Influence of Natural Environments in Spacecraft Design, Development, and Operation

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THE KIND OF ATTITUDE THAT COULD REALLY TAKE THE WIND OUT OF THE SAILS OF THE SPACE PROGRAM!

MOON, MARS, JUPITER, I GOTTA TELL YOU... I'M NOT SEEING A WHOLE LOT OF DIFFERENCE.

Comic video: www.mrbeffe.com
Outline

• Background
• Impact
• Guideline Process
• Environments
• Interactions
  o Contamination
  o Spacecraft Charging
  o Atomic Oxygen
  o Thermal Vacuum
  o Electromagnetic Radiation
  o Micrometeoroids / Orbital Debris
  o Ionizing Radiation
• Space System Anomaly
• Summary
Background

• Spacecraft are growing in complexity and sensitivity to environmental effects.

• The spacecraft engineer must understand and take these effects into account in building reliable, survivable, and affordable spacecraft.

• Too much protections, however, means unnecessary expense while too little will potentially lead to early mission loss.

• The ability to balance cost and risk necessitates an understanding of how the environment impacts the spacecraft and is a critical factor in its design.

• This presentation is intended to address both the space environment and its effects with the intent of introducing the influence of the environment on spacecraft performance.
# THE IMPACT OF THE SPACE ENVIRONMENT ON SPACE SYSTEMS

## Distribution by Anomaly Diagnosis

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Number of Forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESD - Internal Charging</td>
<td>74</td>
</tr>
<tr>
<td>ESD - Surface Charging</td>
<td>59</td>
</tr>
<tr>
<td>ESD - Uncategorized</td>
<td>28</td>
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<tr>
<td>Surface Charging</td>
<td>1</td>
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<tr>
<td><strong>Total ESD &amp; Charging</strong></td>
<td><strong>162</strong></td>
</tr>
<tr>
<td>SEU - Cosmic Ray</td>
<td>15</td>
</tr>
<tr>
<td>SEU - Solar Particle Event</td>
<td>9</td>
</tr>
<tr>
<td>SEU - South Atlantic Anomaly</td>
<td>20</td>
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<tr>
<td>SEU - Uncategorized</td>
<td>41</td>
</tr>
<tr>
<td><strong>Total SEU</strong></td>
<td><strong>85</strong></td>
</tr>
<tr>
<td>Solar Array - Solar Proton Event</td>
<td>9</td>
</tr>
<tr>
<td>Total Radiation Dose</td>
<td>3</td>
</tr>
<tr>
<td>Materials Damage</td>
<td>3</td>
</tr>
<tr>
<td>South Atlantic Anomaly</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total Radiation Damage</strong></td>
<td><strong>16</strong></td>
</tr>
<tr>
<td>Micrometeoroid/Debris Impact</td>
<td>10</td>
</tr>
<tr>
<td>Solar Proton Event - Uncategorized</td>
<td>9</td>
</tr>
<tr>
<td>Magnetic Field Variability</td>
<td>5</td>
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<tr>
<td>Plasma Effects</td>
<td>4</td>
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<tr>
<td>Atomic Oxygen Erosion</td>
<td>1</td>
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<tr>
<td>Atmospheric Drag</td>
<td>1</td>
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<tr>
<td>Sunlight</td>
<td>1</td>
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<tr>
<td>IR background</td>
<td>1</td>
</tr>
<tr>
<td>Ionospheric Scintillation</td>
<td>1</td>
</tr>
<tr>
<td>Energetic Electrons</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total Miscellaneous</strong></td>
<td><strong>36</strong></td>
</tr>
</tbody>
</table>

### Missions Lost/Terminated Due to Space Environment

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Date</th>
<th>Diagnosis</th>
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</thead>
<tbody>
<tr>
<td>DSCS II (9431)</td>
<td>Feb 73</td>
<td>Surface ESD</td>
</tr>
<tr>
<td>GOES 4</td>
<td>Nov 82</td>
<td>Surface ESD</td>
</tr>
<tr>
<td>DSP Flight 7</td>
<td>Jan 85</td>
<td>Surface ESD</td>
</tr>
<tr>
<td>Feng Yun 1</td>
<td>Jun 88</td>
<td>ESD</td>
</tr>
<tr>
<td>MARCOMS A</td>
<td>Mar 91</td>
<td>Surface ESD</td>
</tr>
<tr>
<td>MSTI</td>
<td>Jan 93</td>
<td>Single Event Effect</td>
</tr>
<tr>
<td>Hipparcos*</td>
<td>Aug 93</td>
<td>Total Radiation Dose</td>
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<tr>
<td>Olympus</td>
<td>Aug 93</td>
<td>Micrometeoroid Impact</td>
</tr>
<tr>
<td>SEDS 2*</td>
<td>Mar 94</td>
<td>Micrometeoroid Impact</td>
</tr>
<tr>
<td>MSTI 2</td>
<td>Mar 94</td>
<td>Micrometeoroid Impact</td>
</tr>
<tr>
<td>IRON 9906</td>
<td>1997</td>
<td>Single Event Effect</td>
</tr>
<tr>
<td>INSAT 2D</td>
<td>Oct 97</td>
<td>Surface ESD</td>
</tr>
</tbody>
</table>

*Mission had been completed prior to termination

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Impact

Subsystem In-flight Failure Causes       (Hecht, 1985)

- 600 satellites currently in orbit (1999) are worth $50-$100B with 235 insured for $20B
- 1500 space payloads are expected to be launched 2000 – 2010 with a potential insured value of $80 billion!
- 481 US satellites currently manifested from 2011 - 2020 at a total cost of $150B
Space Environments’ Role in the Mission Life Cycle

Mission Concept
Mission Planning
Design
Launch
Operations
Anomaly Resolution
Lessons Learned

Space Environment information is critical during all phases of spacecraft life cycle

- Space Climate
  - Minimize Risk
- Space Weather
  - Manage Residual Risk
- Both
  + In Space measurements

Programmatic Support
Operational Support
Environment Effects
Design Environments
Guideline Process

1. Define the environments

2. Analyze potential environmental interactions that could occur

3. Implement mitigation strategies to minimize/eliminate adverse interactions

4. Ground test to evaluate engineering performance in relevant environment

5. Analyze the data from the spacecraft to determine effectiveness of the process

6. Integrate information learned into process improvement
Environments

- Atmospheres
- Solar UV Flux
- Atomic Oxygen
- Space Vacuum
- Thermal Cycling
- Plasma / Charging Environments
- Micro-Meteoroid/Space Debris
- Spacecraft Induced Environment
- Charged Particle Radiation
  - Radiation Belts
  - Auroral Region
  - Solar Wind
  - Interplanetary
Contamination

• Particulate and Molecular
  – Particulate Contamination Generated by Handling, Launch Vibration, AO, Moving Parts…
  – Volatiles may Escape Materials due to Outgassing in Space, Venting, Engine Firing…

• Outgassing Rate is Temperature Dependent
• Deposition on other spacecraft surfaces
• Deposition Rate Affected by Solar UV, AO, and Surface Temperature
Contamination

• Contamination Control
  – Contamination Control Imperative for Sensitive Optics and Thermal Control Surfaces
  – Ground Support Equipment is Considered a Potential Contamination Source
  – Standard Material Tests and Modeling for Contamination Exists
    • Databases of Materials are Maintained
  – Contamination Control can be Achieved
    • Material Selection, Thermal Vacuum Bake-out, Clean Room Control, Spacecraft Design
Spacecraft Charging

Surface in Shadow

Plasma Ions

Plasma Electrons

Electrons Repelled By The Negative Surface Charge

Surface in Sunlight

Ions Repelled By The Surface Positive Charge

Plasma Ions

Plasma Electrons

Escaping Photoelectrons

Solar Photons

Photoelectrons Attracted Back By The Surface Charge
Spacecraft Charging

• Spacecraft can Interact with Ambient and Induced Plasma Environments
  – High Voltage Solar Arrays can be Damaged by Arcing
  – Floating Potentials can Charge Spacecraft Leading to Damage on Surfaces
    • Dielectric Breakdown, Contamination from Ejecta, Sputtering due to Ion Impact
  – Currents Collected by Arrays Flow in Structure

Dielectric Breakdown in Anodize Aluminum
Atomic Oxygen (AO)

• The Main Constituent at 200-500 Km is AO
  – The AO Density Decreases Exponentially with Altitude
  – Spacecraft Velocity > Thermal Velocity means that AO Impacts Ram Facing Surfaces with ~ 5eV
  – AO Erodes many Polymeric Materials
    • Mass Loss Affects Thermal, Optical and Mechanical Properties
    • AO Oxidizes Metallic Materials
  – AO Interaction with Exterior Materials can Produce Glow
  – AO Interaction can Enhance Contaminant Deposition
Electromagnetic Radiation (UV, Soft X-Rays)

- Degradation of Material Properties
  - Causes Darkening of Materials such as Silica Glass, Thermal Control Coatings, Polymer Films, Some Composites and Ceramics
  - Embrittlement of Polymer Films
  - Thermal Control Properties may be Seriously Degraded by UV Exposure of Contaminants Adsorbed onto Surfaces

- Simultaneous UV and Contaminant Flux to a Surface can Significantly Enhance Permanent Contaminant Deposition
Micrometeoroid/Space Debris

- Naturally Occurring Particles are Meteoroids, Man-Made Particles are Orbital Debris
  - Average Velocity of 17 Km/s for Micrometeoroids and 8 Km/s for Orbital Debris
    - Models of Environment Exist and Probability of Impact can be Calculated
    - Impacts can Penetrate Walls, Cause Pitting of Optics, Degrade Solar Arrays, and Thermal Control Materials
Environments - Sporadic Meteoroids
Environments - Meteoroids
Environments - Meteoroid Streams

- Consist of particles ejected from the parent comet during a single passage around the Sun.
- Produce meteor showers and storms here on Earth.

<table>
<thead>
<tr>
<th>Shower</th>
<th>Peak</th>
<th>RA</th>
<th>Dec.</th>
<th>Duration (days)</th>
<th>Rate (/hr)</th>
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</thead>
<tbody>
<tr>
<td>Quadrantids</td>
<td>Jan. 3</td>
<td>231</td>
<td>+50</td>
<td>0.5</td>
<td>90</td>
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<tr>
<td>Lyrids</td>
<td>Apr. 21</td>
<td>272</td>
<td>+32</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Eta Aquarids</td>
<td>May 4</td>
<td>336</td>
<td>00</td>
<td>10</td>
<td>30</td>
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<tr>
<td>Northern Delta Aquarids</td>
<td>July 29</td>
<td>339</td>
<td>00</td>
<td>20</td>
<td>10</td>
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<tr>
<td>Perseids</td>
<td>Aug. 12</td>
<td>46</td>
<td>+58</td>
<td>5</td>
<td>70</td>
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<tr>
<td>Orionids</td>
<td>Oct. 21</td>
<td>95</td>
<td>+15</td>
<td>5</td>
<td>20</td>
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<tr>
<td>Taurids</td>
<td>Nov. 1</td>
<td>54</td>
<td>+21</td>
<td>30</td>
<td>5</td>
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<tr>
<td>Leonids</td>
<td>Nov. 16</td>
<td>152</td>
<td>+22</td>
<td>4</td>
<td>5</td>
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<tr>
<td><strong>Geminids</strong></td>
<td><strong>Dec. 13</strong></td>
<td><strong>113</strong></td>
<td><strong>+32</strong></td>
<td><strong>6</strong></td>
<td><strong>100</strong></td>
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<tr>
<td>Ursids</td>
<td>Dec. 22</td>
<td>217</td>
<td>+80</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

Over time

- slight differences between the comet’s and particles’ velocities
- perturbations caused by planetary gravity and solar radiation pressure change the orbit of the stream so that it no longer follows the exact path of the comet.
Environments – Orbital Debris
Environments – Orbital Debris

~19,000 tracked
(≥5 cm diameter)

- Chinese ASAT test FENGYUN 1C in 2007
- 2009 satellite collision between Iridium 33 and Cosmos 2251
- 11 March 2000, a Chinese Long March 4 upper stage exploded in orbit

Courtesy NASA JSC, M. Matney, J.C. Liou
Radiation Environment

• Particle Radiation Displaces atomic Structure and Ionizes Material in its Path
  – Result is Degradation in Material Properties
  – Cross-Linking (Hardening) and Chain-Scission (Weakening) of Polymers
  – Degradation of Solar Cell performance
  – Single Event Upsets (SEU) in Avionics
  – Latch-up in Avionics
  – Total Dose damage in Avionics
  – Darkening of material
Comparison of the Earth and Jovian Radiation Environments

- **Jupiter**: hard electron spectrum
- **Earth**: hard proton spectrum

**Plot Details**
- **Y-axis**: Number of Particles (normalized)
- **X-axis**: Energy (MeV)

**Legend**
- Protons, Earth
- Electrons, Jupiter
- Electrons, Earth
- Protons, Jupiter

**Graph Key**
- **Jupiter**
- **Earth**

**Note:**
- The graph compares the number of particles at different energy levels between Earth and Jupiter.
Comparison of the Earth and Jovian Radiation Environments

Electrons, Jupiter
Protons, Jupiter
Electrons, Earth
Protons, Earth

Jupiter: hard electron spectrum
Earth: hard proton spectrum
Comparison of the Earth and Jovian Radiation Environments

- Protons, Jupiter
- Electrons, Jupiter
- Protons, Earth
- Electrons, Earth

Jupiter: hard electron spectrum
Earth: hard proton spectrum

Number of particles (normalized) vs. energy (MeV)
Comparison of the Earth and Jovian Radiation Environments

Jupiter: hard electron spectrum
Earth: hard proton spectrum
Space System Anomaly – Meteoroid Impact

Mariner IV

What: NASA planetary exploration spacecraft.


Consequences:
- Cosmic dust detector registered 17 hits within 15 minutes;
- 2-3 orders of magnitude more hits estimated over entire craft.
- Bombardment caused temporary change in attitude but no loss of power; torqued about the roll-axis.
- One-degree temperature drop indicative of thermal shield damage.

Outcome: Resumed normal operation within ~1 week.

Chandra X-Ray Observatory

What: NASA observatory.

Event: Struck by a Leonid or sporadic (?) near the time of Leonid shower peak in November 2003.

Consequences:
- Pointing stability discrepancy indicated strike, as no evidence of spurious thruster firings or an indication of an internal cause.
- Change in momentum – caused a “wobble”.

Outcome: All systems continued to operate normally following the event.
Battery Box Covers have a “Betacloth” outer layer. One cover was inadvertently constructed using Chemfab 250 (in which silicone sizing agent is not removed during fabrication) while other cover was correctly constructed using Chemfab 500.
Basic Materials Design + SEE

ATV1 Thermal Blankets show insufficient venting
External Surface Changes on ISS
Space Environmental Effects – Frequent and “New” Visiting Vehicles

Soyuz docked to FGB
Outgassing or Thruster Contamination
Pre-berthing inspection of a Node 1 sealing surface in 2001 identified these circular features as a concern. These features were later determined to be reflections of the camera’s LED lighting system on the smooth, anodized aluminum sealing surface. No such feature actually exists.
Anodized aluminum labels, which darkened quickly, have begun to recover their expected appearance with continued AO exposure!
ISS Observations

- Some worse-than-expected materials degradation effects have been observed on ISS, but only one has created an operational issue (during P6 redeploy) and some surfaces (as with the anodized aluminum labels) appear to be recovering.
- Inadvertent materials substitutions have been observed, but none have created any operational issues.
- Hardware handling contamination effects have been observed, and although none have created operational issues, there is clearly room for improvement in this regard.
- Even with robust materials selections, space environmental effects will be observed.
- Be cautious when interpreting photography, as lighting conditions and the environment affect interpretation.
Visible Infrared Imaging Radiometer Suite (VIIRS)

- Visible/infrared imaging radiometer suite (VIIRS)
  - 10 Silver mirrors
  - Dichroics separate the beam into:
    - Vis/NIR (10 bands)
    - Reflective IR (8 bands)
    - Thermal IR (4 bands)
- Radiometric calibration required for science missions
  - Once each orbit, sunlight illuminates diffuser material
- On-orbit data suggests most likely cause is UV-induced degradation of the telescope mirrors
  - Mirrors coated in 2004
  - Coating has extensive flight heritage
- Root-cause hypotheses proposed:
  - Inherent coating defect
  - Contamination prior to launch
  - Contamination after launch
VIIRS  Space System Anomaly

- UV and/or electron radiation can induce absorptions in protected silver mirrors.
- Tests on a variety of mirror types yielded varying results - susceptibility depends upon materials/processes used.
- These results were reported to the program in 2005, but was considered a low risk for their flight-proven coating - did not pursue testing.
VIIRS  Space System Anomaly

- TWM-Telescope Witness Mirror was made in the same mirror deposition run as the flight mirrors, saw Assembly Integration and Test environment
- CFM1- Contractor Furnished Mirror- was made in the same mirror deposition run as the flight mirrors, but stored in pristine conditions
- A3-31- The same type of mirror, but made at a different time and stored in pristine conditions.
- CERES mirror- A different type of mirror that was attached to a different instrument during Assembly Integration and Test

- Control Materials
  - 2-mil Rear-Surface-Aluminized Kapton
  - 2-mil Rear-Surface-Silverized Teflon (AgFEP)
  - Z93-P White Paint

- Contamination Monitors
  - Vapor Deposited Aluminum (VDA) Front-Surface Mirror
  - 7980 Fused Silica
  - Polished Silicon Wafer

A3-31 Mirror of the same design as Flight mirrors but produced in a different coating run, was unaffected by the UV exposure.

Samples were exposed to Xe illumination equivalent to 1-sun intensity.
• UV-induced degradation of tungsten oxide contaminated witness mirrors (TWM, CFM1) from the Flight (RTA) coating run

• Uncontaminated witness mirrors from other coating runs did not respond to UV exposure.

• WO$_{3-x}$ is a known photochromic and electrochromic material. Loss of oxygen induces a strong near infrared absorption.
• After discovery of tungsten oxide on the surface of TWM, the vendor’s coating records were reviewed.

• Vendor explained that the coating process includes cleaning substrates (prior to deposition) using an oxygen ion source.
  – Oxygen ion source possesses Tungsten neutralizer filaments
    – Explains tungsten oxide at coating/substrate interface
  – The ion source remains off during the coating process

• Rotating Telescope Assembly (RTA) mirrors initially exhibited low reflectance, thought to be due to a lack of oxygen in the top dielectric layer of coating.
  – The delivery of these completed mirrors was already behind schedule…
The Smoking Gun

- Proposed using the oxygen ion source to further oxidize top-coating
- Unqualified process - tested once on a single witness sample
- Not discussed with program’s subject-matter experts
- Process was hastily implemented (on a Sunday)
- No further testing of witness samples was considered

Travelling witness samples are very valuable!
Summary

- Define the environment
- Be aware of the combined environmental effects: Synergisms
- Test materials and systems to ensure engineering performance is well above end of life requirements at the end of mission
- Literature search/appropriate flight heritage can save time and lower cost
- Flight heritage in one environment does not qualify for use in another environment
- Processes need to be fully qualified - and strictly followed
- Schedule pressures should not induce process deviations
- Changes need to be discussed with all stakeholders
- Beware unintended consequences of creative solutions
- Even good ideas need to be tested and verified
- Even with robust materials selections, space environmental effects will be observed.
- Test as you fly (and fly as you test) - ensure that test specimens are fully representative of the flight article and test environments are representative of flight.

*** Ground-based testing remains a key facet of mission assurance
Thank You for your Time
Space Environments and Interactions References

**BASIC CONCEPTS**

ENVIROMENTS

Sun

Earth

Atmosphere

Ionosphere

Magnetosphere

General


Magnetic Field

Plasma Dynamics

Radiation Models
SPACE ENVIRONMENTS AND INTERACTIONS REFERENCES


Jupiter


Space Debris


Meteoroids


Man-Made


Interactions

Ozone Erosion


Glow


Contamination


Hypervelocity Impacts


Spacecraft Charging


Conferences


Standards and Guidelines


General Information


Plasma Interactions


**Radiation Interactions**

**Books**

**Summaries**

**Papers**
USEFUL INTERNET SITES FOR SPACE ENVIRONMENT EFFECTS

- http://envnet.gsfc.nasa.gov/
- http://see.msfc.nasa.gov/
- http://akebono.tksc.nasda.go.jp/
- http://nppp.jpl.nasa.gov/
- http://standards.nasa.gov/
- http://eis/engstnd/standard/engstnd.htm
- http://www.sel.noaa.gov/today.html
- http://spaceweather.com/
- http://www.sec.noaa.gov/
- http://www.ngdc.noaa.gov/
- http://geomag.usgs.gov/
- http://www.ngdc.noaa.gov/seg/potfld/tabli grf.html#IGRP95
- http://medicine.wustl.edu/~kronkg/leonids.html
- http://www.astro.ufl.edu/~oliver/xyz/
- http://www.imo.net/index.html
- http://www.geo.mtu.edu/weather/aurora/
- http://www.pfrr.alaska.edu/~pfrr/AURORA/ACTV.HTM
- http://www.ngdc.noaa.gov/dmsp/
- http://www.npi.ms.u.ca/INF/SPRD/lop.html
- http://www.stsci.edu/pubinfo/Latest.html
- http://spacelink.msfc.nasa.gov/index.html
- http://www.jpl.nasa.gov/
- http://www.sni.net/ssa/digest.htm
- http://www.spacecom.af.mil/usspace/links.htm#wx
- http://umbra.nascom.nasa.gov/spd/
- http://list.cup.cam.ac.uk

GSFC (EnviroNET) Homepage
MSFC SEE Homepage
Japanese SEE Homepage
CREME96 Homepage
Recent Satellite Outages and Failures
NASA EEE Space Parts Program
NASA TECHNICAL STANDARDS PROGRAM
Space Engineering Standards (JPL)
Today's Space Weather
The NASA Space Weather Bureau
NOAA Space Environment Center
National Geophysical Data Center
USGS Geomagnetism Program
International Geomagnetic Reference Field
Canadian Digital Magnetometer Data
Leonid Meteor Shower
METEM Model FTP Site (Prof. John Oliver)
International Meteor Organization Index
Jupiter's rings
Debris Models
The Aurora
Alaska Aurora Movies
D MSP Auroral Photos (Latest Aurora)
GOES Daily Satellite Data (Geosynchronous)
NSSDC CD Catalog of Space Data
Russian Radiation Models
Astronomical Sites (Asteroid Orbits, etc.)
HST Pictures
Space Link Educational Data Base/PC Programs
JPL Homepage
Space Analytics Associates List of Useful URLs
US Space Command Space Weather Links
NRL Clementine Site
AFRL Space Hazards Branch Projects
NASA Space Physics--Mission Descriptions
My Spacecraft-Environment Interactions Book
Environments

Potential Shuttle Damage

- Window Replacement
- EVA Suit Penetration
- Radiator Penetration
- RCC Penetration
- TPS Tile Penetration
- Cabin Penetration
- Cargo Bay Damage

Debris Diameter in Centimeters

- Spacecraft Surface Inspections
- Haystack Auxiliary Radar
- Haystack Radar

Space Surveillance Network

Nick Johnson – NASA JSC

December 2, 2013