Jet Propulsion Laboratory
California Institute of Technology

Radiation Assessment for JPL Missions: Models and Tools

Insoo Jun, JPL/NASA

May 31, 2019
AP9/AE9/IRENE Meeting
Sykia, Greece

Jet Propulsion Laboratory
California Institute of Technology

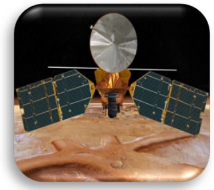
20 Spacecraft and 8 Instruments in Operation Across the Solar System and Beyond


1977
Voyagers 1 & 2


2001
Mars Odyssey


2003
Opportunity


2003
Spitzer


2005
Mars Reconnaissance Orbiter

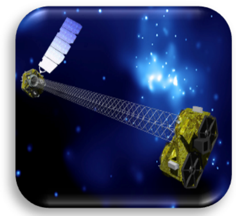

2006
CloudSat


2008
Jason 2


2009
NEOWISE

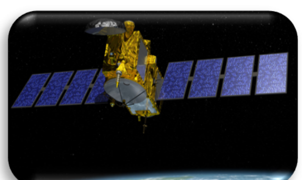

2011
Juno

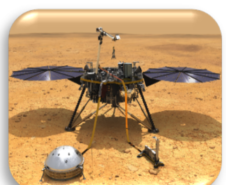

2011
Curiosity


2012
NUSTAR

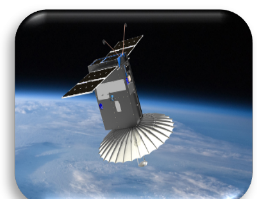

2014
OCO-2

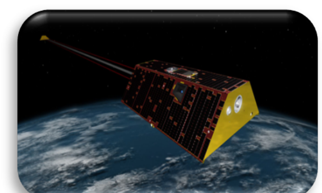

2015
SMAP


2016
Jason 3


2018
InSight


2018
MarCO


2018
RainCube


2018
Grace Follow-On

Instruments

Earth Science

• MISR (1999) • AIRS (2002) • MLS (2004) • ASTER (2009)
• OPALS (2014) • ECOSTRESS (2018) • CAL (2018) • OCO-3 (2019)

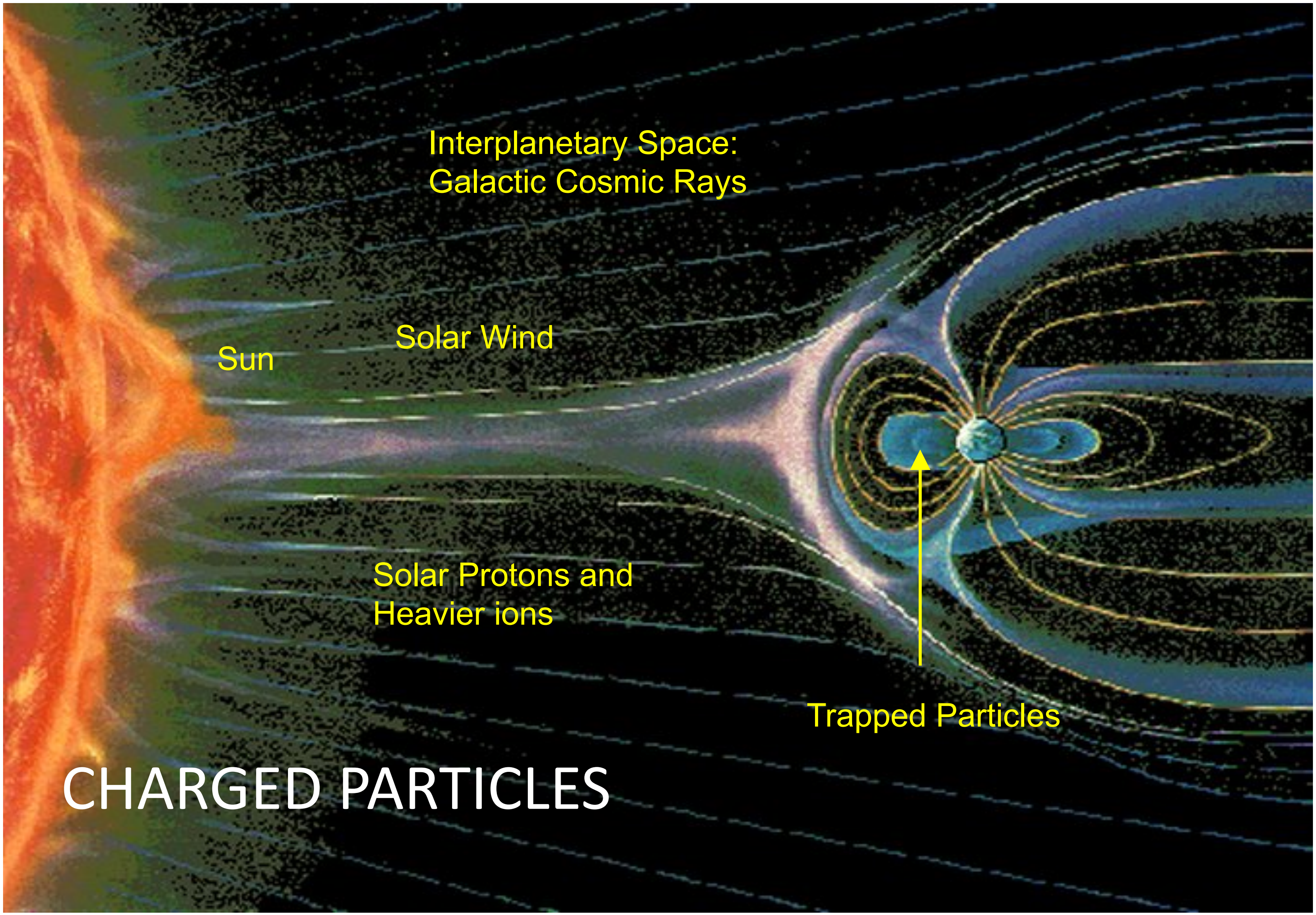
Planetary

• MARSIS (2003)

JPL Missions

- Robotic Solar System Exploration
  - Mars
  - Outer Planets
    - Gas Giants
    - Ice Giants
    - …
  - Deep Space
    - Asteroids
    - …
- Earth Science
  - Mostly LEO orbits
  - …
- Astrophysics
  - Spitzer
  - WISE
  - Hubble (instrument)
  - JWST (instrument)
  - …
- ….

The Space Radiation Environment



Jet Propulsion Laboratory
California Institute of Technology

Environment Models

Environment	Models (Present)	Models (Future)
GCR	CREME96	
SEP	JPL	SAPPHIRE (?)
Trapped • Earth • Jupiter • Saturn • Uranus • Neptune	• AE8/AP8 • GIRE3 • SATRAD • UMOD • NMOD	• AE9/AP9/IRENE (*) • GIRE4 with Juno data (+) • • •

(*)
Continue to validate against on-orbit data
Waiting for communities buy-in

(+)
Just started working for some noise background data available in PDS

Information for discussions only.

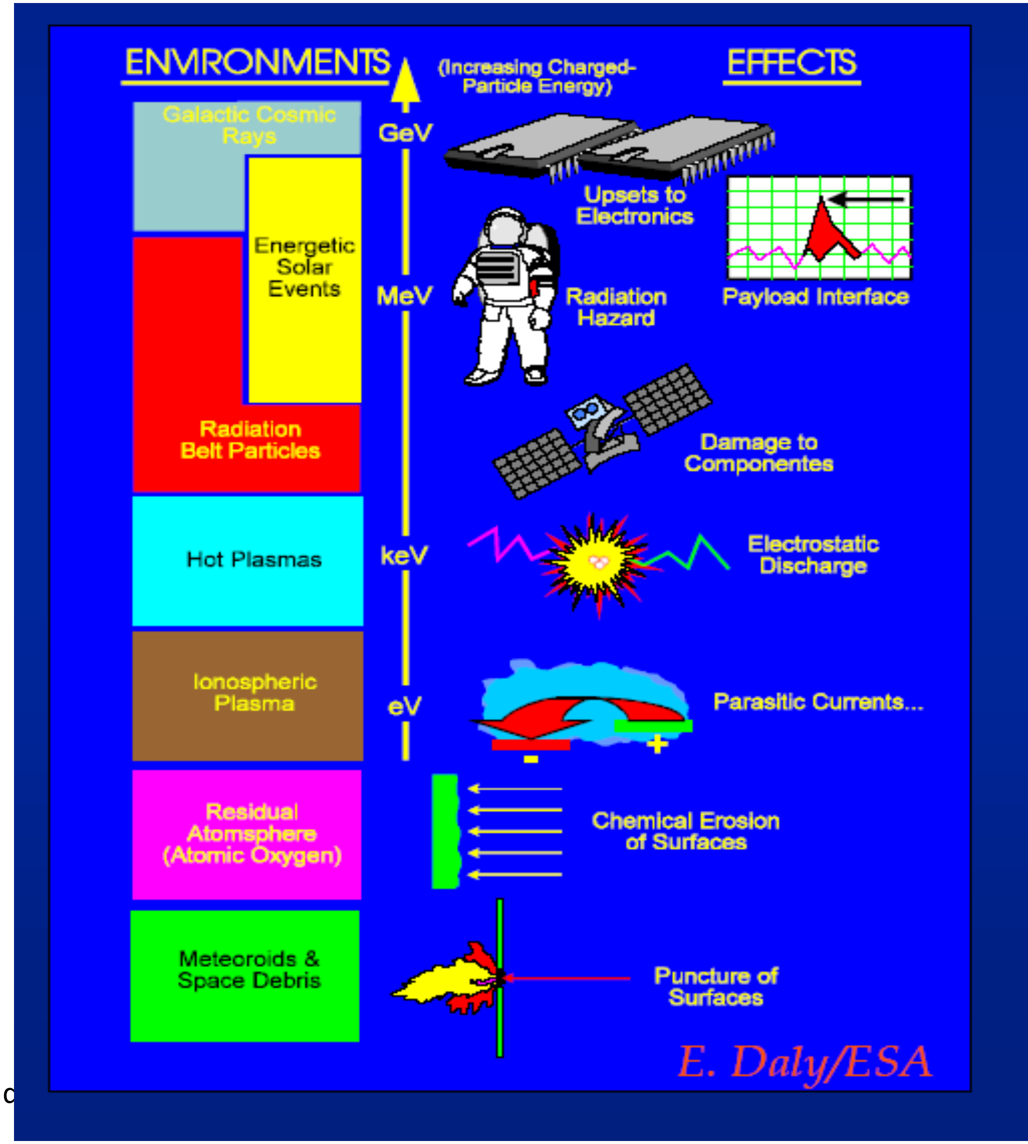
Summary: Environment -> Effect

Source Particles	Environment Effects
Trapped electrons; Trapped protons ; Solar protons	Total Ionizing Dose (TID) and Displacement Damage Dose (DDD)
Auroral electrons; Plasma electrons/ions	Surface Charging
High energy (> 1 MeV) trapped electrons	Internal Charging (IESD)
Trapped protons; Solar protons; Galactic cosmic ray	Single Event Effects (SEE)
MMOD	Structural Damage; ESD
Atomic oxygen UV	Material Degradation

Jet Propulsion Laboratory
California Institute of Technology

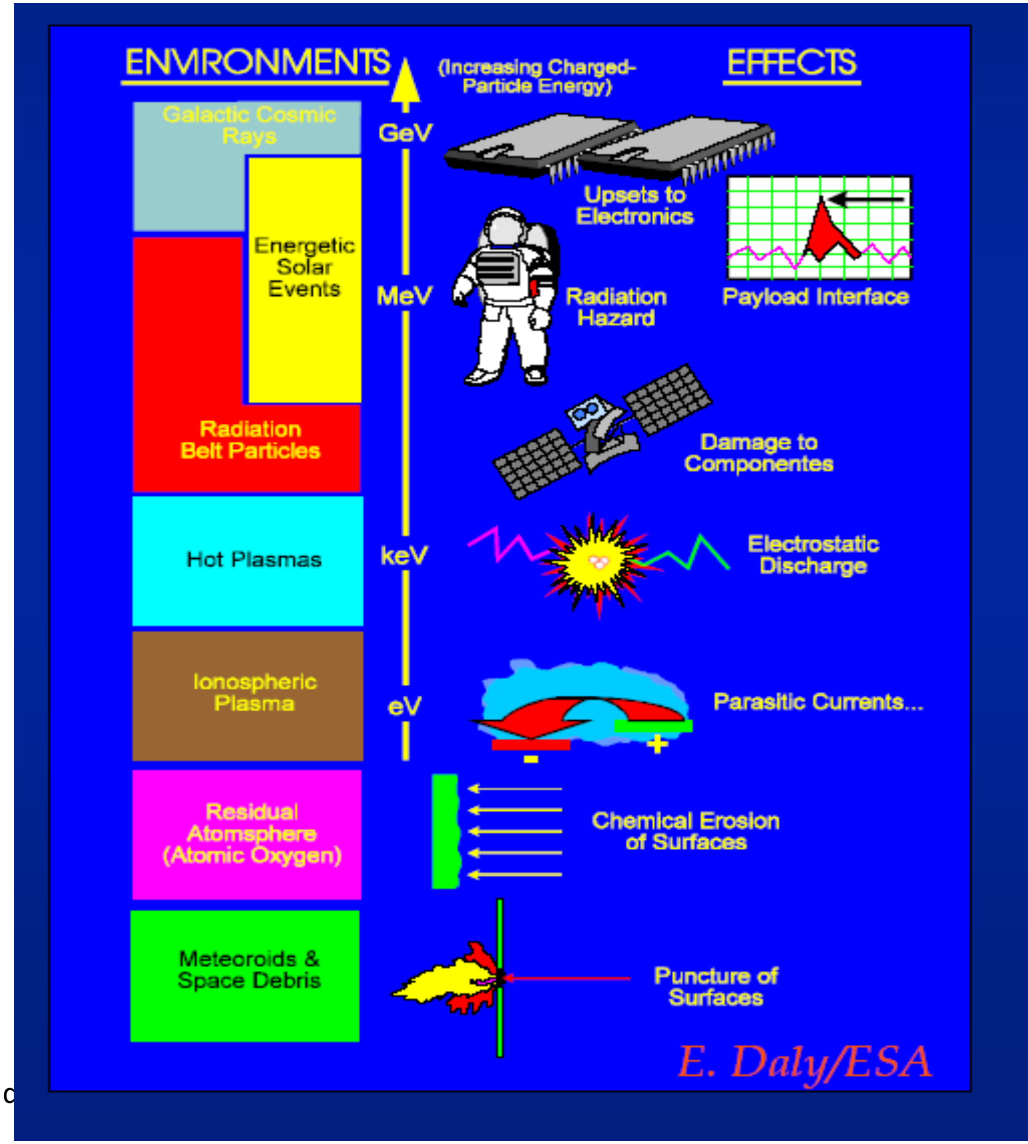
Overview: Radiation and Effects

- Charging
- Total Ionizing Dose
- Displacement Damage Dose
- Single Event Effects
- Radiation induced noise in scientific sensors/detectors
- Radiation effects on astronauts

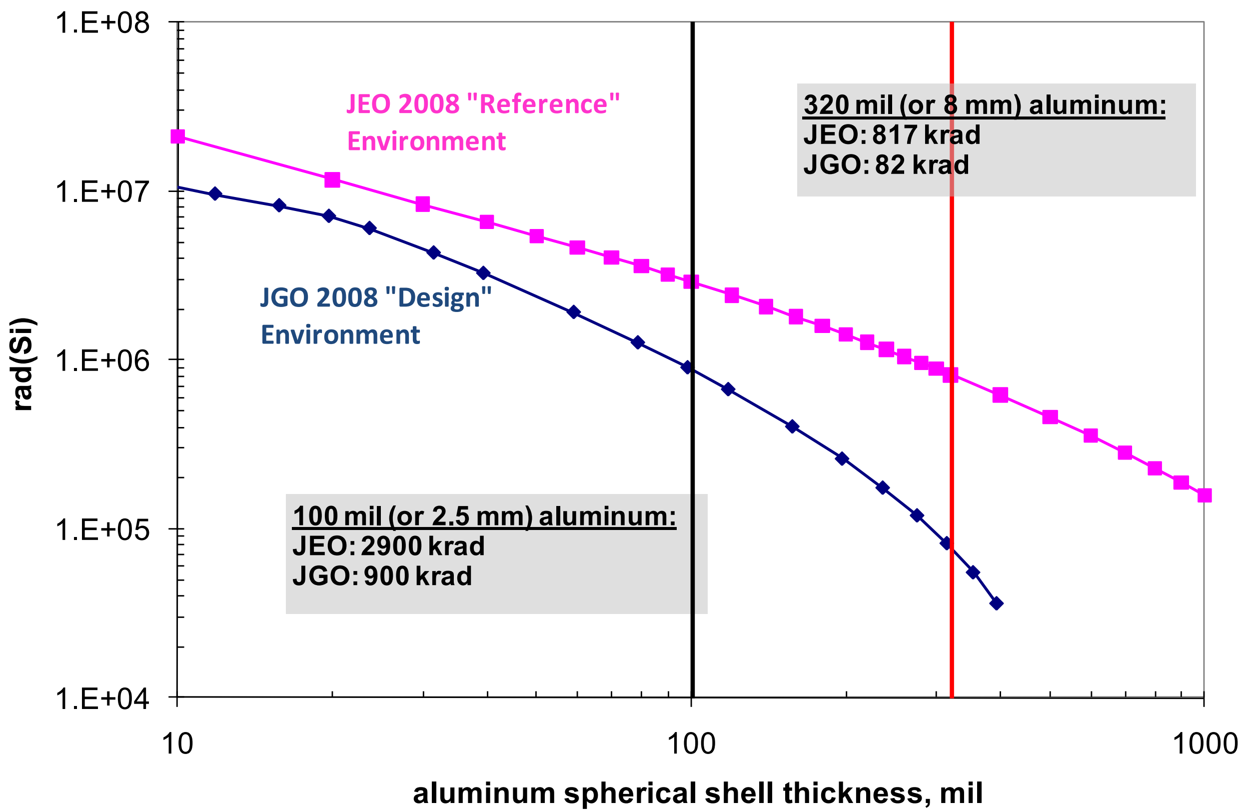


Overview: Radiation and Effects

- Charging
- **Total Ionizing Dose**
- **Displacement Damage Dose**
- Single Event Effects
- Radiation induced noise in scientific sensors/detectors
- Radiation effects on astronauts



Dose-Depth Curves for JEO and JGO



A dose-depth curve provides the TID level at the center of a "spherical shell" or "solid sphere" spacecraft for various aluminum thicknesses

Beyond Dose-Depth Curve

- The use of dose-depth curve for shielding design is convenient and fast
  - However, ray-tracing is not an accurate radiation transport method because it does NOT include:
    - Different material effects (e.g., dose-enhancement effect)
    - Multiple scatterings of electrons
    - Nuclear reactions
    - Secondary particles
- Thus, the shielding mass estimate using a dose-depth curve is an approximation

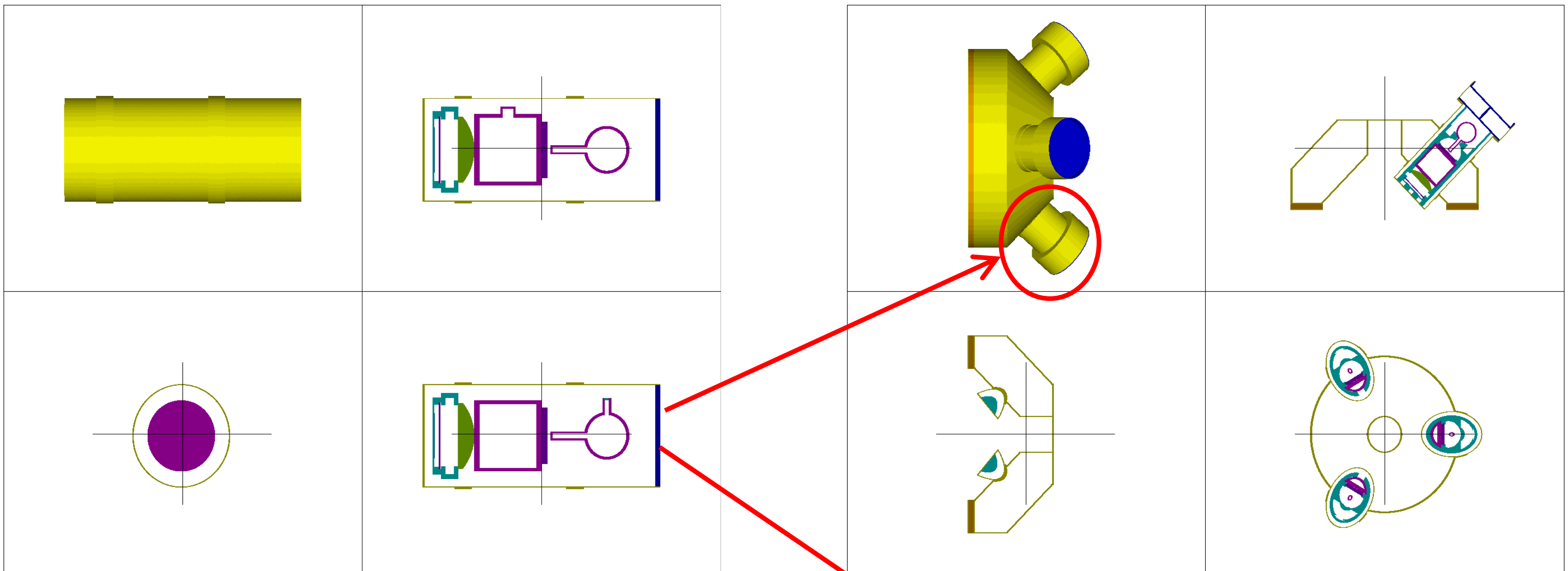
Comprehensive particle transport codes are required for detailed shielding design and analyses

Shielding Design Process

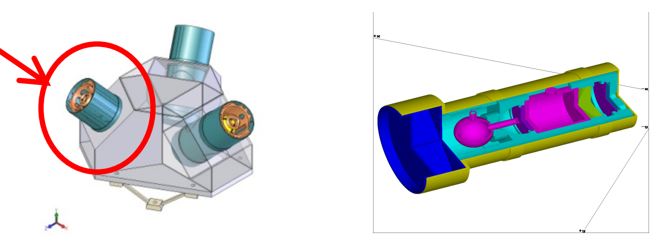
- After the initial use of dose-depth curve, the same set of tools should be used throughout the shielding design process across the project
- The fidelity of mass model will increase as the hardware design matures (see next chart for an example)
- The shielding design will require many rounds of iterations or trades
  - Simple tools in the initial design stage
  - More complex tools as design matures

The careful selection of the right tools up front is critical

Example: Progress of Mass Modeling Fidelity



Mass model of a preliminary design
(e.g., at PDR): Simple model



Mass model of the final design
(e.g., at CDR): Detailed model

Shielding Design Lesson Learned from Juno

- SNR shielding analysis and testing required multiple iterations
- SNR analysis required transport analysis tool with comprehensive physics package (i.e., correct treatment of secondary particles)
- Shielding enclosure of instruments required multiple design iterations to optimize implementation and shielding effectiveness
- Board and component level analyses were required to optimize shield mass
- Graded shielding approach sometimes turned out to be difficult to implement

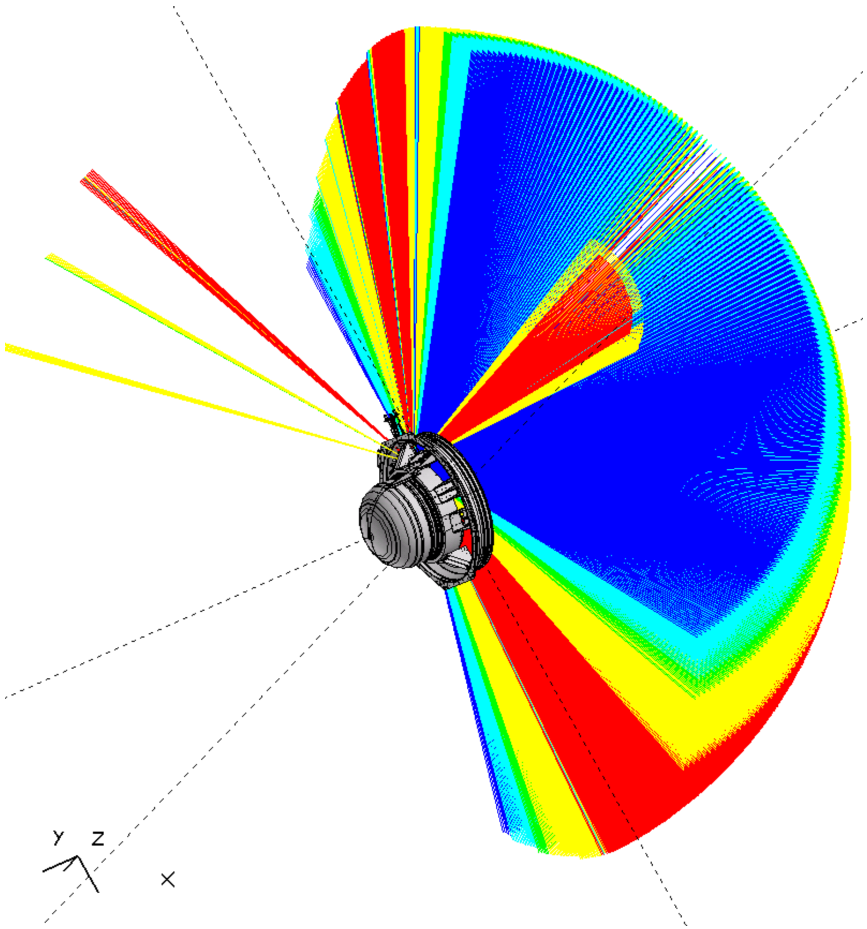
Transport Codes – Applications

- Transport codes are needed to consider the following
  - Total ionizing dose
  - Displacement damage dose
  - Single event effects
  - Internal charging
  - Secondary particle environment behind shield

- Transport codes can be used for particle detector simulation

Radiation transport analyses will be required to cover a wide range of radiation effects

Ray Tracing Codes



- Ray tracing codes are useful to quickly perform system level trade studies
- Ray-tracing codes with CAD interface capability are most useful
- Tools available:
  - FASTRAD: http://trad.fr/
  - MEVDP: http://www-rsicc.ornl.gov/
  - "SIGMA" option in Novice: tj@empc.com
  - *etc.*

Transport Codes – Species

- Transport codes model actual particle interactions in the material (Ray tracing codes do not)
- It is important to model all particle species when performing transport analyses
  - Electrons
  - Photons
  - Protons
  - Neutrons
  - Heavy Ions
- Each transport code considers only a specific set of particles

Radiation transport analyses will be required to cover a wide range of particle species

Commonly Available Radiation Transport Codes

	Electron	Photon	Proton	Neutron	Heavy Ion
CREME96 creme96.nrl.navy.mil			√		√
TRIM www.srim.org			√		√
ITS3.0 www-rsicc.ornl.gov	√	√			
FASTRAD (FMC) Trad.com	√	√	√	?	?
NOVICE tj@empc.com	√	√	√		√
MCNP(X) mcnpx.lanl.gov	√	√	√	√	√
Geant4 geant4.web.cern.ch/geant4/	√	√	√	√	√

Information for discussions only.

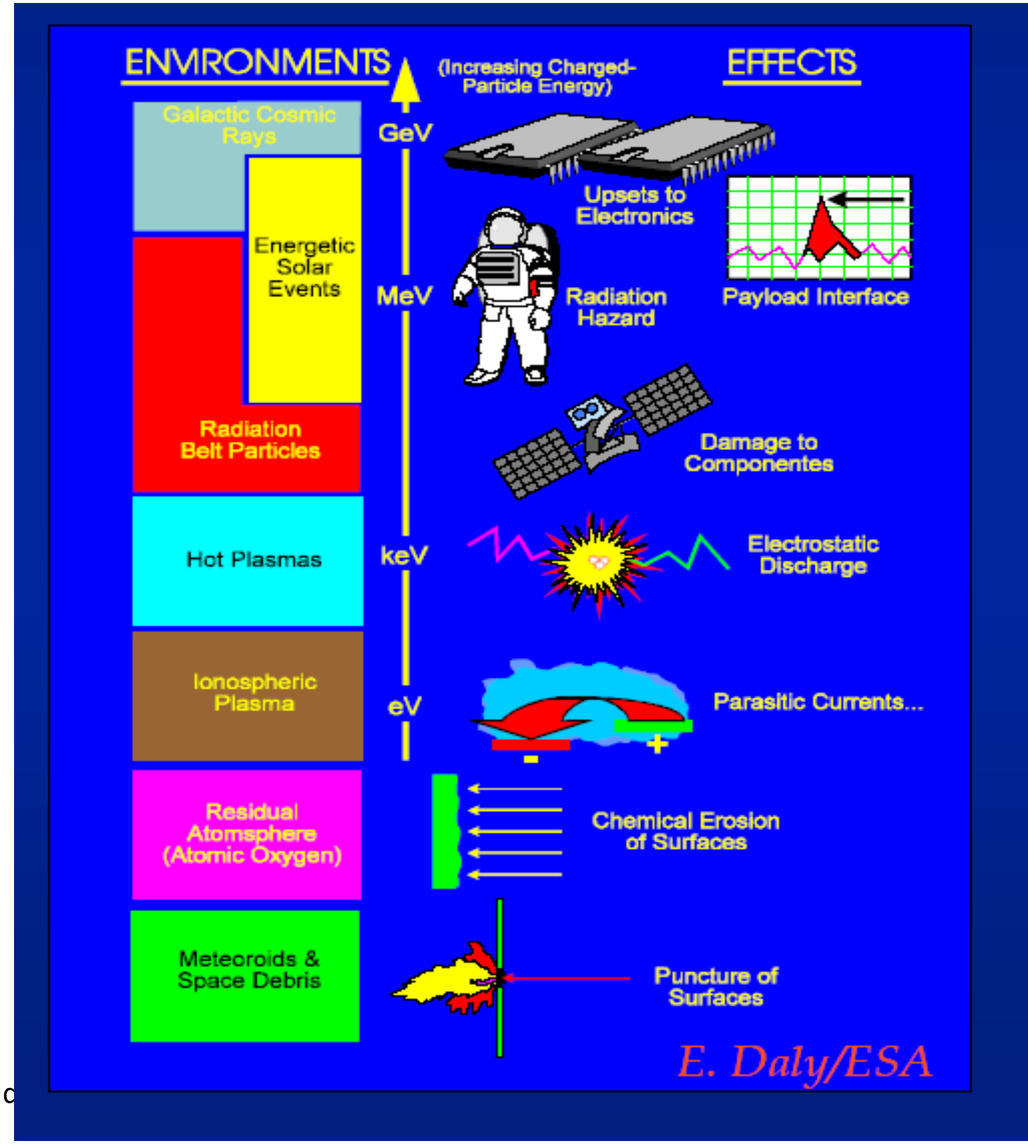
Features of Common Transport Codes

Code	Primary Application	Comments
CREME96	Heavy Ion LET Spectra	Limited to spherical shell aluminum shielding
TRIM	Proton or heavy ion beam simulation	1-dimensional Only Coulomb interaction
ITS3.0 (TIGER)	Electron or photon beam simulation for dose and charging rate profiles	Excellent electron/photon physics Extensively benchmarked
FASTRAD	Spacecraft level shielding analysis	Ray tracing and Forward MC
NOVICE	Spacecraft level shielding analysis	"Adjoint" (fast for space environment application) No secondary neutrons Not accurate for secondary electrons
MCNP(X)	Full 3-D detector/sensor simulation Transients calculation	Good physics and extensive development history Slow for space application
Geant4	Full 3-D detector/sensor simulation Transients calculation	Good physics Many Geant4-based "tools" are available Slow for space application

Comments are based on current JPL experience

Overview: Radiation and Effects

- **Charging**
- Total Ionizing Dose
- Displacement Damage Dose
- Single Event Effects
- Radiation induced noise in scientific sensors/detectors
- Radiation effects on astronauts

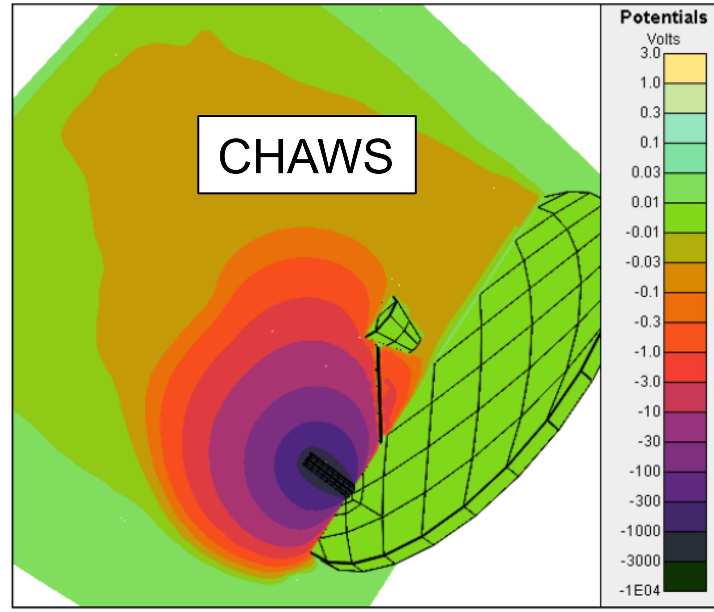


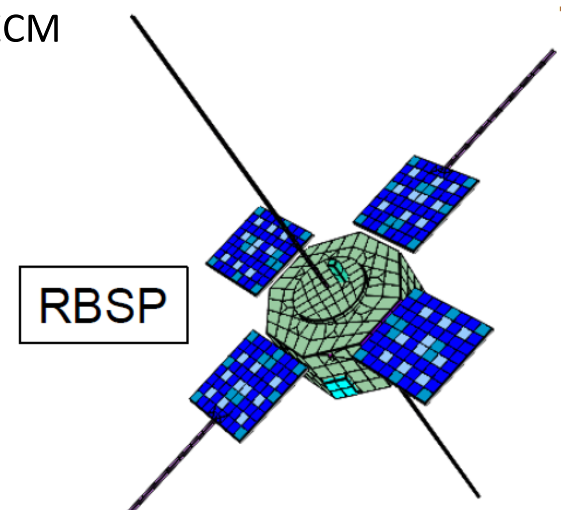
Charging Tools

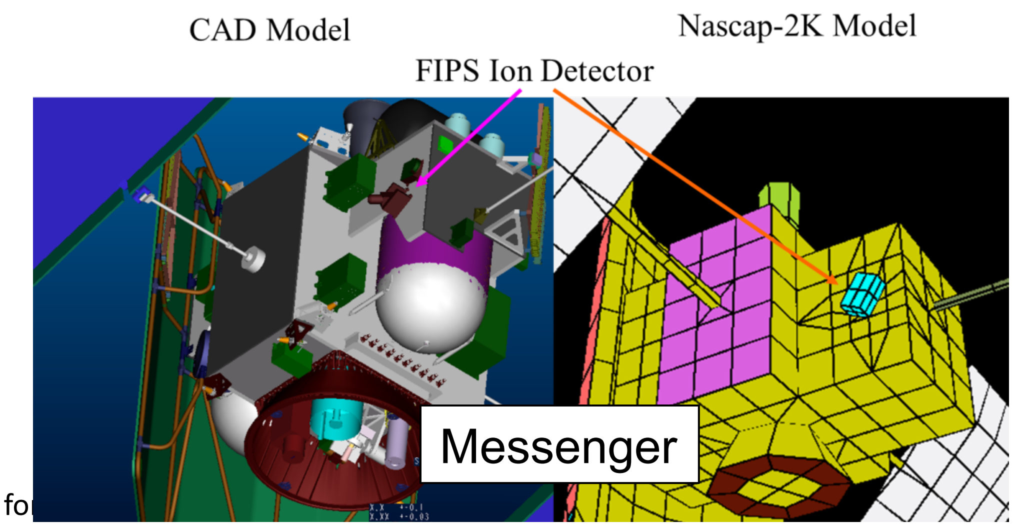
- Surface Charging
  - NASCAP-2K
- Internal Charging
  - NUMIT
  - NUMIT 2.0
  - 3D NUMIT → 3 dimensional charging analysis "package"

What is NASCAP (or NASCAP-2k)?

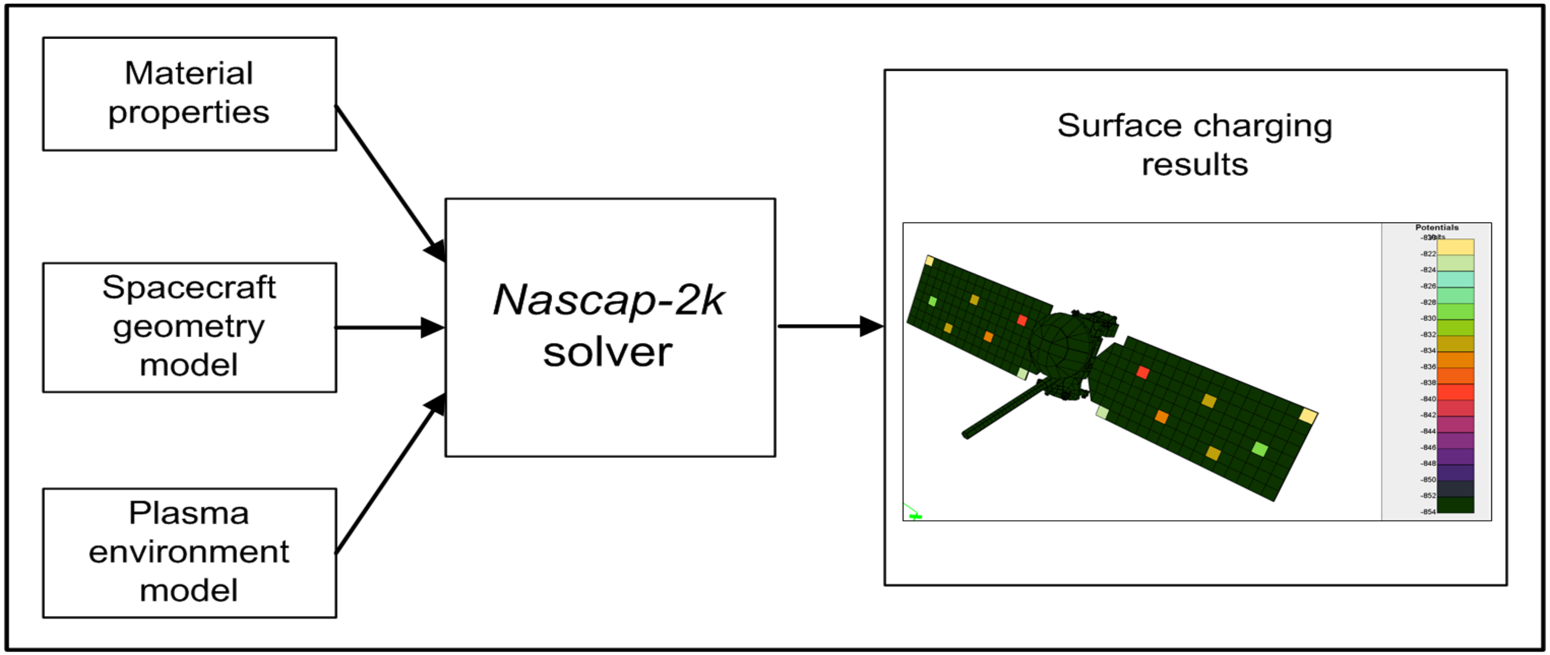
- 3-D spacecraft charging code developed by Leidos for NASA & AFRL
- Used by many science missions, e.g.
  - Messenger – JHU/APL
  - Multi-Scale Magnetosphere (MMS) – NASA/GSFC
  - Van Allen Probe (VAP) – JHU/APL
  - Communication/Navigations Outage Forecasting Systems (C/NSOFS) - AFRL
  - STEREO – NASA/GSFC
  - CHAWS (Wake shield) – AFRL
  - Juno – JPL/LM
  - ECM







Modeling Flow with Nascap-2k



IESD Assessment Tools

- 1-D assessment tool: NUMIT 2.0 (does not need a Monte Carlo simulation)
- 3-D assessment tool: 3D NUMIT
- Tools are already developed and in use.
- Needs good material properties (resistivity and coefficient for radiation induced conductivity (RIC)) to warrant good simulation results
  - Prerequisite for accurate assessments.

  $\sigma = \sigma_d + k_p \dot{D}^{\Delta}$,

  σ_d: dark conductivity, reciprocal of the resistivity

  k_p: coefficient of RIC

  Δ: exponent of RIC

  $\dot{D}$: dose rate

NUMIT

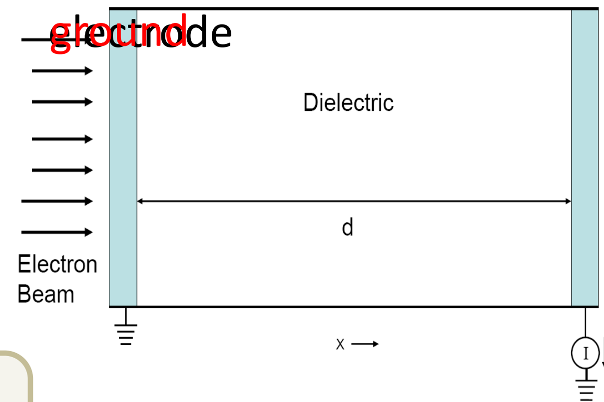
NUMIT 2.0

1-D internal charging simulation tool
10 keV - 20 MeV

- Time-varying spectrum
- Vertical incident

Very thin electrode

w/ and w/o ground



Charge and Energy Deposition Rates → Charge Movement

$\dot{\rho}_s$ charge deposition rate →

$\dot{D}$ energy deposition rate →

- $\frac{\partial \rho}{\partial t} = \dot{\rho}_s - (\nabla \cdot \boldsymbol{J})$ — Continuity Equation
- $\boldsymbol{J} = \sigma E$ — Ohm's law
  - $\sigma = \sigma_d + k_p \dot{D}^{\Delta}$
- $\nabla \cdot (\varepsilon E) = -\rho$ — Poisson's Equation

Calculated by
Frederickson's algorithm ($\dot{\rho}_s$, 0.1-20 MeV)
JPL's algorithm ($\dot{\rho}_s$, 10-100 keV)
and
Tabata's algorithm ($\dot{D}$, 0.1-20 MeV)
JPL's algorithm ($\dot{D}$, 10-100 keV)

Calculated by
JPL's Algorithm Empirical Equations
or
Monte Carlo Simulation

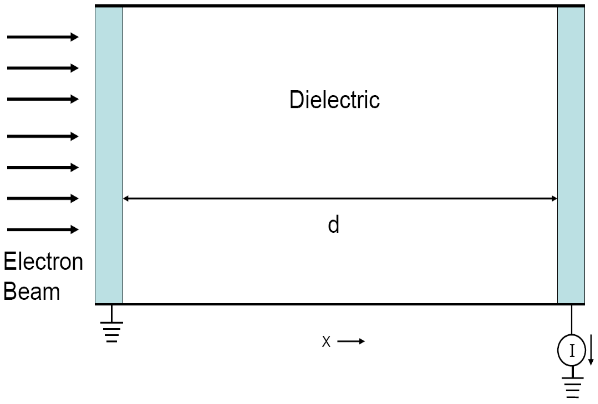
Calculated by NUMIT
E: Electric field
ρ: Charge density
$\boldsymbol{J}$: Current density

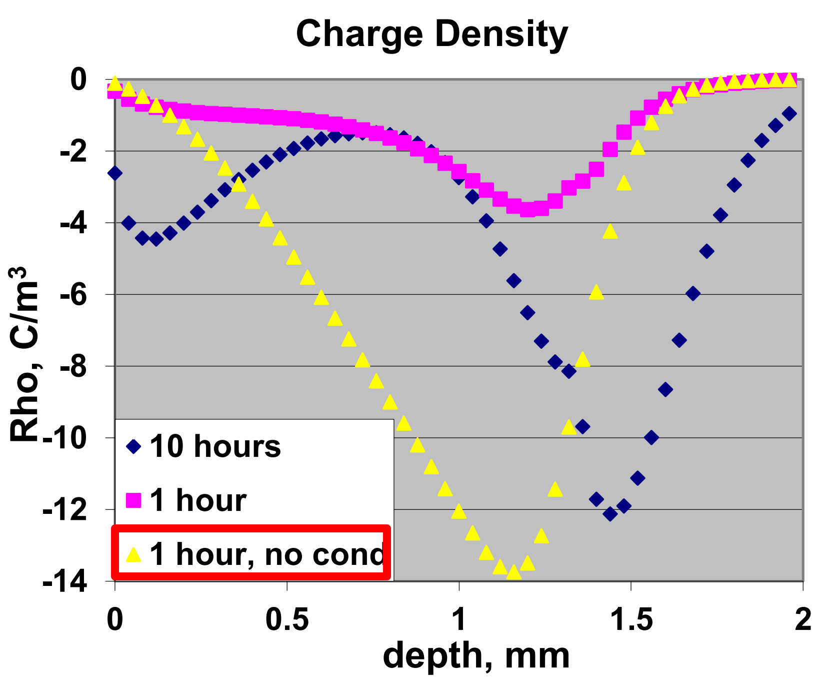
Material Constants
σ_d: dark conductivity
k_p: coefficient of RIC
Δ: exponent of RIC
ε: permittivity

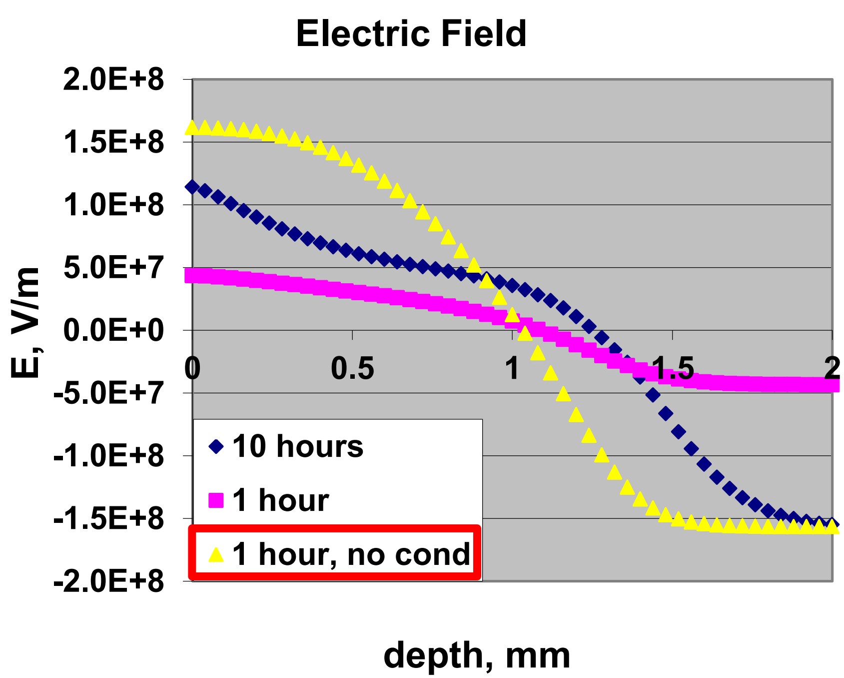
NUMIT -- Example

Small but non-zero conductivity alters dynamics significantly.

$\sigma = 1 \times 10^{-18} / \Omega \cdot cm$





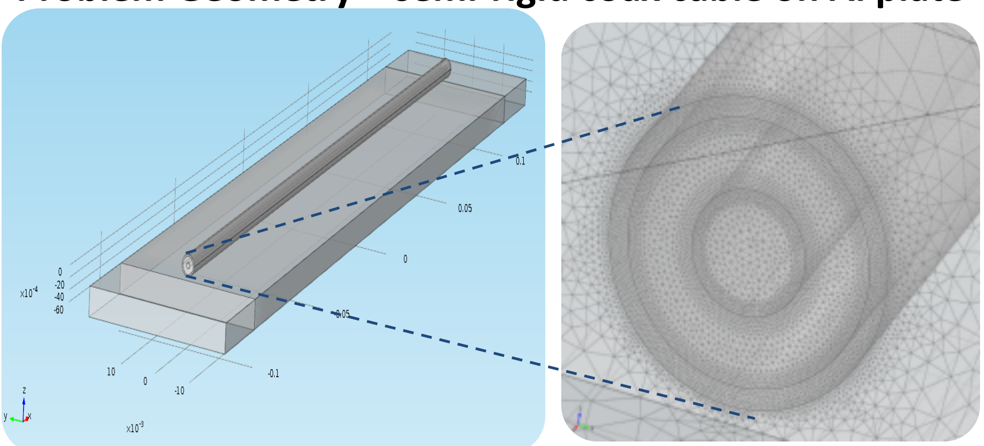


Jet Propulsion Laboratory
California Institute of Technology

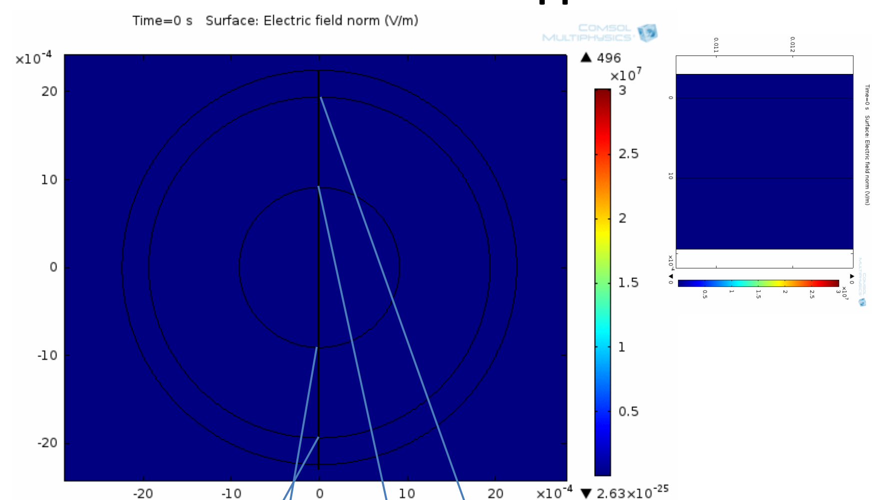
3D NUMIT -- Example

3D NUMIT is a general 3D internal charging simulation tool, further improved from a previously developed 3D Internal charging simulation tool CB_IESD (by Ira Katz and Wousik Kim) which can be applied only to circuit board with a maximum of one floating trace.

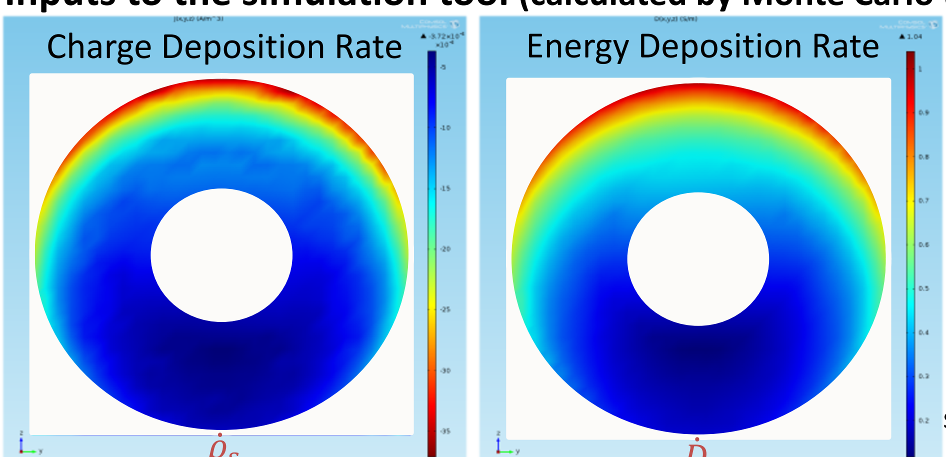
Problem Geometry – semi-rigid coax cable on Al plate



3D - cross section vs 1D approximation

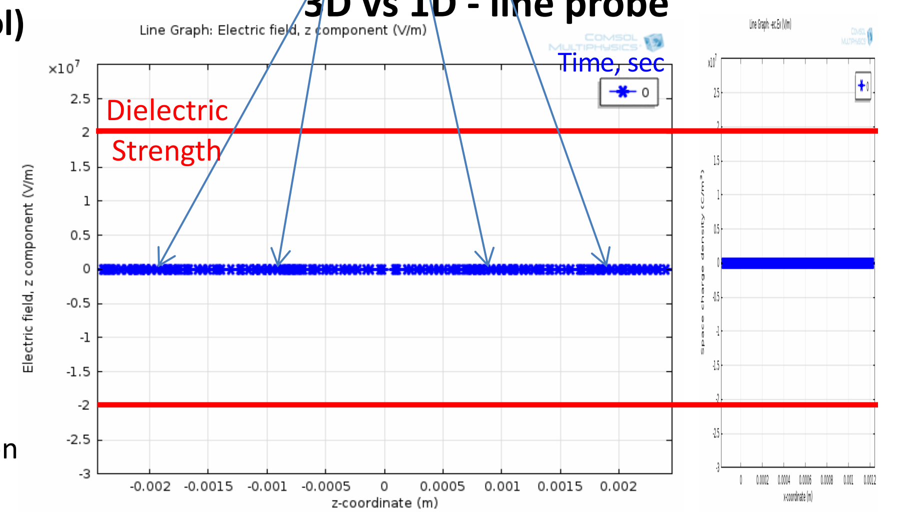


Inputs to the simulation tool (calculated by Monte Carlo tool)



ssion

3D vs 1D - line probe



Summary

- Many models and tools are being used to ensure adequate radiation design for space missions
- Proper understanding of capabilities and limitations of those models and tools is critical
  - Models and tools are continuously being updated with mode in-flight data or lab test data
  - Validation and verification are important steps before using them for spacecraft design
- Open and sufficiently frequent communications within the international community is also important