INTERNATIONAL SPACE STATION SPACECRAFT CHARGING HAZARDS: HAZARD IDENTIFICATION, MANAGEMENT, AND CONTROL METHODOLOGIES, WITH POSSIBLE APPLICATIONS TO HUMAN SPACEFLIGHT BEYOND LEO

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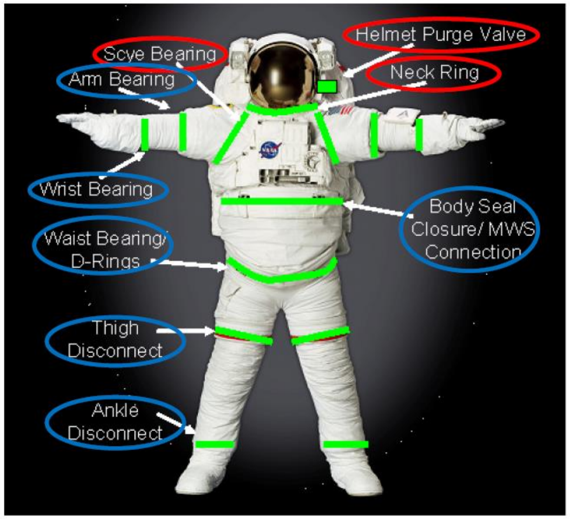
Background: ISS Spacecraft Charging Hazard

- This presentation will provide a review of how the International Space Station (ISS) safety engineering methodology for controlling extravehicular activity (EVA) crew electrical shock hazards has evolved over the past 25+ years, and will provide an overview of the present methodology
- The specific EVA crew electrical shock hazard is due to the ISS floating potential (FP, the electrical potential difference between ISS conducting structure and the surrounding ionospheric plasma) which ranges from small positive voltages (~+10) generated at one truss tip to larger negative voltages (~-40 V) at the other end tip due to:
  - Current collected by the 160 V solar arrays
  - Electrical power system operations
  - Electric field induced by the geomagnetic field at high latitudes
  - Large vehicle size (~ 100 yards between truss tips)
  - Auroral electrons encountered at high latitude



Ruled out as a possible contact point

Possible direct contact point
Ankle*, Arm*, BSC, OBS/DCM, Thigh*, Waist* or Wrist* contact ISS

External EMU Surfaces

Crew electrical shock hazard is present when electrically conducting EMU components make contact with ISS conducting structure, and charge passes across the EVA crew person’s body

ISS Spacecraft Charging Hazard Management Process

- ISS Program requires two-fault tolerant hazard controls for catastrophic hazards
- Replacing an ISS Program hazard control process requiring two-fault tolerant hazard controls with a detection and warning process is possible if and only if it can be demonstrated through a combination of in-flight measurements, ground based testing, and probabilistic analysis that the following criteria are true:
  - (1) The probability of hazardous FP values (both positive and negative) on ISS is nominally low
    - Depends on ionospheric electron density and temperature at ISS flight altitude, which depends on solar activity and the magnitude of the 11 year solar cycle
    - Depends on ISS vehicle flight attitude and orientation with respect to the velocity vector, especially orientation of the active surface of the photovoltaic arrays and the 100 meter truss.
    - Depends on the specifics of ISS electrical power system operations
  - (2) Space weather events and/or vehicle configuration changes can be identified with sufficient lead-time to enable activation of controls or rescheduling of the EVA
    - Note: In addition, the frequency of occurrence of hazard control activation or rescheduling of EVAs must be small
  - (3)The probability (P2) of completing the EVA crew-hazard shock-circuit during any EVA is low
  - (4) The net probability of an EVA crew shock event, Ps, as a function of P1 and P2, is small enough for the ISS Program to accept the residual risk when EVA is conducted without any active hazard controls

ISS Floating Potential Measurements

- Long-term measurements of ISS charging severity and frequency-of-occurrence have been made that provide support for the basis for the present electrical shock hazard methodology
- Early measurements were obtained with the ISS floating potential probe and ISS plasma contactor unit (PCU) emission currents (CY 2000 and 2001). These measurements demonstrated that the severity and duration of ISS charging events were far less than predicted early in the ISS Program
- More recently, Floating Potential Measurement Unit (FPMU) measurements have been made from CY 2006 to the present. These FPMU measurements include ISS FP, as well as ionospheric electron temperature (Te) and density (Ne). FPMU data has been validated against comparable ground-based and satellite measurements of ionospheric temperatures and densities at or near ISS operating altitudes
- These measurements have confirmed the earlier result that the severity and duration of ISS charging events are less than predicted early in the ISS Program, and are a key part of the EVA shock hazard detection and warning process
- Note: the observed lower-than-expected ISS charging measurements are largely the result of:
  - 1) Unusually low solar activity between 2008 and the present, corresponding unusually low ionospheric density and,
  - 2) ISS photovoltaic arrays are only rarely in a worst-case ram-oriented configuration at eclipse exit leading to less than worst-case electron collection in most cases

Criteria 1: Probability (P1) Of Hazardous FP Values on ISS (1 of 2)

- Between CY 2006 and the present, thousands of FPMU measurements have been made. Those measurements have demonstrated that hazardous ISS charging environments occur infrequently (though, not infrequently enough to ignore)
- Note, low solar activity contributes to the lower charging environment. Increases in solar activity may affect these conditions, so a detection and warning process is required to monitor for possibly hazardous conditions
- Negative potential hazard exceedances are provided here

	Total FPMU Measurement Time (sec)	Tip Exceedance (sec)	SARJ Exceedance (sec)	Center Exceedance (sec)
Year				
2006	9.6E+03	0	0	0
2007	5.2E+04	0	0	0
2008	1.3E+06	111	38	18
2009	2.4E+06	221	26	1
2010	2.3E+06	37	24	23
2011	3.8E+06	49	36	34
2012	3.4E+06	50	44	44
2013	9.7E+06	136	130	130
2014	9.4E+06	115	112	108
2015	9.3E+06	162	107	105
2016	6.7E+06	184	117	103
2017	1.2E+07	708	371	229
2018	8.7E+06	609	296	149
Sum (sec)	6.9E+07	2383	1300	943
Fraction of exceedances:		1/	1/	1/
		28818	52824	72792

Annual FPMU Data Review for Exceedances

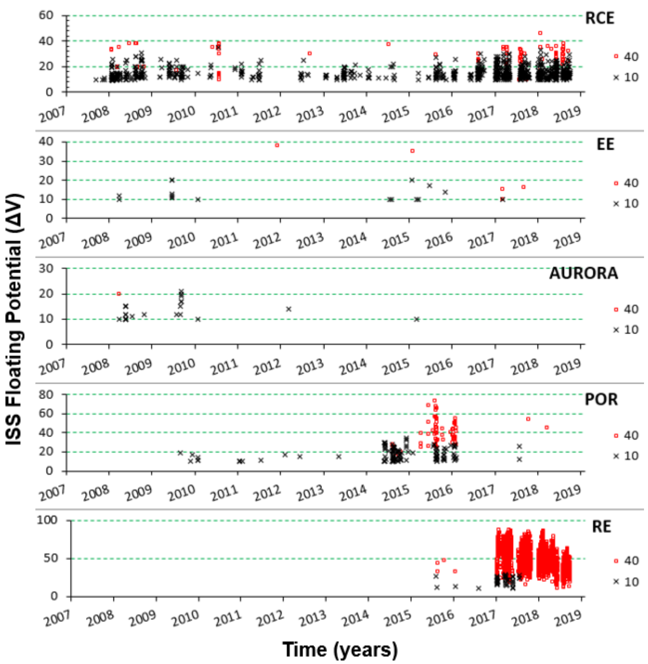
Probabilities (Fraction of Exceedances) provided to the PRA team at pre-defined ISS locations:

-Centerline of the vehicle location: 1/72792
-Solar Array Rotary Joint (SARJ) location: 1/52824
-Truss Tip location: 1/28818

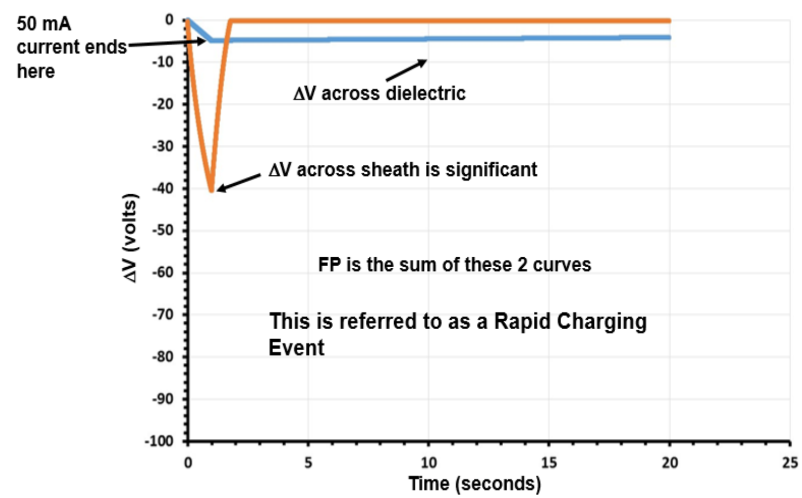
Criteria 1: Probability (P1) Of Hazardous FP Values on ISS (2 of 2)

- In addition, negative voltage spacecraft charging events were reviewed
  - ISS charging events can be grouped into two categories:
    - 1) PV array driven charging and motional EMF charging
    - 2) Shorter duration Rapid Charging Events (RCE) such as Eclipse Entry (EE) Charging, Auroral Charging at high latitude, Power on Reset (POR), and electrical power system Regulation Events (RE)
- Effect of potential drop across the ionospheric plasma sheath in contact with ISS external surfaces on the hazard was also investigated and compared to the potential drop across exposed ISS dielectric surfaces

FPMU Data Review

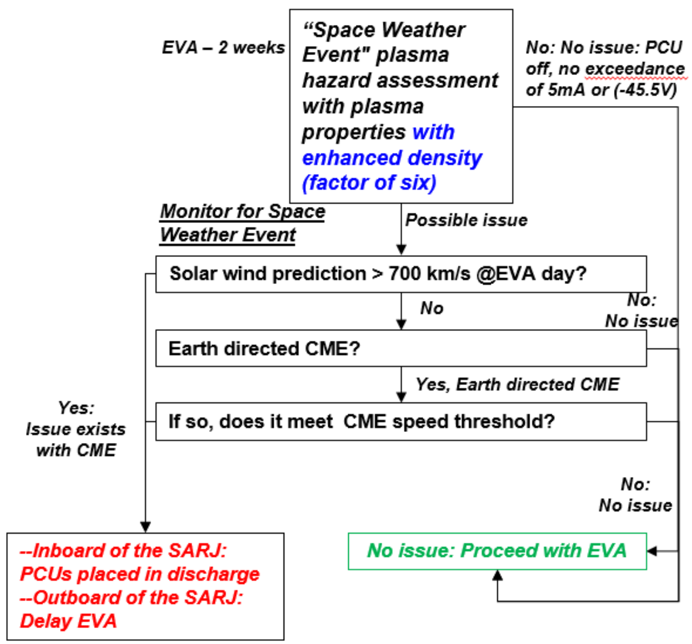


Potential Drop Across Anodized Aluminum and the Sheath



Criteria 2: Events Leading to Hazardous FP Values Can be Identified with Sufficient Lead Time

- The detection and warning approach was developed to support the EVA shock hazard control process
- For each EVA, a forecast is requested prior to the EVA. The FPMU provides ionospheric Ne and Te variability data as well as ISS FP variability data and a conservative assessment is performed
- After the forecast is issued, the space weather is monitored for significant events that may affect the hazard environment
- The ISS Program has accepted that a low likelihood does exist that the forecast result may be affected by space weather events (possibly 1 every 6 years that may require review)



Plasma Hazard Monitor and Notification Criteria and Process

Criteria 3: Probability (P2) of Completing the EVA Crew-Hazard-Shock-Circuit During Any EVA is Low (1 of 2)

- To determine the probability of completing an EVA crew-hazard shock-circuit during EVA, the ISS PRA team performed an assessment
  - ISS specialists met to determine possible shock circuit pathways, and galvanic contact probabilities
  - ISS PRA team obtained and reviewed video records of possible EVA galvanic contact
- Results from this assessment/survey provided the basis for the probability of completing the circuit
- PRA team performed a discrete event simulation to model the EVA plasma shock events

Outer Loop (batches)

Sample a per-hour (per-crewmember) contact rate for each direct and indirect continuity path

Inner Loop (reps)

Sample the times and durations of all types of contacts (for one crewmember)

- *For example, in 8 hours, for each crewmember, MWS Tools are expected to contact ISS about 10 times and to contact Wrist 2 or 3 times; the safety tether wire is expected to contact EMU once or not at all; each contact has its own sampled time and duration*
- *Direct contacts are rare and, as with indirect contacts, must be coupled with contact between the safety tether wire and EMU*

Compare all the crewmember's contacts to each other for overlap

- *All contacts must occur during the total time period (e.g., 8 hours)*
- *The second contact (and, if applicable, the third contact) must occur within the duration of the first contact*
- *The gauntlet/TMG must be in a position to expose metal (4/13)*
- *The portion of the ISS that is contacted must be either stainless (5%) or damaged (1%)*

End inner loop

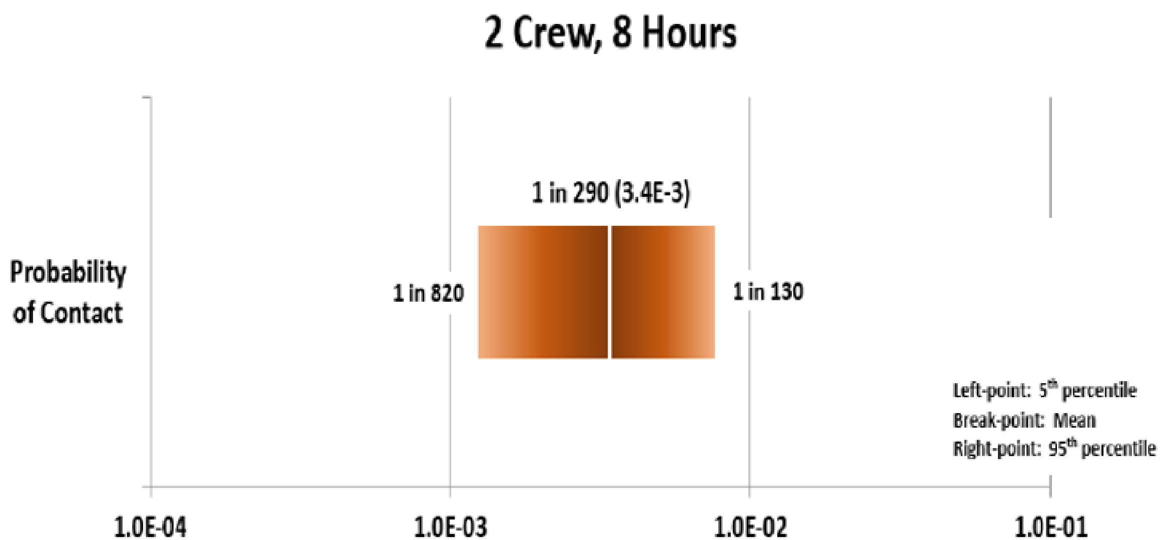
The mean of the batch is the average number of overlapping contacts that occurred

End outer loop

<u>Discrete Event Simulation Logic</u>

Criteria 3: Probability (P2) of Completing the EVA Crew-Hazard-Shock-Circuit During Any EVA is Low (2 of 2)

- Results were determined for the mean (1/290), 5th percentile, and 95th percentile



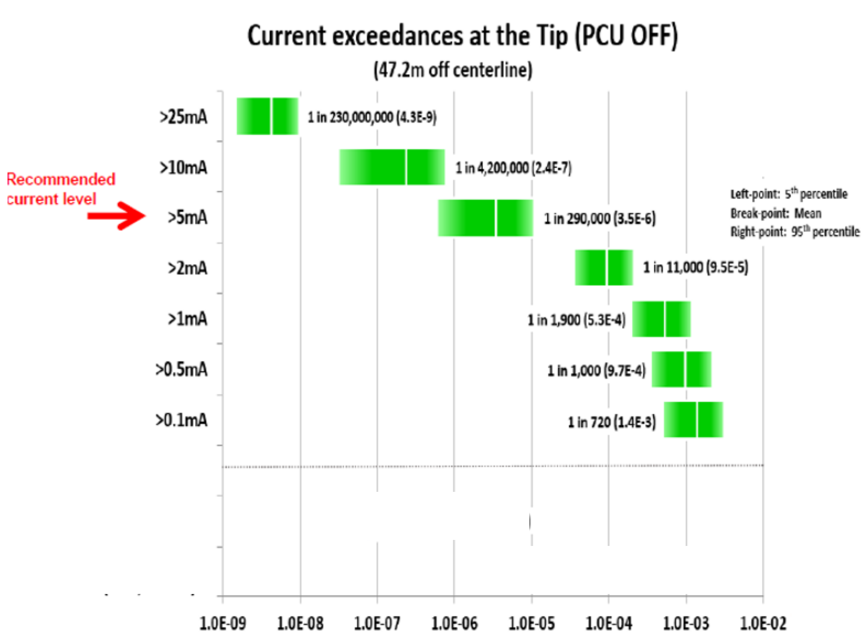
Probability of Completing the Hazard Circuit/Contact (P2)

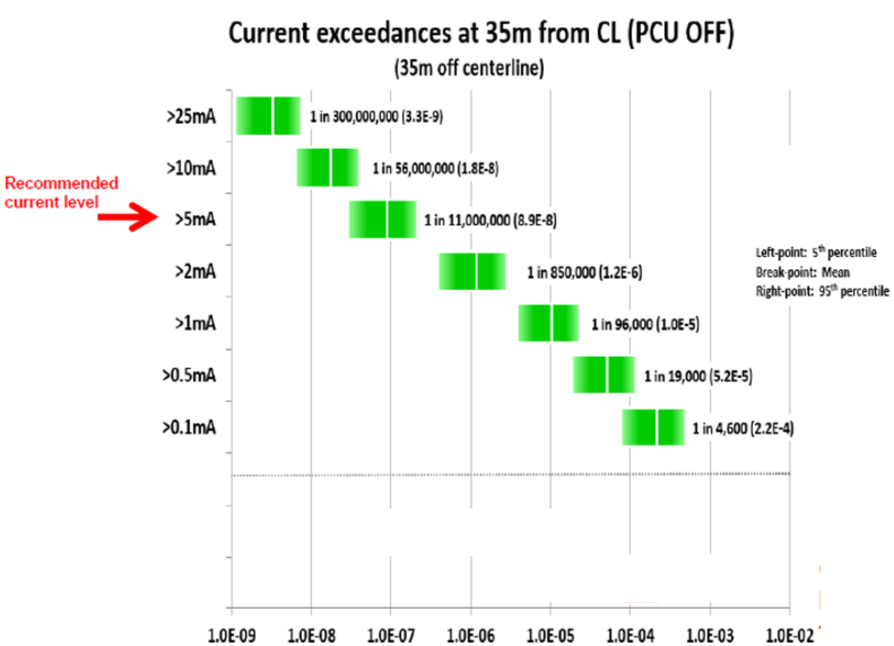
The probabilities were determined by the PRA team using a discrete event simulation that modeled the system as discrete events occurring at particular points in time.

The figure shows results for the mean (1/290), 5th percentile (1/820) and the 95th percentile (1/130)

Criteria (4): Net Probability of an EVA Crew Shock Event, and the Detection and Warning Product (1 of 2)

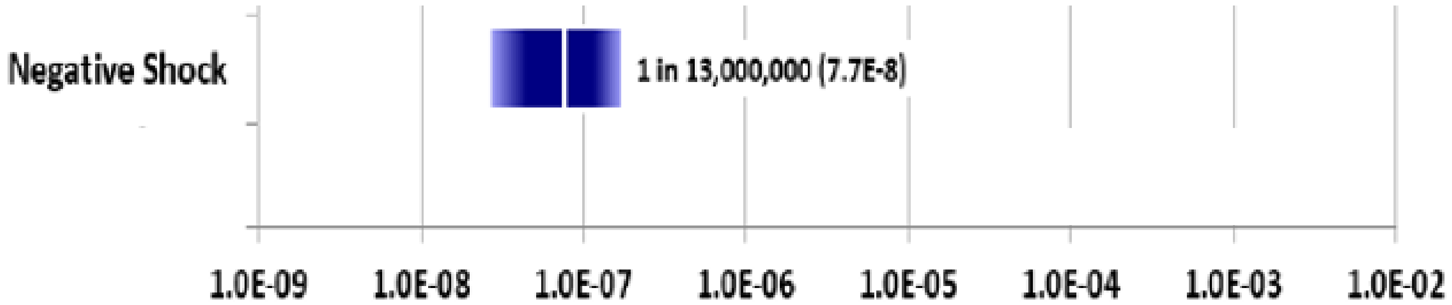
- The ISS Program plasma hazard control process is based on a detection and warning process
- The detection and warning product is based on an analysis of the hazardous scenarios and their probabilities
- Scenarios vary depending on shock hazard (negative and positive), EVA location, PCU operational state, and conductive area. Example results are provided for two positive potential scenarios are shown here
  - Chart on the left is for the Truss Tip location, and the chart on the right for the SARJ location
  - The 5mA current level is indicated with the red arrow
  - Similar to the previous chart, results are provided for the mean, 5th, and 95th percentiles (for the Tip, mean= 1/290,000, and for the centerline, mean= 1/11,000,000)





Criteria (4): Net Probability of an EVA Crew Shock Event, and the Detection and Warning Product (2 of 2)

- The negative potential hazard results are shown below. Note: the negative potential hazard probability included all negative FP limit violations (for example, all RCE events were included)
- Similar to the previous chart, results are provided for the mean, 5th, and 95th percentiles (for the mean, the negative shock hazard is 1/13,000,000)



Validation and Programmatic Approval of the Detection and Warning Approach

- For high exceedances, driven by space weather events, the ISS Program may utilize PCUs (for EVA inboard of the SARJ). For EVAs outboard of the SARJ, the ISS Program maintains the option to defer the EVA until the event passes
- The detection and warning approach has been approved by the ISS Program safety review process
- As part of the process, a back-up methodology was requested, developed, and approved/implemented. The methodology, IRI Real-Time Assimilative Mapping (IRTAM) provides near real-time ionospheric environment measurements based on global ground based digisonde measurements
  - IRTAM has been developed and is provided by the University of Massachusetts at Lowell (UML) Space Science Lab
  - IRTAM uses real time measurements from ~70 digisonde instruments
  - In the event of an FPMU failure, IRTAM would be utilized to determine the environment variability for the plasma hazard forecast.
  - In addition, IRTAM provides data daily, while the FPMU has to be activated, so IRTAM can be used to monitor for a changing environment at any time

Applicability of Probabilistic Spacecraft Charging Hazard Control Methods to Human Spaceflight Beyond LEO

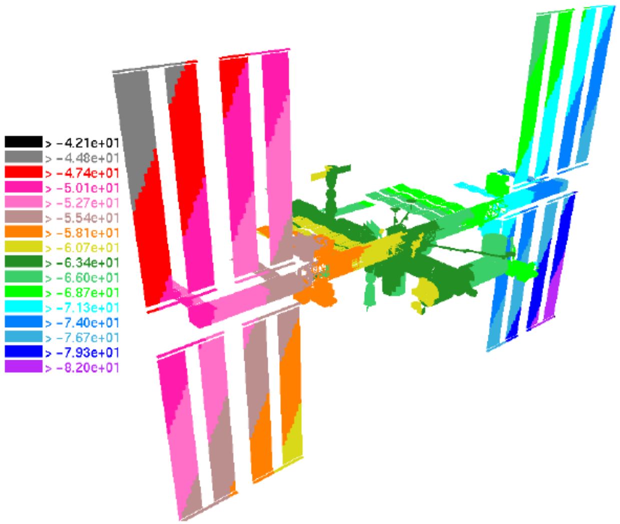
- ISS Space Environments Team has developed an EVA Shock Hazard Detection and Warning Process that meets the criteria for acceptance by the ISS Program
- The general approach has applicability to future human spaceflight missions, as risk trades will need to be performed to support mission success
- For future missions, the spacecraft charging risks will be different (cis-lunar environment, missions that pass through the Van Allen belt, GEO, and GEO tail environments, etc…)
- Designing spacecraft specifically for the more severe charging environments beyond LEO will be the best approach. However, when the material selection does not support that approach, spacecraft charging assessments and hazard analysis will be required.
- The frequency of occurrence and severity of expected charging environments will need to be quantified to determine whether or not a detection and warning approach to managing spacecraft charging hazards will be acceptable to support future space flight missions in environments beyond LEO

Summary

- This presentation provided a summary of how the process utilized by the ISS Program for managing the EVA crew electrical shock hazard evolved over the years
  - Successful implementation of a detection and warning approach depends on: (1) the probability of hazardous FP values (both positive and negative) on ISS remaining nominally low, and (2) space weather events and/or vehicle configuration changes being identified with sufficient lead-time, (3)the probability of completing the EVA crew-hazard shock-circuit during any EVA remaining low, and (4) the net probability of an EVA crew shock event remaining small enough for the ISS Program to accept the residual risk
- In addition, an overview of the present methodology was provided
  - Detection of a potentially hazardous environment before the EVA with time to implement hazard controls has been approved by the ISS Program safety review process and accepted by the ISS Program
  - In addition, a back-up methodology, IRTAM, was approved/implemented
- Finally, the applicability of the probabilistic spacecraft charging hazard control methods to human spaceflight beyond LEO was discussed. Applicability for those missions will depend on the frequency of occurrence and severity of the expected charging environments

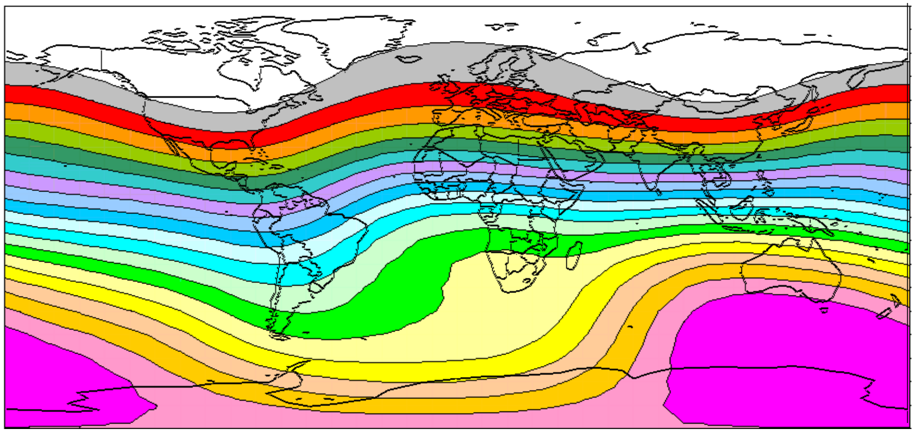
Back-up

Back-up: ISS Vehicle Charging



+XVV, PCU Off, Eclipse Exit: Southern Hemisphere -Summer Season, Negative (Port) Case

Example to demonstrate the possible potential difference between ISS and Plasma for a worst case environment and solar array position



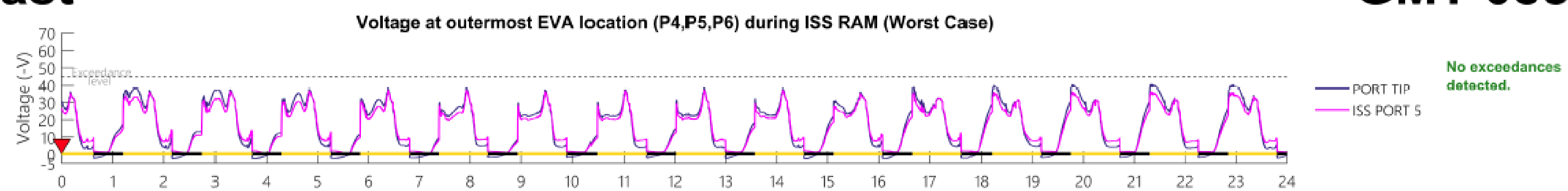
Magnetic Field (Bz Component)

ISS spacecraft charging prediction depends on the location and time of the EVA (and the corresponding location with respect to the Earth's magnetic field)

Forecast

Solar Storm Assessment for EVA on GMT 088 (Fri Mar. 29, 2019) Hours 0-24

GMT 088



Example ISS spacecraft charging prediction shows that depending on the ISS solar array operations, the environment, and the EVA location, there may be negative potential exceedances