Mission Assurance 2.0 - S&MA in the SmallSat Paradigm

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Overview

- SmallSat Market
- Quality and Reliability for Spacecraft Classes
- Mission Assurance Structure
- Comparison of Mission Assurance Across Mission Classes
- Highlights of Recent Mission Activities at JPL
  - EEE parts comparison
  - Inspection analysis
- Conclusions
Summary of Cube/SmallSats so far...and into the future

- Significant growth in number of launches expected through end of decade
- Smallsat trend is away from technology demonstration towards commercial remote sensing using constellations
- Large financial investments means higher expectations of performance and reliability
Quality vs. Reliability

- Quality issues (defects) are the root cause for infant mortality region
  - Manufacturing variation
  - Incoming material
  - Poor design margin to variation
  - Early sensitivity to application of voltage/temperature/current

- Reliability issues (wear-out) drive end of life region
  - Physics of failure related
    - Dielectric breakdown
    - Electromigration
    - Etc..
Reliability of “heritage” satellites > 100kg

- Total sample size = 1584
- >99% operational at time of launch
  - (<1% DOA / Early Fails)
- Continued decreasing reliability as time increases
What about CubeSat reliability...?

- 178 CubeSats launched through mid-2014.
- Very steep initial drop in reliability => large number of deployment/DOA failures
- Reliability continues to decrease with increasing time

Figure 1: CubeSat reliability with 95% confidence interval – first year in orbit
Heritage and CubeSat Reliability Plotted on Same Curve

- Both CubeSat and Heritage show *decreasing* reliability with *increasing* time
- Failure Rate, \( \lambda(t) \), for both Heritage and CubeSat *also* decreases with increasing time
- Implies both types of missions in a failure regime dominated by defects in design, materials, and variation
- Increasing failure rate with time (ageing/wear out) is not seen
- *Importance of mission assurance to address defects and quality related issues*

\[
\lambda(t) = \frac{f(t)}{R(t)}
\]
Mission Assurance Flight Project Practice (FPP) Structure

FPP

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Total</th>
<th>Policy</th>
<th>Requirements</th>
<th>Standard</th>
<th>Procedures</th>
<th>Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2</td>
<td>Reliability Engineering</td>
<td>10</td>
<td></td>
<td>Reliability</td>
<td></td>
<td>Analysis of FHW, System Fault Tree, Fault Tree Handbook, PRA Procedures</td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>Quality Assurance</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td>Plan Project QA, Handling etc. of Critical flight HW, HW Inspection, QA responsibility for ATLO, QA Contractors</td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td>Deleted</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>7.5</td>
<td>Electronic Parts</td>
<td>8</td>
<td>IPPR</td>
<td>PETS</td>
<td></td>
<td>Derating, PEMS</td>
<td></td>
</tr>
<tr>
<td>7.6</td>
<td>Problem Reporting</td>
<td>16</td>
<td></td>
<td>Anomaly Resolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.7</td>
<td>Mission Operations</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MAM Handbook</td>
</tr>
</tbody>
</table>

Total: 57

- FPPs are the framework requirements that form the structure of all missions
  - Over 600 total
- Mission Assurance discipline FPPs are organized into 7 main topic areas:
  - MA Management
  - Reliability
  - Quality Assurance
  - EEE parts
  - Problem Report
  - Mission Operations
  - Systems Safety
- Codified in a variety of different types of documents
  - Different amounts of technical detail, waiver requirements, etc.
- **Smallsat missions require intelligent subset of FPP’s for risk and cost management**
- **Emphasis on QA and EEE parts disciplines (and Safety)**
Define three types of projects:

- **Type I**: Primarily contains *space flight* projects with NPR 8705.4 risk classifications A, B, & C.
- **Type II**: Primarily contains risk class D *space flight* projects, or other *space flight* projects that do not get risk classified (e.g. NPR 7120.8)
- **Type III**: Primarily contains projects that do not go into space (i.e., sounding rockets, balloons, aircraft payloads, and ground based projects)
# DTAB process and FPP

<table>
<thead>
<tr>
<th></th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FPP/DP compliance</strong></td>
<td>➢ Document on compliance matrices</td>
<td>➢ Document on compliance matrices</td>
<td>➢ N/A except for human safety</td>
</tr>
<tr>
<td>attached to PIP</td>
<td>➢ Cat A waiver required for non-compliances</td>
<td>➢ Projects expected to comply with the intent (CI) of applicable requirements</td>
<td></td>
</tr>
<tr>
<td><strong>PIP signature</strong></td>
<td>Programmatic Director For advised by</td>
<td>Programmatic Director For advised by</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>- JPL CE</td>
<td>- PEMG delegates (DTAB)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Dir For OSMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Dir For ESD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Manager PSO</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subsequent FPP/DP</strong></td>
<td>Cat A waiver*</td>
<td>Cat A waiver*</td>
<td>N/A except for human safety</td>
</tr>
<tr>
<td>non-compliance</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Cat A waivers process is defined separately (internal JPL document)*
Type II Implementation

- Tailoring is the key concept
- Each mission has unique requirements, constraints, and risks
- Careful and disciplined approach to tailoring decisions and requirements is fundamental to successful Smallsat Mission Assurance program

Dfor recommends Type & AD FPMS selects Type

Projects prepare PIP with help of PSO, OCE, OSMS, and Tailoring Guidelines

DTAB* reviews PIP (including compliance matrices) to check appropriateness & consistency of tailoring

DTAB advises Dfor regarding appropriateness & consistency of Project’s tailoring

Dfor advises FHD** of the approved Project risk posture

Dfor approves PIP (with compliance matrices)

PSO enters compliance matrix CI & NC with explanations into Cat A waiver tool

PSO prepares 7120.5E waiver if necessary

* DTAB = Class-D/Technology Advisory Board, consisting of PEMC delegates
** FHD = JPL CE, Dir For OSMS, Dir For ESD, Dfor

JPL Directorate Staff
## Mission Assurance Across different Class Missions

### Cassini Mission to Saturn

<table>
<thead>
<tr>
<th>Mission Attribute</th>
<th>MA Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission Class</strong></td>
<td>Class A</td>
</tr>
</tbody>
</table>
| **Architecture**  | Dual string, cross-strapped architecture, few Single Point Failures  
Graceful degradation  
Multiple combinations of instruments to meet mission success |
| **Lifetime**      | 11-year prime mission, 9-year extended mission  
Class S parts, extensive parts qualification program  
Thorough reliability analyses and review |
| **Environments**  | Outer planet, high radiation (~100 krad TID)  
Increased margins testing (thermal, lifetime)  
Tests at assembly, subsystem and system-level |
| **Inheritance**   | Little inheritance  
Extensive HQA presence at JPL and vendors, extensive MIPS program |

### Mars Science Laboratory - Mars Surface Rover Mission

<table>
<thead>
<tr>
<th>Mission Attribute</th>
<th>MA Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission Class</strong></td>
<td>Class A/B</td>
</tr>
</tbody>
</table>
| **Architecture**  | Dual string, Block-redundant, limited cross-strapped architecture, few Single Point Failures  
Multiple combinations of instruments to meet mission success |
| **Lifetime**      | 23 month prime mission, 3+ year extended mission  
Class B+ parts, full lifetime and environmental parts assessment  
Thorough reliability analyses and review |
| **Environments**  | Daily deep thermal cycles  
Significant component thermal cycle testing (thermal lifetime)  
Tests at assembly, subsystem and system-level  
Low TID radiation (<10 krad) |
| **Inheritance**   | Little-no inheritance  
Extensive HQA presence at JPL and vendors, extensive MIPS program |

### Soil Moisture Active Passive Earth Orbiter

<table>
<thead>
<tr>
<th>Mission Attribute</th>
<th>MA Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission Class</strong></td>
<td>Class C</td>
</tr>
</tbody>
</table>
| **Architecture**  | Single string with selected block redundancy  
Two instruments share key single string elements; both required to meet mission success |
| **Lifetime**      | 3 year prime science mission  
Class B parts  
Selected reliability analyses and review |
| **Environments**  | Earth orbital shallow thermal cycling  
Limited component thermal cycle testing  
Tests at assembly (limited), subsystem and system-level  
Low TID radiation (<10 krad)  
South Atlantic Anomaly |
| **Inheritance**   | Significant inheritance on Engineering hardware and software  
Moderate HQA presence at JPL and vendors, reduced MIPS program |

### Lunar Flashlight Cubesat Technology Demonstration Mission

<table>
<thead>
<tr>
<th>Mission Attribute</th>
<th>MA Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission Class</strong></td>
<td>Class D, Technology Demonstration</td>
</tr>
<tr>
<td><strong>Architecture</strong></td>
<td>Single string cubesat</td>
</tr>
</tbody>
</table>
| **Lifetime**      | 8 month prime deep space mission  
Mix of screened COTS and formal Rad tolerant parts  
Destructive SEE parts assessment & TID analysis and measurement  
No reliability analyses and review |
| **Environments**  | Deep space thermal cycling  
Workmanship test at system-level  
Board/system level TID assessment  
Low TID radiation (<10 krad) |
| **Inheritance**   | Some cubesat components inherited  
Very limited HQA presence at JPL, vendors have some heritage, no MIPS program |
Case Study – Type I vs Type II - HQA In-Process/Testing Inspections
Part Quantity Rejected/Accepted

- Percentage rejection rate higher for Type I => additional requirements
- However Type II rejection rate is still significant
- HW used by Type II projects is **not** significantly lower quality (higher defectively)
HQA In-Process/Testing Inspections
Dispositions of Rejected Line Items

- **Type I Projects**
  - Accept, 101, 10%
  - LU-Limited Use, 31, 3%
  - RPR-Repair, 32, 3%
  - RWK-Rework, 85, 8%
  - SA-Suspend Action, 193, 19%
  - Transfer to another IR, 22, 2%
  - SCRAP, 22, 2%

- **Type II Projects**
  - Accept, 4, 8%
  - LU-Limited Use, 3, 6%
  - RPR-Repair, 5, 9%
  - RWK-Rework, 11, 20%
  - SCRAP, 2, 4%
  - SA-Suspend Action, 4, 7%

- **Type II projects tend to scrap and/or rework more than Type I**
High-Impact HQA In-Process/Testing Defects with LU/RTV/RPR/RWK/SCRAP Dispositions

- Defects are dominated by workmanship and damage
- Formal defect reduction plans and overall process capability improvement (both internal and external) required
## Examples of Type II Defects

<table>
<thead>
<tr>
<th>Type of Defect</th>
<th>Use-As-Is Disposition Pulled from QARS</th>
<th>Rework Disposition Pulled from QARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage</td>
<td>Damage found on microcircuit. Damage is contained within the package and does not appear to start a crack in the package but more like a chip-out</td>
<td>C52 has a gouge out of the end cap. Remove and replace C52 with a new part.</td>
</tr>
</tbody>
</table>
NASA NEPP CubeSat Parts Data Base

- >2200 individual lines of data
  - Line = Part and corresponding part number
- Consistent trends
  - 33% of total parts are common to at least two or more board designs
  - ~98% of parts are rated for industrial (-40C to 85C) or more temperature
- Almost all passives are SMD 0402 or larger
  - Only 25 parts are listed as SMD 0201, nothing smaller
- Approximately 33% of passives are qualified for automotive use (AEC-Q200)
  - 30% of passives are manufactured by non-QML vendors
  - Polymer tantalum capacitors are 33% of all tantalum capacitors
    - (Special attention required due to moisture sensitivity)
Types of IC Packages used in NASA NEPP CubeSat database

- SOP package types completely dominate
- Being able to handle and process these types of packages will substantially improved quality
Spacecraft Environment Stress

- Mechanical, temperature and radiation effects will stress entire system and magnify weakness associated with defects.
- CubeSats design practices and assembly operations must take these into account.
- Cannot be ignored simply to save cost.
Designing in Quality

- While inspection and verification remain at the heart of identifying and reducing defects, the initial design effort is the key to identifying sensitivity and building in margin to defects
- Mission Assurance evolving to more part of early phase design decisions
  - Example – simulation of PCB mechanical vibration frequency modes
    - Use of thinner/smaller scale COTS can provide significant increase in margin to mechanical vibration

![Graph of vibration frequency modes](jpl.nasa.gov)
Summary

• Small/CubeSats face many of the same defect based quality issues that larger heritage missions face
• **This results in significant decrease in satellite reliability as mission time increases**
• Small/CubeSats still require a formal FPP based design methodology
  • Tailoring FPP to Small/CubeSat is key contribution/collaboration of S&MA
• **Emphasis on defect identification and elimination throughout entire assembly and manufacturing processes (internal and external) is where S&MA discipline can be best leveraged to maximize risk mitigation effect for Small/CubeSats**
• Developing and supporting the use various types of sensitivity analysis early in the design phase are areas for future evolution of S&MA discipline