Applying CubeSat-scale low resource on-orbit instrumentation to Root-Cause Analysis of Anomalous Solar Array Degradation

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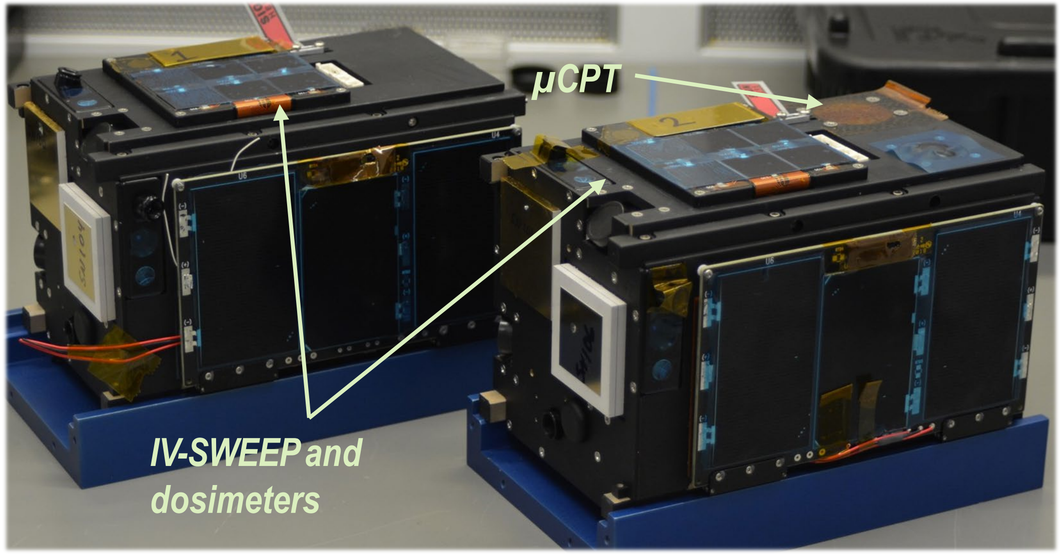
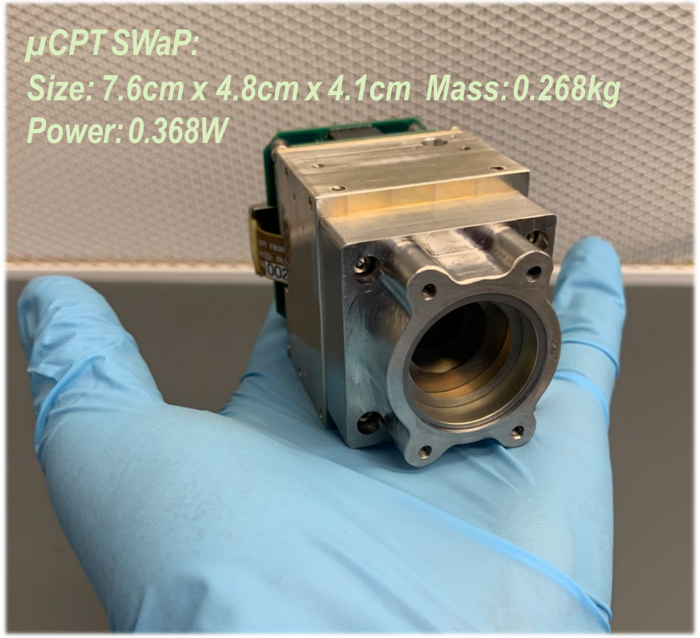
AeroCube-10 (AC10) radiation measurements

- *AC10 is a 2x 1.5U CubeSat mission*
- *Launched with Antares on Cygnus ISS resupply mission on 17 April 2019; deployed from Cygnus and successfully began operations 7 August 2019*
- *Micro-charged particle telescope (μCPT) is a prototype instrument that measures:*
  - Ions: >80 keV to 1 MeV across 12 channels with ΔE/E = 0.25
  - Hydrogen isotopes: 1.5 to 3.9 MeV across 4 channels at ΔE/E = 0.42
  - Alphas: 1.0 to 4.0 MeV across 7 channels at ΔE/E = 0.17
  - Electrons: >100 keV to 2.5 MeV across 12 channels at ΔE/E = 0.27

AeroCube-10



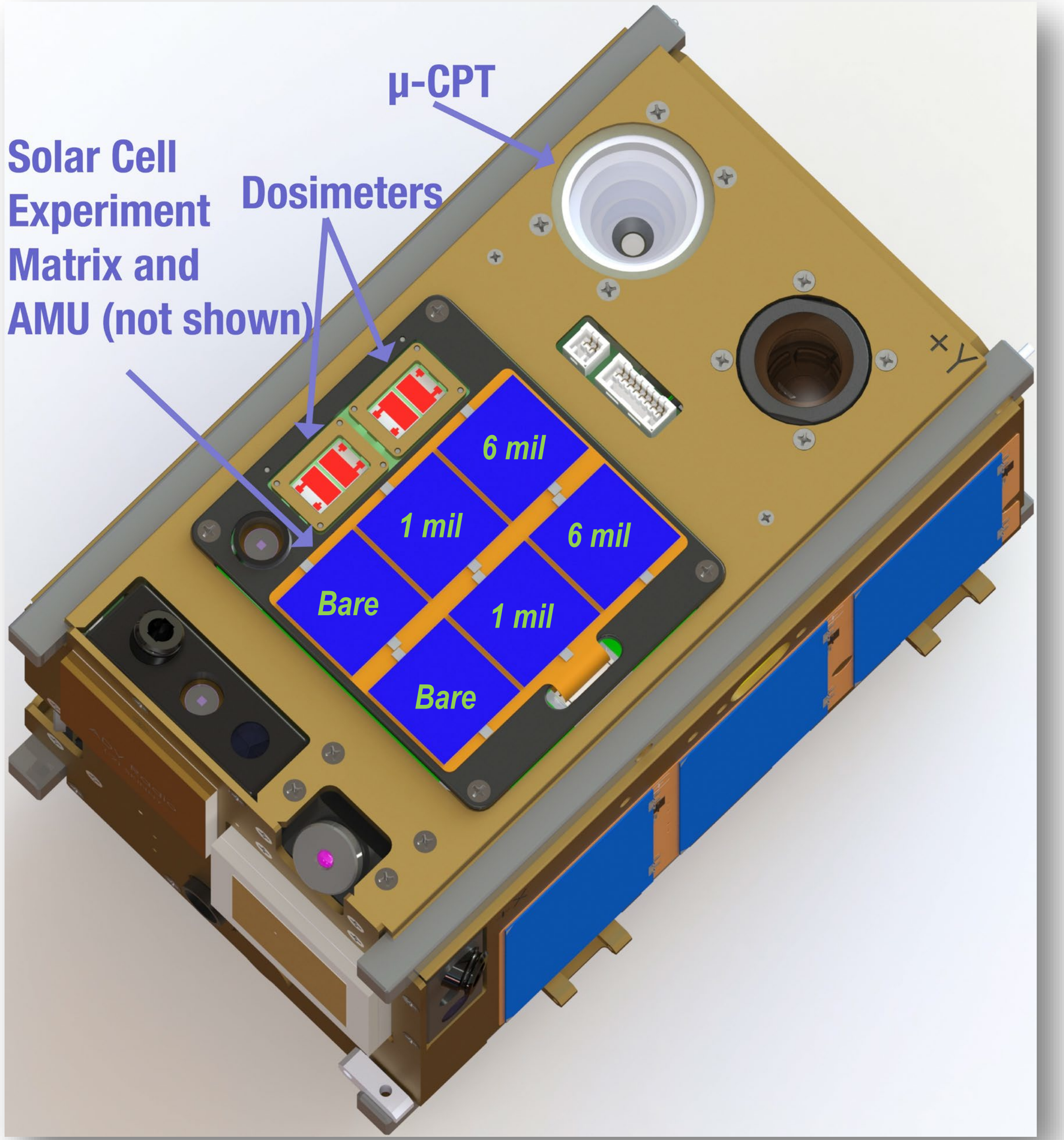


μCPT monitors the LEO radiation environment at the same time as the AMU monitors the space solar cell test matrix.

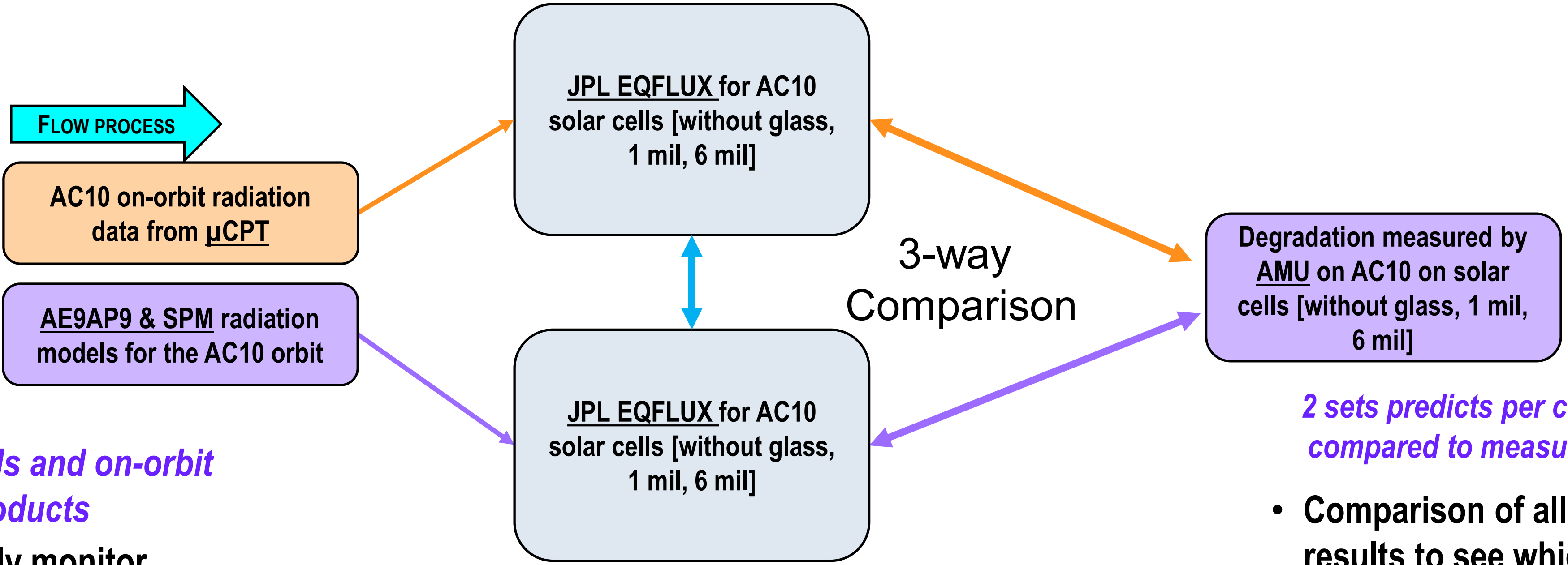
AeroCube-10 (AC10) Solar Cell IV-SWEEP Experiment

Current Voltage-Space Weather and Environment Effects Payload (IV-SWEEP)

- Charged particle radiation flux measurements provided by the micro-Charged Particle Telescope (μ-CPT) for application to solar cell degradation modeling
  – Integral radiation dose provided by the dosimeters
- IV-SWEEP [Lee+ 2018, 2020] enables quantitative comparison of solar cell degradation measured in-situ to model and data-driven predictions.
  – Precise solar cell degradation data from solar cell experiment matrix measured by the Aerospace measurement unit [AMU; Mann+ 2018]



AeroCube-10 Experiment Process



Radiation models and on-orbit data products

- µCPT to directly monitor radiation (thought to be most relevant) for degrading typical space solar cells
- Particle fluences provided by the AE9AP9 & SPM environment models

JPL EQFLUX [Anspaugh, 1996] degradation prediction using models and data products

- Input the outputs from the AE9AP9 models as well as µCPT radiation data into solar cell degradation models.
- This will yield at least two predictions (AE9AP9+SPM model environment and measured environment) per degradation model for the AC10 orbit per solar cell configuration

2 sets predicts per cell configuration compared to measured degradation

- Comparison of all degradation results to see which are closer to the AC10 on-orbit data.
- Analyze and interpret the results in the context of modeling solar cell degradation and ground irradiation testing
- Results could have implications for improving environment and/or degradation models as well as ground testing

AeroCube-10 Micro-Charged Particle Telescope (μCPT) data

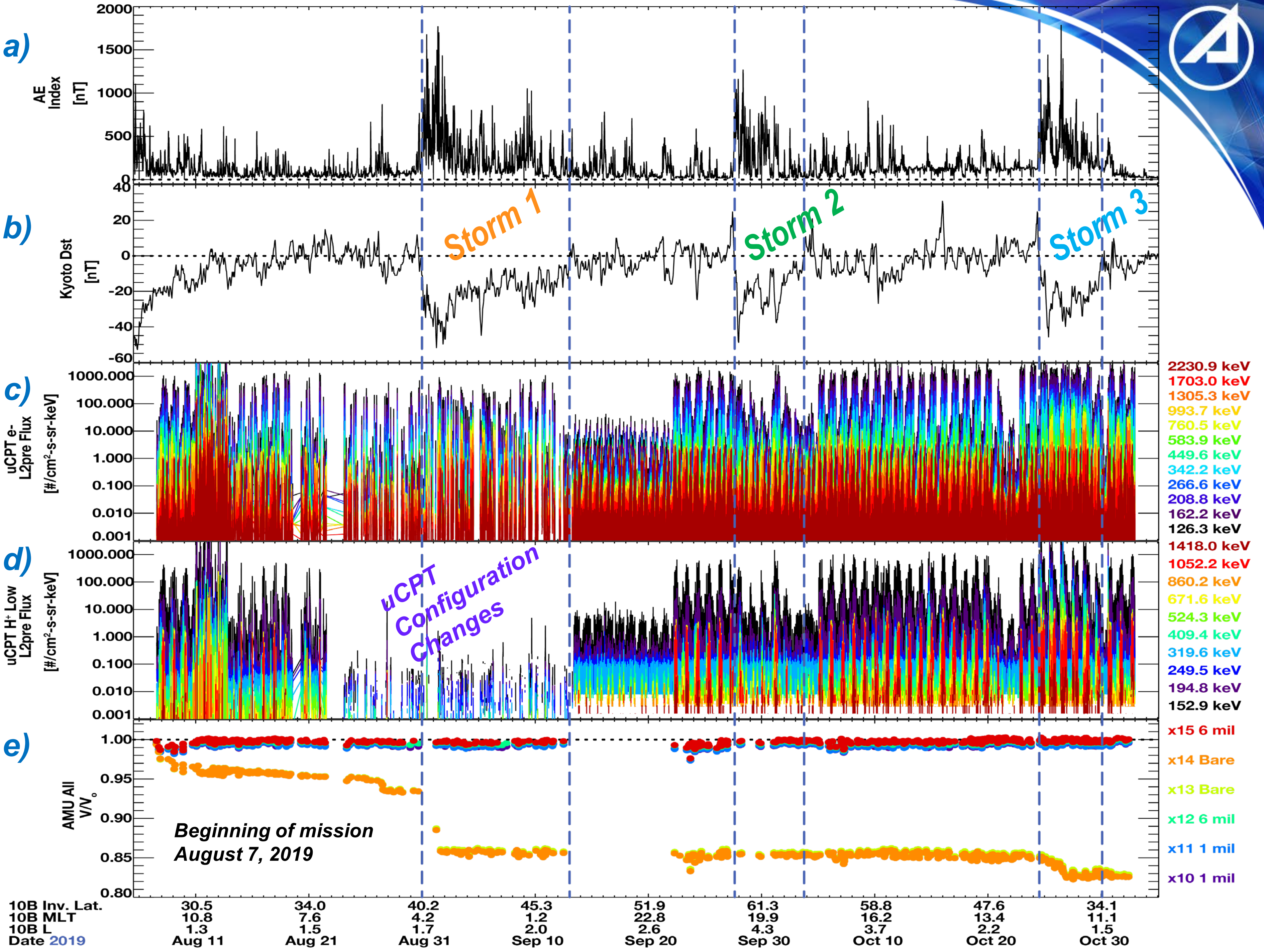
Level 2 preliminary flux products applied to interpret solar cell degradation

- Measurements of electrons and protons acquired over >~100 keV energy range
  - *Proton measurements from 2 lowest energy channels covering >80 to ~120 keV energy range were discarded due to limited triggering of these channels and unreliable fluxes*
- Preliminary Level 2 flux data (“L2pre data”) were calculated and applied to this effort focused on Storm 3
  - *μCPT instrument efficiency estimate comes from “boxcar” approximation that does not fully represent the response over all particle energy ranges*
  - *L2pre data are not corrected for penetrating background radiation that may result in modest increases in the particle fluxes calculated for both electrons and protons*
  - *Bowtie analysis (Selesnick & Blake, 2000) is in progress to inform production of final Level 2 flux data that will include additional flux correction for penetrating background*
- L2pre fluxes were used to calculate differential fluences accumulated per unit time interval separating neighboring flux samples
  - *Assumption that fluxes were stable between the neighboring time samples*
  - *Assumed symmetry over all particle pitch angles in conversion of directional to omnidirectional particle fluxes*

Selesnick, R. S., and Blake, J. B. (2000), On the source location of radiation belt relativistic electrons, *J. Geophys. Res.*, 105(A2), 2607– 2624, doi:10.1029/1999JA900445.

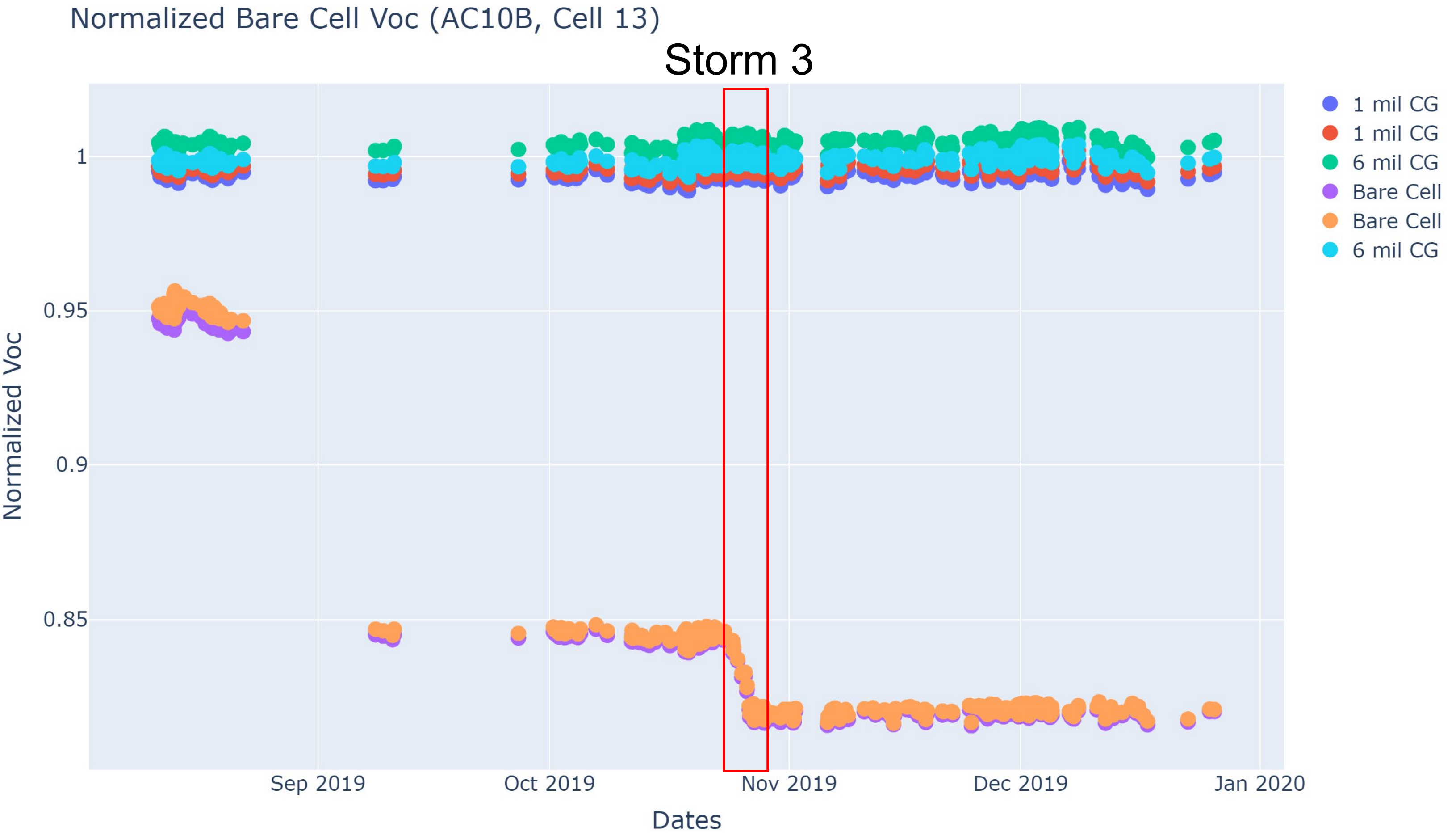
Early mission summary plot

- Auroral Electrojet (AE) and Disturbance storm time (Dst) indices measure current perturbation in terms of magnetic field by ground-based magnetometers.
- Based on AE and Dst indices, identified 3 storm intervals occurring near beginning of AC10 mission
  - µCPT configuration changes were being implemented before and throughout ***Storm 1*** and data generated were unreliable
  - Did not notice obvious solar cell degradation signatures associated with ***Storm 2***
  - Focus analysis and modeling efforts on ***Storm 3*** due to good data coverage



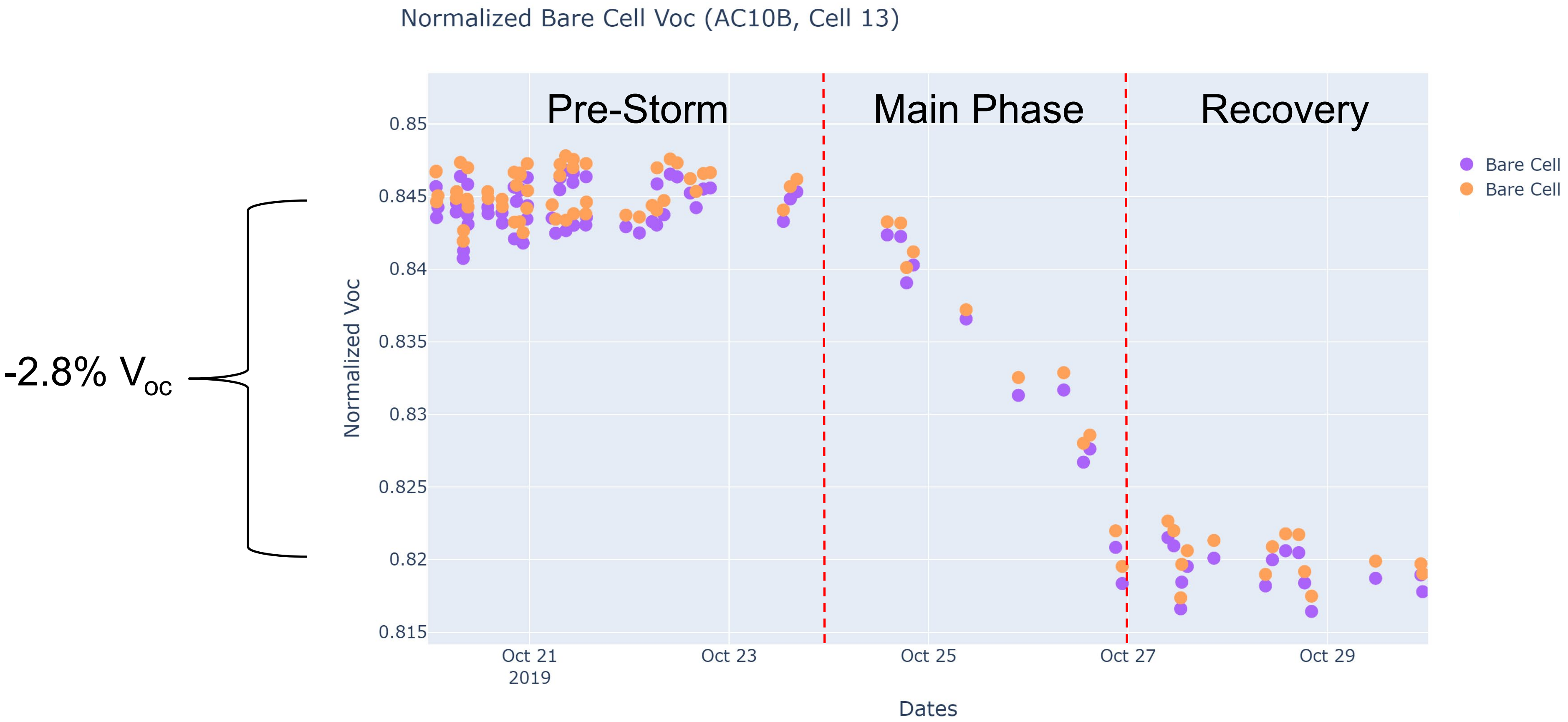
AE and Dst indices were provided by the WDC for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html).

V_{OC} Data During Storm 3



- Storm 3 is a period with simultaneous radiation data and V_{OC} telemetry
- Cells with 1 mil & 6 mil coverglass showed minimal degradation
- Bare cells of interest because of their large Voc degradation and exposure to full environment (unshielded)

Storm 3: Was decrease in V_{OC} due to Radiation?



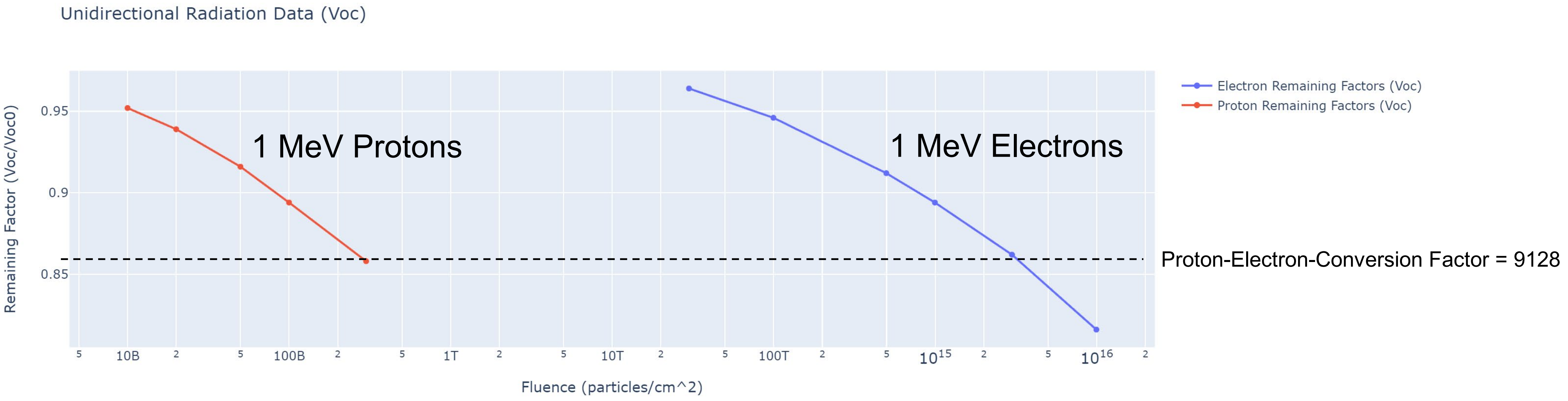
Task:

- Compare environments from 3-day periods: pre-storm, main phase, and recovery

Questions:

- Can on-orbit radiation environment data help determine the cause of decreasing Voc in bare cells?
- Is the radiation measured enough to create ~ 3% drop in V_{oc}?

AC10 is in Proton Dominated Environment



10/20/2019-11/1/2019:

- Electron Total Fluence: 2.87e9 1 MeV e/cm^2
- Proton Total Fluence: 3.603e13 1 MeV e/cm^2

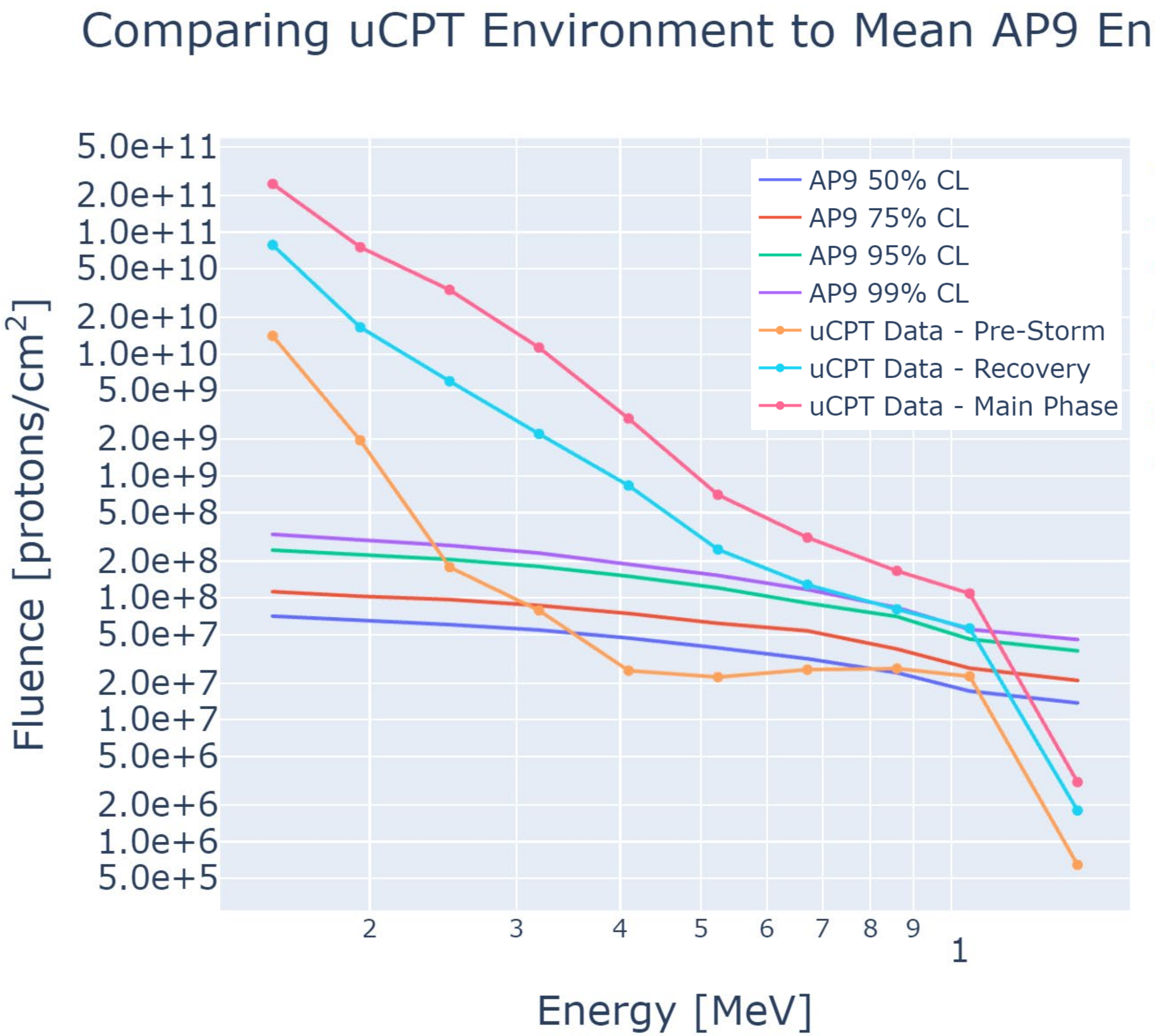
Conclusion: Proton Contribution 4 Orders of Magnitude > Electron Contribution

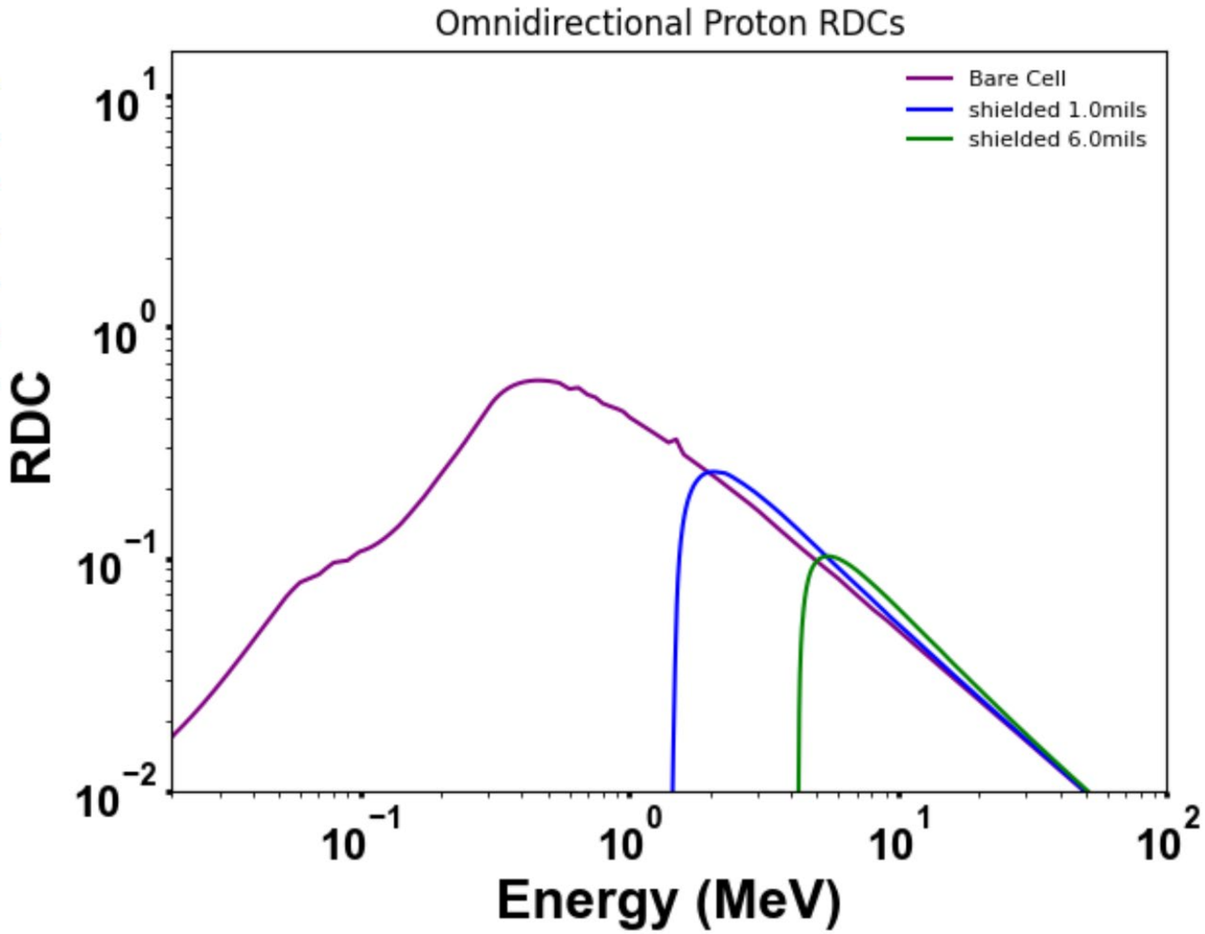
Actions:

1. Will only calculate Proton Contribution
2. Reduce calculation errors by using proton RDCs and 1 MeV proton equivalent fluence

AP9 & μCPT Environments vs RDC

- Elevated proton fluence during storm compared to AP9 and μCPT data before and after storm period
- Low energy protons appear elevated for all μCPT spectra
  - Only the storm data is elevated above 99% CL for higher energies

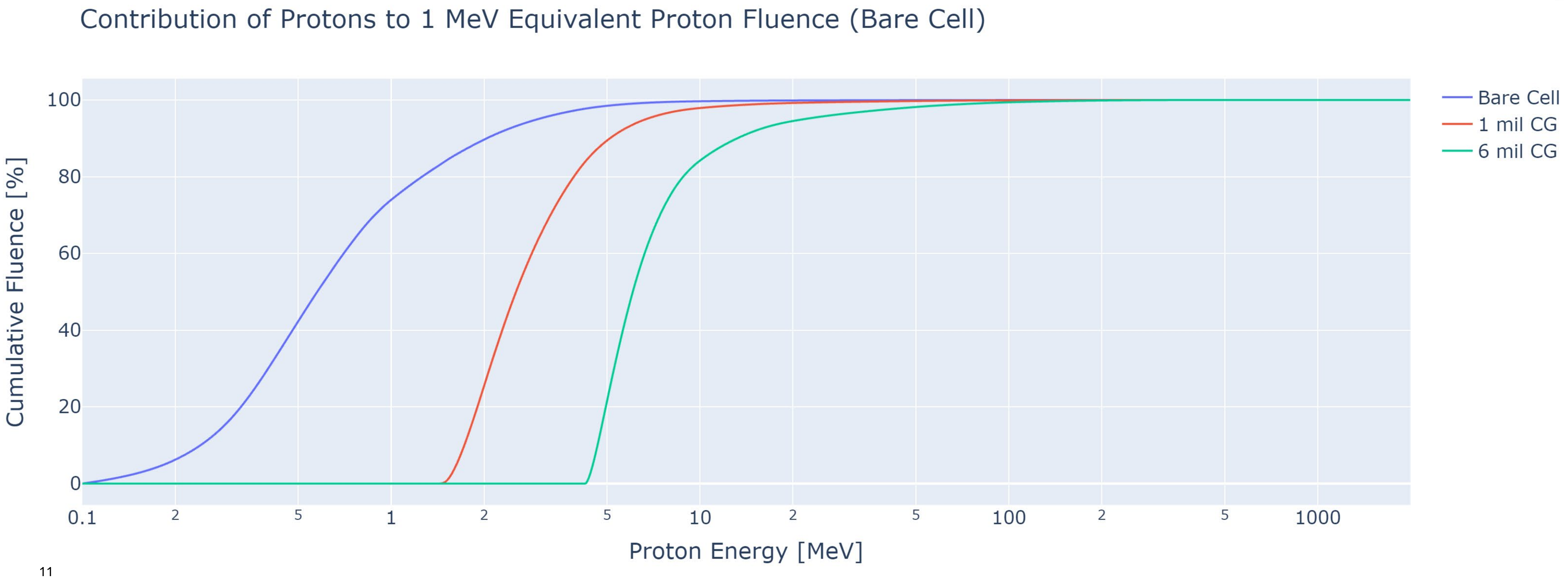




uCPT Captures Majority of Damaging Proton Energy Range

- Convolving the Bare Cell RDC with the particle spectra reveals the contribution of each energy bin to the 1 MeV proton fluence

- Low Energy Protons cause the majority of damage according to AP9 (99% CL) predictions
  - 84% of contribution to equivalent fluence from protons < 1.5 MeV
  - 90% of contribution to equivalent fluence from protons < 2 MeV

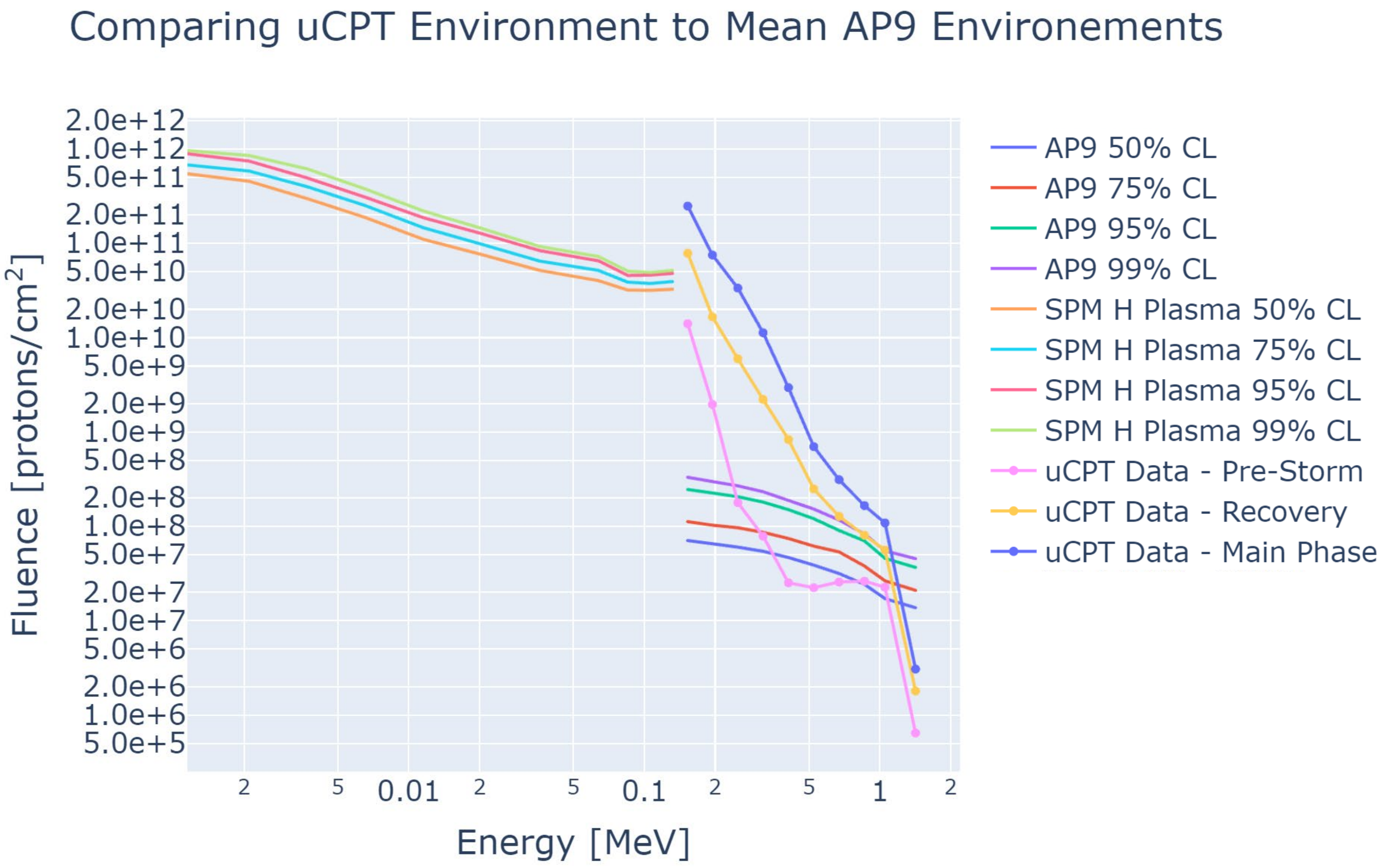


Plasma Environment

- Including Proton Plasma increases equivalent dose by 1 order of magnitude during storm
- Dramatic rise in µCPT environment appears to close gap between AP9 and SPM H (Proton Plasma)

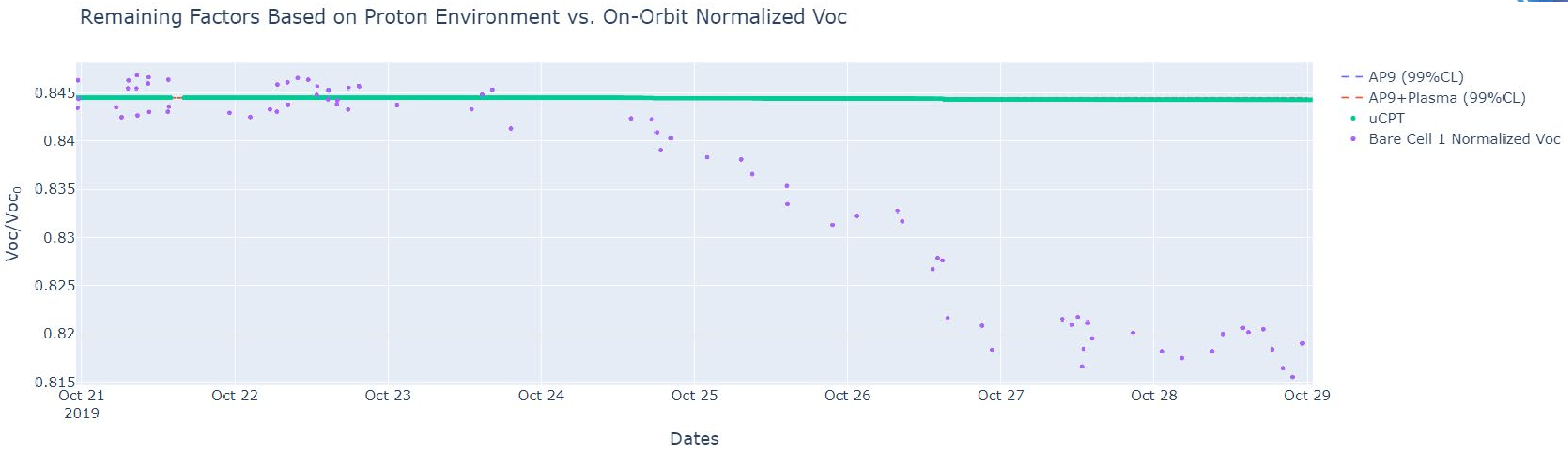
Takeaway:

- Understanding low energy proton/plasma environment as well as proton RDC is important for more accurate determination of bare cell behavior.



	Cumulative Storm Fluence (1 MeV p/cm²)		
Date	AP9 (99% CL)	AP9 + Plasma (99% CL)	µCPT
10/24/2019	3.75E+06	3.74E+07	6.28E+08
10/25/2019	7.51E+06	7.47E+07	1.24E+09
10/26/2019	1.13E+07	1.12E+08	3.02E+09

Effect of Storm on Predicted Remaining Factors (Continued)

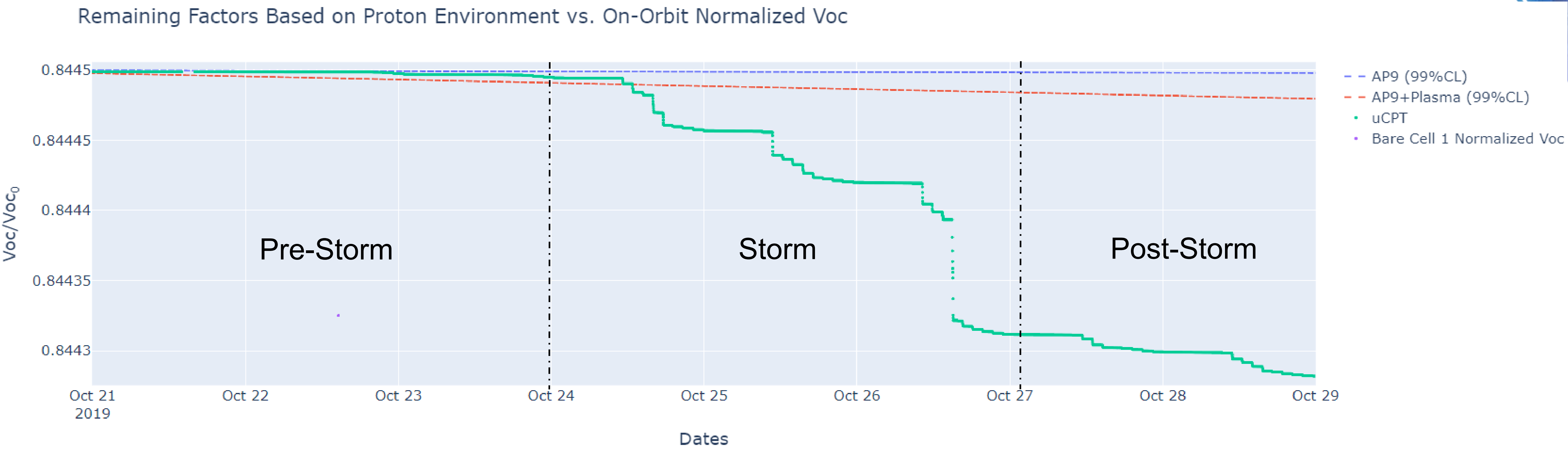


The calculated change in Voc due to the µCPT environment, is much smaller than the measured decrease.

Proton radiation alone cannot explain degradation:

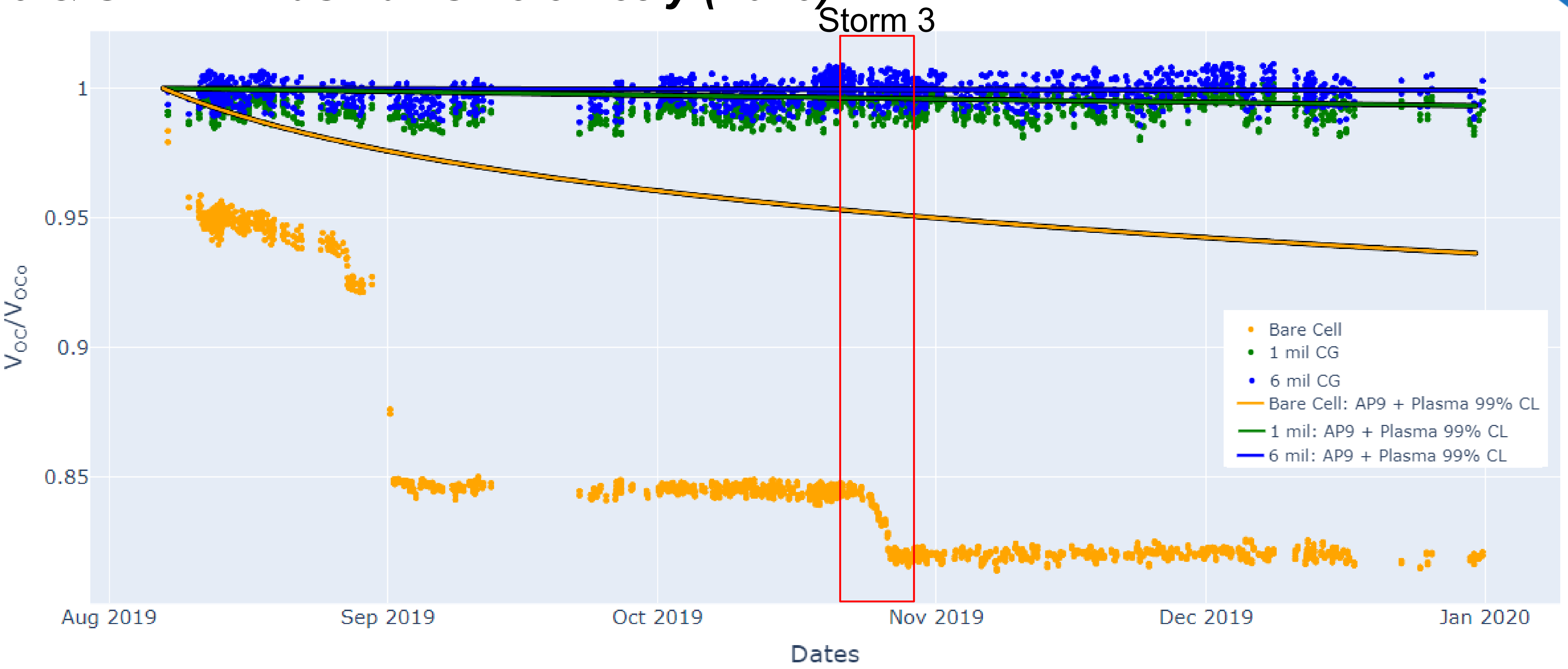
- ~$3x10^9$ 1 MeV p/cm^2: Fluence produced by Storm 3
- ~$6x10^{11}$ 1 MeV p/cm^2: Fluence required for 3% V_{OC} drop

Effect of Storm on EQFLUX Predicted Remaining Factors



- Comparing measured environment compared to AP9 & AP9+Plasma shows expected trend
- Magnitude of decrease is much smaller than 2.8%.
  - We assumed a starting RF of 0.8445

AP9 & SPM H Plasma vs Telemetry (2019)



- **Bare Cells:**
  - Several large drops that deviate from 99% CL of mean environment
- **1 mil & 6 mil CG Cells:**
  - Reveal marginal degradation
  - Appear close to mean degradation as calculated by AP9+SPM (99% CL)

Summary

- AC10 demonstrated value in combining on-orbit radiation data & solar cell telemetry for:
  - Anomaly investigation
  - Comparing effectiveness of solar cell cover glasses

- During 24 Oct 2019 storm interval, the AC10 on-orbit environment was shown to be elevated beyond what is expected based on AP9 Mean
  - Coincided with decrease in Voc of Bare experimental cells

- µCPT validated relevant particle and energy regimes in AC10 orbit:
  - Measured fluence (of 100 keV – 1.4 MeV protons) was only able to produce a fraction of observed Voc degradation
  - Provides motivation for continuing to investigation into other contributors to degradation, including <100 keV particles

- Implications of Low Energy Proton environment
  - 1 mil & 6 mil cover glass protected solar cells similarly in the AC10 environment
  - Radiation monitors that detect low energy protons are critical for modeling PV degradation in cells with low or no shielding
  - Low Energy Proton irradiation testing is necessary to fully model solar cell behavior in proton dominated environments

References

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Supplemental Slides

Filtering Telemetry and Extracting Normalized V_{oc}

- AC10-B

- Filtering based on performance of CIC w/ 6 mil CG (because it experienced virtually no degradation)
  - V_{oc} Min: 2.6 V
  - Fill Factor Min: 0.83
  - I_{sc} Min: 0.0635 mA

- Only selected data in which bare cell was pointing at sun (“warm”)
  - Temperature Min: 25 °C
  - Temp Corrected to 28 °C

- Averaged bare cell data to obtain daily average values of V_{oc}

- Normalization for each cell based on that cell’s ground LIV measurements

AX9 50% CL & Only Low Energy Protons

uCPT

Date	Total Mission Fluence (1 MeV e/cm^2)
10/24/2019	3.26E+08
10/25/2019	6.72E+08
10/26/2019	1.60E+09
10/27/2019	1.71E+09
10/28/2019	1.89E+09
10/29/2019	1.90E+09
10/30/2019	2.01E+09
10/31/2019	2.04E+09
11/1/2019	2.08E+09

AX9: Perturbed

Date	Total Mission Fluence (1 MeV e/cm^2)
10/24/2019	1.38E+06
10/25/2019	2.75E+06
10/26/2019	4.13E+06
10/27/2019	5.51E+06
10/28/2019	6.88E+06
10/29/2019	8.26E+06
10/30/2019	9.64E+06
10/31/2019	1.10E+07
11/1/2019	1.24E+07

Used on-orbit ephemeris data

- Starting w/ Voc RF of 0.854, equates to 3.355e15 1 MeV e/cm^2.
- Fluences for during storm are far bellow mission fluence

uCPT Only Low Energy Protons vs AX9 50% CL

uCPT

Date	Total Mission Fluence (1 MeV p/cm^2)	Remaining Factor
10/24/2019	3.65E+11	0.853973
10/25/2019	3.65E+11	0.853944
10/26/2019	3.67E+11	0.853868
10/27/2019	3.67E+11	0.853858
10/28/2019	3.68E+11	0.853844
10/29/2019	3.68E+11	0.853843
10/30/2019	3.68E+11	0.853834
10/31/2019	3.68E+11	0.853831
11/1/2019	3.68E+11	0.853828

AX9: Perturbed

Date	Total Mission Fluence (1 MeV p/cm^2)	Remaining Factor
10/24/2019	3.64E+11	0.8539998
10/25/2019	3.64E+11	0.8539997
10/26/2019	3.64E+11	0.8539996
10/27/2019	3.64E+11	0.8539995
10/28/2019	3.64E+11	0.8539994
10/29/2019	3.64E+11	0.8539993
10/30/2019	3.64E+11	0.8539992
10/31/2019	3.64E+11	0.8539990
11/1/2019	3.64E+11	0.8539989

- Extracting RFs yields little measurable change in RF over course of storm
  - Both in AX9 and when using uCPT environment