Validation of NASA's Radiation Analysis Tools with ISS Radiation Environment Monitor (REM) Measurements

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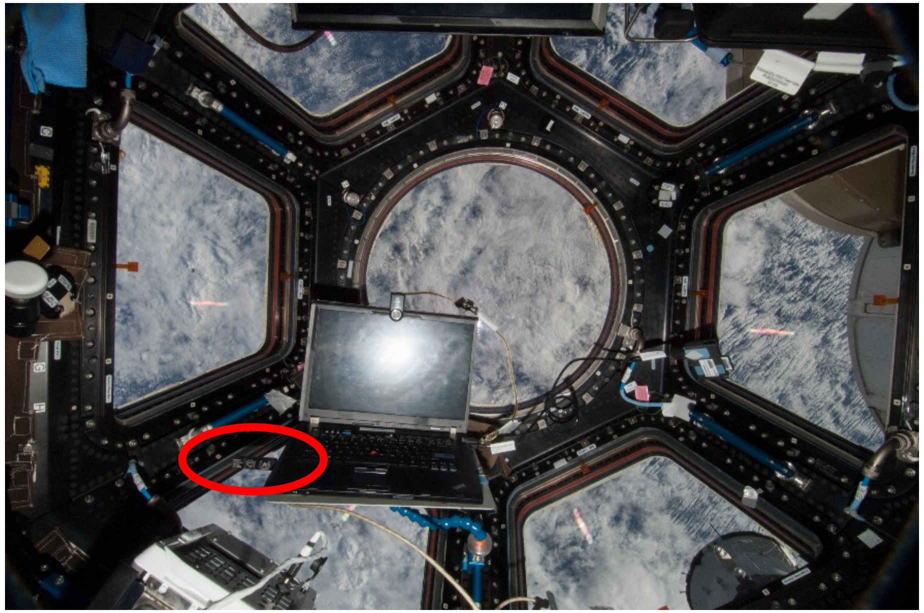
Outline

- Overview
- Radiation exposure analysis process
- ISS models and detector locations
- Computational procedures and assumptions
- Comparison of calculated results with measurements using HZETRN with straight-ahead approximation
- Investigation into under-prediction of calculated dose and dose equivalent
- Comparison of calculated results with measurements using latest version of 3DHZETRN
- Summary

Overview

- Measurements made with the Radiation Environment Monitor (REM) units currently onboard the International Space Station (ISS) provide an opportunity to perform end-to-end validation of radiation analysis tools used by NASA to predict astronaut exposure.
- This validation effort is being performed under the NASA Advanced Exploration Systems (AES) RadWorks project.
- This work is on-going. The current status is reported in this presentation.

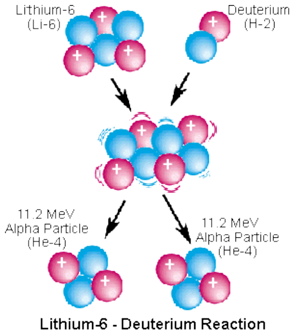


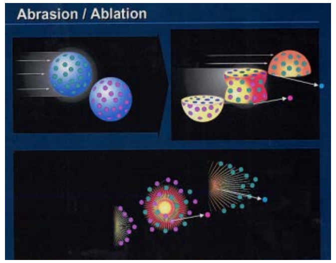
REM Unit in the Cupola[1]

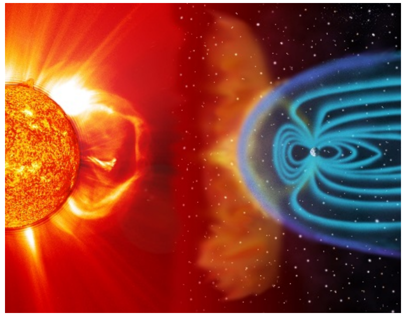
ISS REM unit[2]

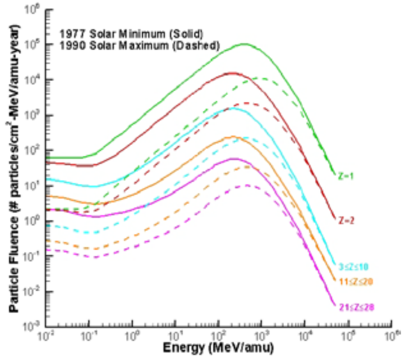
[1]NASA JSC Imagery Online website
[2]Kroupa, M., et al. A semiconductor radiation imaging pixel detector for space radiation dosimetry. *Life Sci. Space Res.* (2015)

Radiation Exposure Analysis Process









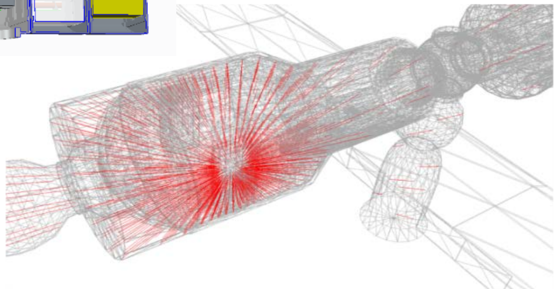
Physics Parameters

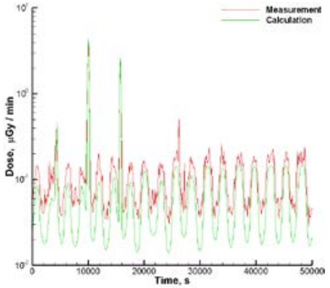
Environment Model

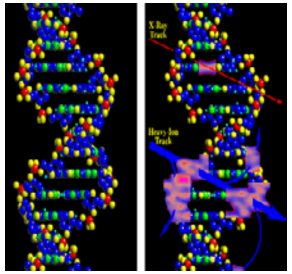
Shield Model (Geometry)

Radiation Transport Model

Response

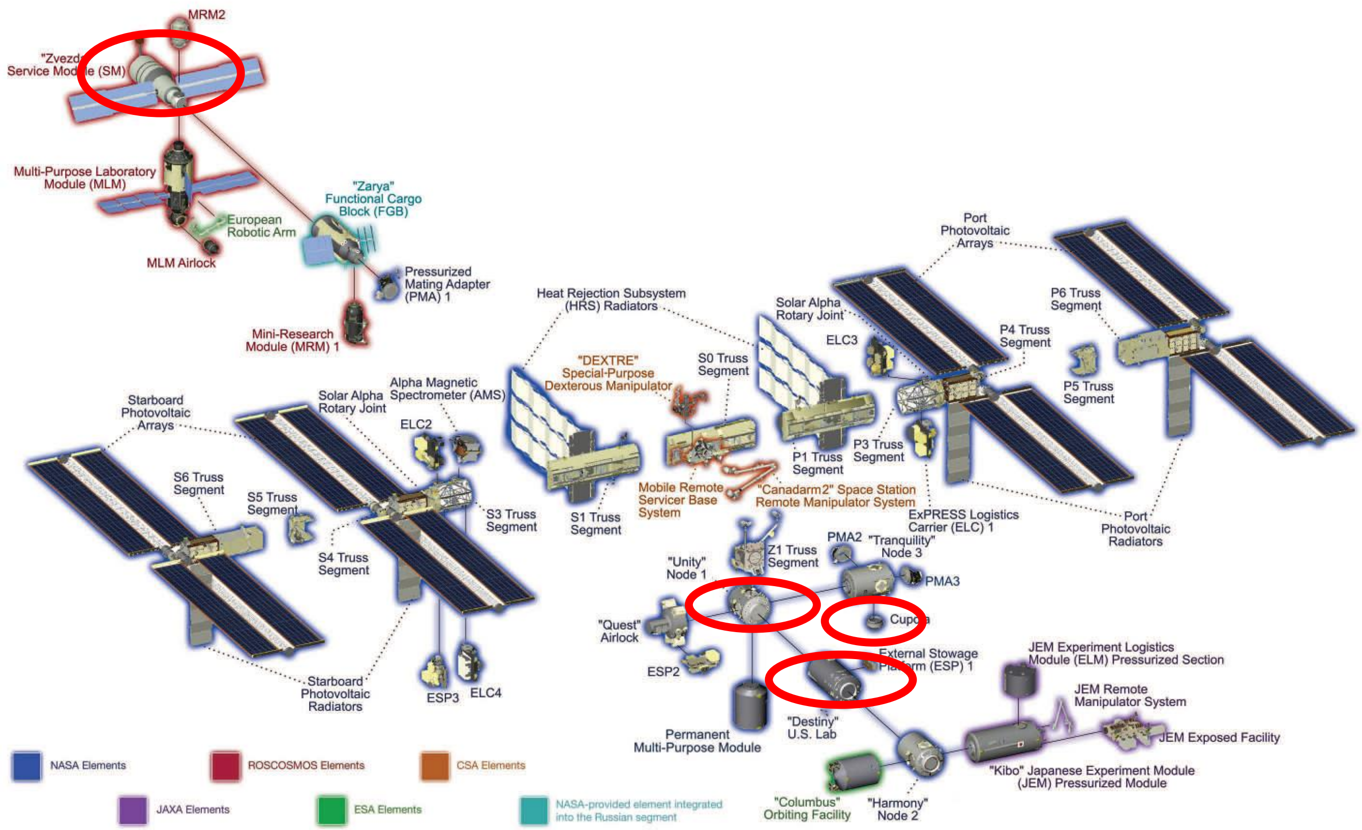






Detector Locations

- Dose has been calculated for 3 ISS REM locations: US Lab, Node 1, and Cupola
- As an additional check, dose in tissue has been calculated for the Tissue Equivalent Proportional Counter (TEPC) location in the Service Module (SM)

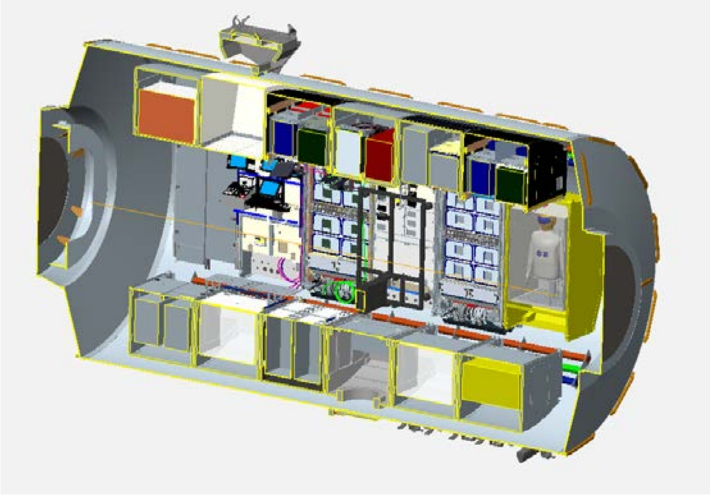


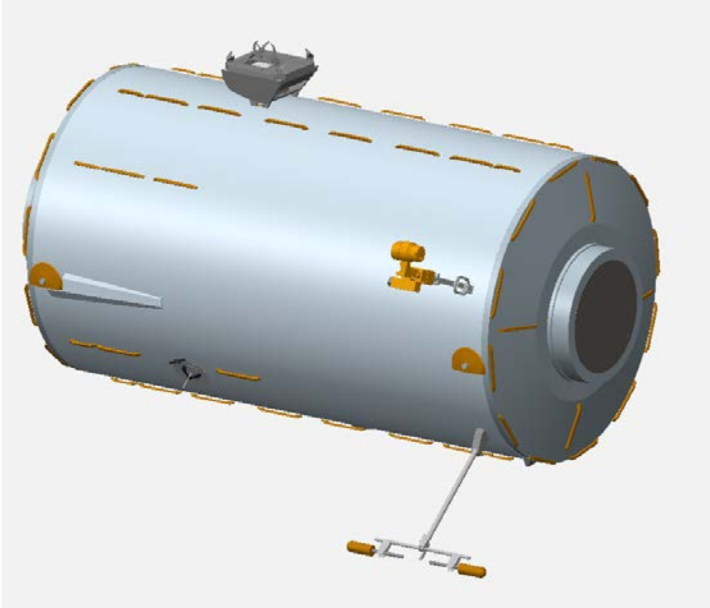
Updates to ISS CAD Models

ISS CAD models were updated to accurately reflect the shielding mass surrounding the detectors:

- Overlapping parts and holes in the models fixed
- Volumetric models created for parts represented only as surfaces
- Internal rack placement updated to match current configuration
- Part masses updated to agree with best available information at the rack and large component level

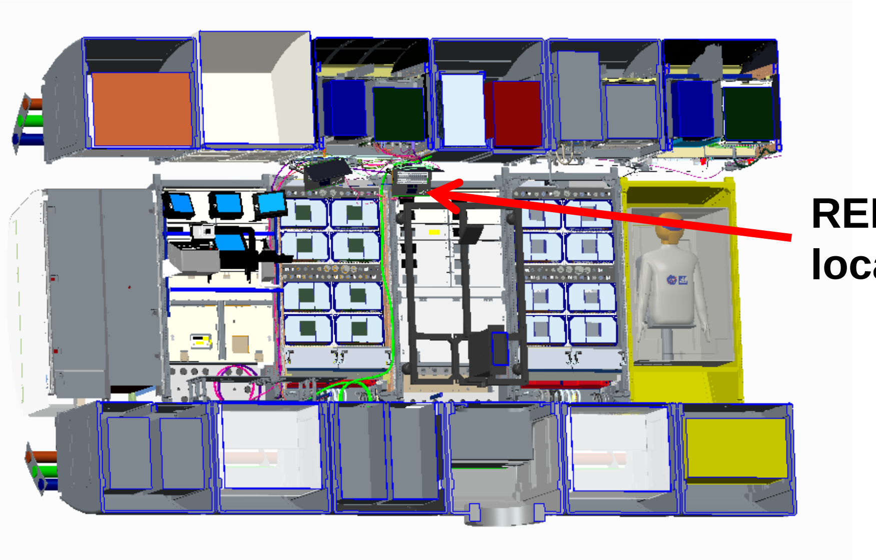
Module	Final CAD Model Mass	In Space Module Mass
Airlock	22,604.37	22,594.00
Columbus	36,158.75	38,138.36
JEM	88,128.28	87,610.94
Node 1	22,986.37	22,986.38
Node 2	30,646.38	35,933.72
Node 3	49,170.18	46,238.64
PMA 1	2,494.82	2,494.59
PMA 2	2,494.47	2,494.59
PMA 3	2,492.76	2,494.59
SM	53,264.57	54,260.64
US Lab	55,676.12	55,676.00

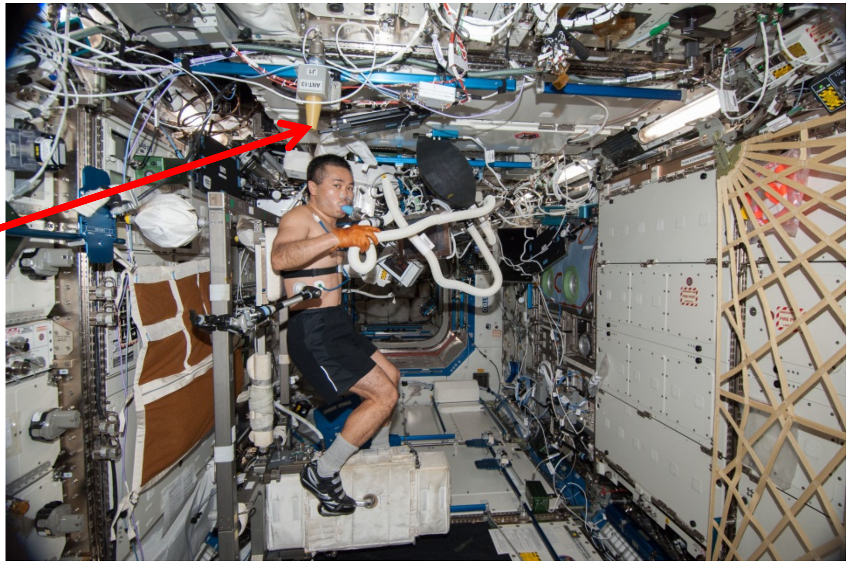




US Lab CAD Model

US Lab REM Detector Location



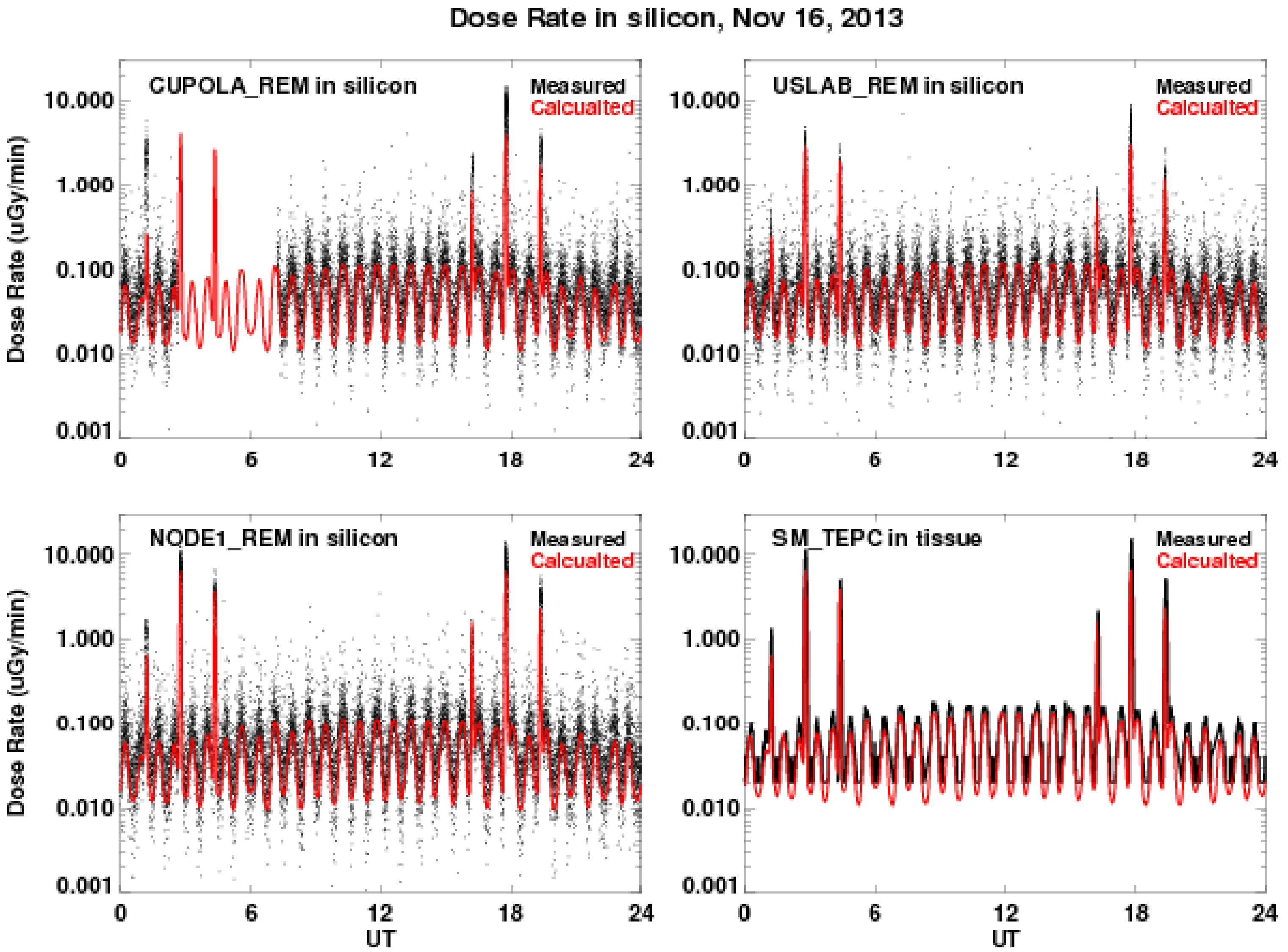


Once the CAD models were updated and the detector locations were identified within the CAD models, the entire ISS model was ray-traced at each location, providing a distribution of the shielding materials surrounding each of the detectors.

Baseline Analysis Assumptions

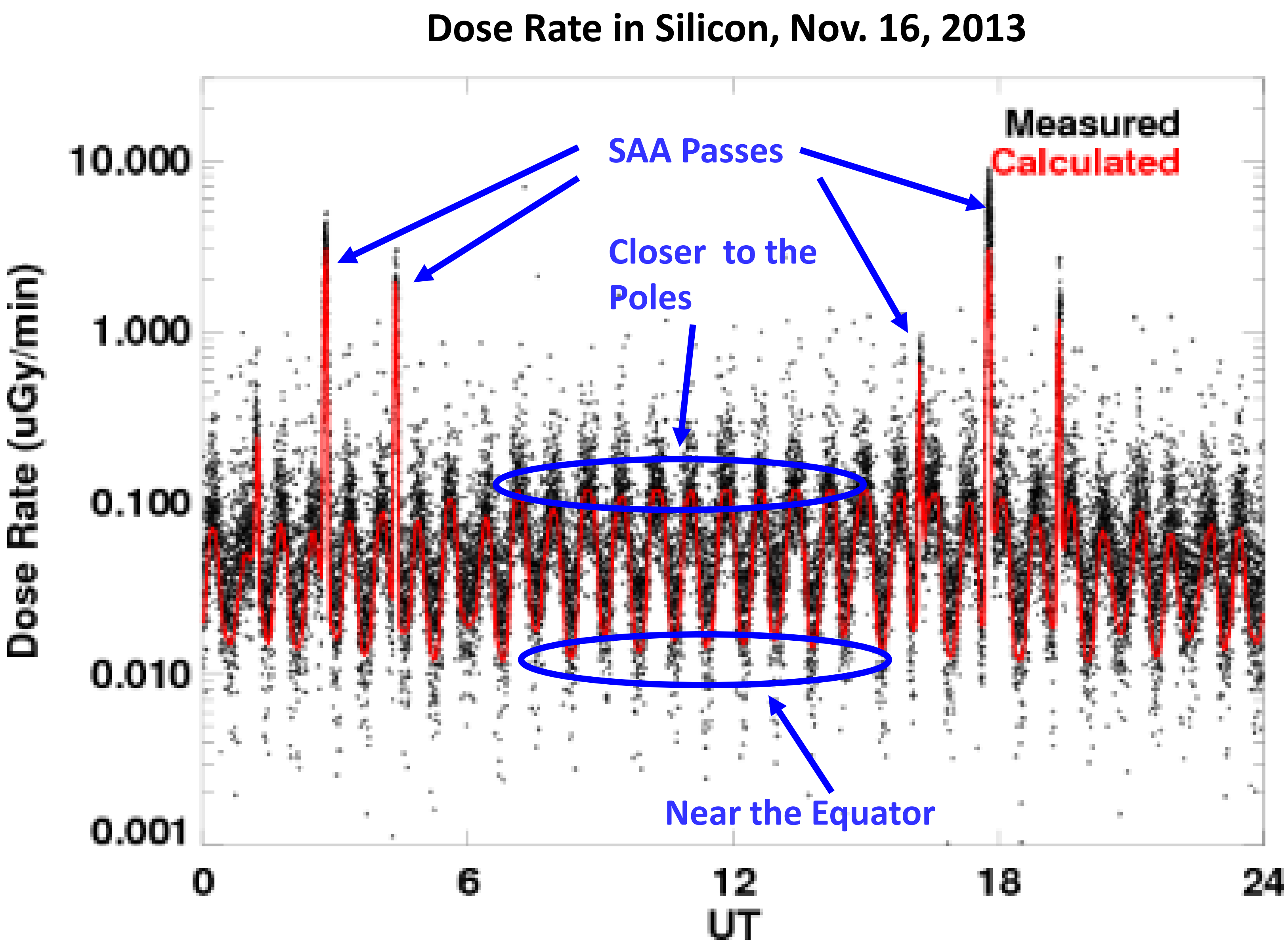
- External radiation environments impinge on the ISS isotropically, except where the Earth’s shadow blocks the GCR environment
- All trapped protons with enough energy to penetrate the ISS pressure vessel occur within the South Atlantic Anomaly (SAA)
- GCR environment model: Badhwar-O’Niell
- Vertical cutoff rigidity model: Stormer’s model as modified by Cooke
- Trapped proton environment model: AP8 (Badavi time dependence and normalization)

Dose Rate – HZETRN with Straight-Ahead Approximation

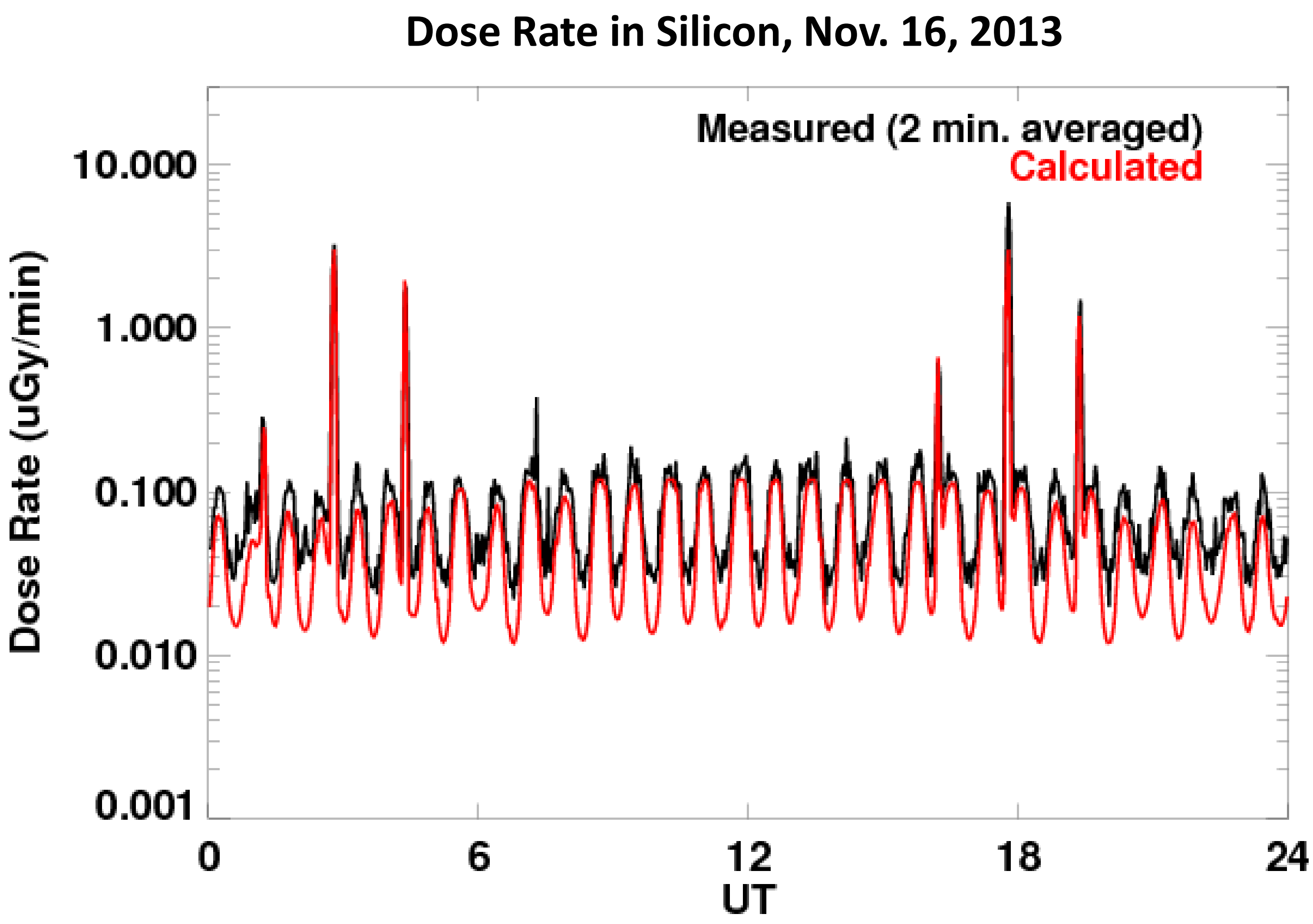


- Calculated results appear to accurately model the time dependence of the varying dose rate within ISS
- Similar trends for all 4 detectors

US Lab Dose Rate

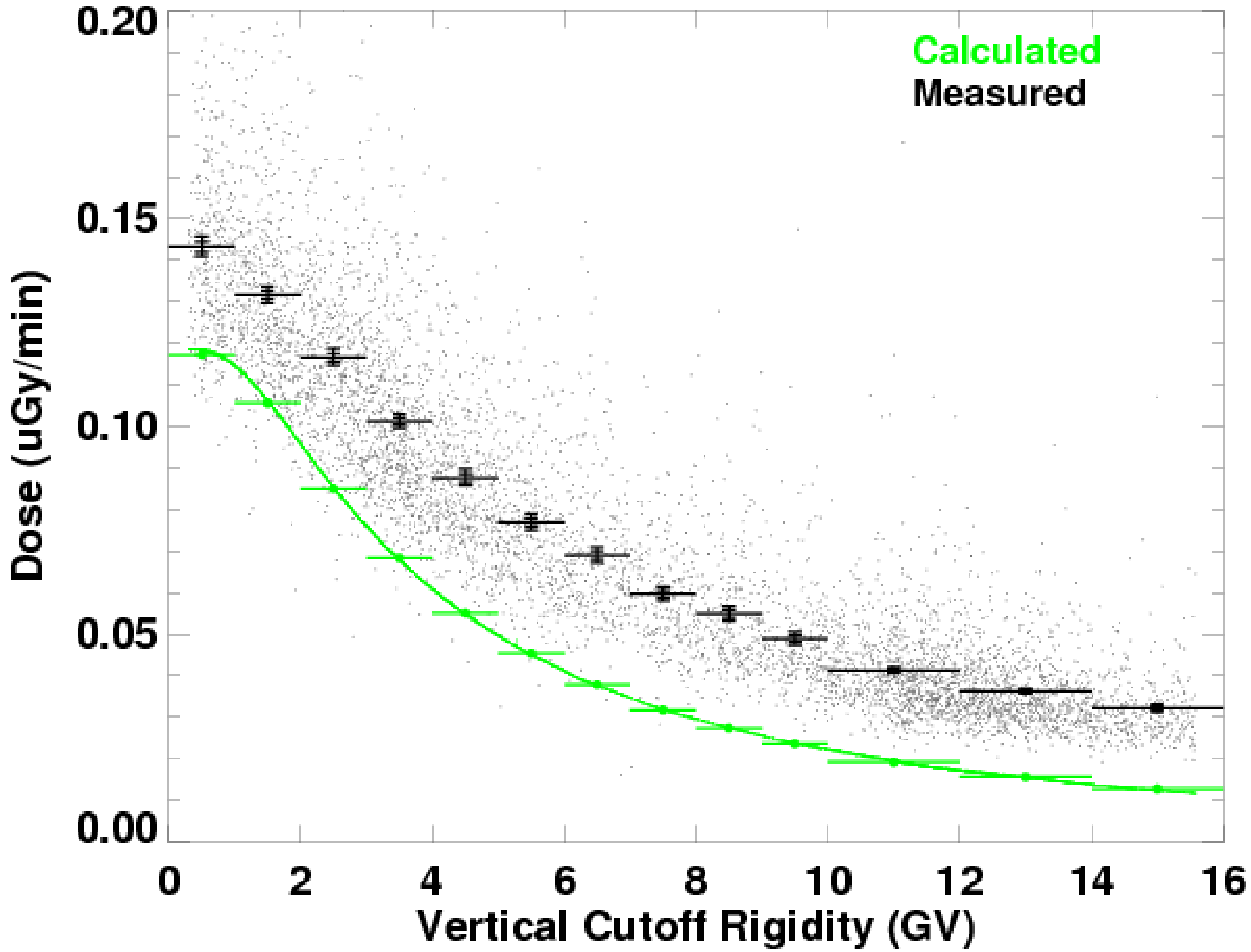


Average Dose Rate (2 Minute Bins)



- Calculated results appear to under-predict measurements
- The under-prediction appears to be larger near the equator, where the magnetic field rigidity is largest

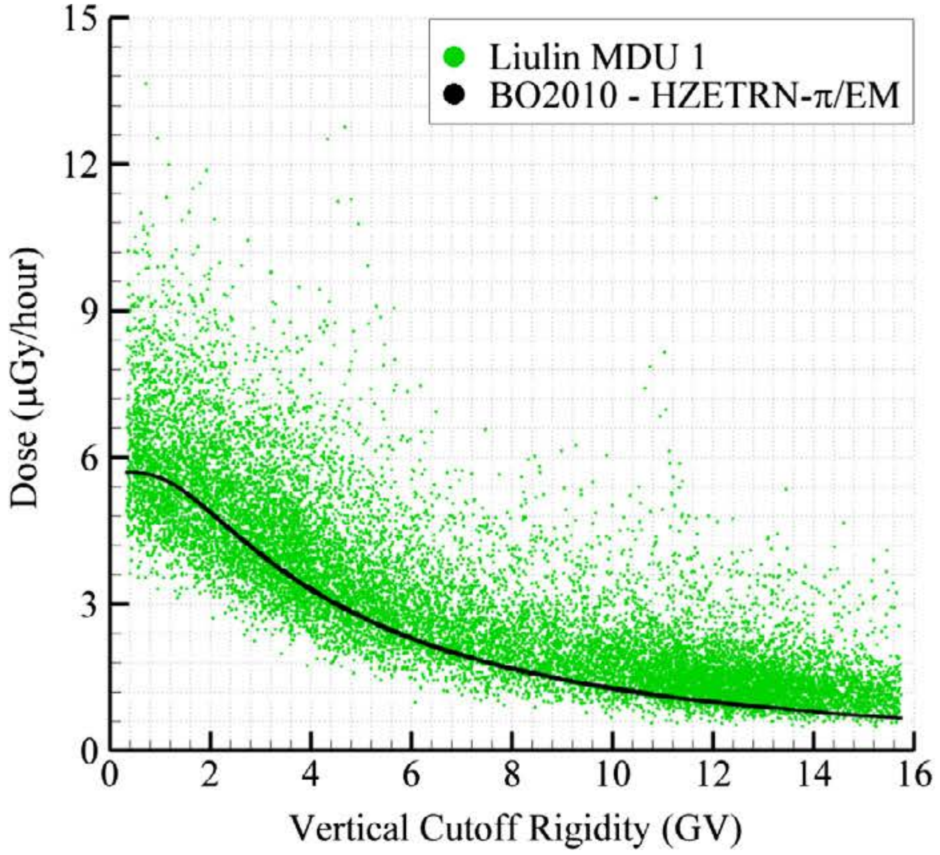
Dose Rate vs. Rigidity – HZETRN with Straight-Ahead Approx.

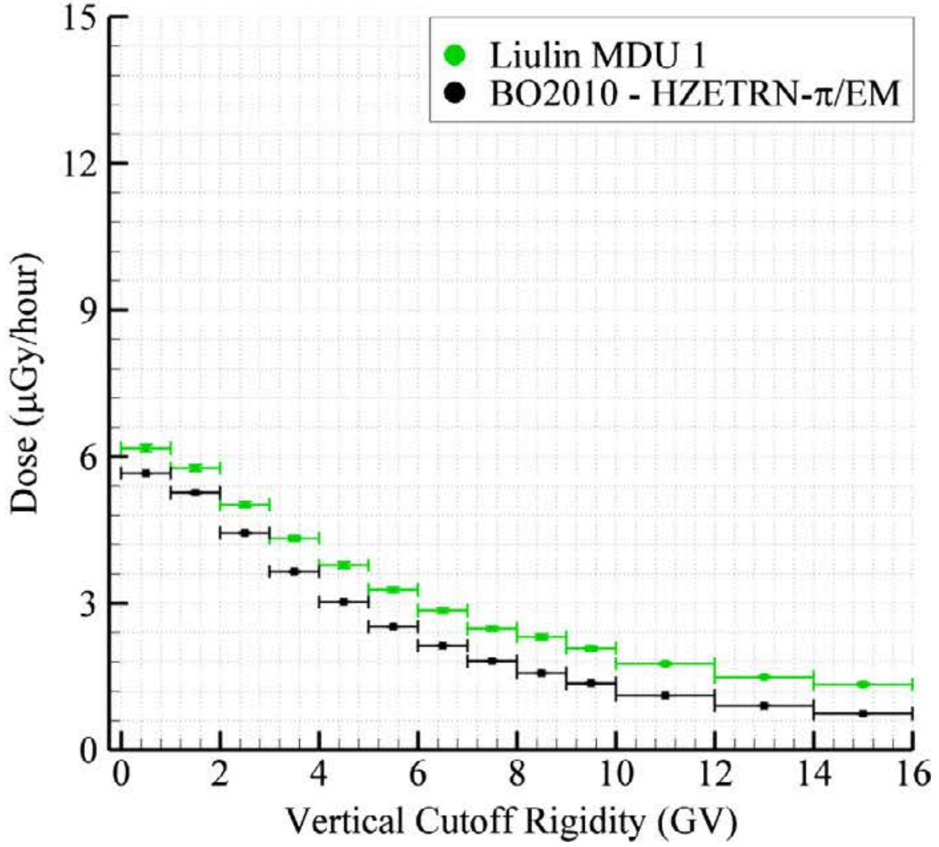


- Dose rate plotted against the rigidity of the Earth's magnetic field
- Mean under-prediction varies from ~18% at low rigidity (most like free space) to ~60% at high rigidity
- Results were similar for the other detector locations:
  - Cupola: ~28% - ~65% under-prediction
  - Node 1: ~26% - ~65% under-prediction
  - Dose in tissue in TEPC in Service Module: ~16% - ~45% under-prediction

Dose Rate vs. Rigidity – Previous Results

Difference Between Model and Liulin Detector Measurements for July 6-13, 2001





Similar under-predictions were seen in previous comparisons between calculated results and measurements with TEPC and Liulin detectors

[1]Slaba et al. *Adv. Space Res.* **47**; 2011.
[2]Slaba et al. *Adv. Space Res.* **52**; 2013.

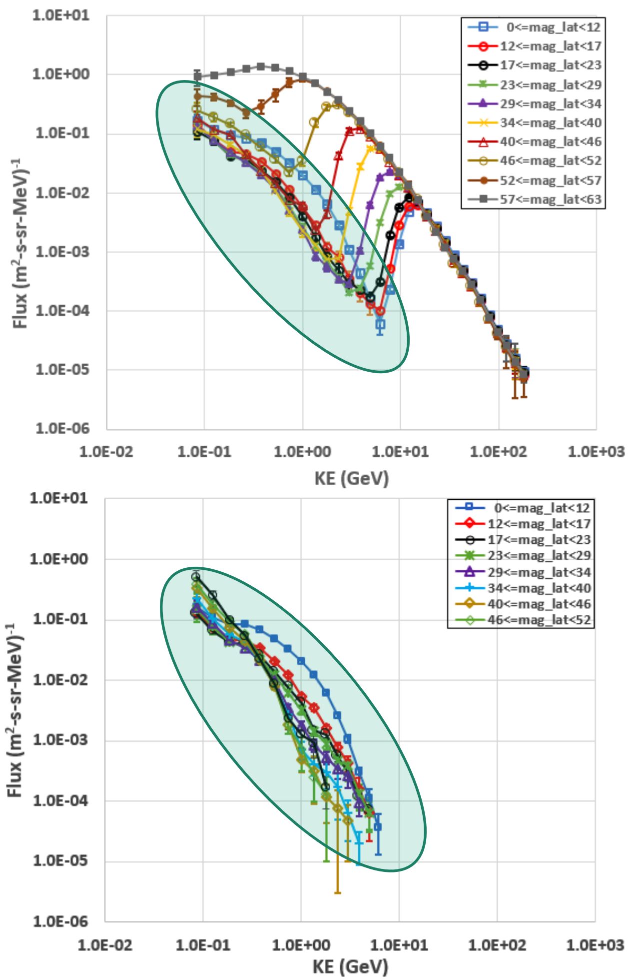
Investigation of Calculation Under-Prediction

The sensitivity of calculated results to variety of model assumptions has been examined:

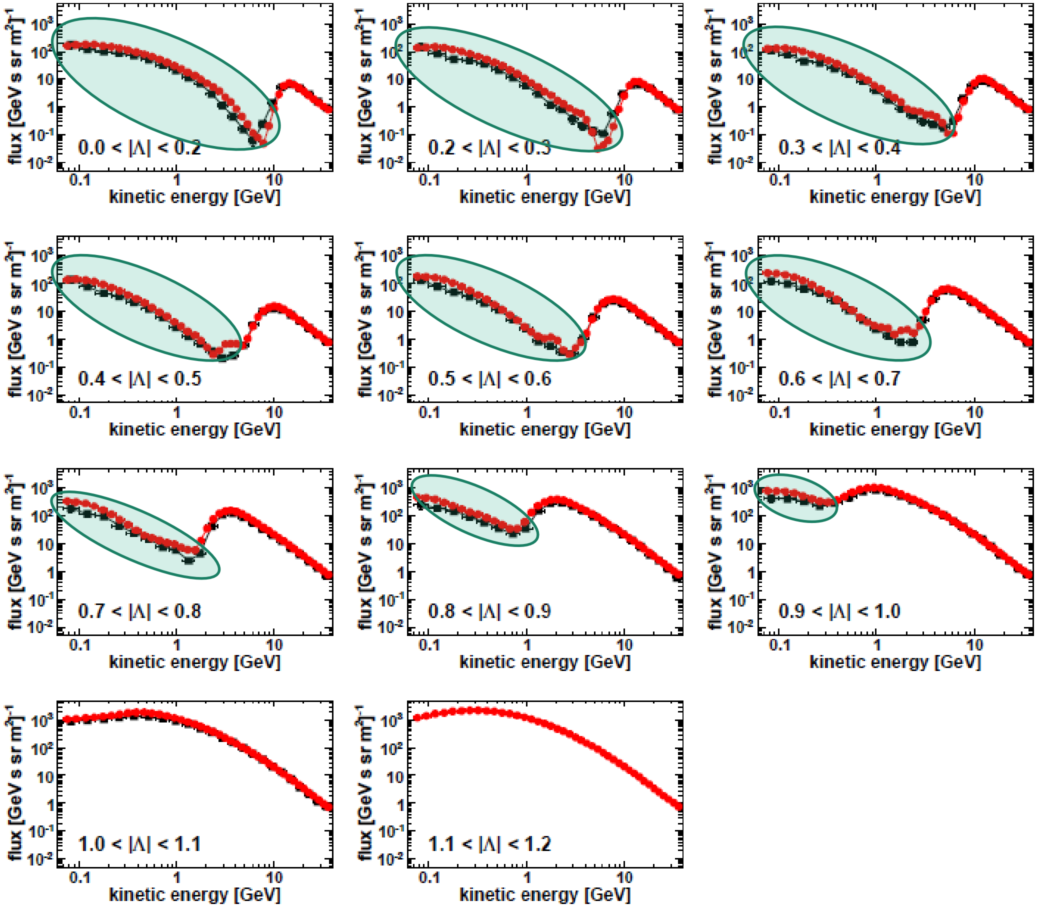
- Geometry/Shielding
  - Pressure Shell Areal Density – minimal impact on calculated dose
  - Materials Definition in CAD Models – underestimation of the quantities of heavy metals in the ISS could result in a small underestimation of dose rate
  - Number of Rays in Ray-Trace – 1002 rays shown to be adequate
- Environment Modelling
  - GCR Model – Dose rates using various versions of Badhwar-O'Neill and Matthia models are similar
  - Magnetic Field Models – Tsyganenko model compared to simpler IGRF model, simpler model adequate for ISS orbit <u>during quiet time</u>
  - Use of Isotropic GCR Environment - adequate for calculated dose inside ISS
  - Assumption that Energetic Trapped Protons only occur in the SAA – not entirely correct, see next page
- Transport Calculation
  - 3DHZETRN vs. using the straight-ahead approximation
  - Improved coupling of pion and nucleon transport
  - Improved gamma production database

Improvements to the transport code had the largest impact on calculated dose

Pseudo Trapped Protons



AMS1 Downward (top) and Upward (bottom) Moving Proton Spectrum Measurements*



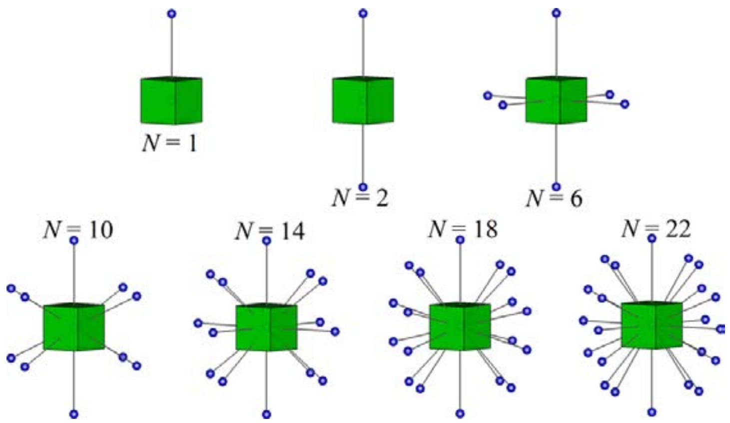
PAMELA Proton Spectrum Measurements as a Function of Geomagnetic Latitude+

*Alcaraz et al. *Physics Letter B*. **472**; 2000.
+Adriani et. al. *Journal of Geophysical Research: Space Radiation*. **120**; 2015.

- In-space measurements include a proton component not represented in current trapped proton models
  - AMS1 (Alpha Magnetic Spectrometer 1) aboard STS-91 in 1998
  - PAMELA (Payload for Antimatter Exploration and Light-nuclie Astrophysics) 2006-2009
- These pseudo trapped protons may account for up to 0.01 µGy/min inside ISS at high magnetic latitude trajectory points
  - Based on parameterization of AMS1 data
- More data would be needed to model the angular distribution and time dependence of this environment

HZETRN Transport Code Upgrades

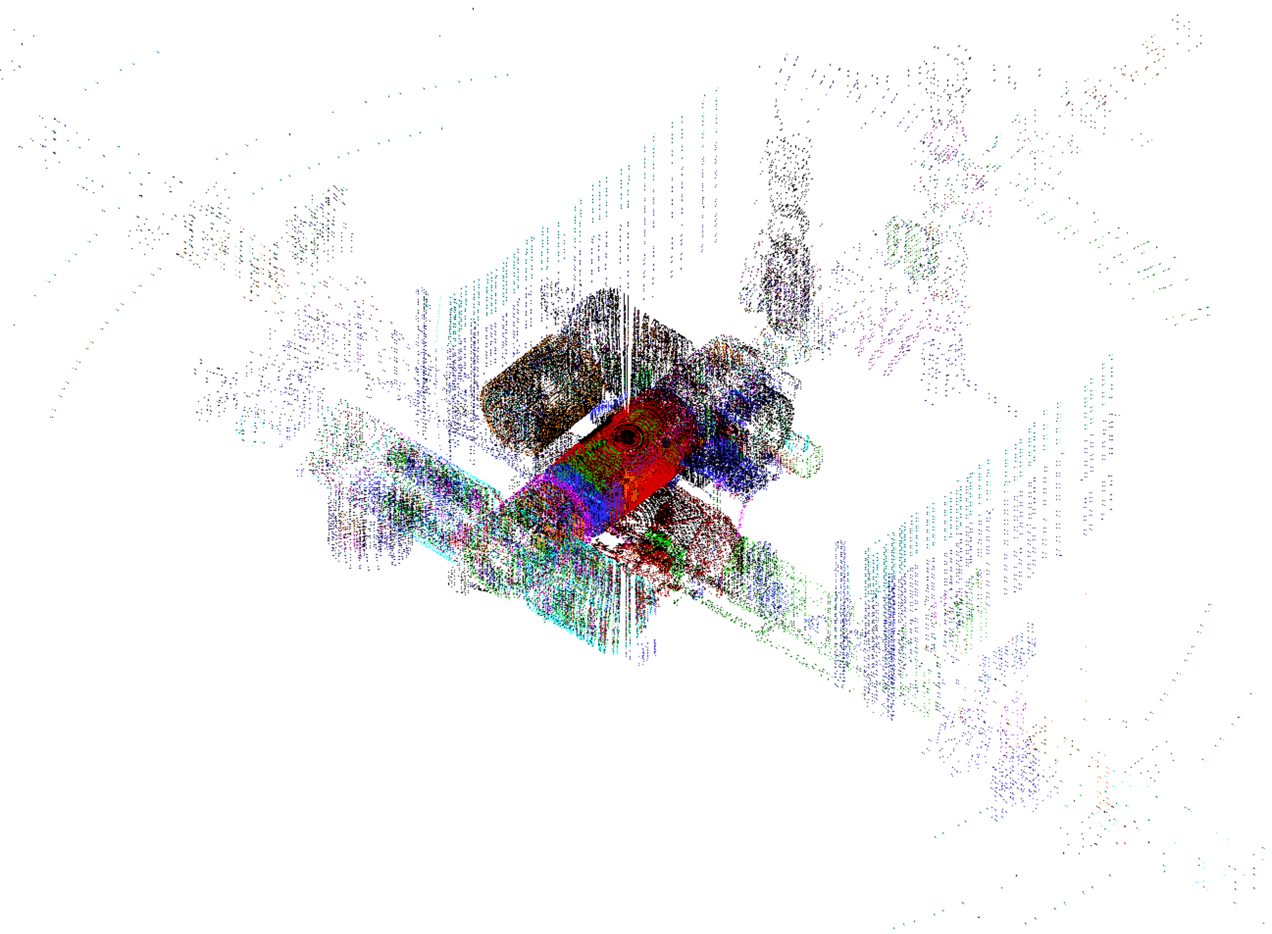
- 3-dimensional transport
  - the 3-d transport of all tracked particles is now modelled by tracking particle production and motion in a larger number of directions[1,3]
- Methods to support 3-d transport calculations in complex CAD geometry[2]
- Coupling of pion transport to the nucleon production transport
  - Nucleons produced from pions now included
- Ability to import cross sections from other codes
  - Enabling cross code comparisons
  - Corrects deficiencies in nucleon production models from pions
  - Corrects deficiencies in the angular distributions for nucleon and pion production

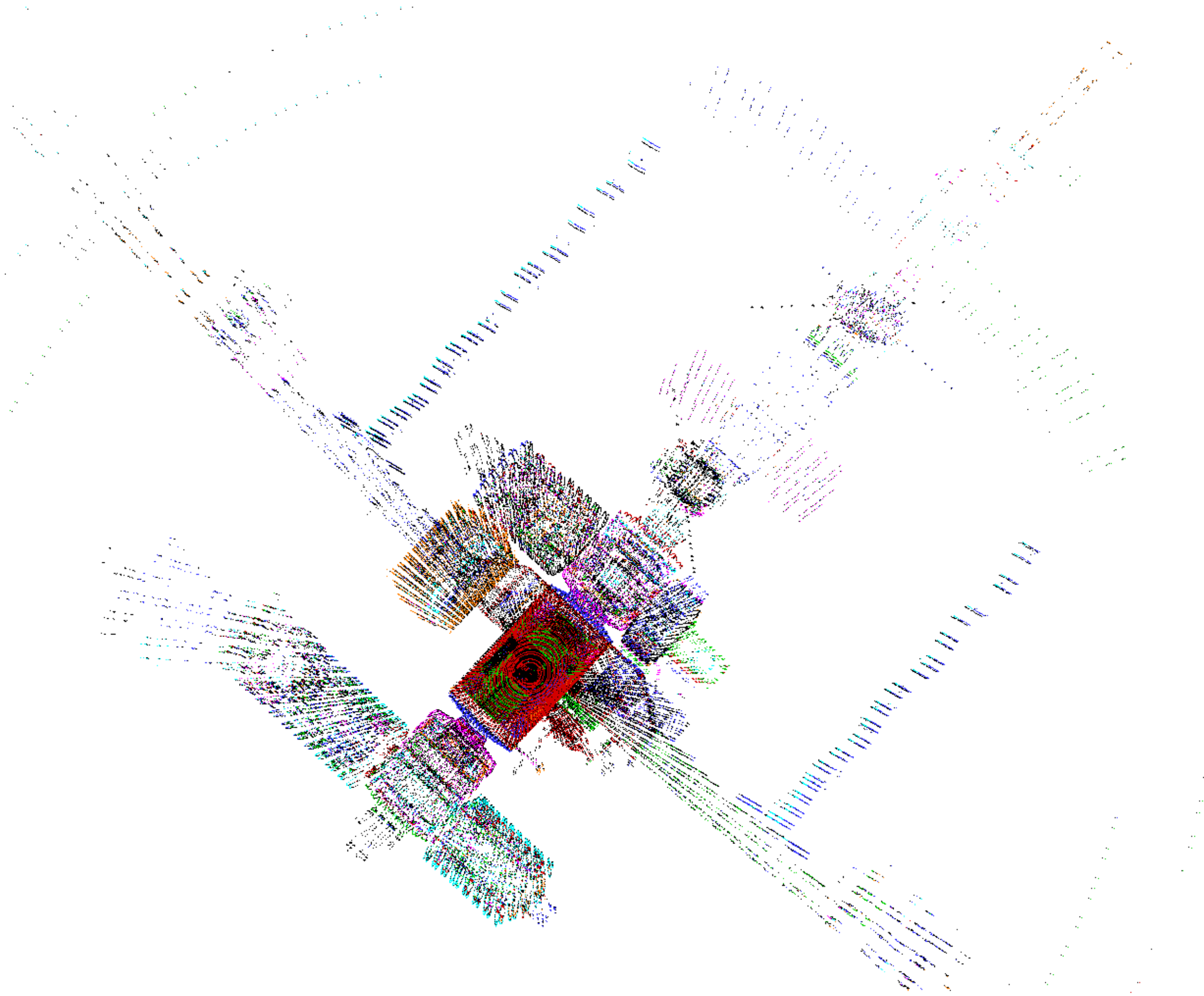


Convergence testing has shown that tracking 22 transport directions is adequate for most applications

[1]Wilson et al. *Life Sciences in Space Research.* **2**; 2014.
[2]Slaba et al. *Life Sciences in Space Research.* **9**; 2016.
[3]Wilson et al. NASA TP 219665; 2017.

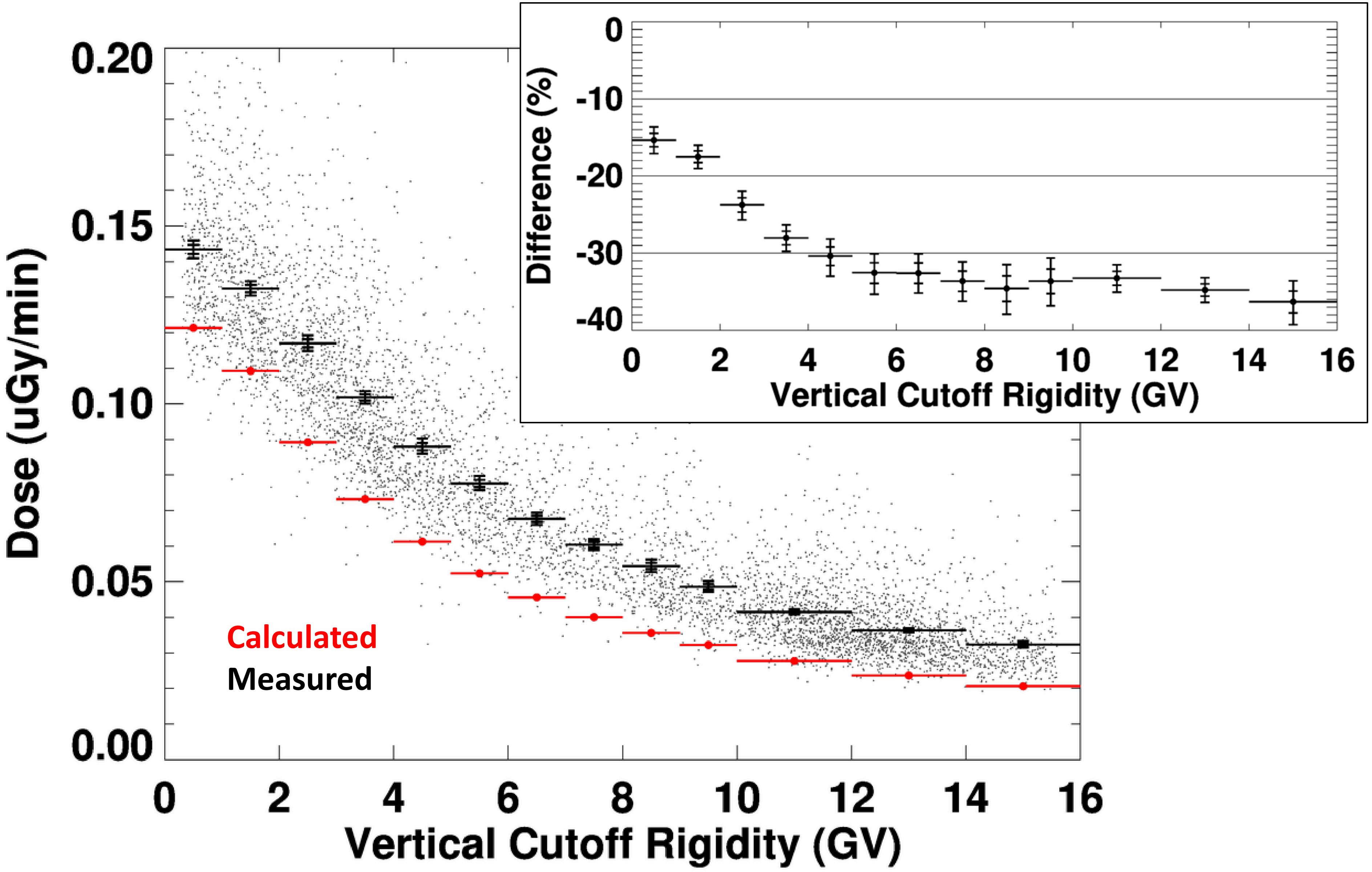
Ray-trace Geometry Interpreter for 3-d Transport Calculations





Mass included in ISS transport calculation for the US Lab location

Dose Rate vs. Rigidity – 3DHZETRN



Mean under-prediction is ~15% at low rigidity, where the environment is most like free space, and ~36% at high rigidity

Summary

- An effort to validate radiation analysis tools with ISS REM measurements is underway.
- Dose rates have been calculated and compared to ISS REM and TEPC measurements.
- Calculated results accurately model the time dependence, but under-predict the total dose and dose equivalent rates.
- Updates to the HZETRN transport code have reduced, but not eliminated this under-prediction.
- This under-prediction varies from ~15% at high latitudes to ~36% near the equator.
- A number of model assumptions related to geometry, environments, and transport calculation have been investigated to better understand their impact on the calculation under-prediction.
  - Most of the model assumptions examined had minimal affect on results.
  - Updating the transport code, had the largest impact on calculated results

Back-up

AMS1 vs. PAMELA Detector Specification

AMS1 **(Alpha Magnetic Spectrometer 1)**

STS 91

June 2 - 12, 1998 (10 days)

Data collection June 2 - 12, 1998 (10 days)

Perigee/Apogee: 350 - 390 km.

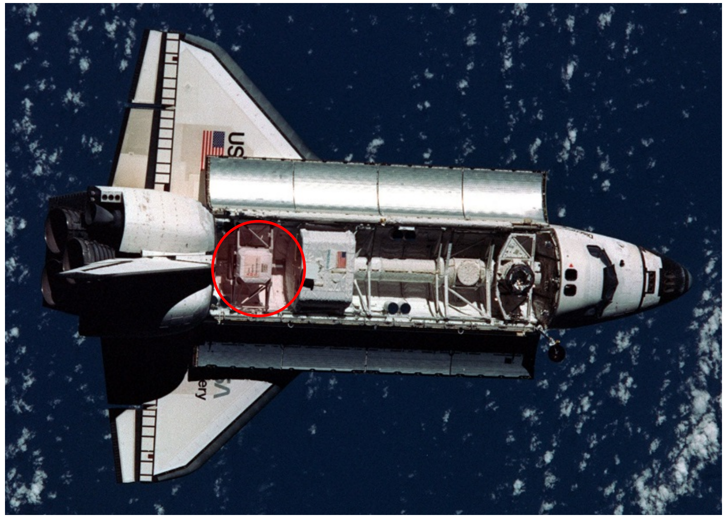
Inclination: 51.7°

Period: 92 min.

FOV=64° (wrt. Z axis) with accuracy of 1°

Proton E_K range: 0.1 - 200 GeV

SAA data are excluded



PAMELA **(Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics)**

Host Satellite, Resurs DK1 (Soyuz-FG)

June 15, 2006 - present

Data collection July 2006 - September 2009 (~800 days)

Perigee/Apogee: 360 - 604 km. (~600 km. circular since 2010)

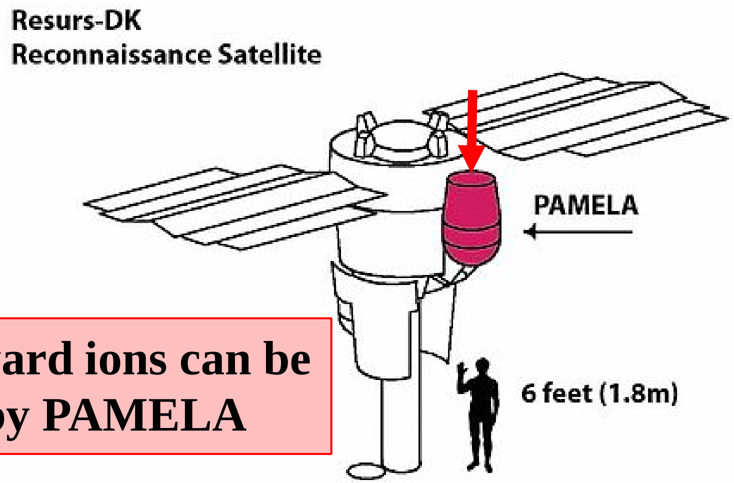
Inclination: 70°

Period : 94 min.

FOV~60°

Proton E_K range: 0.1 - 70 GeV

SAA/SEP data are excluded



***Only downward ions can be collected by PAMELA**