# Lessons Learned from the Juno Project

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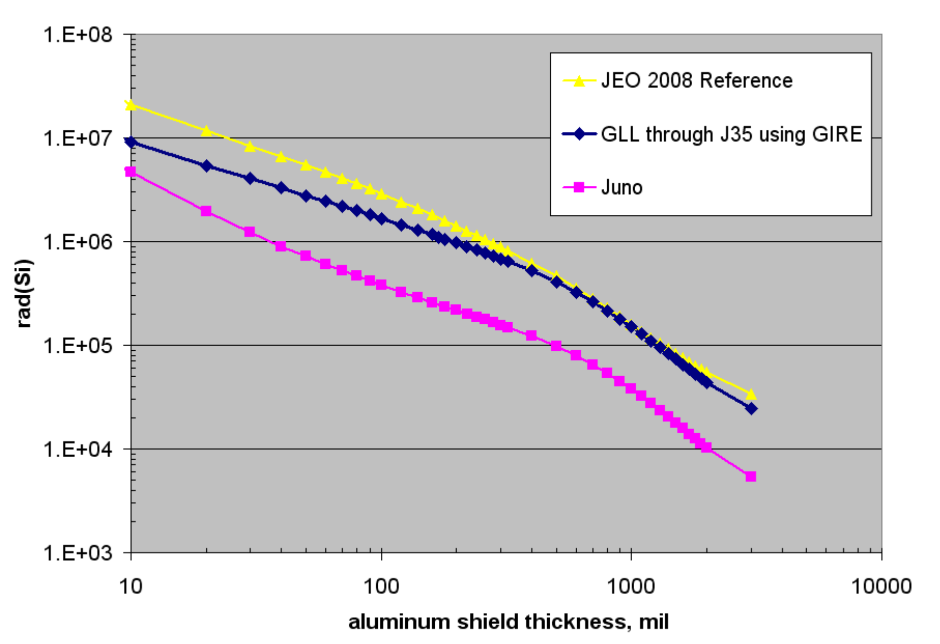
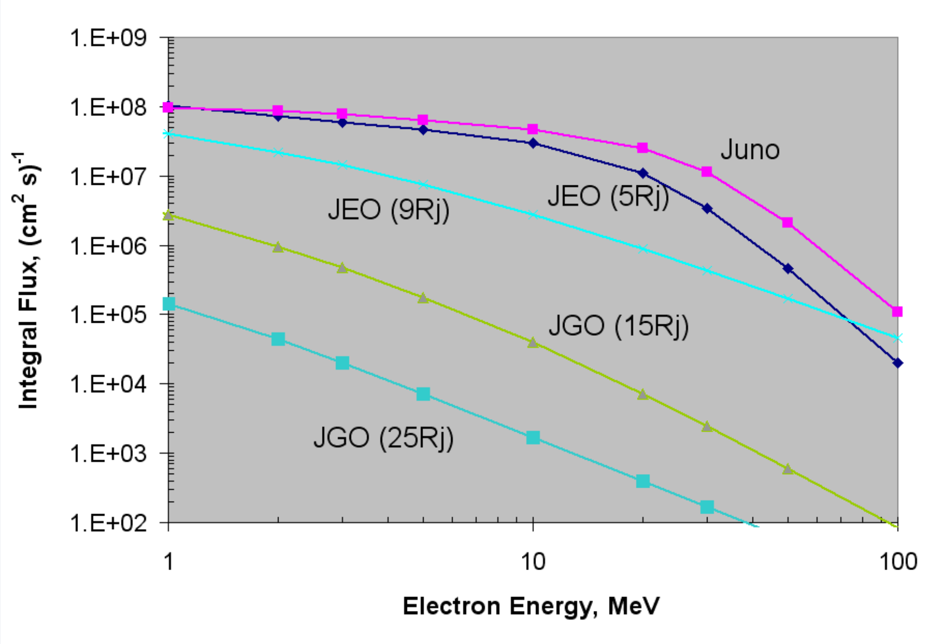
# Topics Covered

- Radiation environment
- Radiation control program
- Radiation control program lessons learned

# Juno Radiation Environments

# Radiation Environment Comparison




- Juno TID environment is about a factor of 5 less than JEO
- Juno peak flux rate is about a factor of 3 above JEO

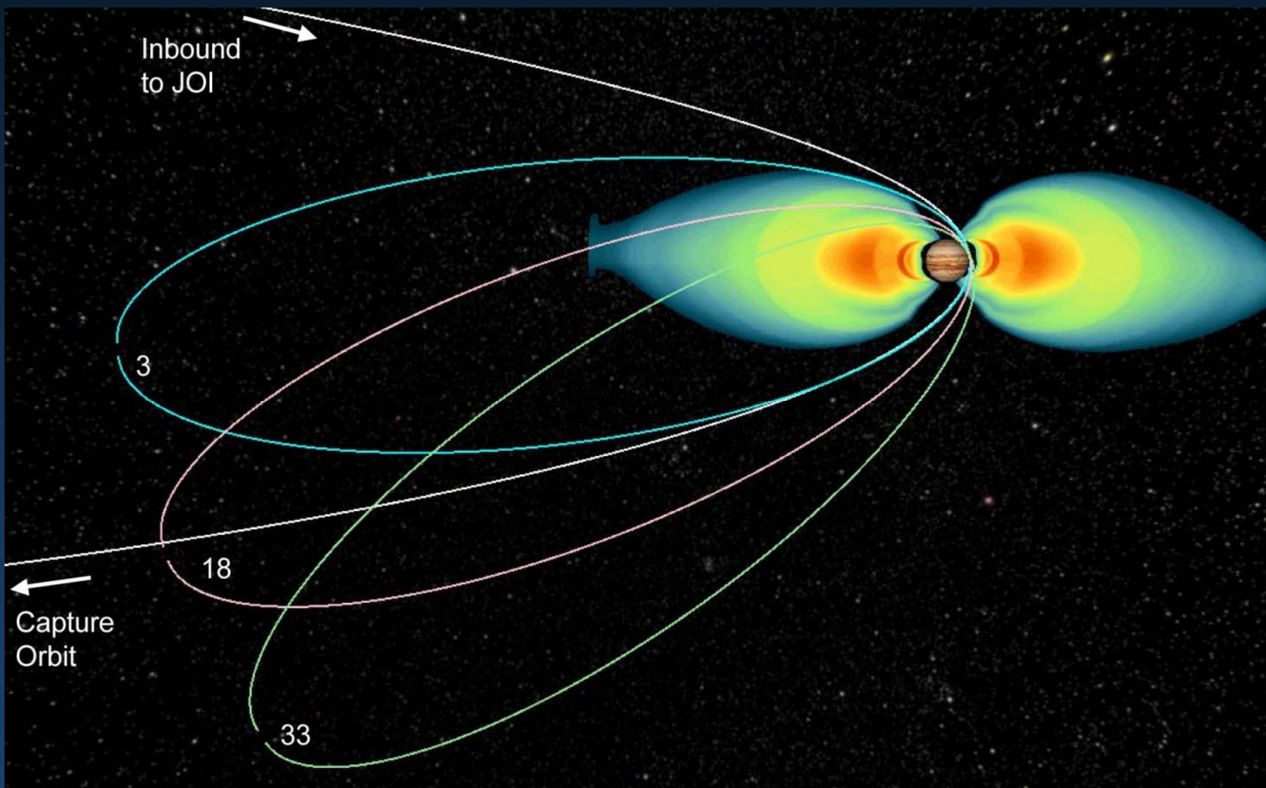
# Approach for Mitigating Radiation (1)

- 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

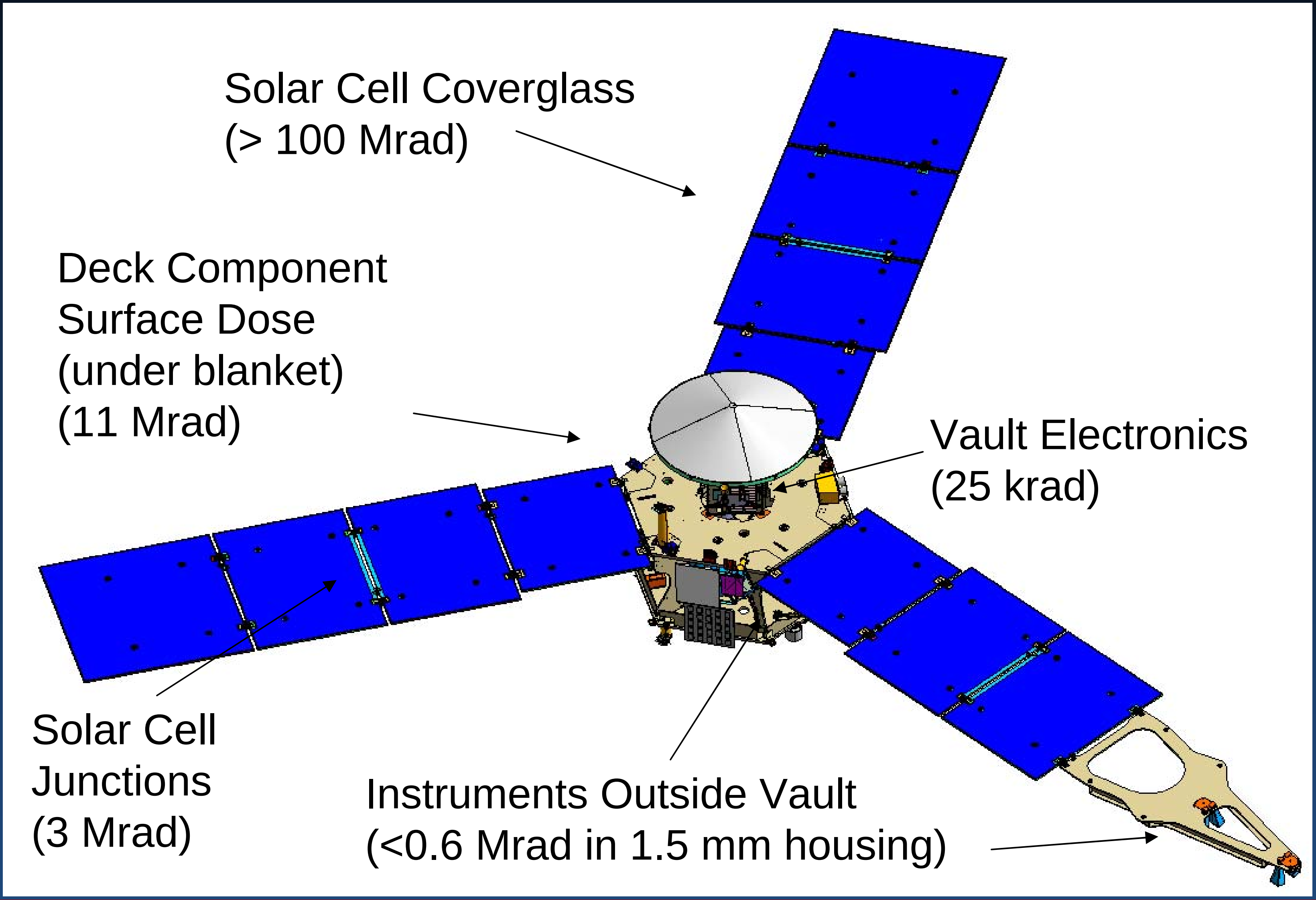
# Juno Trajectory Through Radiation Belts




**Perijove Passage through Jupiter's Radiation Environment**

- 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

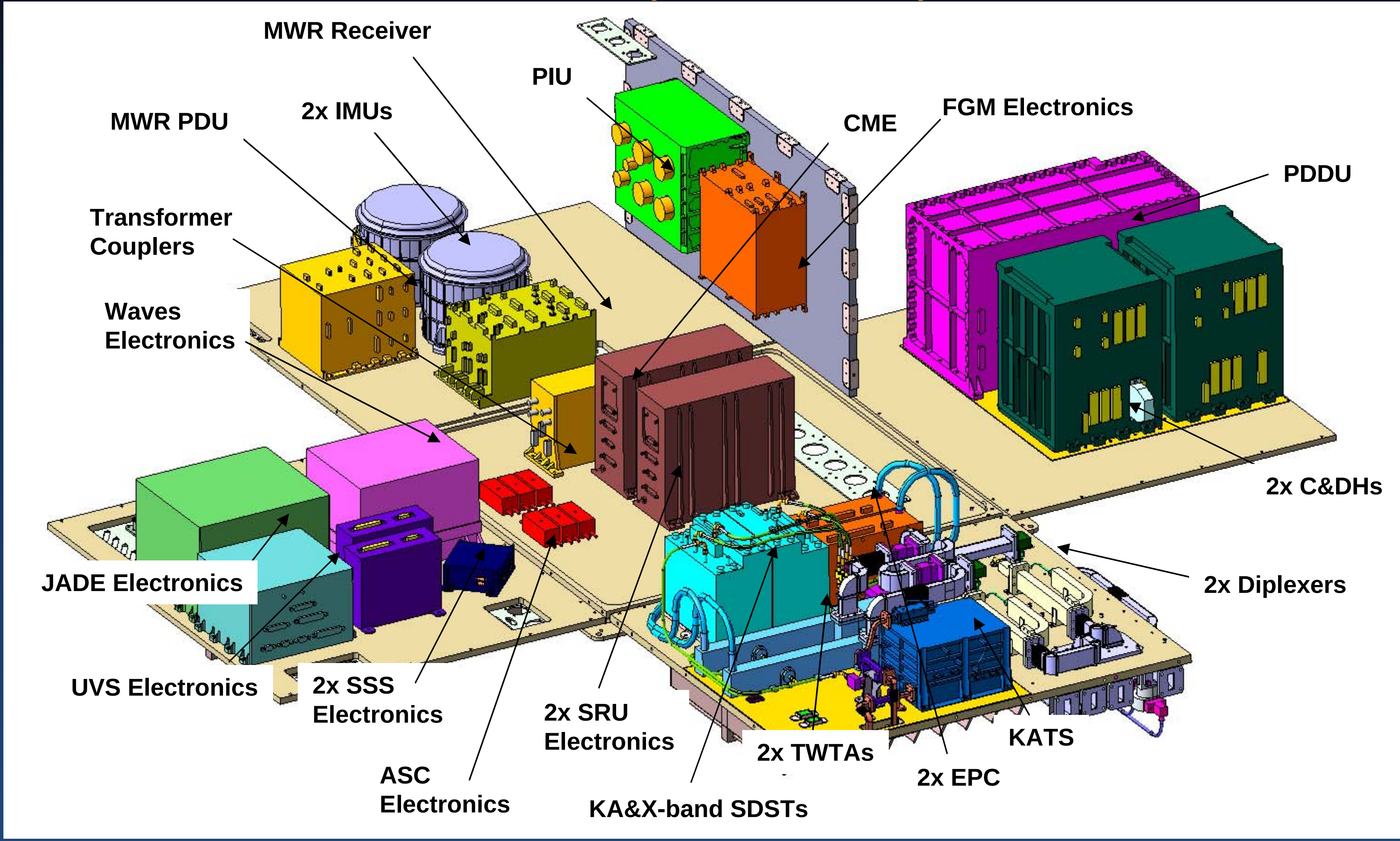
# End of Mission Radiation TID Levels



# 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



# 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
  - Process further evolved from Europa Orbiter (1999) and Prometheus (2004)
- 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 that 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)

- *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*

# 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*