# NASA Welcome and
# Space Environment Interactions with ISS

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***Space System Anomalies and Failures (SCAF) Workshop 2022***
***11-12 January 2022, virtual***
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- Why are we using the acronym "SCAF" for the Space Systems Anomalies and Failures (SSAF) Workshop?
  - SCAF is the legacy acronym from the Spacecraft Anomalies and Failures Workshop series which is the predecessor to this workshop
  - The name was changed in 2021 from "Spacecraft" to "Space Systems" so anomalies and failures in ground systems and launch vehicles can be included along with spacecraft:  consider the complete system required to deploy and operate a space system
  - The organizers continued to use "SCAF" for a while since it is recognized by workshop participants, but we will move to the "SSAF" acronym with SSAF 2023

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- The organizers are very pleased at the turnout and ongoing support for the virtual workshop this week, we hope to meet in person for SSAF 2023!

# SCAF 2022 Logistics

- Microphones and cameras are disabled to minimize background noise and bandwidth

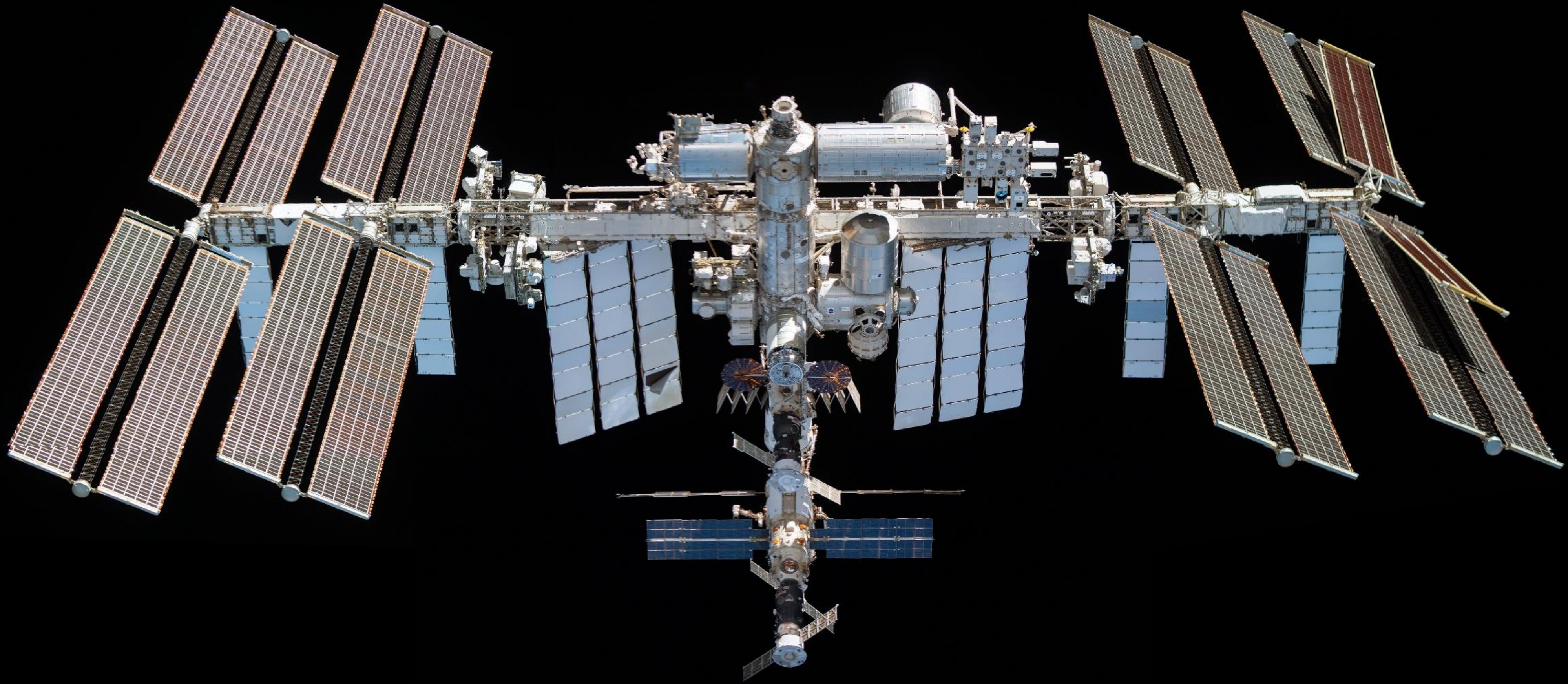
- Type questions in chat or request we unmute your microphone

- Day 1 presentations will be posted on a NASA website for participant download (pending approval by speakers). Information will be sent out after the workshop.

# Impact of Space Environments on Space Systems

| Mechanism | Effect | Source |
|---|---|---|
| **Surface Charging** | • Biasing of instrument readings<br>• Power drains<br>• Physical damage | • *Dense, cold plasma*<br>• *Hot plasma* |
| **Deep Dielectric Charging** | • Biasing of instrument readings<br>• Electrical discharges causing physical damage | • *High-energy electrons* |
| **Structure Impacts** | • Structural damage<br>• Decompression | • *Micrometeoroids*<br>• *Orbital debris* |
| **Drag** | • Torques<br>• Orbital decay | • *Neutral thermosphere* |
| **Total Ionizing Dose (TID)** | • Degradation of microelectronics | • *Trapped protons*<br>• *Trapped electrons*<br>• *Solar protons* |
| **Displacement Damage Dose (DDD)** | • Degradation of optical components and some electronics<br>• Degradation of solar cells | • *Trapped protons & electrons*<br>• *Solar protons*<br>• *Neutrons* |
| **Single-Event Effects (SEE)** | • Data corruption<br>• Noise on images<br>• System shutdowns<br>• Electronic component damage | • *GCR heavy ions*<br>• *Solar protons and heavy ions*<br>• *Trapped protons*<br>• *Neutrons* |
| **Surface Erosion** | • Degradation of thermal, electrical, optical properties<br>• Degradation of structural integrity | • *Particle radiation*<br>• *Ultraviolet*<br>• *Atomic oxygen*<br>• *Micrometeoroids Contamination* |

NASA CCMC



ISS from SpaceX Crew Dragon Endeavour during 8 November 2021 fly around

https://www.nasa.gov/image-feature/the-station-pictured-from-the-spacex-crew-dragon-0

# International Space Station (ISS)

- Initial ISS module deployed in 1998 with on orbit assembly over a period of 20+ years
- Many space exposed materials have been on-orbit for 15 to 20 years
- White House directs NASA to extend ISS operations through 2030 (December 2021):
  - By 2030, space exposed materials and hardware currently on orbit will have experienced LEO space environment exposures ranging from 9 to 32 years!
  - Ionizing radiation, UV/EUV, atomic oxygen, MMOD
  - https://blogs.nasa.gov/spacestation/2021/12/31/biden-harris-administration-extends-space-station-operations-through-2030/
- NASA is working life extension planning and refurbishment activities to assure materials and systems exposed to space environment for decades continue to meet program requirements

| Module/Component | Partner | Launch Date (mm/yyyy) | Years on Orbit* |
|---|---|---|---|
| Zarya Module (FGB) | Russia | 11/1998 | 23+ |
| Unity Module (Node 1) | US | 12/1998 | 23+ |
| Zvezda Module (Service Module) | Russia | 07/2000 | 21+ |
| Z1 Truss | US | 10/2000 | 21+ |
| P6 Truss – US solar array 1 | US | 12/2000 | 20+ |
| Destiny Laboratory Module | US | 02/2001 | 20+ |
| S0 Truss | US | 04/2002 | 19+ |
| P1 Truss, S1 Truss | US | 10/2002, 11/2002 | 19+,19+ |
| P3/P4 – US solar array 2, S3/S4 Truss – US solar array 3 | US | 09/2006, 06/2007 | 15+,14+ |
| P5 Truss, S5 Truss | US | 12/2006, 08/2007 | 15+,14+ |
| Harmony Module (Node 2) | US | 10/2007 | 14+ |
| P6 Truss – US solar array 1 (relocation) | US | n/a | 20+ |
| Columbus Facility Module | ESA | 02/2008 | 13+ |
| Kibo Japanese Experiment Module | Japan | 2008-2009 | ~13-12 |
| S6 Truss – US solar array 4 | US | 03/2009 | 12+ |
| Poisk Mini-Research Module 2 | Russia | 11/2009 | 12+ |
| Rassvet Mini-Research Module 1 | Russia | 05/2010 | 11+ |
| Bigelow Expandable Activity Module | US | 04/2016 | 5+ |
| Nauka Multipurpose Laboratory Module | Russia | 07/2021 | <1 |
| Prichal Docking Module | Russia | 11/2021 | <1 |
| *As of December 2021 | | | |

# Material Contamination, Degradation, and Atomic Oxygen

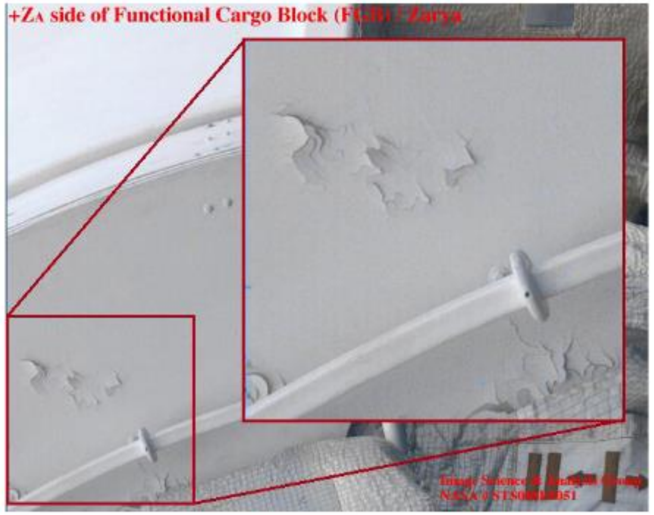



**Figure 5:** Flaking of the FGB MM/OD shield paint (2A, STS088-E5051)

**Figure 6:** Flaking of the FGB MM/OD shield paint (4A, STS 97-304-001)

Soares et al., 2002

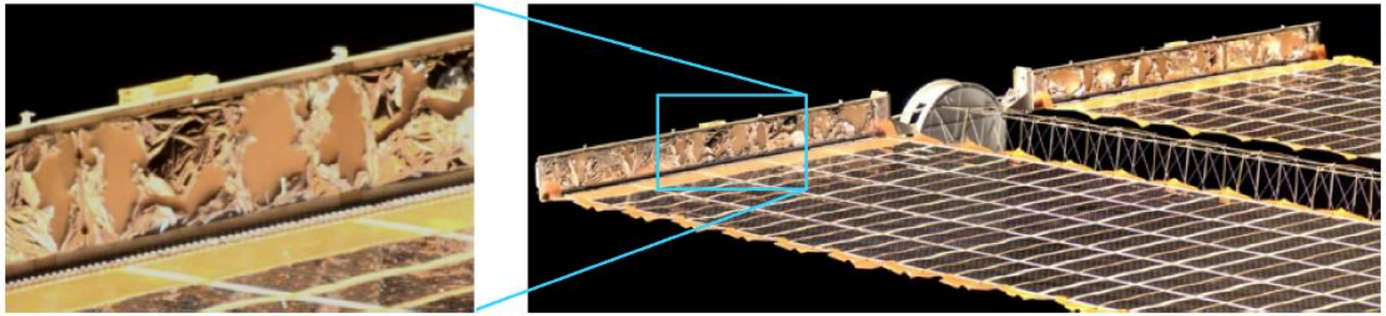


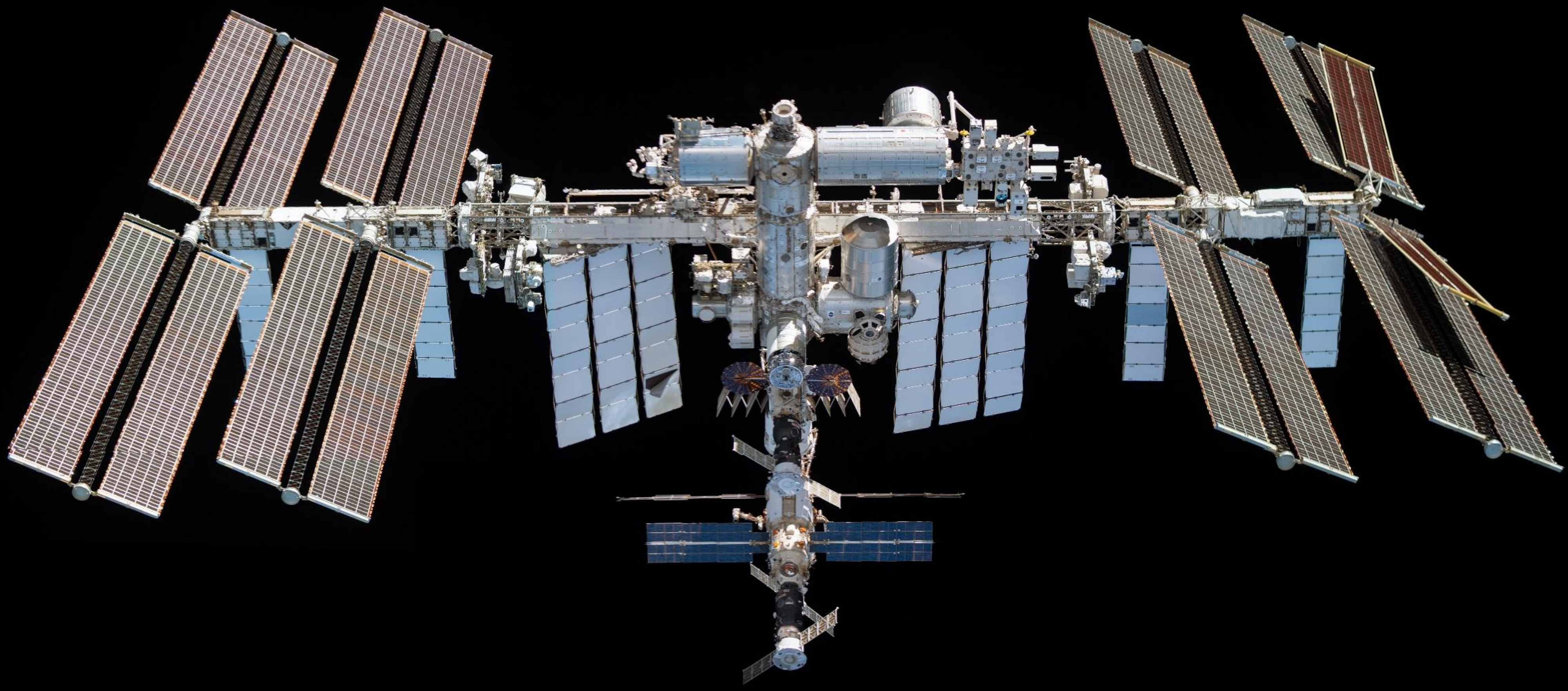
Figure 3.—Atomic oxygen undercutting degradation of the P6 Truss solar array wing blanket box cover on the ISS after only 1 year of space exposure.[10]

de Groh and Banks, 2019


**Figure 14:** Observed contamination patterns surrounding Service Module zenith side thruster block (5A, STS098-706-011)

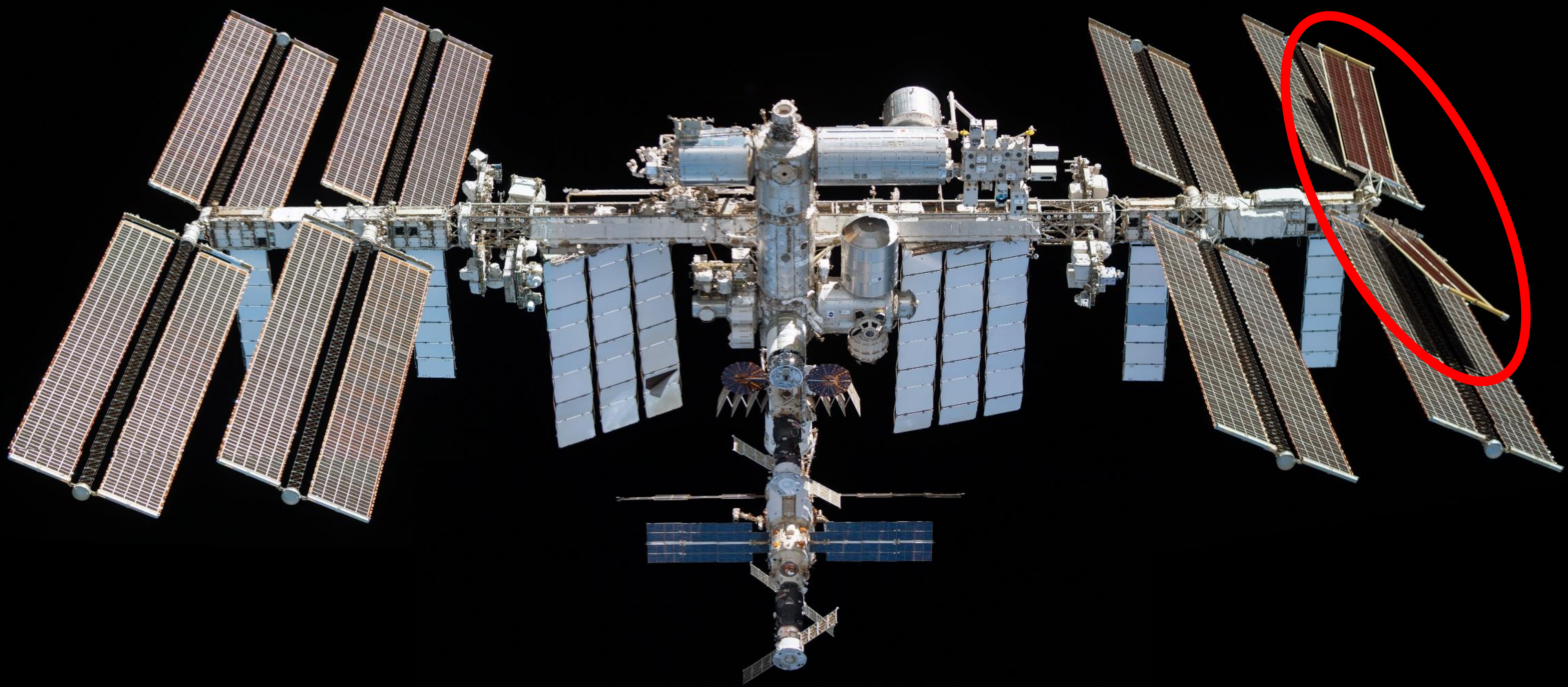
Soares et al., 2002

Soares et al. 2002: https://doi.org/10.1117/12.481654
K. de Groh and B. Banks, 20019: https://ntrs.nasa.gov/api/citations/20190025445/downloads/20190025445.pdf



https://www.nasa.gov/image-feature/the-station-pictured-from-the-spacex-crew-dragon-0

- First pair of ISS solar arrays have been operating on orbit for 20+ years and are showing signs of radiation degradation
- NASA is installing deployable ISS Roll-Out Solar Array (iROSA) to assure adequate power through ISS end of life

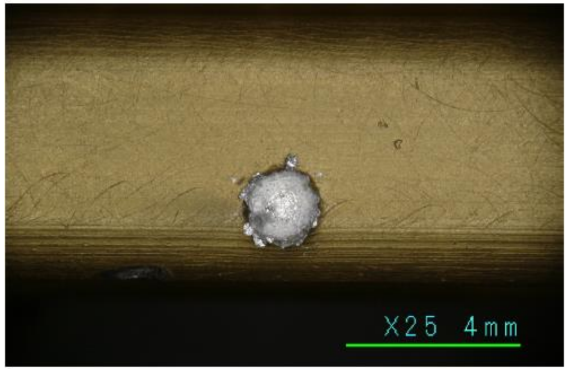


https://www.nasa.gov/feature/new-solar-arrays-to- power-nasa-s-international-space-station-research
https://www.nasa.gov/image-feature/the-new-iss-roll-out-solar-array-irosa-is-deployed

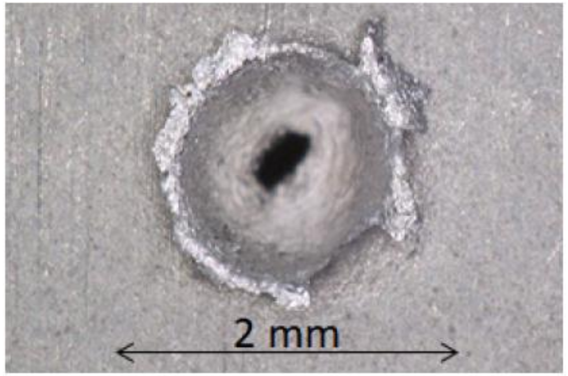
https://www.nasa.gov/image-feature/the-station-pictured-from-the-spacex-crew-dragon-0

# ISS MMOD Impacts

- Meteoroid and orbital debris (MMOD) impacts are a continuing issue for spacecraft in LEO including the ISS
- NASA's Hypervelocity Impact Technology (NVIT) group maintains an ISS impact database
  - Current database contains over 1400 records of impact damage
  - Data obtained from ground-based surveys of space-exposed hardware returned to Earth




Impact on ISS handrail

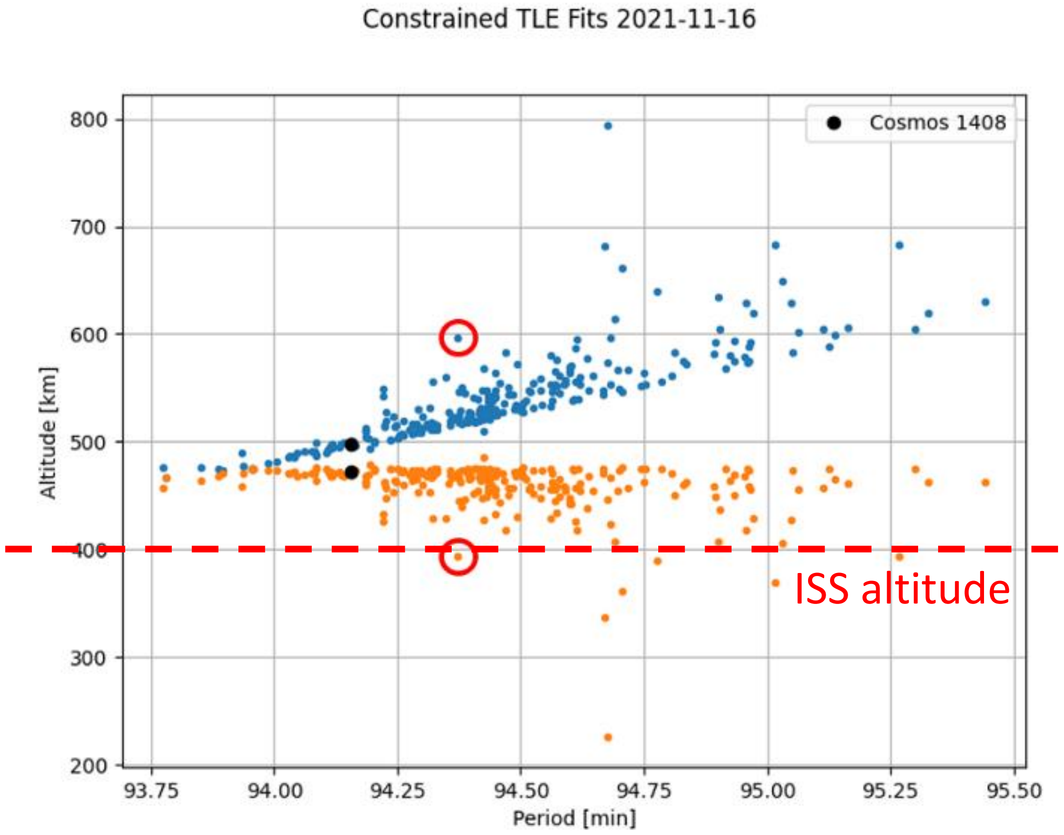


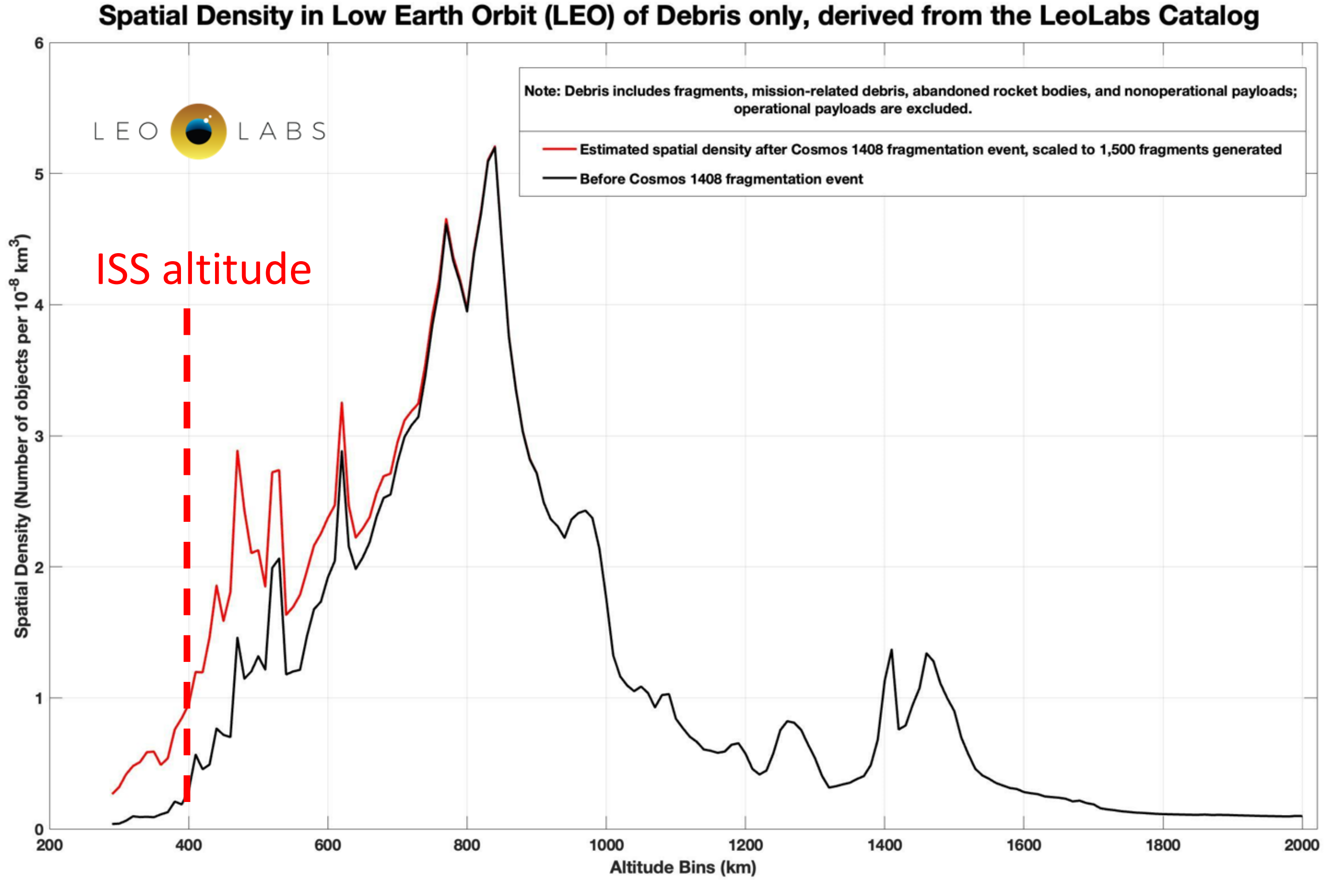

Impact in aluminum MPLM shield

Hyde et al., Observations of MMOD Impact Damage to the ISS, 2019
https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6001.pdf

| # | Database Table Name | Hardware Class | Exp. Days | Insp. Date | MMOD Impacts | Samples |
|---|---|---|---|---|---|---|
| 1 | Node 1 port CBM hatch cover | blanket/shield | 3,182 | Oct-07 | 16 | 16 |
| 2 | PMA 1 MDM Sunshade | blanket/shield | 2,984 | Mar-08 | 15 | 1 |
| 3 | Airlock shield panel 01-04B | blanket/shield | 3,195 | Feb-11 | 24 | 4 |
| 4 | Airlock shield panel 02-04B | blanket/shield | 3,195 | Feb-11 | 34 | 6 |
| 5 | PMA 2 cover | blanket/shield | 596 | Mar-16 | 26 | 6 |
| 6 | EVA Safety Tether Housing | EVA | 733 | Feb-01 | 5 | 2 |
| 7 | Node 3 Avionics Bag | EVA | 579 | Mar-16 | 30 | 0 |
| 8 | MPLM FM1 Flight 1 | Logistics | 6.06 | Apr-01 | 3 | 3 |
| 9 | MPLM FM1 Flight 2 | Logistics | 6.20 | Aug-01 | 3 | 1 |
| 10 | MPLM FM2 Flight 2 | Logistics | 6.05 | Dec-01 | 8 | 8 |
| 11 | MPLM FM1 Flight 3 | Logistics | 6.08 | Jun-02 | 12 | 12 |
| 12 | MPLM FM2 Flight 3 | Logistics | 7.20 | Aug-05 | 22 | 2 |
| 13 | MPLM FM1 Flight 4 | Logistics | 7.20 | Jul-06 | 24 | 24 |
| 14 | MPLM FM1 Flight 5 | Logistics | 9.28 | Dec-08 | 123 | 97 |
| 15 | MPLM FM1 Flight 6 | Logistics | 7.22 | Sep-09 | 64 | 25 |
| 16 | MPLM FM1 Flight 7 | Logistics | 7.42 | Apr-10 | 75 | 11 |
| 17 | MPLM FM2 Flight 4 | Logistics | 7.03 | Jul-11 | 64 | 6 |
| 18 | SpaceX Demo 2 | Logistics | 5.82 | Jun-12 | 18 | 18 |
| 19 | SpaceX CRS-1 | Logistics | 18.11 | Nov-12 | 18 | 8 |
| 20 | SpaceX CRS-2 | Logistics | 23.02 | Apr-13 | 14 | 7 |
| 21 | SpaceX CRS-3 | Logistics | 28.09 | May-14 | 17 | 4 |
| 22 | SpaceX CRS-4 | Logistics | 32.13 | Oct-14 | 20 | 0 |
| 23 | SpaceX CRS-5 | Logistics | 29.35 | Feb-15 | 13 | 2 |
| 24 | SpaceX CRS-6 | Logistics | 34.01 | May-15 | 25 | 2 |
| 25 | SpaceX CRS-8 | Logistics | 31.08 | May-16 | 20 | 2 |
| 26 | SpaceX CRS-9 | Logistics | 36.97 | Sep-16 | 17 | 1 |
| 27 | SpaceX CRS-10 | Logistics | 23.94 | Mar-17 | 14 | 6 |
| 28 | SpaceX CRS-11 | Logistics | 27.70 | Jul-17 | 15 | 3 |
| 29 | SpaceX CRS-12 | Logistics | 31.88 | Sep-17 | 12 | 2 |
| 30 | SpaceX CRS-13 | Logistics | 26.96 | Jan-18 | 11 | 3 |
| 31 | SpaceX CRS-14 | Logistics | 31.11 | May-18 | 9 | 3 |
| 32 | SpaceX CRS-15 | Logistics | 32.24 | Aug-18 | 18 | 4 |
| 33 | SpaceX CRS-16 | Logistics | 36.47 | Jan-19 | 20 | 4 |
| 34 | SpaceX CRS-17 | Logistics | 27.92 | Jun-19 | 9 | 1 |
| 35 | TUS-2 housing and cable | ORU | 1,561 | Oct-07 | 13 | 13 |
| 36 | S-band Ant. Support Assy (SASA) E-box | ORU | 1,842 | Jan-08 | 48 | 12 |
| 37 | P1 Nitrogen Tank Assembly (NTA) | ORU | 1,906 | Mar-08 | 26 | 17 |
| 38 | SASA mast | ORU | 1,842 | Mar-08 | 24 | 18 |
| 39 | S1 Nitrogen Tank Assembly (NTA) | ORU | 2,239 | Jan-09 | 24 | 13 |
| 40 | P6 battery | ORU | 3,149 | Aug-09 | 92 | 18 |
| 41 | P1 Ammonia Tank Assembly (ATA) | ORU | 2,474 | Oct-09 | 51 | 5 |
| 42 | S1 Ammonia Tank Assembly (ATA) | ORU | 2,736 | Apr-10 | 49 | 4 |
| 43 | P6 battery | ORU | 3,447 | Jun-10 | 34 | 3 |
| 44 | P6 battery | ORU | 3,447 | Jun-10 | 29 | 2 |
| 45 | P6 battery | ORU | 3,447 | Jun-10 | 16 | 0 |
| 46 | P6 battery | ORU | 3,447 | Jun-10 | 21 | 2 |
| 47 | P6 battery | ORU | 3,447 | Jun-10 | 20 | 1 |
| 48 | P6 battery | ORU | 3,447 | Jul-10 | 21 | 2 |
| 49 | 4B guidewire cable | ORU | 2,527 | Oct-10 | 1 | 1 |
| 50 | Pump Module Assembly | ORU | 3,196 | Aug-11 | 37 | 8 |
| 51 | Large Adapter Plate Assembly (LAPA) | ORU | 3,196 | Aug-11 | 19 | 2 |
| 52 | BCDU | ORU | 4,631 | Jul-19 | 64 | 0 |
| | | **Totals** | **66,992** | | **1,407** | **415** |

# Russian ASAT Test, 15 November 2021




https://leolabs-space.medium.com/analysis-of-the-cosmos-1408-breakup-71b32de5641f

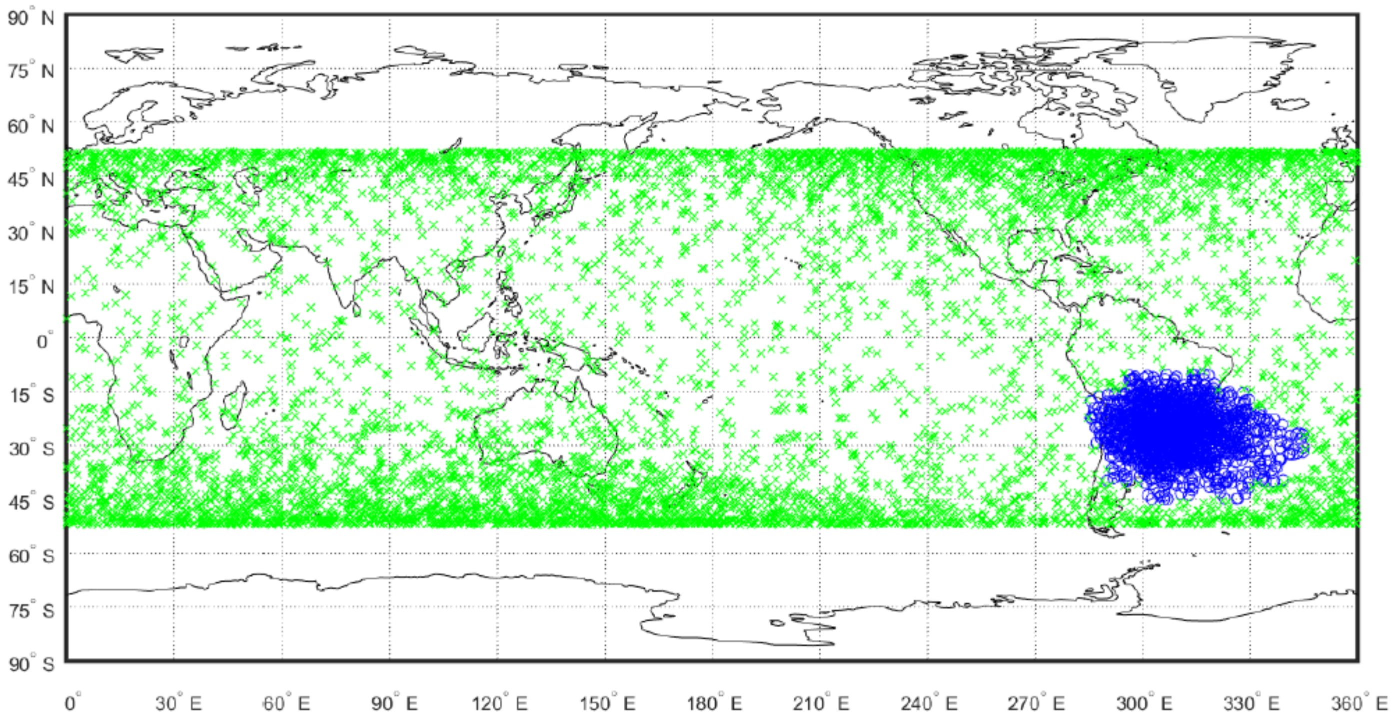
# ISS MDM DRAM Single Event Upsets (SEU)

- Geographic distribution of SEUs in ISS Command and Data Handling System Multiplexer de-Multiplexers (MDM).

- ISS operates nearly 50 standard MDMs on the vehicle (as of 2016) that provide system wide, subsystem, and numerous sensor and effector controls

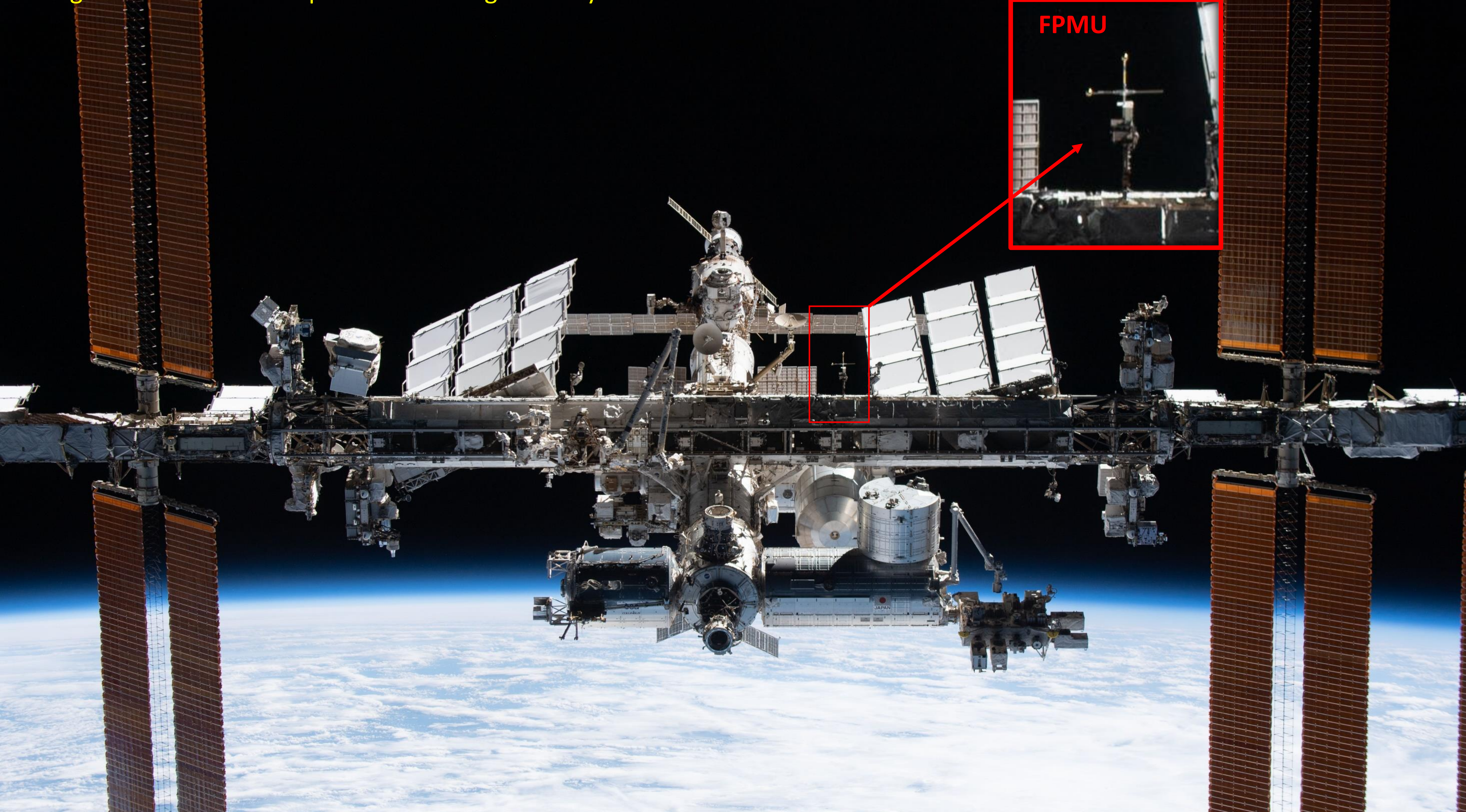
- Events attributed to
  - Galactic cosmic rays
  - Inner radiation belt in South Atlantic Anomaly

- DRAM SEU events with time and location information are reported in ISS telemetry




From Koontz et al., 2020
https://ntrs.nasa.gov/api/citations/20200001591/downloads/20200001591.pdf

Image from 8 Nov 2021 SpaceX Crew Dragon ISS fly around

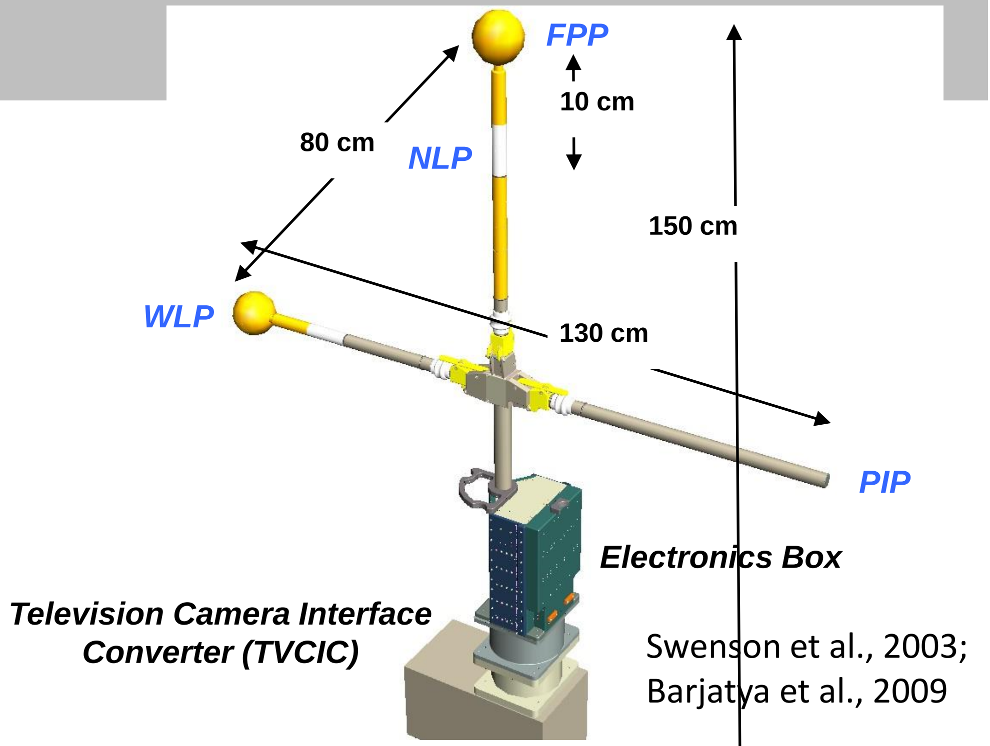


# Floating Potential Measurement Unit (FPMU)

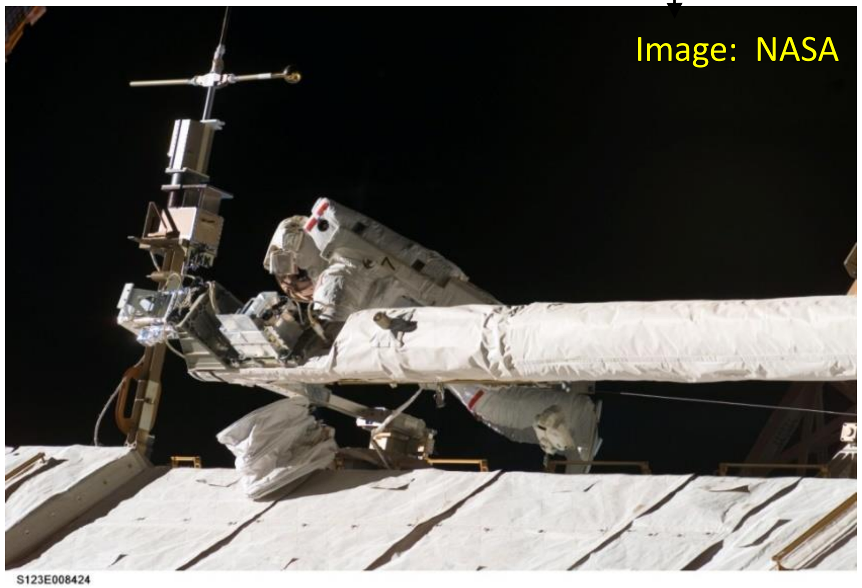
- FPMU is a suite of four plasma instruments originally deployed on the ISS in August of 2006, new instrument deployed September 2021
  - Narrow Langmuir Probe (NLP) 1 Hz Ne, Te, Ni, Vf, Vp
  - Wide Langmuir Probe (WLP) 1 Hz Ne, Te, Ni, Vf, Vp
  - Floating Potential Probe (FPP) 128 Hz Vf
  - Plasma Impedance Probe (PIP) 1 Hz Ne

- Primary use: ISS engineering
  - Characterize US high-voltage (160 V) solar array interactions with plasma environment.
  - Evaluate extravehicular activity plasma hazard environments and vehicle charging.
  - Validate the Plasma Interaction Model used to compute ISS frame potentials.
  - Anomaly investigations.

- Secondary use: ionospheric science applications
  - Collaborations with ISS science payloads, other spacecraft, and ground-based ionosphere observations.
  - Support studies of the topside ionosphere near electron density peak.
  - Data provided to science community through Goddard Space Flight Center's (GSFC's) Space Physics Data Facility (SPDF).
  - Auroral charging and ISS space weather interactions.
  - Characterize geophysical events and spacecraft plasma interactions.




Swenson et al., 2003; Barjatya et al., 2009



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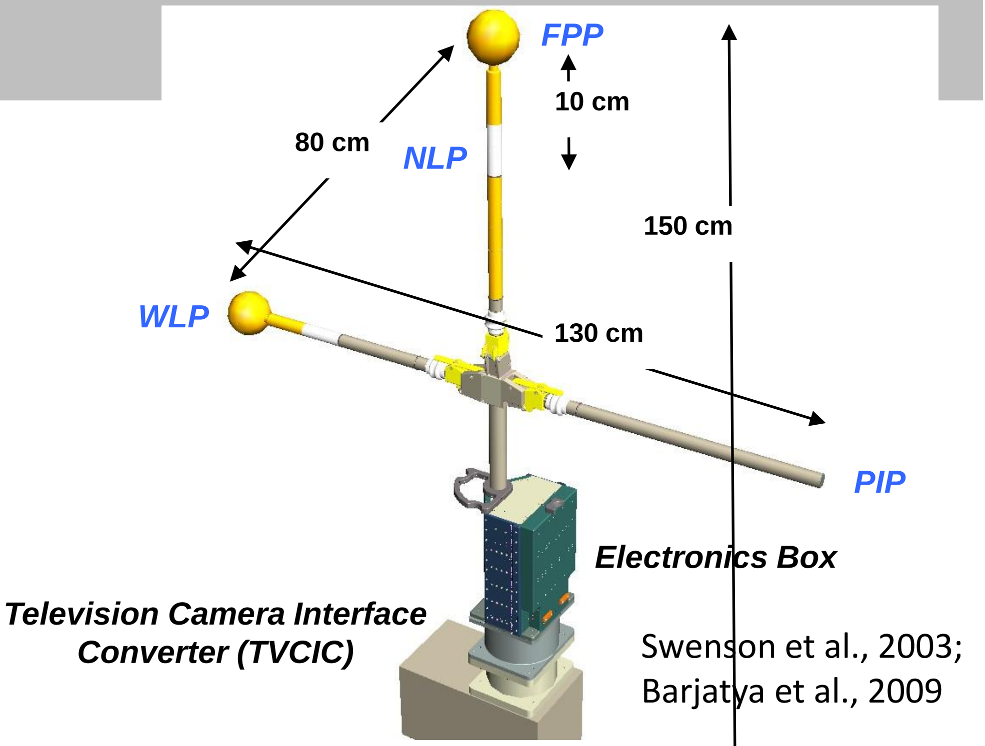


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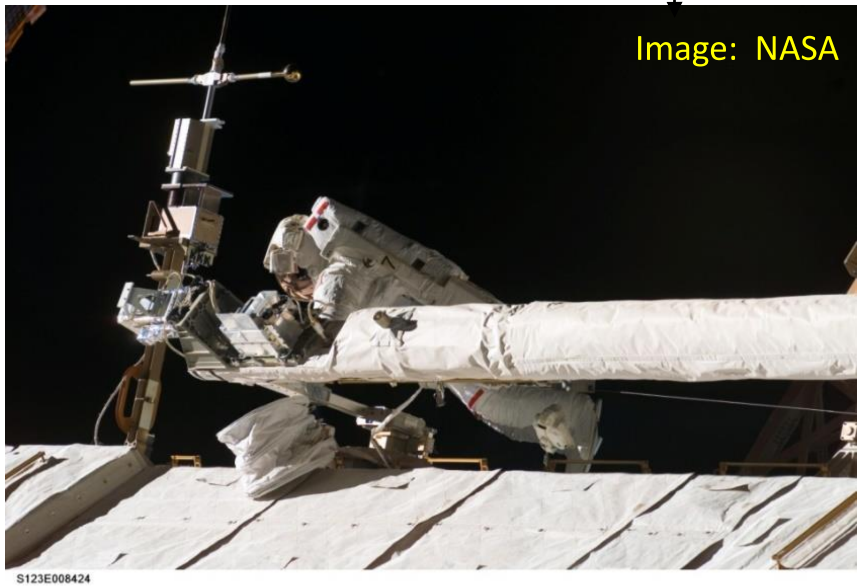
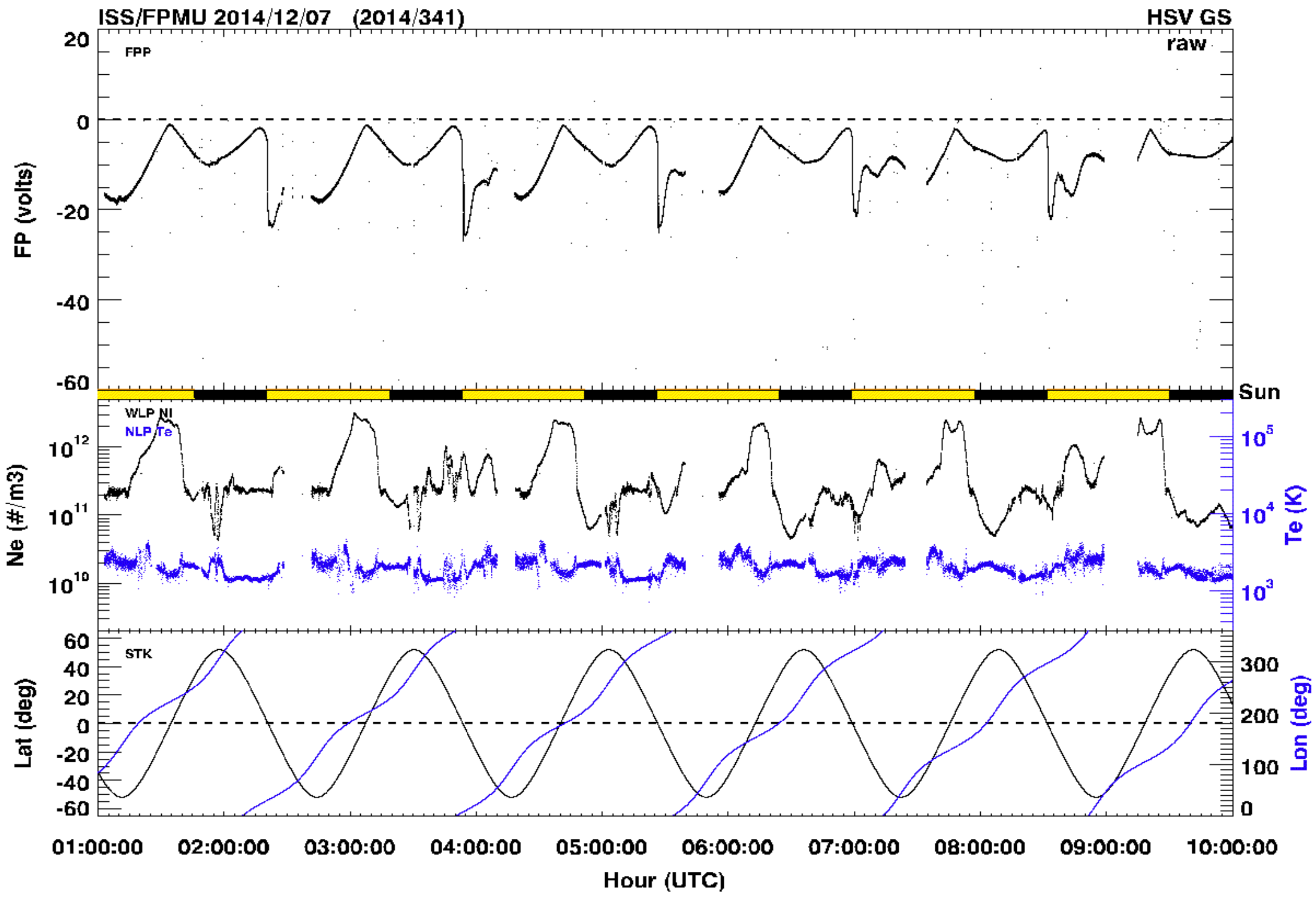


# Example FPMU Records, 7 December 2014

- 5 orbits

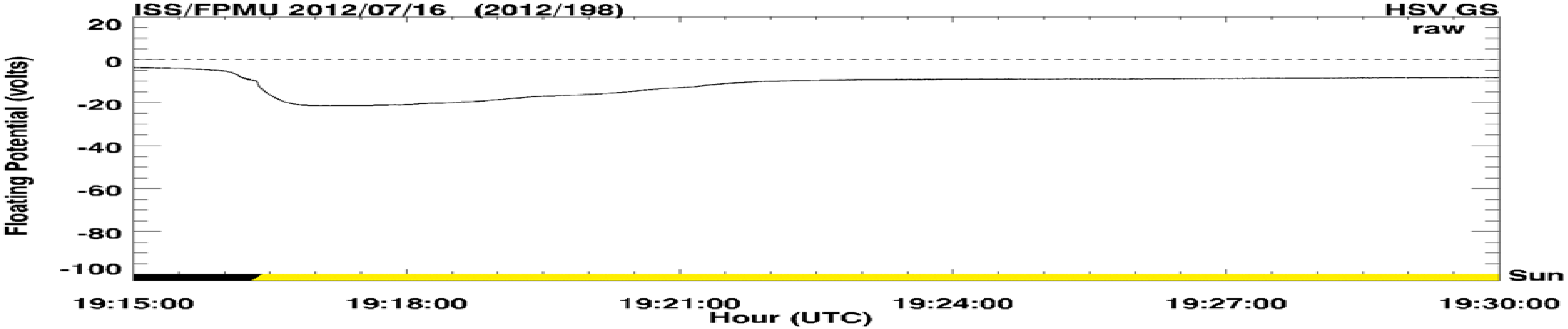
- Variation in floating potential (FP) at FPMU location is due to the combined effects of
  - Current collection by US solar arrays (dominates after eclipse exit)
  - Inductive (v x B).L potential (~0.4 V/m)

- Equatorial plasma density peak (equatorial or Appleton “anomaly”)

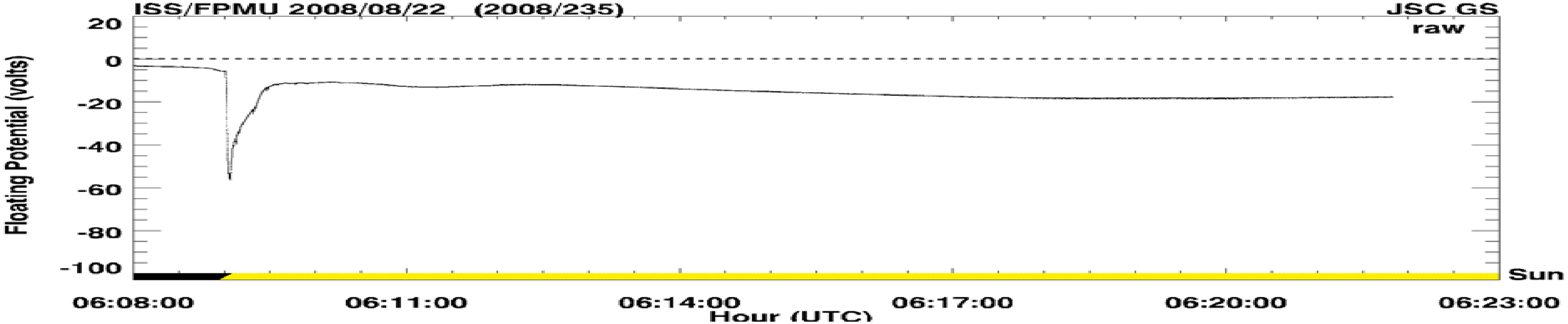


# ISS Negative Charging

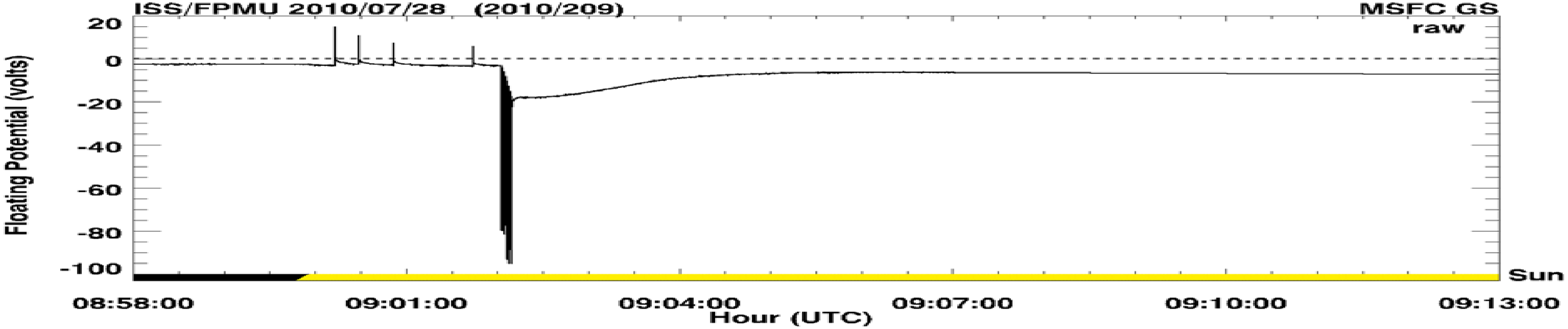
**Normal**




**Rapid Charging Event (RCE)**




**Sunlight Unshunt**




Minow et al., 2018

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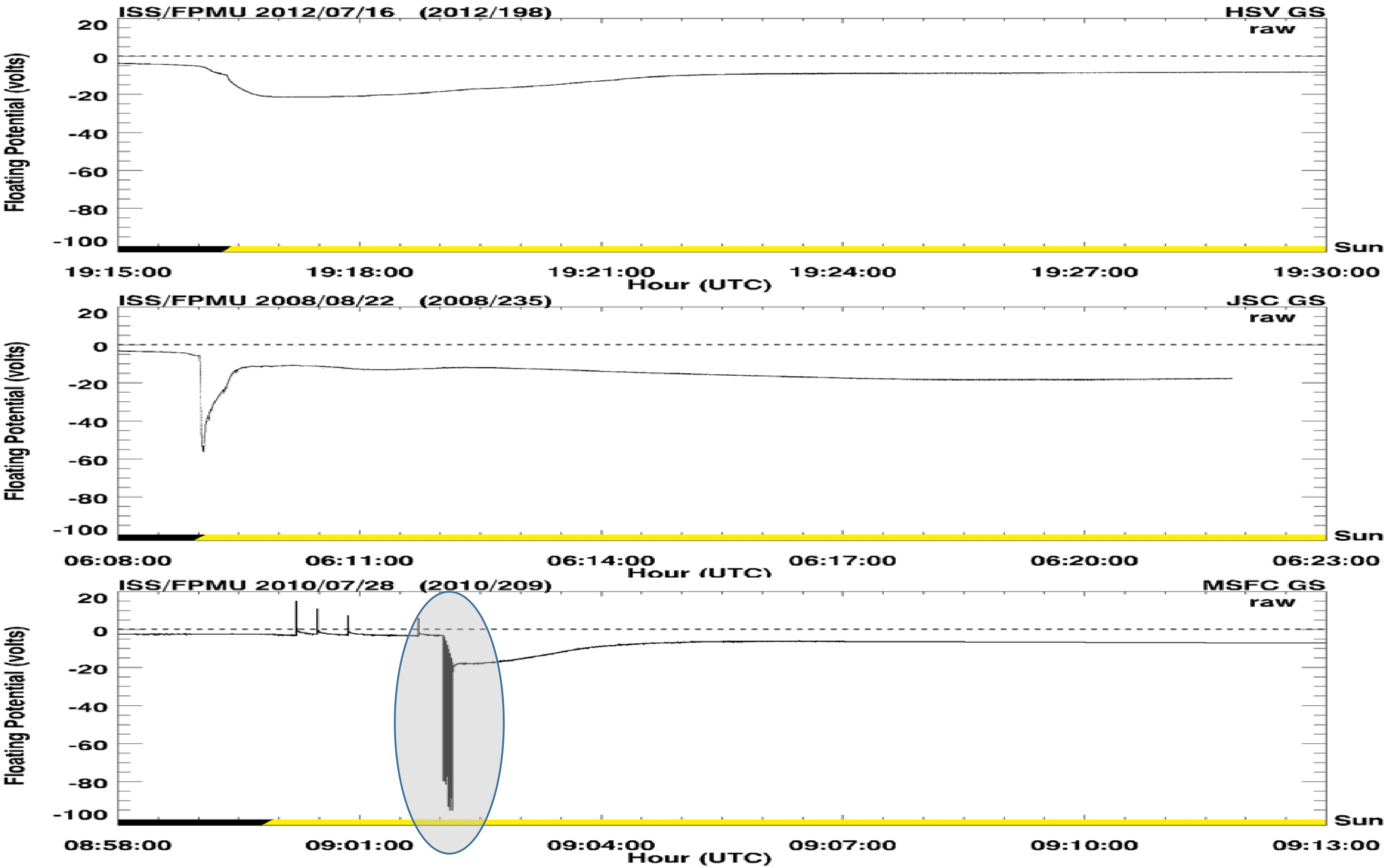


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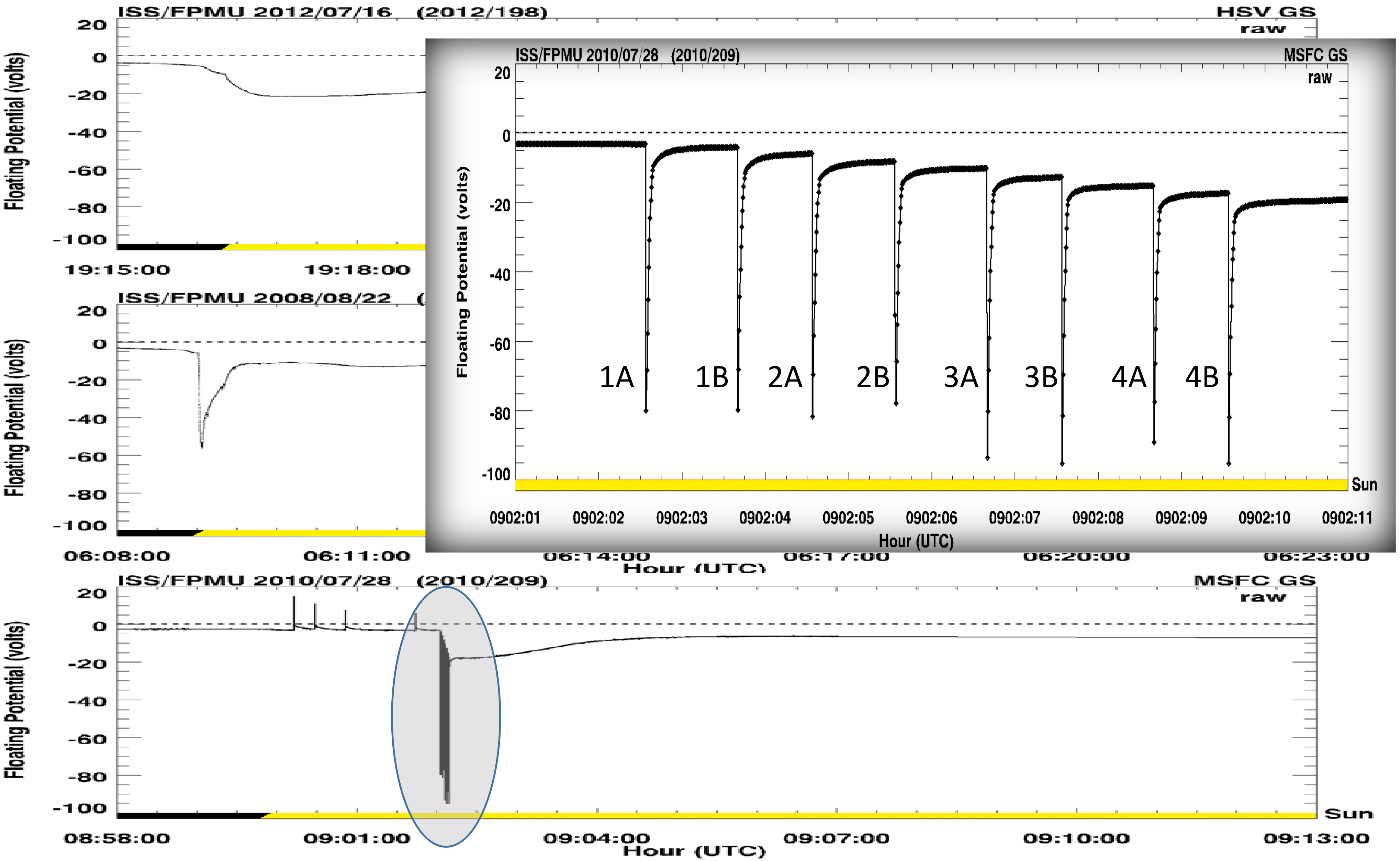
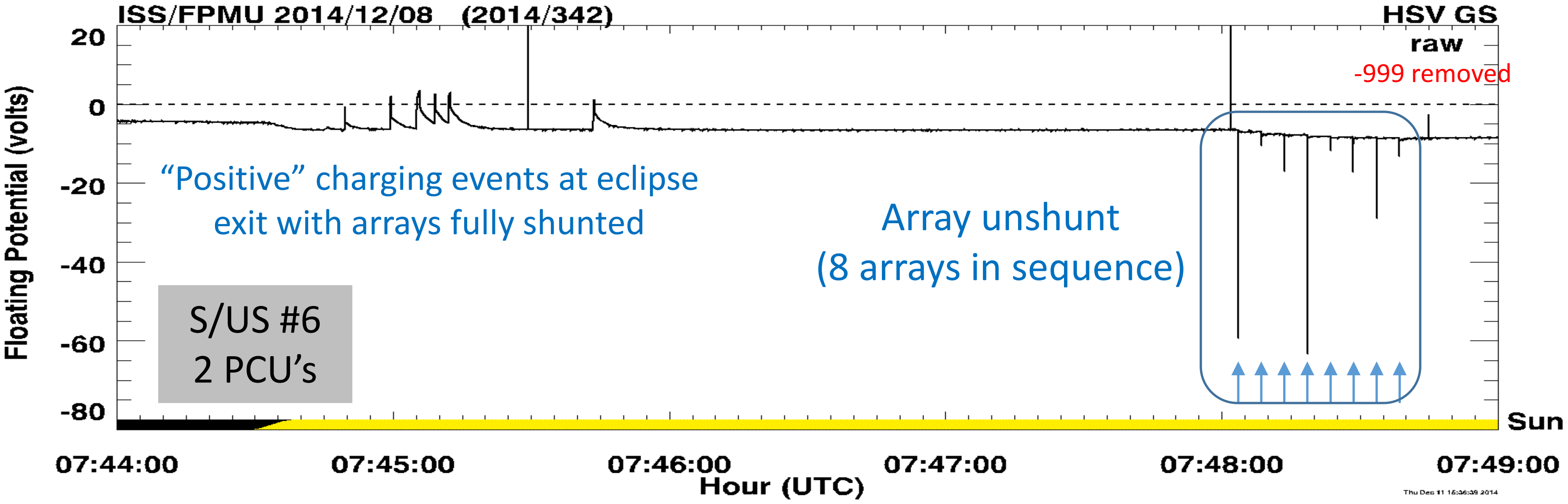
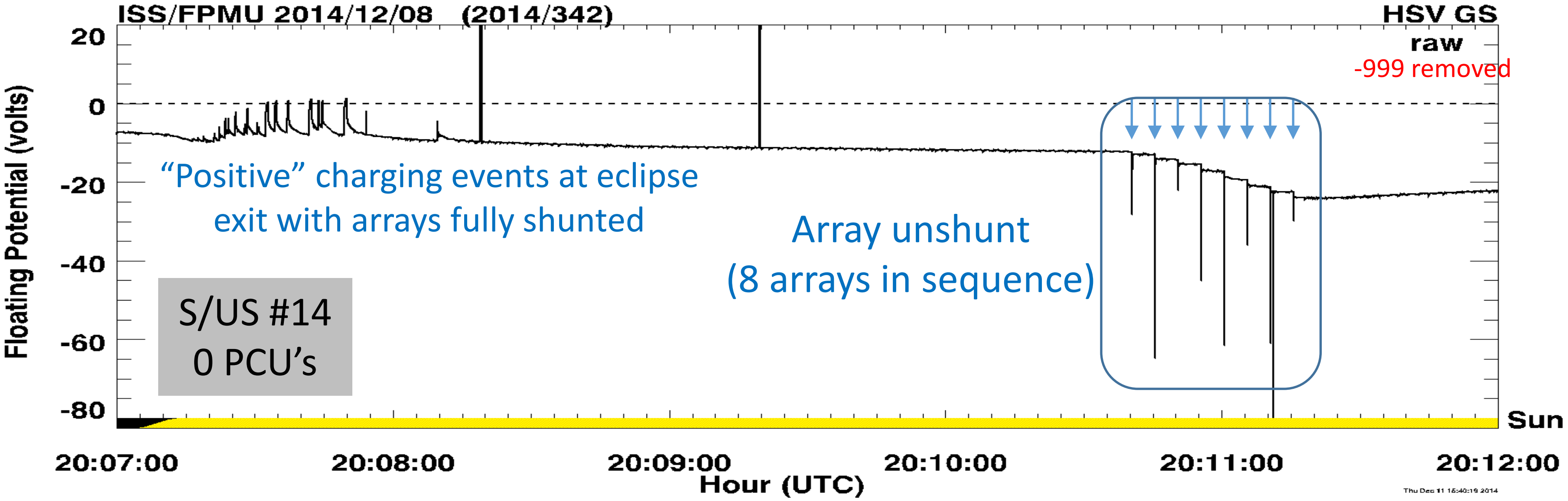



Minow et al., 2018

# Sunlight Shunt/Unshunt Experiments

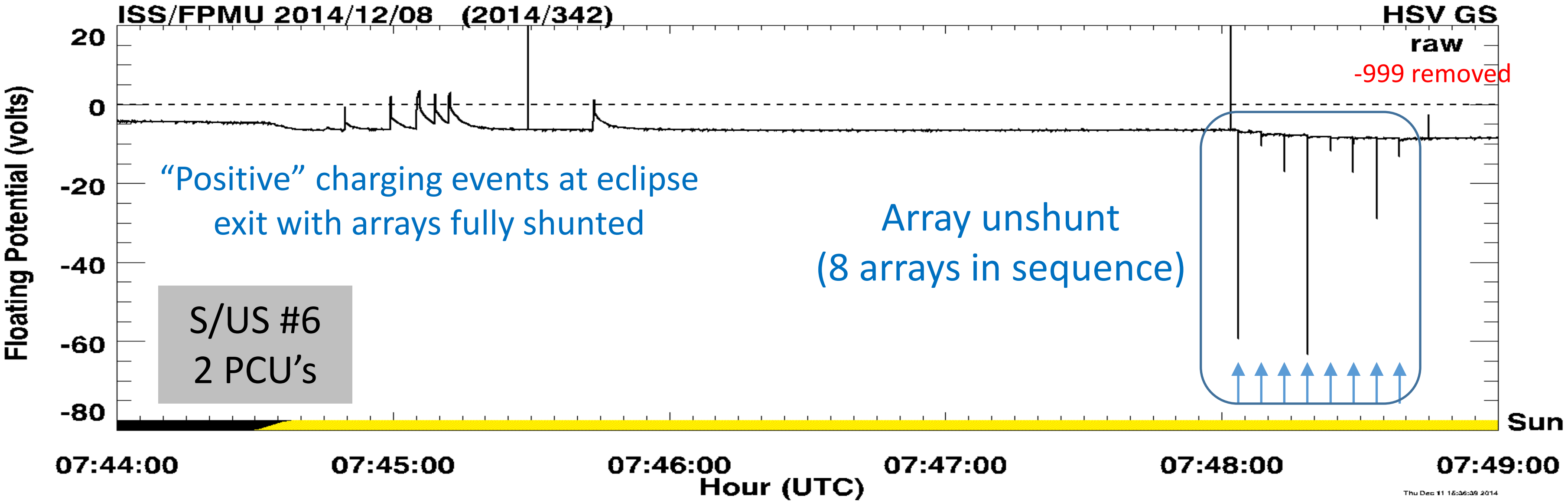


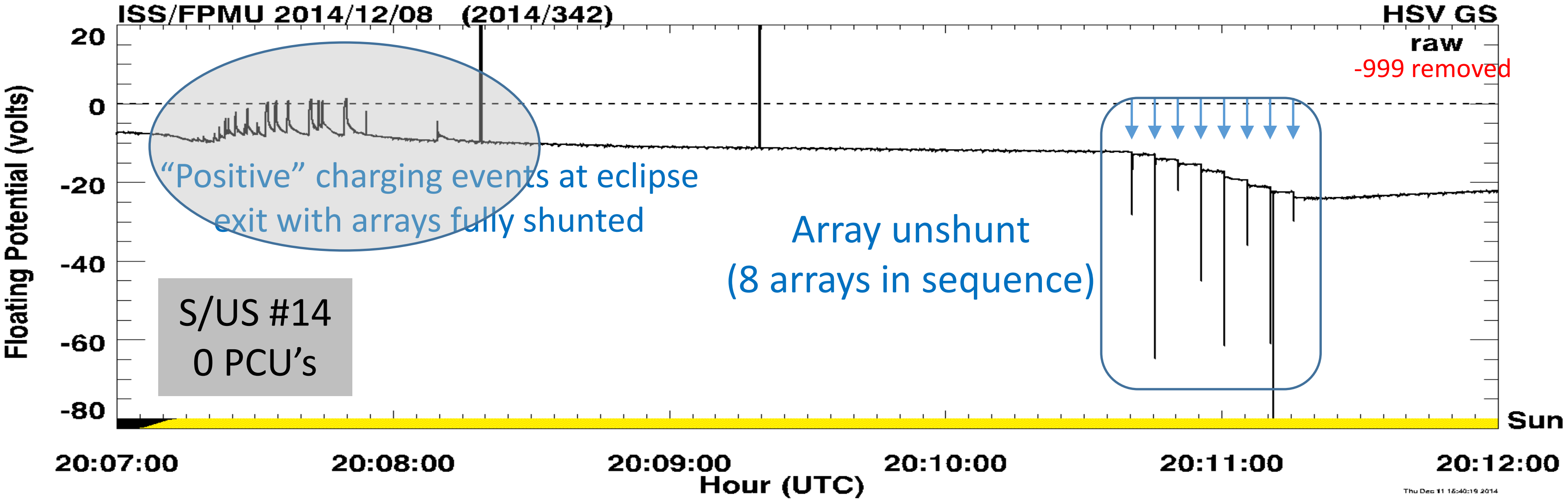




Minow et al., 2018

[*Minow and Willis*, 2014]

# Sunlight Shunt/Unshunt Experiments




Minow et al., 2018

[*Minow and Willis*, 2014]

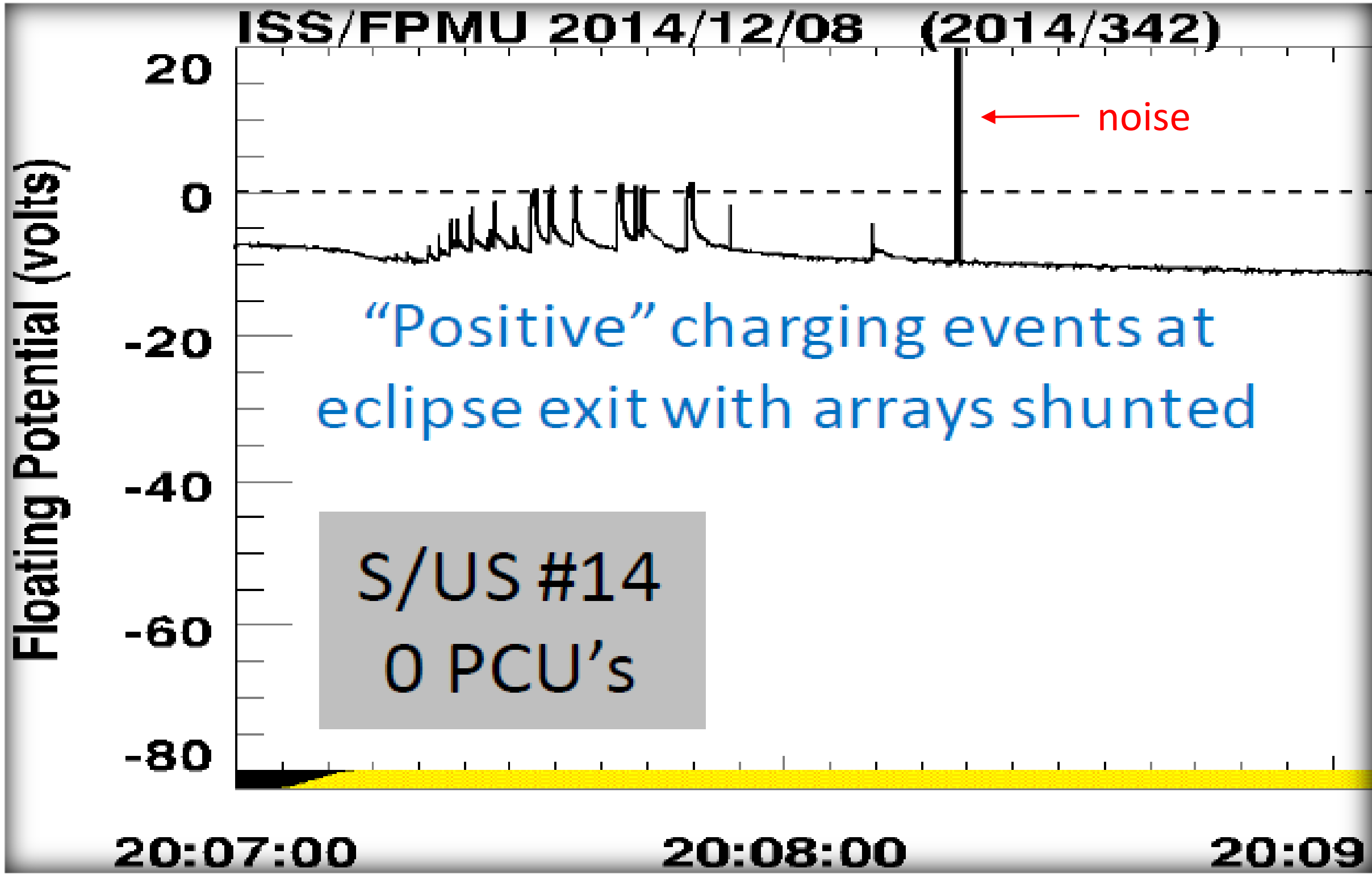
# "Positive Charging" Events

- Transient "positive" potential changes at ISS eclipse exit measured by the FPMU during Command Shunt/Unshunt experiments

- All arrays are fully shunted at the time of the "positive" events

- Label:
  - S/US #14: 14th shunt/unshunt operation
  - 0 PCU's: PCU's are not operating

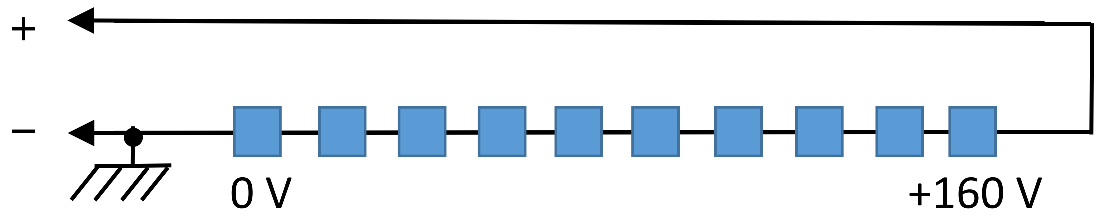
- For many years the origin of these "positive" charging signals were not understood



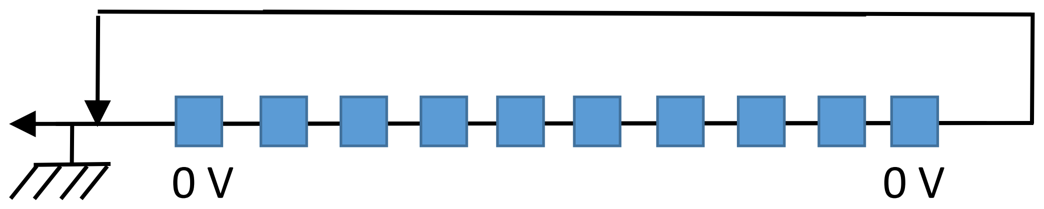

Minow et al., 2018

# Arcing on Damaged, Open-Circuit Strings

- ISS string potentials are nominally regulated to 160 V




Unshunted (active) string – collects current

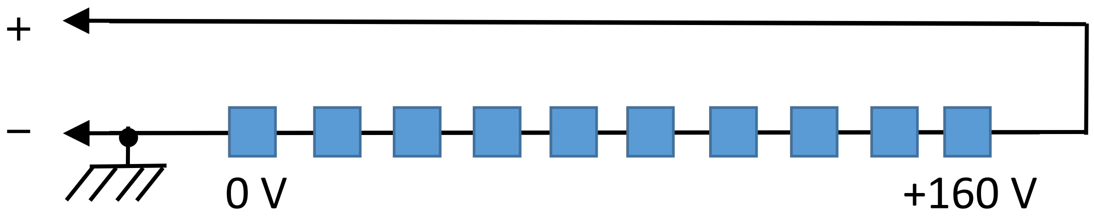



Shunted string – no current collection

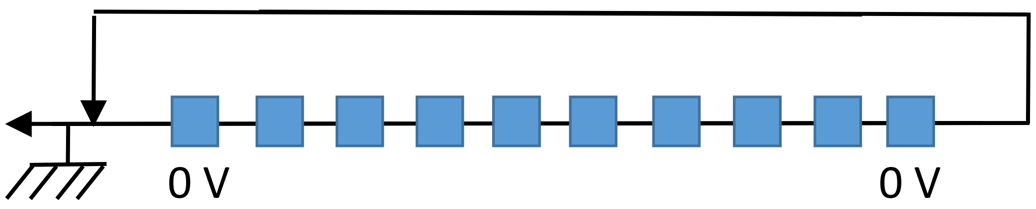
Minow et al., 2018

# Arcing on Damaged, Open-Circuit Strings

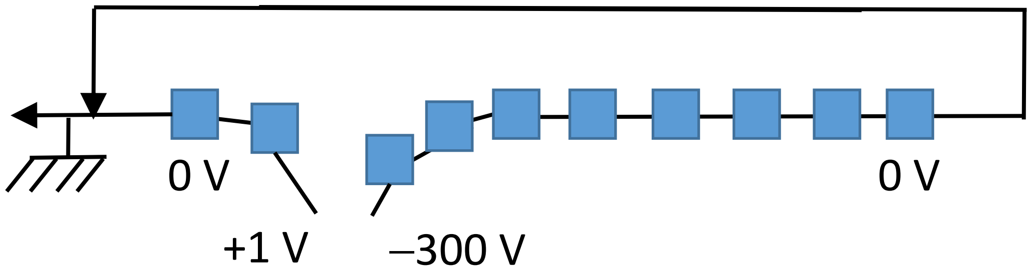
- ISS string potentials are nominally regulated to 160 V
- However, open circuit string voltages when the arrays are cold coming out of eclipse can run as high as 320 V, twice the nominal operating voltage
  - Voltages on damaged, open-circuit strings can exceed -300 V when the strings are shunted
  - ISS structure is grounded to the positive end of an open-circuit, shunted string




Unshunted (active) string – collects current




Shunted string – no current collection

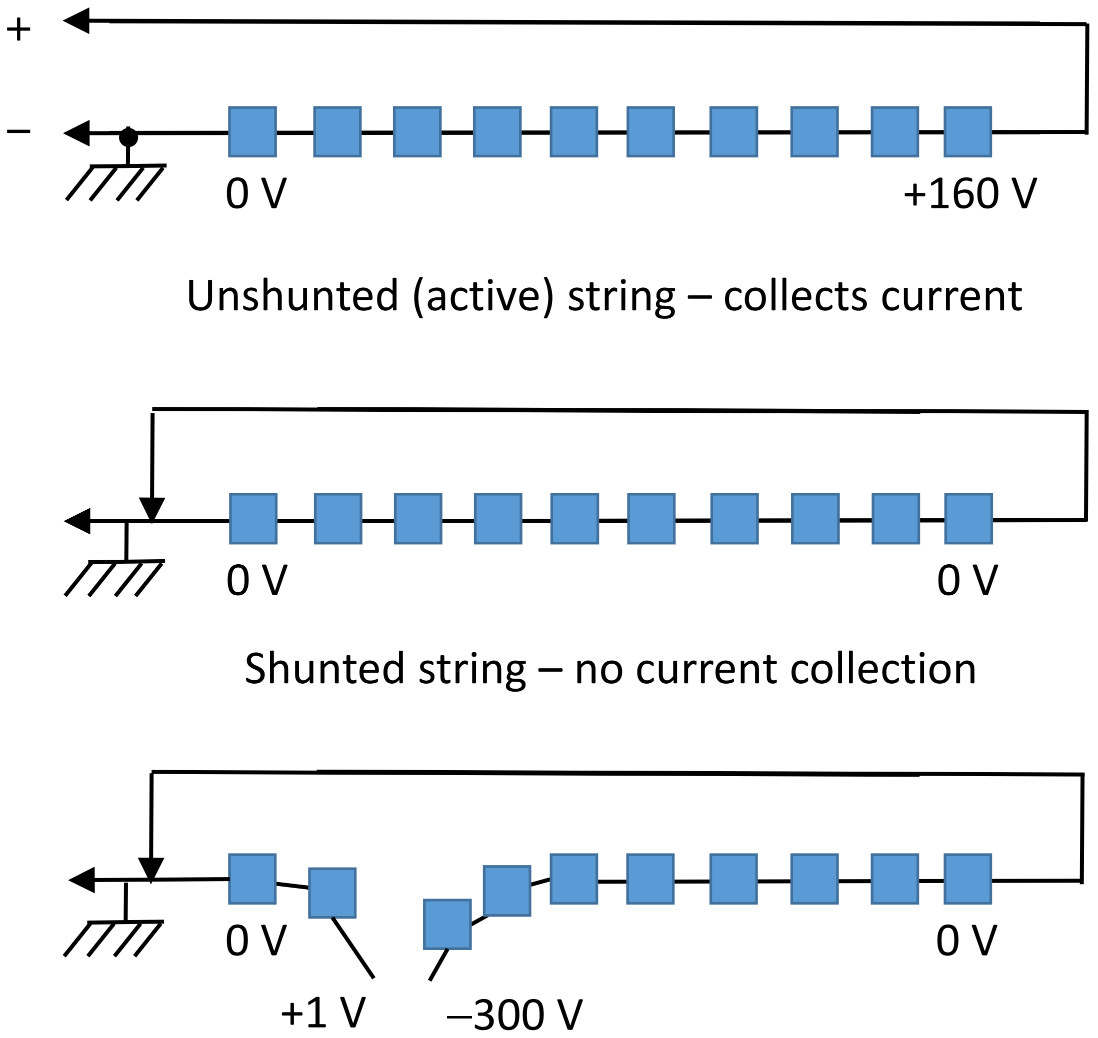



Damaged shunted string – collects current and arcing is possible due to large open circuit voltage

Minow et al., 2018

# Arcing on Damaged, Open-Circuit Strings

- ISS string potentials are nominally regulated to 160 V
- However, open circuit string voltages when the arrays are cold coming out of eclipse can run as high as 320 V, twice the nominal operating voltage
    - Voltages on damaged, open-circuit strings can exceed -300 V when the strings are shunted
    - ISS structure is grounded to the positive end of an open-circuit, shunted string
- Arcing thresholds of ISS strings have been measured to range from -210 V to -457 V depending on the plasma density [*Nahra et al.*, 1990]
- Under these conditions the local potential on the damaged string can easily exceed arcing thresholds at the low end of the -210 V to -457 V range for ISS PVAs

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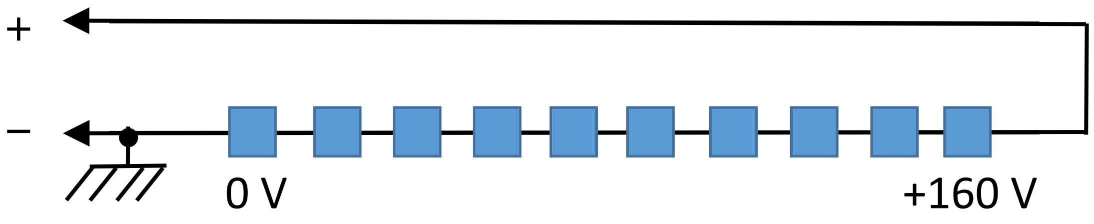
Arcing can occur on damaged strings!

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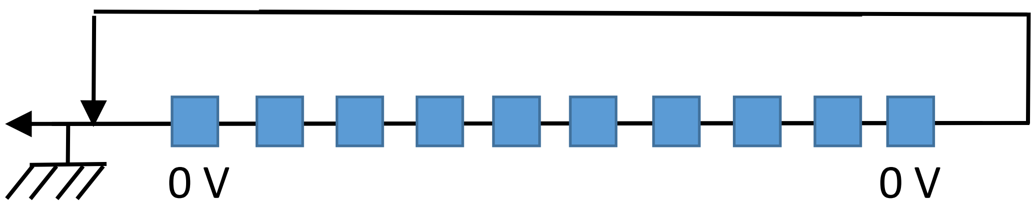


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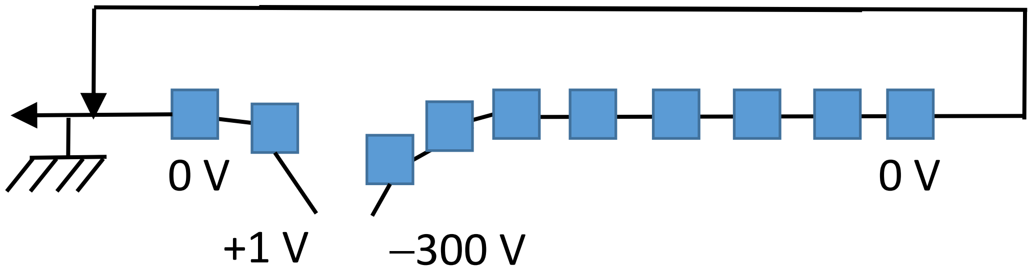



Damaged shunted string – collects current and arcing is possible due to large open circuit voltage

Minow et al., 2018

# Arcing on Damaged, Open-Circuit Strings

- Arcing to space on the array will remove some fraction of the net negative charge on the ISS

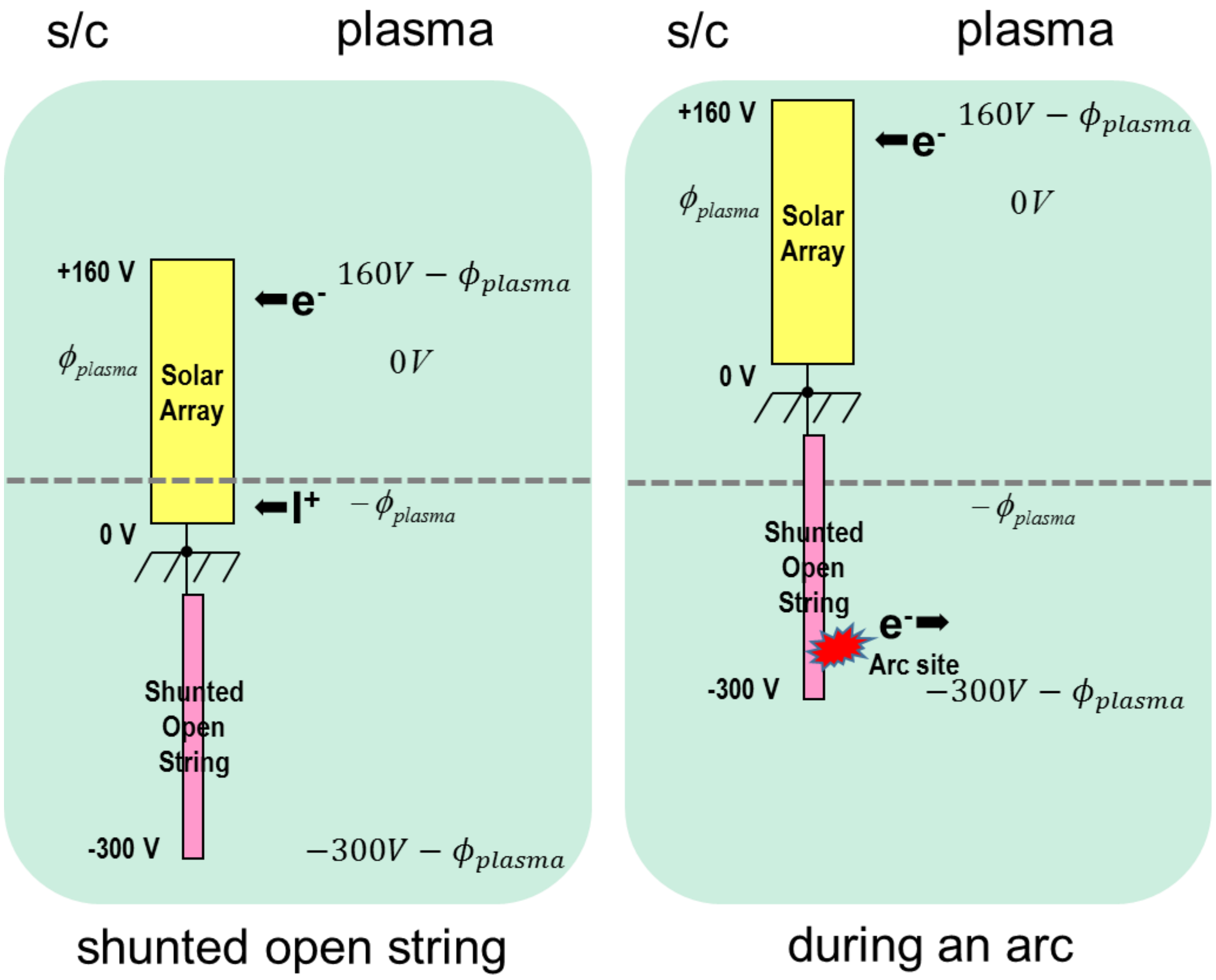
- Transient variations in the frame potential are expected during the electrostatic discharge events

- ISS potentials for a shunted string with an open-circuit fault near the beginning of the string on eclipse exit

    Left panel: before arc

    Right panel: during arc

- Potential of ISS structure becomes less negative as charge is lost through arc event, and may even become positive

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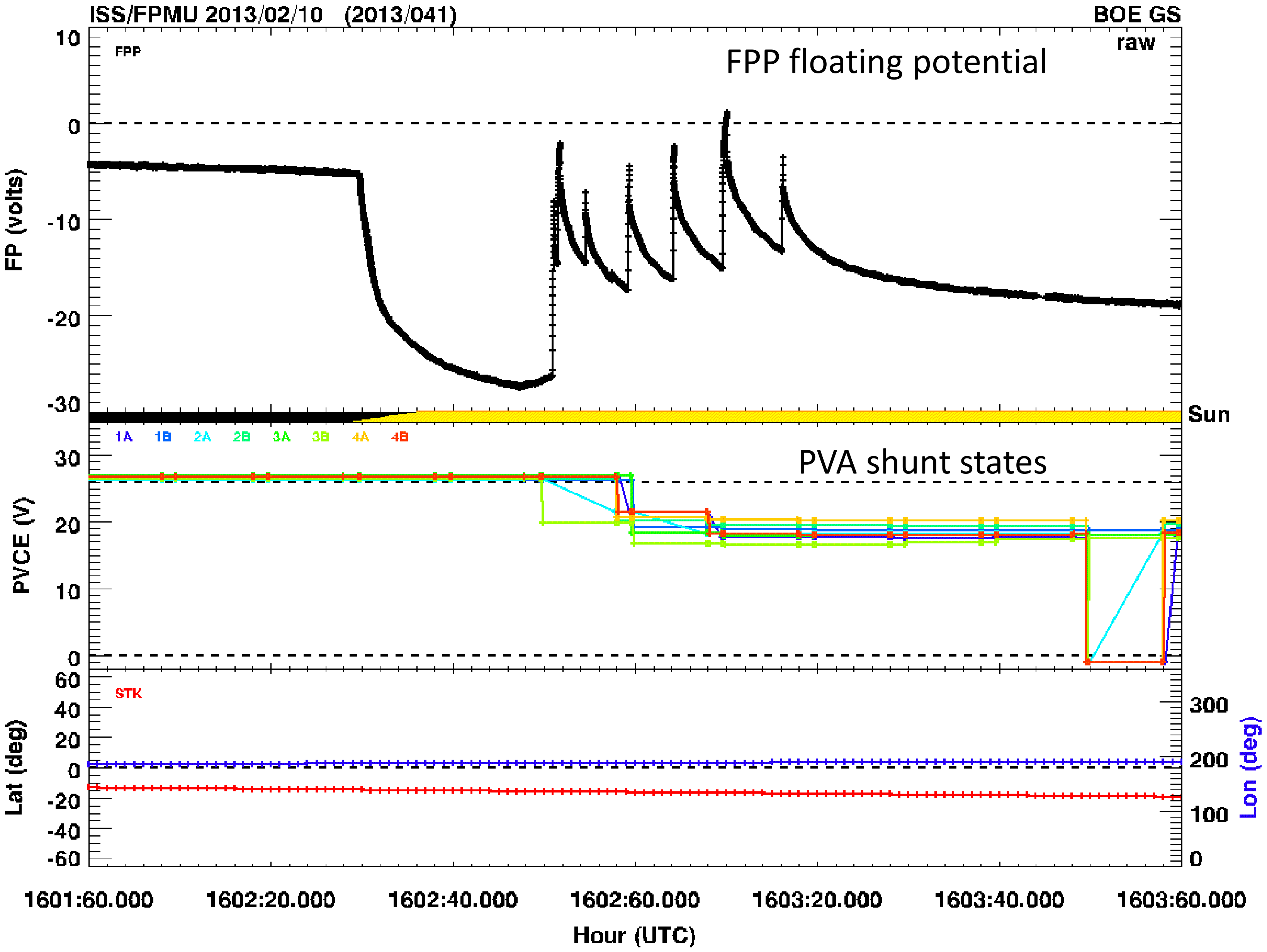
# Example:  10 February 2013

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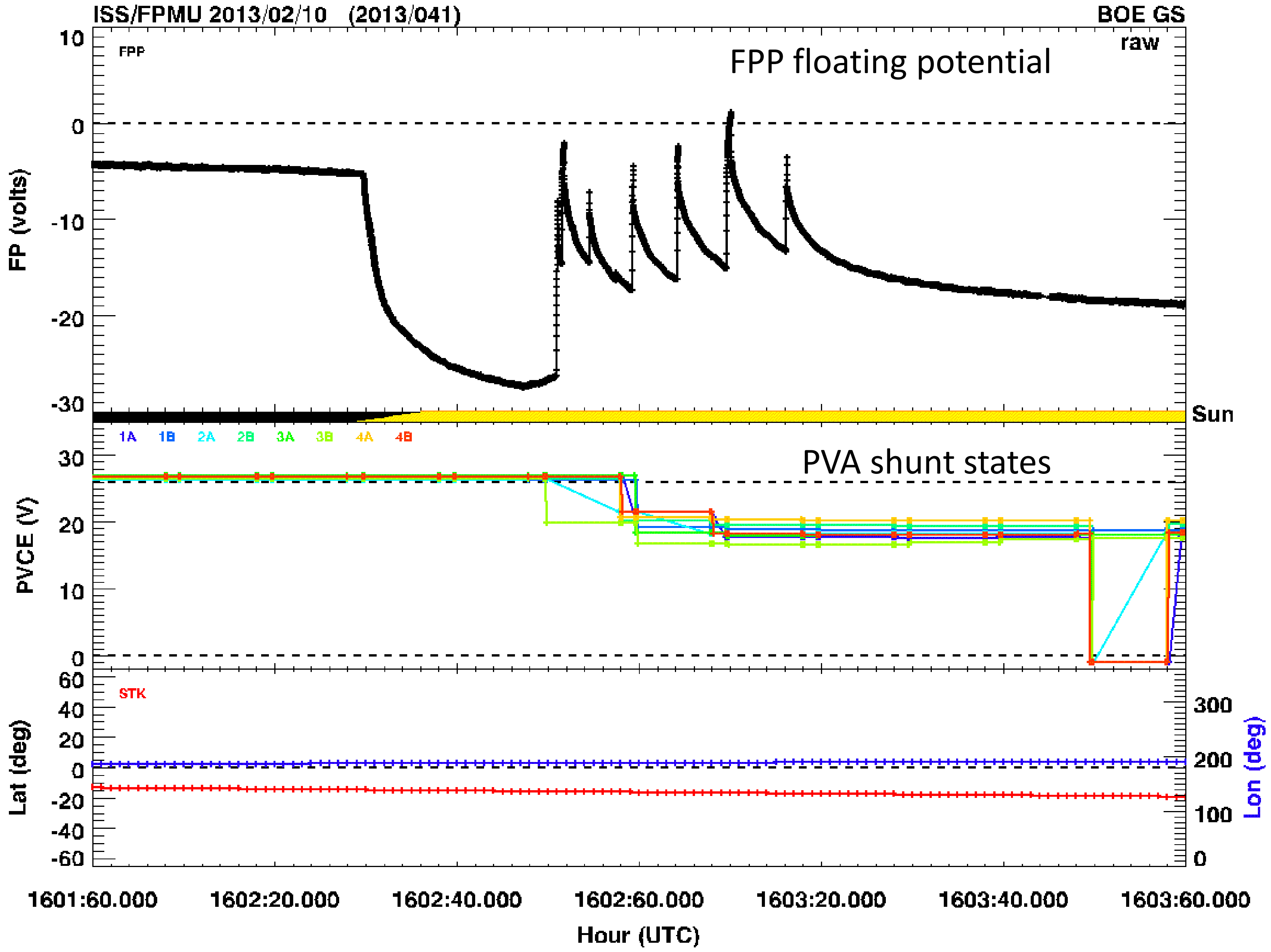


Insight into ISS PVA interaction with plasma environment only possible because of high quality FPMU data…

Minow et al., 2018

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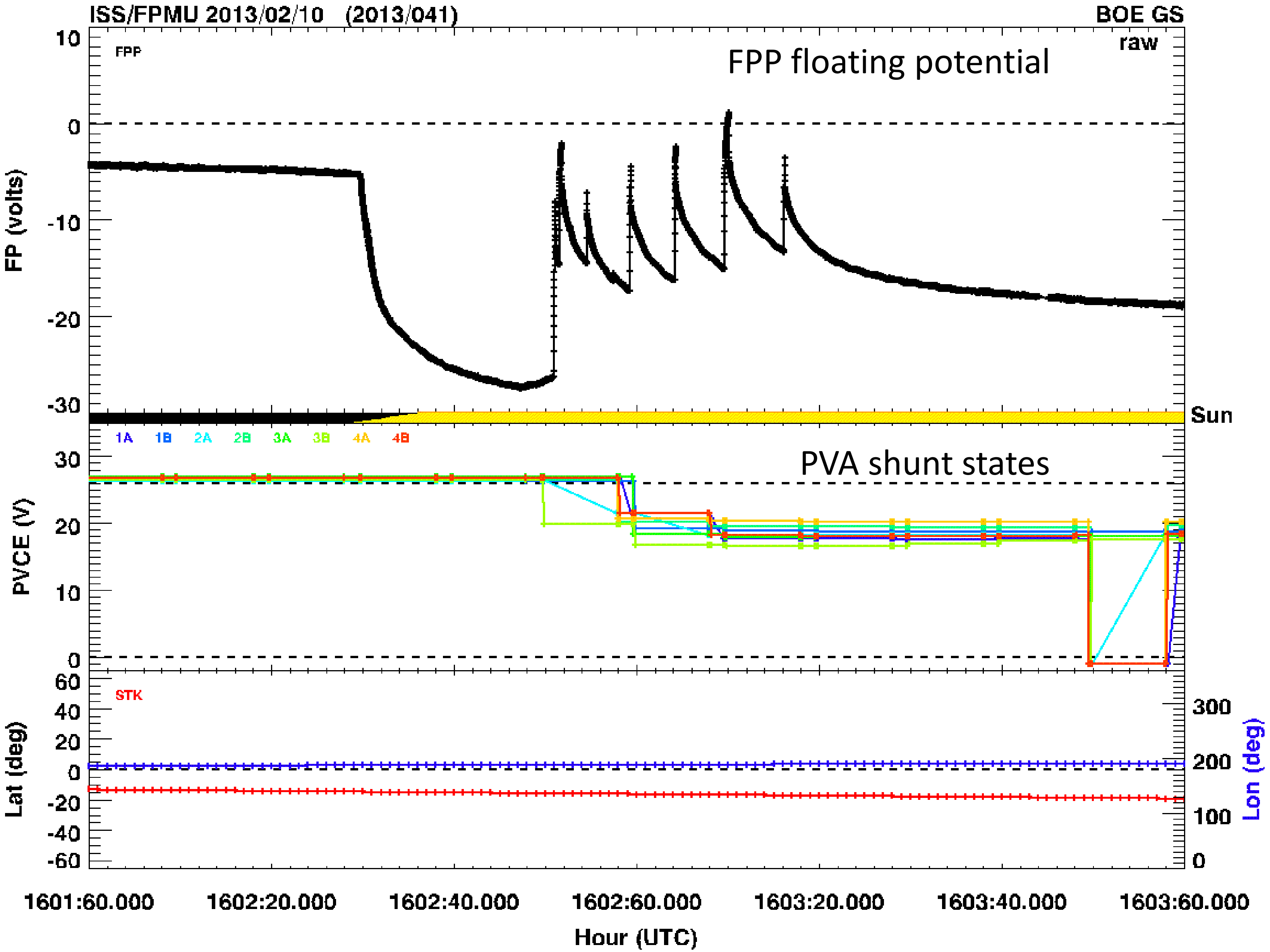


Insight into ISS PVA interaction with plasma environment only possible because of high quality FPMU data…

…in-situ space environment sensors are very useful for diagnosing interaction of space environment with spacecraft

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# Questions?