Spacecraft Example**
  - **Predicted bus reliability at 10 years was 6% (Ps only ~1-2% with payloads included)**
  - **Still operating with multiple payload cameras (see image)**
- **NRL's WindSat Payload Example**
  - **Predicted payload reliability at 7 years was 3% (Ps <1-2% with bus included)**
  - **Still operating 24-7 (see image)**
- **Surrey Satellite Technology LTD (SSTL) Data and Approach**
  - **Company data on twenty satellites from 1981 to 2003 show an average Mean Time To Failure (MTTF) for their satellites of 6.4 years, yet the average design life was only 2.1 years.**
  - **SSTL uses commercial parts extensively and avoids quantified reliability analysis**
  - **"Concentrate efforts on improving reliability, not quantifying it"**



April 2010 Eruption of Eyjafjallajökull Volcano from the EO-1 spacecraft

At 9.5 Years life



March 2010 Hurricane Tomas Imagery from the Windsat Payload

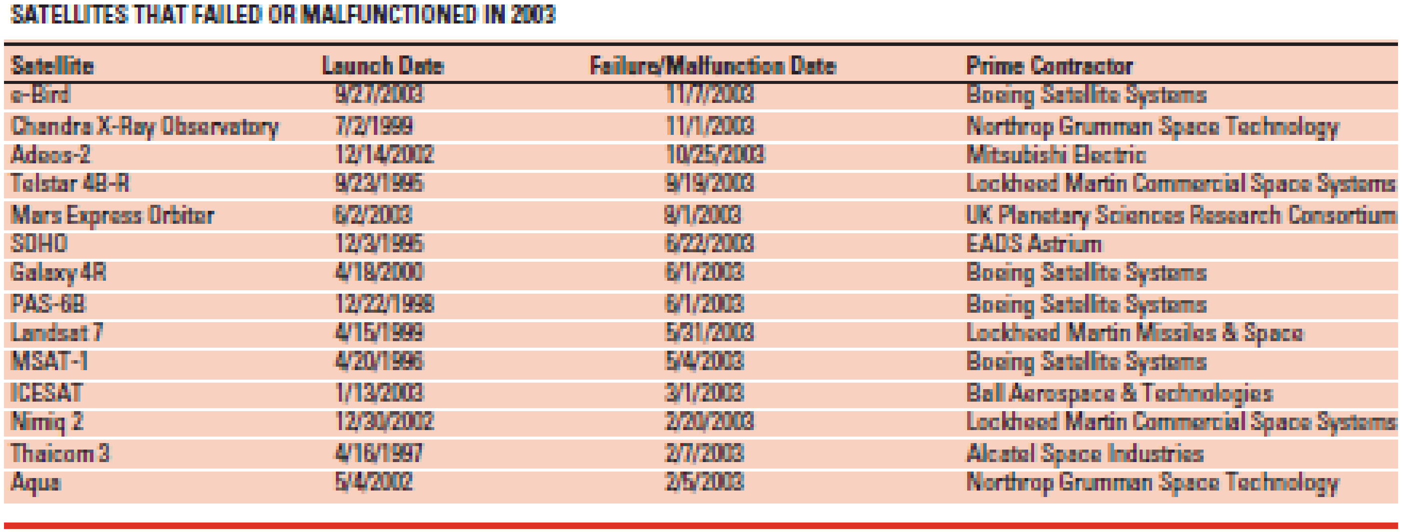
At 7 Years life

Reliability Analysis
Does NOT Predict On-Obit Performance (4 of 4)

Examples: Short Life Contrary to Prediction

- **High Reliability Satellite Examples**
  - **Typical Ps>95% at 5yrs & Ps>90% at 10yrs**
  - **Over 24 high reliability satellites had failures during 1999-2003, most with lives shortened to <~ 5 years after launch [3]**
    - **Galaxy 3R,4,7,11, DirecTV-1&3, PAS-4, AMSC-1, MSAT-1, TDRSII-F1 & F2, Anik F1, LandSat-7, Adeos-2, XM Rock, XM Roll, etc.**
- **Absolutely impossible if Calculated R = On-orbit Ps! … 6E-30% chance**

REF: “Satellites & Launches Trend Down,” Aerospace America, January 2004, Marco Cáceres, Teal Group, http://www.aiaa.org/aerospace/images/articleimages/pdf/insightsjanuary04.pdf



SATELLITES THAT FAILED OR MALFUNCTIONED IN 2003

Satellite	Launch Date	Failure/Malfunction Date	Prime Contractor
e-Bird	9/27/2003	11/7/2003	Boeing Satellite Systems
Chandra X-Ray Observatory	7/2/1999	11/1/2003	Northrop Grumman Space Technology
Adeos-2	12/14/2002	10/25/2003	Mitsubishi Electric
Telstar 4B-R	9/23/1995	9/19/2003	Lockheed Martin Commercial Space Systems
Mars Express Orbiter	6/2/2003	8/1/2003	UK Planetary Sciences Research Consortium
SOHO	12/3/1995	6/22/2003	EADS Astrium
Galaxy 4R	4/18/2000	6/1/2003	Boeing Satellite Systems
PAS-6B	12/22/1998	6/1/2003	Boeing Satellite Systems
Landsat 7	4/15/1999	5/31/2003	Lockheed Martin Missiles & Space
MSAT-1	4/20/1996	5/4/2003	Boeing Satellite Systems
ICESAT	1/13/2003	3/1/2003	Ball Aerospace & Technologies
Nimiq 2	12/30/2002	2/20/2003	Lockheed Martin Commercial Space Systems
Thaicom 3	4/16/1997	2/7/2003	Alcatel Space Industries
Aqua	5/4/2002	2/5/2003	Northrop Grumman Space Technology

One Reason Why R is Sometimes Misapplied

- **Simplified, Incorrect Understanding that the Numerical R is Strongly Related to On-Orbit Performance**

- **But Simple is Easy to "Understand", so Often Misapplied Either…**
  - **Implicitly as a driving mission objective onto itself**
  - **Or even explicitly for program support**

"It must work, R must be 90% or higher."

- **Actual Example**
  - **At a SRDR, we witnessed a program office order that the reliability analysis be completed by PDR and at the same time announce that the reliability for the space system including launch will be 90%!**
  - **"90%" may have been useful to create perceived on-orbit reliability for sponsors necessary to support the program, but such political emphasis and simplified understanding can be major obstacles to properly applying reliability analysis and balanced processes.**

Practices to Avoid Failure Modes and Increase On-Orbit Reliability

Collectively these practices are how programs address true On-Orbit reliability, by addressing all failure modes.

Failure Modes

Practice to Address Failure Mode	Failure Modes: Meets Mission Performance	Survives Environments - Stress & Thermal	Avoidance of parts failure, radiation, & wear out	Built as Designed	Meets Budget	Meets Schedule	Operator Error	Software Failure
Good Design	++ strong benefit	++ strong benefit	+ weak benefit via simplicity	NA	- moderately higher cost	++ strong benefit via simplicity	+ weak benefit via simplicity	++ strong benefit
Good Testing	++ strong benefit	++ strong benefit	NA	++ strong benefit	- moderately higher cost	- moderately longer schedule	++ if test like you fly	++ strong benefit
Flexibility & Margins	NA	++ ability to survive after component failures	+ margins enable work around for some part failures	NA	- moderately higher cost	++ strong benefit	++ more likely can recover from [illegible]	NA
Redundancy	NA	++ ability to survive after component failures	++ strong benefit	NA	- - high cost of parts & complexity	- increased build and test schedule	NA	NA
Use of Mass Production Components if Available	NA	+ part capabilities known in advance	++ measured reliability data exists & learning curve complete	+ weak benefit	++ production efficiency	++ production efficiency or truly off the shelf	+ ops of component often well understood	depends on specific component type
Reliability Analysis	+ circuit improvements	+ parts thermal stress analysis	++ strong benefit	NA	- or -- because of cost of Hi-REL parts if chosen	- or -- because of lead time of Hi-REL parts if chosen	NA	NA
Rigorous Manufacturing & QA Controls	NA	NA	++ strong benefit	++ strong benefit	- or -- pending level chosen	- moderately longer schedule	+ QA & config control of ops procedures	++ strong benefit through software QA
Mission Simulation & Training	++ "flying" scenarios before launch, increases on-orbit availability	NA	NA	NA	- cost for mission simulator & training	+ often enables parallel testing	++ strong benefit	++ wring out errors & inefficiencies in both ground & flight SW
Constellation design (multiple S/C) or launch on demand replacement	NA	NA	NA	NA	- or -- cost pending specifics of the mission	++ strong benefit	++ learning curve ops benefits if multiple spacecraft	NA

Discussed in detail in the paper

Practices For Improving Reliability

Notice reliability analysis & redundancy represent only 2 of 9 practices and help only 3 of 9 failure modes.

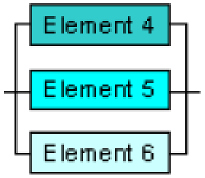
A Few Legible Rows from the Table

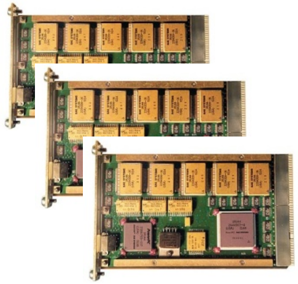
- **Qualitative, but a Sound Exercise for Evaluating where to Invest Resources and to Check All Failure Modes are being Addressed**

	Failure Modes							
Practice to Address Failure Mode	**Meets Mission Performance**	**Survives Environments - Stress & Thermal**	**Avoidance of parts failure, radiation, & wear out**	**Built as Designed**	**Meets Budget**	**Meets Schedule**	**Operator Error**	**Software Failure**
Good Design	++ strong benefit	++ strong benefit	+ weak benefit via simplicity	NA	- moderately higher cost	++ strong benefit via simplicity	+ weak benefit via simplicity	++ strong benefit
Good Testing	++ strong benefit	++ strong benefit	NA	++ strong benefit	- moderately higher cost	- moderately longer schedule	++ if test like you fly	++ strong benefit
Flexibility & Margins	NA	++ ability to survive after component failures	+ margins enable work around for some part failures	NA	- moderately higher cost	++ strong benefit	++ more likely can recover from op errors	NA
Redundancy	NA	++ ability to survive after component failures	++ strong benefit	NA	- - high cost of parts & complexity	- increased build and test schedule	NA	NA

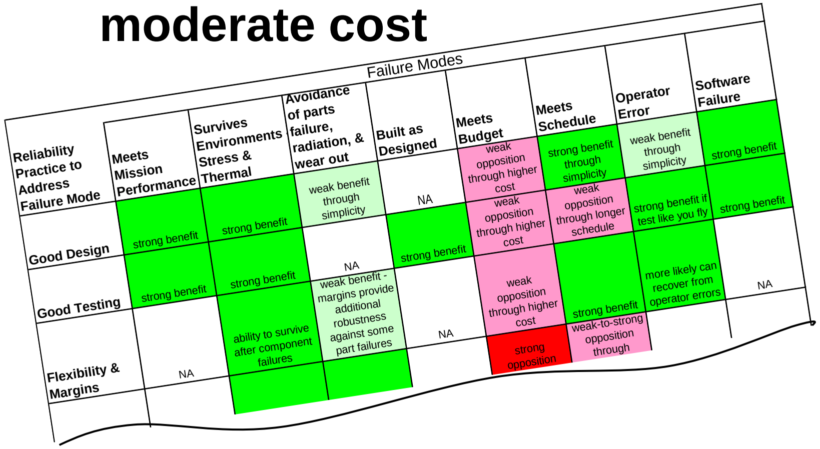
Common Examples – To Avoid & Pursue

- **Avoid: Setting hard (inflexible) requirements to implement full redundancy or mandating all class 1 electronics parts.**
  - Great protection against parts failure
  - Poor-to-no protection against common failures modes like design & assembly failures
  - Adds complexity
  - High cost threatens reliability
  - Long procurement schedule threatens reliability





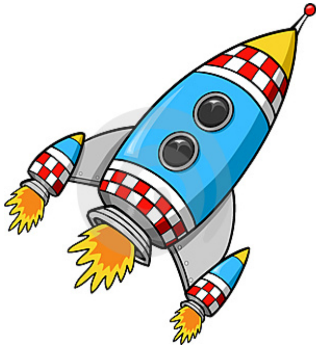
- **Pursue: Practices with relatively high reduction in failure modes vs. cost of implementation.**
  - Good Design and Testing provide nice improvements at low-to-moderate costs
  - Smart Redundancy provides nice improvements at low-to-moderate, vice large cost
  - Reliability Analysis provides nice improvement at low-to-moderate cost



	Failure Modes							
Reliability Practice to Address Failure Mode	**Meets Mission Performance**	**Survives Environments Stress & Thermal**	**Avoidance of parts failure, radiation, & wear out**	**Built as Designed**	**Meets Budget**	**Meets Schedule**	**Operator Error**	**Software Failure**
Good Design	strong benefit	strong benefit	weak benefit through simplicity	NA	weak opposition through higher cost	strong benefit through simplicity	weak benefit through simplicity	strong benefit
Good Testing	strong benefit	strong benefit	NA	strong benefit	weak opposition through higher cost	weak opposition through longer schedule	strong benefit if test like you fly	strong benefit
Flexibility & Margins	NA	ability to survive after component failures	weak benefit - margins provide additional robustness against some part failures	NA	weak opposition through higher cost	strong benefit	more likely can recover from operator errors	NA
					strong opposition	weak-to-strong opposition through		

Related Items

- **Launch Reliability is 90-95% Best Case**
  - **Space systems can not exceed the launch vehicle's reliability**
  - **An inherent reliability advantage for using small and medium size spacecraft**
  - **Total loss of mission is, at best, a 1 in 20 chance for a perfect reliability satellite**



Launch R=90-95% Best Case

- **Aircraft Reliability Practices are Different because of Demand**
  - **Demand for spacecraft, at 80-125 per year, is fundamentally much smaller than for aircraft**
  - **Airlines flew over 10,000,000 flights in 2009**
  - **High demand allows the airlines to manage reliability differently & predict more accurately**
    - **Mass production, design upgrades, regular maintenance, proven flight simulation modeling, highly matured operations, etc.**

The odds of dying on your flight are 1 in 9,200,000

Small & Large Satellites Each Contribute to Reliability

- **Small Satellites and Systems**
  - **Have some inherent benefits mathematically & in real terms**
  - **The quantity of small satellites tends to be larger for given costs.**
    - **Missions with more than one satellite typically degrade gracefully.**
  - **Lower costs & shorter schedules are important elements of reliability**
  - **Good engineering, manufacturing, & testing often provide long on-orbit life despite limited protection against parts failure**
  - **Launch or satellite failure has lower user and resource impact**

- **Large Satellites and Systems**
  - **Larger size (aperture and higher power), enable mission simply not physically possible on smaller systems due to physics.**
    - **Can afford to develop and qualify new parts and technologies.**
  - **Can afford and justify more thorough quality assurance, testing (such as parts radiation testing), independent reviewers, etc.**
  - **The extensive use of redundancy and large margins more affordable as they cost a relatively small percentage of overall program.**
  - **Large margins and extensive redundancy can provide the confidence necessary for mission users to plan for very long satellite lifetimes**

A mix of both small and large space systems can best address the wide range of space missions, users, and reliability needs

Summary

- **“Designing and Managing for a Reliability of Zero”, means:**
  - **Some practices intended to improve reliability actually degrade reliability through complexity, schedule delays, and cost overruns**

- **Reliability analysis is fundamentally misapplied as a predictor of spacecraft success on orbit.**
  - **Both the MIL-STD-217F and on-orbit data confirm this**
  - **Misuse can result in bad program decisions**

- **For on-orbit reliability, addressing all failure modes, developers should create availability plans based on conscious value judgments of the true, on-orbit reliability provided by each of the available practices.**
  - **Conceptually shifting focus from 2 practices, redundancy and reliability analysis, to the full set of 9 practices available**

The "New SMAD" Book is Coming Soon

Summer 2011

Space Mission Engineering: The New SMAD

edited by:

James R. Wertz
Microcosm, Inc.
University of Southern California

Jeffery J. Puschell
Raytheon

David F. Everett
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- **A 10 year update to Space Mission Analysis and Design, "SMAD", is coming out this summer.**
- **One section called "Cost and Schedule vs. Reliability – Focusing on Mission Objectives" is based on the material and research in this presentation**
- **PS- We get no royalties, we just would like to see this information help the industry.**