Lessons Learned from the Juno Project

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Topics Covered

- Radiation environment
- Radiation control program
- Radiation control program lessons learned
Juno Radiation Environments
- Juno TID environment is about a factor of 5 less than JEO
- Juno peak flux rate is about a factor of 3 above JEO
Approach for Mitigating Radiation (1)

• Assign a radiation control manager to act as a focal point for radiation related activities and issues across the Project early in the lifecycle
  – Requirements, EEE parts, materials, environments, and verification
• Establish a radiation advisory board to address challenging radiation control issues
• Hold external reviews for challenging radiation control issues
• Establish a radiation control process that defines environments, defines requirements, and radiation requirements verification documentation
• Design the mission trajectory to minimize the radiation exposure
Approach for Mitigating Radiation (2)

- Optimize shielding design to accommodate cumulative total ionizing dose and displacement damage dose and instantaneous charged particle fluxes near Perijove
  - Vault shielding for the bulk of the spacecraft bus electronics
  - Individual shield designs for equipment outside the vault
- Perform EEE parts radiation characterization and lot acceptance testing to quantify parametric degradation from radiation exposure
- Materials radiation tolerance evaluation and testing to determine material survivability
Juno Trajectory Through Radiation Belts

- Juno trajectory exposes spacecraft to the Jovian radiation belts one day per orbit
  - Electrons
  - Protons
- Early orbits are relatively benign
  - ~25% of the mission TID received by the end of Orbit 17
- Late orbits are severe
  - ~25% of the mission TID received over the last 4 orbits

Perijove Passage through Jupiter's Radiation Environment
End of Mission Radiation TID Levels

- Solar Cell Coverglass (> 100 Mrad)
- Deck Component Surface Dose (under blanket) (11 Mrad)
- Solar Cell Junctions (3 Mrad)
- Vault Electronics (25 krad)
- Instruments Outside Vault (<0.6 Mrad in 1.5 mm housing)

Pre-decisional, For Planning and Discussion Purposes Only
Titanium Vault Protects Electronics

- Juno spacecraft electronics are shielded by a titanium vault
  - The thickness of the vault six walls are optimized to attenuate Juno’s mix of electrons and protons using the minimum mass
  - Vault equipment packing factor maximizes shielding from neighboring electronics boxes
  - Vault shielding designed to limit the TID of all internal electronics to 25 krad or less
  - Divided into zones for equipment with different lifetimes and radiation hardness
    - Mass of walls 157 kg
- Electronics outside the vault have local shielding designed for their location and part hardness
Vault Component Layout

- MWR PDU
- MWR Receiver
- Transformer Couplers
- Waves Electronics
- JADE Electronics
- UV Electronics
- ASC Electronics
- 2x IMUs
- PIU
- CME
- FGM Electronics
- PDDU
- 2x C&DHs
- 2x SRU
- 2x SSS Electronics
- 2x Diplexers
- 2x TWTAs
- KA&X-band SDSTs
- KATS
- 2x EPC
- Pre-decisional, For Planning and Discussion Purposes Only
Juno Radiation Control Program
Juno Radiation Control Program Overview

• Radiation control and verification objective:
  – Provide certification that radiation requirements have been met prior to launch

• Radiation key issues
  – Juno flight system must survive radiation from multiple sources
    ▪ Sun and Interplanetary space (protons and heavy ions)
    ▪ Jupiter (electrons, protons and heavy ions)
  – Juno radiation levels are higher than heritage levels
    ▪ High energy electrons and protons cause total ionizing dose (TID) and displacement damage dose (DDD) in electronics and materials significantly higher than MRO or New Horizons

• Juno radiation control program must apply to the spacecraft and instrument equipment providers
  – LM spacecraft bus with significant subcontracted equipment
  – There are eight science instruments
Radiation Control Process

• The Juno radiation control process is adapted from the process used on the Galileo and Cassini spacecraft projects
  – A radiation control process is usually reserved for high value/visibility projects with significant radiation environments
• The process provides a structured approach that provides documentation in support of hardware certification prior to integration and test
  – Radiation models and environments
  – Mechanical configuration
  – Transient effects for sensors and detectors
  – TID/DDD mission exposure levels
  – Part radiation performance
  – Worst case analysis
  – Shielding design
  – Radiation design factor calculations
  – Single event effects
  – RACS documentation
Juno Radiation Control Lessons Learned
Juno Lessons Learned - Summary

- The Right Radiation Test Facilities Were Difficult to Find
- High Energy Electron Flux Transients Were Difficult to Mitigate
- Early Radiation Testing Reduced Risk
- EEE Parts Review, Test Planning, and Testing Reduced Risk
- Communicate Early and Often
- The Vault Design was Affected by More Than Radiation
- Multiple Environment Changes Occur Over Time
- Materials Radiation Evaluation and Testing Was Required
- Iterative Analyses Were Required
- Maintain Focus on Reliability Analyses
The Right Radiation Test Facilities Were Difficult to Find

• The Jovian radiation environment and operating conditions made appropriate radiation test facilities difficult to locate
  – Many tests required beam sources, the ability to cool the test sample, and the desire to take radiation test data in-situ or post irradiation without breaking vacuum

• Electron beam sources were difficult to find and schedule
  – Limited beam energy, current, or beam size combinations
  – Many sources are pulsed rather than continuous beam
  – The ability to cool the device or materials under test had to be added to one beam facility, causing some test schedule delays and added cost

• Many facilities are used in the medical field
  – EEE part testing is not their primary concern, so expertise may be limited
  – Scheduling can be an issue (i.e. test only at night)

Identify test facilities early, investigate beam and target characteristics as early as possible, and allow significant schedule slack in test planning
Test Facilities used on Juno

- JPL (0.5 to 2 MeV electrons, LN2 cooling of device under test)
- Goddard Space Flight Center (0.5 to 2 MeV electrons)
- Marshall Space Flight Center (45 KeV protons, vacuum UV)
- Grey Laboratory (5 MeV electrons, LN2 cooling of device under test)
- RPI (10 to 60 MeV electrons, LN2 cooling of device under test)
High Energy Electron Flux Transients Were Difficult to Mitigate

- High energy electron flux induced transients affect flight system sensors and payload instruments
  - SRU, Junocam, JADE, JEDI, UVS and FGM (ASC)
- Signal to noise and transient noise issues have been mitigated, but the analysis and testing required was significant
  - High energy electron testing
  - Multiple iterations of shielding design and transport analysis
  - Noise rejection methods
  - Sensor performance modeling in a transient environment
  - Outage frequency and duration
  - Science observation strategy and science data quality

Do not underestimate the effects of transient noise, or the effort required to mitigate transient noise effects, on spacecraft hardware
Early Radiation Testing Reduced Risk

- EEE devices and cables that had significant risk to the project were identified early in phase B and selected for risk reduction testing in phase B
  - CCD
  - MCP
  - Solar cells
  - High voltage coax cables

- These test campaigns characterized these devices were performed to ensure that end of life or transient performance could be estimated with reasonable uncertainties
  - CCD and MCP (transient behavior)
  - Solar cells and high voltage coax cables (end of life performance)

- Testing did reflect flight conditions when possible
  - CCD (electron irradiation and cold temperature)
  - MCP (electron irradiation and shielding effects)
  - Solar cells (low intensity illumination, cold temperature and electron irradiation)
  - High voltage coax cables (electron irradiation and cold temperature)

Identify and test high risk parts and materials as early as possible
EEE Parts Review, Test Planning, and Testing
Reduced Risk

- EEE parts list were reviewed for radiation data pedigree
  - Done for every assembly and payload instrument
  - Reviewed early in design phase and as the designs matured to keep up with device changes over time
  - Characterization, RLAT, and SEE test devices identified
  - Allowed for common testing and prioritization of testing
- ELDRS test standard was created for the Project
  - Defined dose rate and sample size
- Test plan review prior to test initiation
  - Signoff by both line and radiation control manager
- Test report after test completed
  - Signoff by both line and radiation control manager
- Test results flowed into worst case parts parameter database to close the loop with the worst case analysis

Rigorous EEE parts review and testing program limits radiation surprises later in the Project
Communicate Early and Often

- Regular radiation control meetings every two weeks up to project CDR
  - Includes representatives from system engineering, flight system, and the payload instruments
- Regular Project Management Team communications were mandatory
  - MMRs were used to regularly communicate rad issues to the PM and PSE
- Face to face meetings were held early in phase B for the flight system and each payload instrument
  - Radiation control objectives, process, and requirements
  - SDRL requirements
  - Agreements on roles and responsibilities
- Radiation workshops held prior to all major project reviews
  - Provides radiation control status and open issues before the review
    - Provides an opportunity to resolve issues are establish work off plans that can be briefed at the review
    - Typically held two months prior to SRR, PDR, and CDR
- Post CDR face to face meetings are planned to close verification analyses

Establish radiation control organization and start discussions as early as possible
The Vault Design was Affected by More Than Radiation

- The Juno vault design was driven by many issues
  - Thermal control
  - Harness layouts
  - EMI/EMC requirements
  - Random vibration levels
  - Radiation protection
  - Internal and external charging
  - Buildup scheduling
  - Hardware access during functional testing
  - Environmental testing
  - Rework

- The Vault design must not solely focus on radiation
- Many disciplines will affect the implementation of the vault
Materials Radiation Evaluation and Testing Was Required

- Materials radiation test data that is relevant to the Jovian environment rarely exists in the literature without interpretation or evaluation
  - Much of the existing materials radiation data was tested in air causing more severe degradation than expected in flight
  - Much of the test data is too old (typically 30-40 years)
    - Materials can change composition over time
- Material evaluations were performed to determine which materials needed to be tested for all assemblies
- Materials radiation testing was performed when existing data could not be used to establish or increase the TID limit of the material
  - Teflon insulation
    - ETFE, FEP, PTFE
  - Adhesives and tapes
  - Harness
    - TSP, TKT, high voltage coax

Identification of radiation soft materials and testing will be required
Multiple Environment Changes Occur Over Time

- Juno spacecraft trajectory changes caused several small changes to the environment through CDR
  - Launch date changes
  - Delta V optimization changes
  - JOI engine burn changes
  - Earth flyby altitude changes

- These types of trajectory changes can alter the radiation environment by 10% or more if several of these occur in combination

- Testing program can also introduce changes to the environments
  - Surface radiation effects testing caused the extension of the charged particle environment to low energies (down to 10 KeV)

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- Put some additional margin in zone radiation requirements (or JEO equivalent) to accommodate small changes
- Track small changes to the environment that occur over time and implement requirements change when the delta margin threshold is crossed

Pre-decisional, For Planning and Discussion Purposes Only
Iterative Analyses Were Required

- Iterative shielding analyses have been performed on Juno
  - Radiation environment changes
    - Changes in mission trajectory
  - Spacecraft shielding design changes
    - Change in the vault material and dimensions
  - Equipment relocation
    - Thermal constraints and equipment growth
  - Signal to noise and transient noise suppression
    - Iterative shielding design around visible, IR, and UV detectors
  - EEE parts with TID sensitivity or RDF < 2
    - Shielding analyses down to the EEE device level required on many assemblies

• Iterative shielding analysis will be required as the design matures
• Build in multiple analyses passes and tests if necessary
Maintain Focus on Reliability Analyses

- Radiation related reliability analyses needed to support verification analyses
  - Worst case circuit analysis
  - Single event effects analysis
- Reliability analyses generation and review was not completed at CDR
  - Caused by designers trying to finalize their designs and not having the time to work the reliability analysis
- Reliability analyses content differed across hardware suppliers, causing some additional iterations with the review process
  - Specific analysis content was expected, but not received
  - Additional iterations were needed on the review and approval cycle

- Focus on reliability analyses starting at subsystem PDR paying particular attention to who is assigned to perform the analysis and reviews
- Establish acceptable format and content prior to analysis the analysis generation and review cycle
Did the Juno Radiation Control Program Work?

• Radiation was identified as one of the top risks to the Juno project early at the beginning of the project
• Significant project resources were applied to address radiation related issues
• Risk reduction activities, parts and materials testing, and shielding design analysis have reduced the risk over time
  – At CRR (10/06), radiation was listed in 2 of 9 topics in the PM worry list
  – At PMSR (5/07), radiation was listed in 2 of 9 topics in PM top 10 issues
  – At PDR (5/08), radiation was listed in 1 of 6 topics in the PM top 10 issues
  – At CDR (4/09), radiation was not in the PM top 10 issues
• No significant findings or actions items related to radiation control were found at subsystem or Project CDR
• Only a handful of radiation related waivers have been generated to date
  – ~4 TID (all low risk)
  – ~3 SEE (low risk)

The Juno radiation control program approach was successful, and lessons learned would be useful to the proposed JEO mission