An Empirical Model of Electron Flux from the Seven-Year Van Allen Probe Mission and Its Application to Interpret GPS On-orbit Solar Array Degradation

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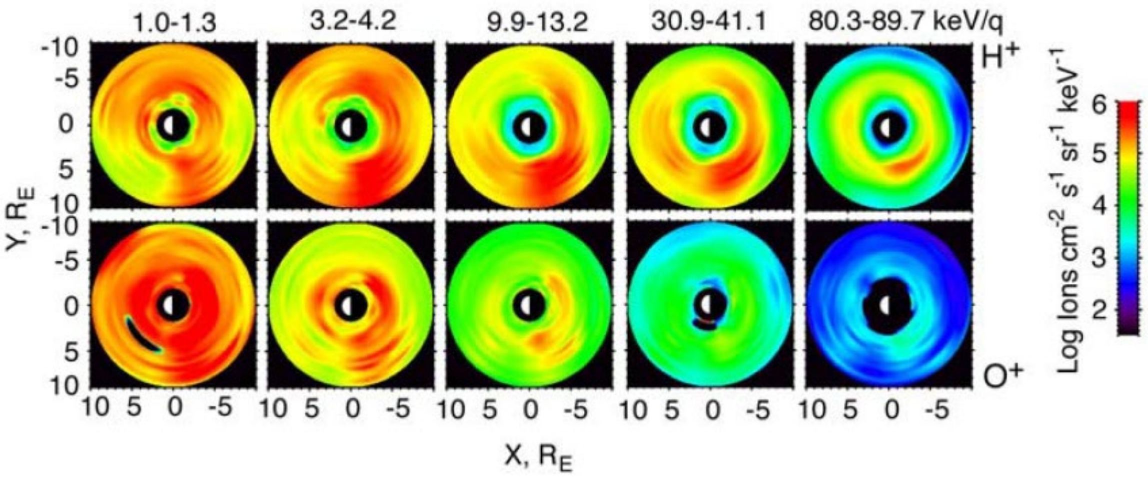
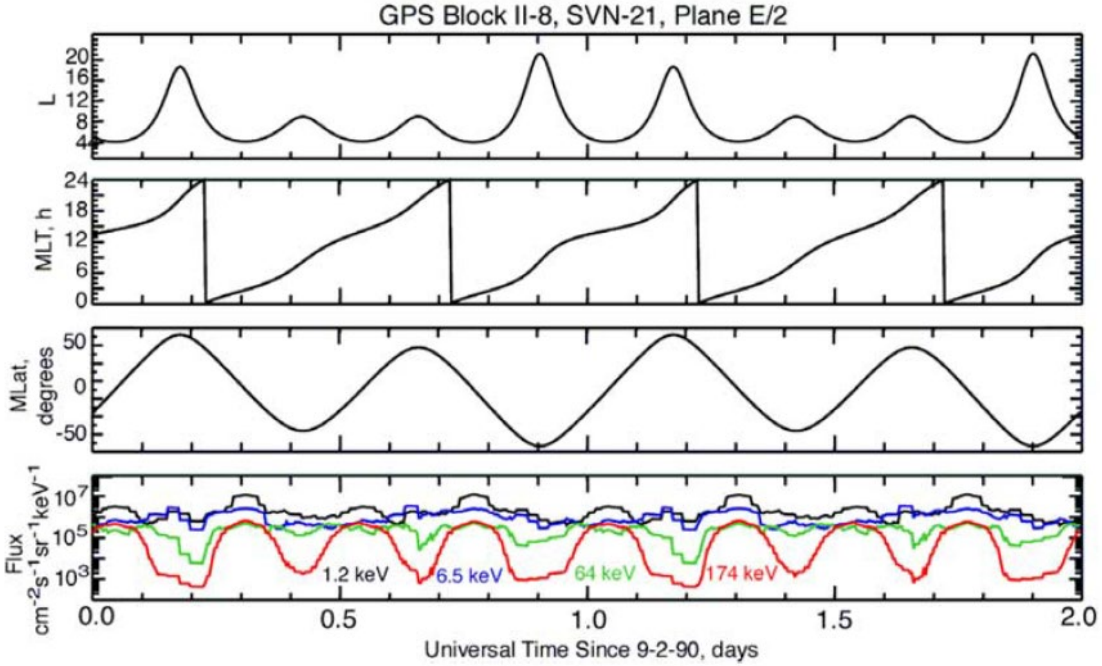
Background and Motivation

Desire data-based model on day-long timescales

- **Motivation:** Want to know the radiation environment that any given satellite encountered (e.g., GPS) in order to understand failures, degradation over time, etc. Not all satellites have radiation monitors.
- Empirical models have been designed to predict radiation environment (e.g., Roeder et al., 2005; Chen et al., 2014; Claudepierre et al., 2016), but they **may not capture actual fluxes observed a particular day**



Maps of the CAMMICE/MICS equatorial H^+ and O^+ flux in L and MLT for five energy ranges. Averages were determined from a year's worth of data. Note date-specific.
(Roeder et al., *Space Weather*, 2005)

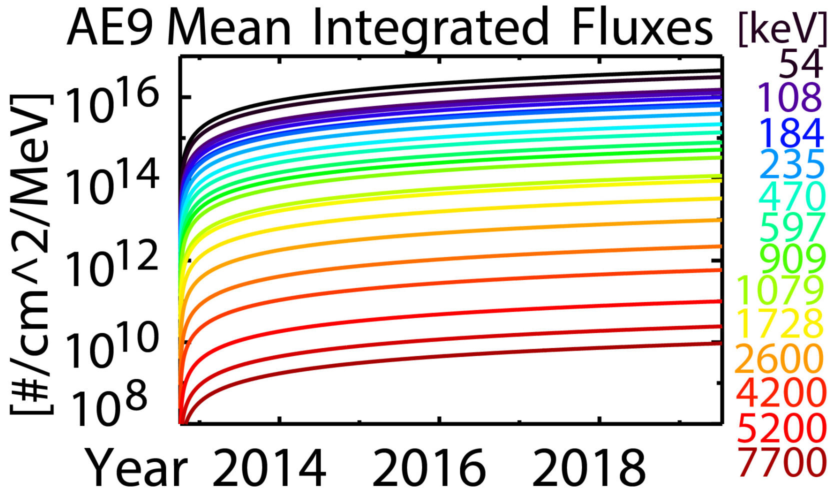


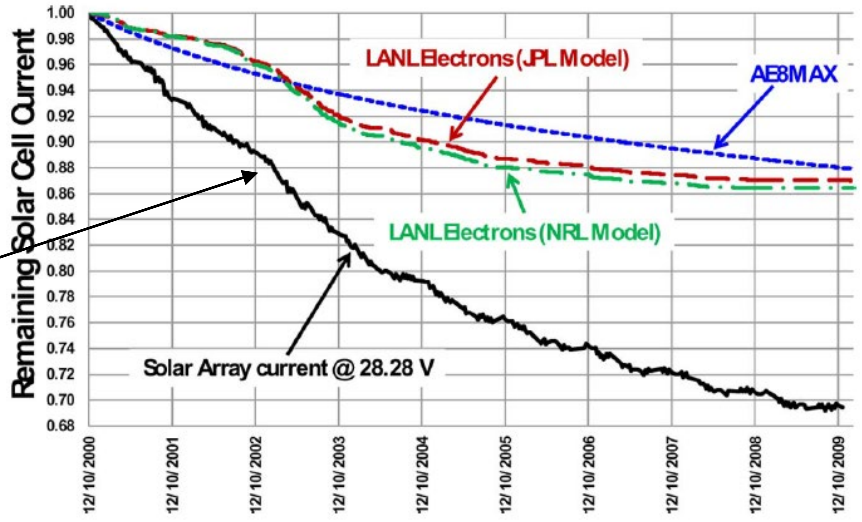
Using GPS ephemeris data to fly SVN-21 through the model to determine fluxes observed.
(Roeder et al., *Space Weather*, 2005)

Background and Motivation

Desire data-based model on day-long timescales

- AE9 provides probability of occurrence (percentile levels) for flux and fluence averaged over different exposure periods—**not meant to capture daily variations**
- Effects that require shorter-term integrals of the outer radiation belt may need special attention when it comes to environmental assessments.
  - *Spacecraft charging (DeForest, 1972; Olsen, 1983; Koons et al., 2006; Fennell et al., 2008)*
- Practical example: GPS IIR on-orbit solar array performance observed to degrade faster than predicted by any solar cell degradation-radiation environment model combination (e.g., Messenger et al., 2011)—**Are we correctly modeling the radiation environment?**





Black line is remaining factor of on-orbit solar array current.
Red, green and blue lines: modeled solar array current degradation using different radiation environment models.

Messenger et al., 2011
IEEE TRANSACTIONS ON NUCLEAR SCIENCE

What is missing?

Background and Motivation

Use Van Allen Probe data to provide actual daily fluence estimates, mapped to secondary satellite

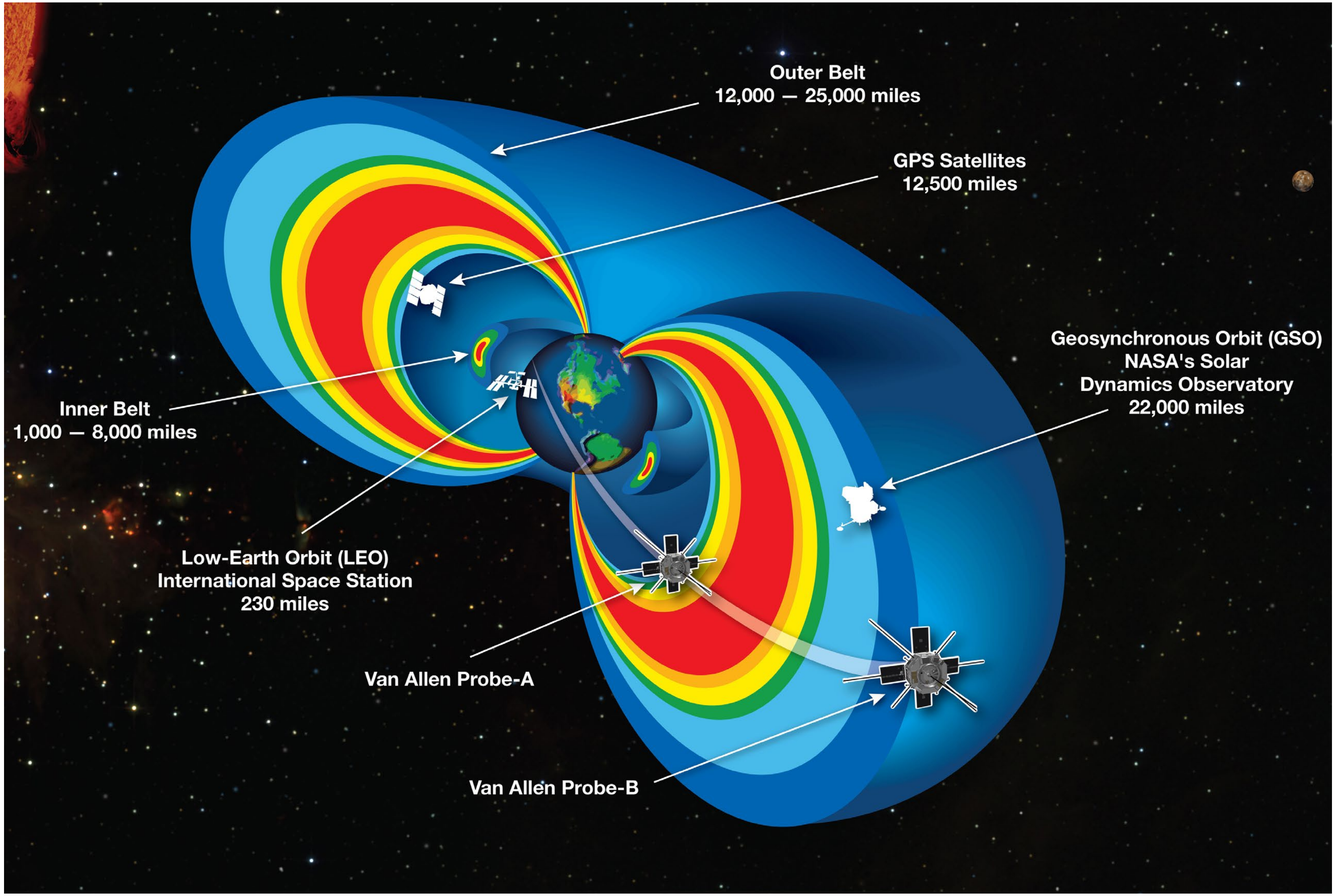


Image Credit: NASA

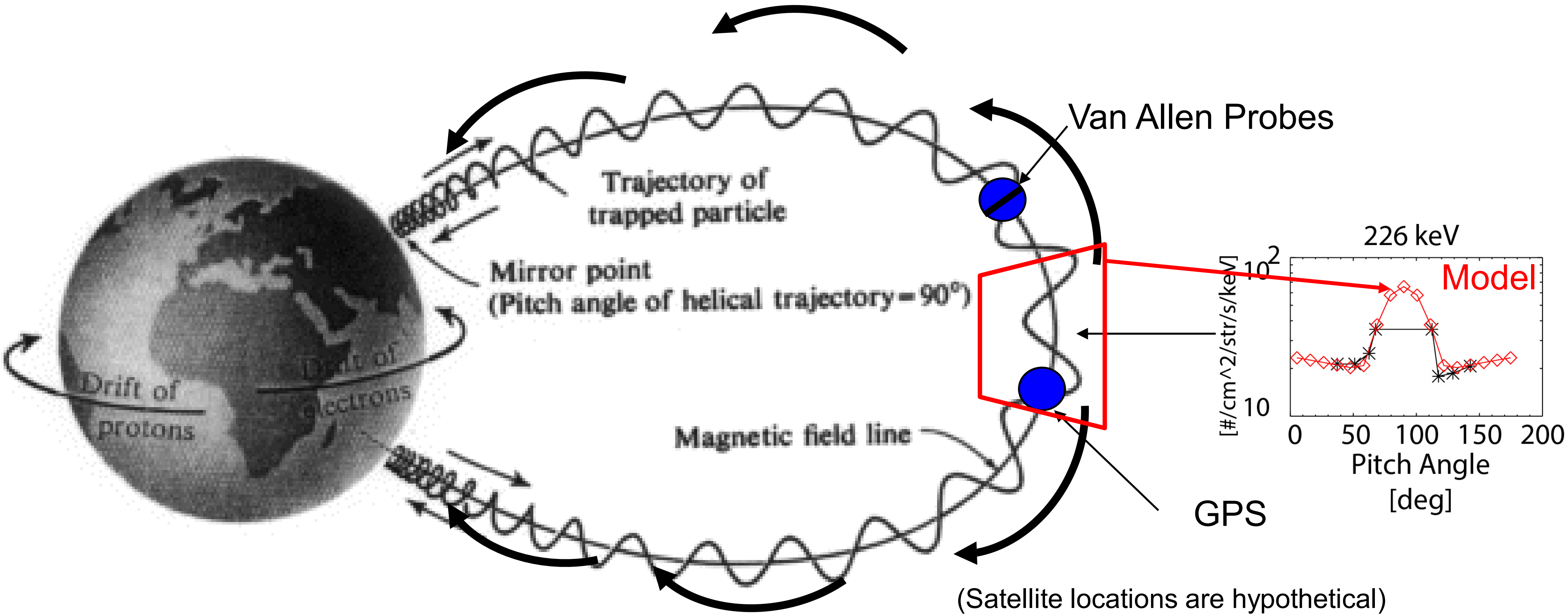
Model Background

Obtaining equatorial pitch angle distributions

We want to know what are electron fluxes everywhere along the field line.

But we only know the fluxes for electrons that bounce past Van Allen Probes.

So if GPS was near the equator, Van Allen Probes wouldn't see those electrons.



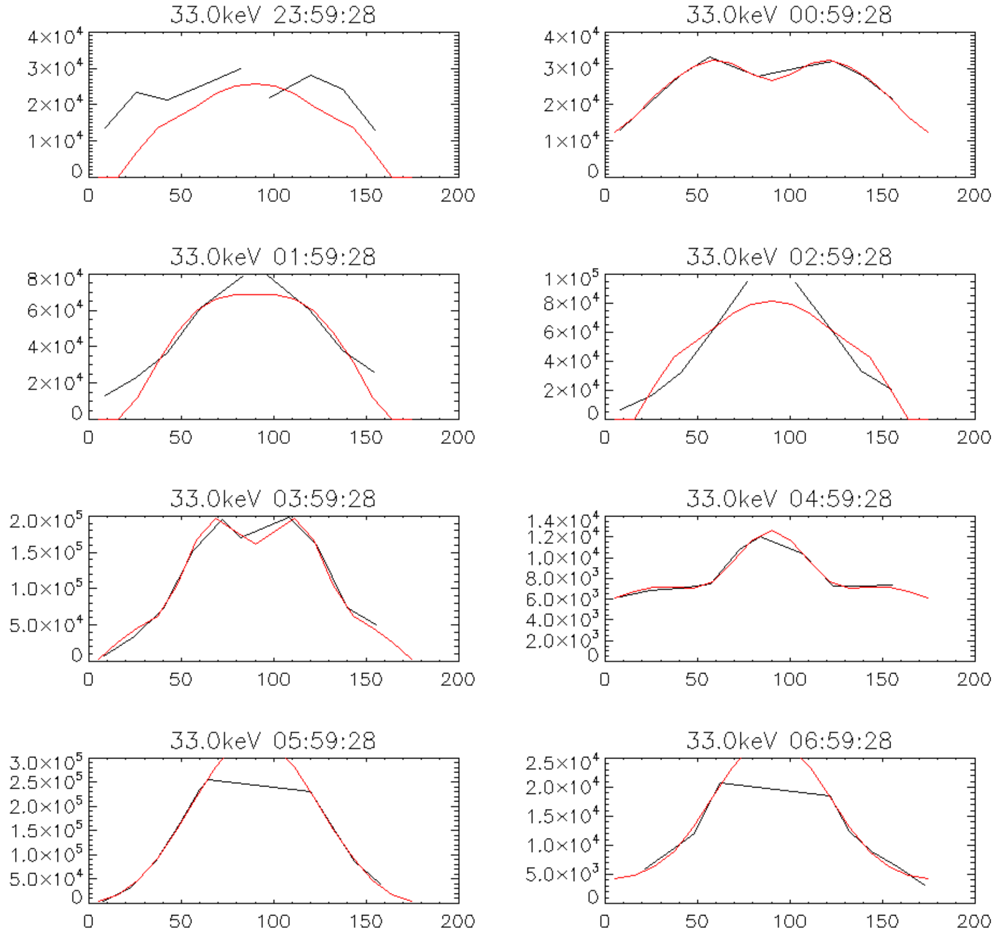
(Satellite locations are hypothetical)

R.E. Mars, 2002, Lawrence Livermore National Laboratory Report UCRL-ID-151402

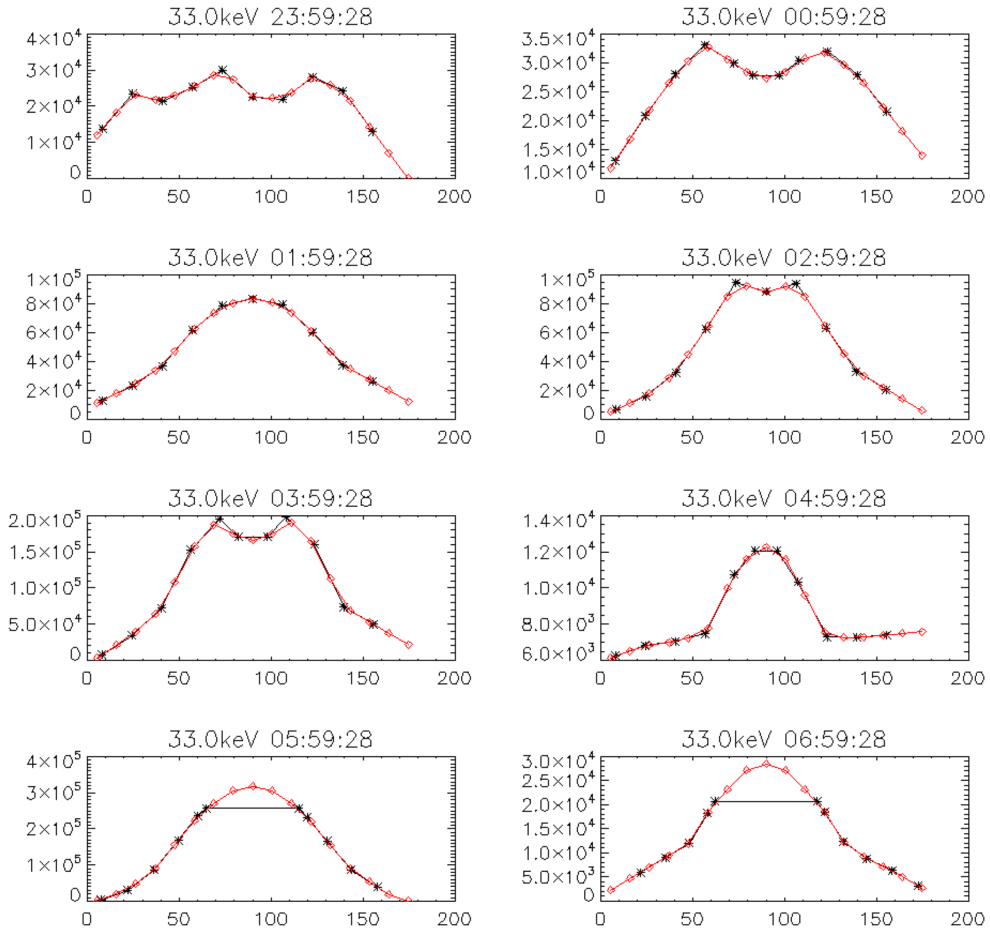
Modeling Pitch Angle Distributions

Legendre Polynomial Fitting vs. Filling the Gap with a Sine Function

Legendre Polynomial fits



Data interpolates + Sine Function



Legendre Polynomial fitting may be good for statistics (e.g. Chen et al., 2014), but we want actual daily fluences

Modeling Pitch Angle Distributions

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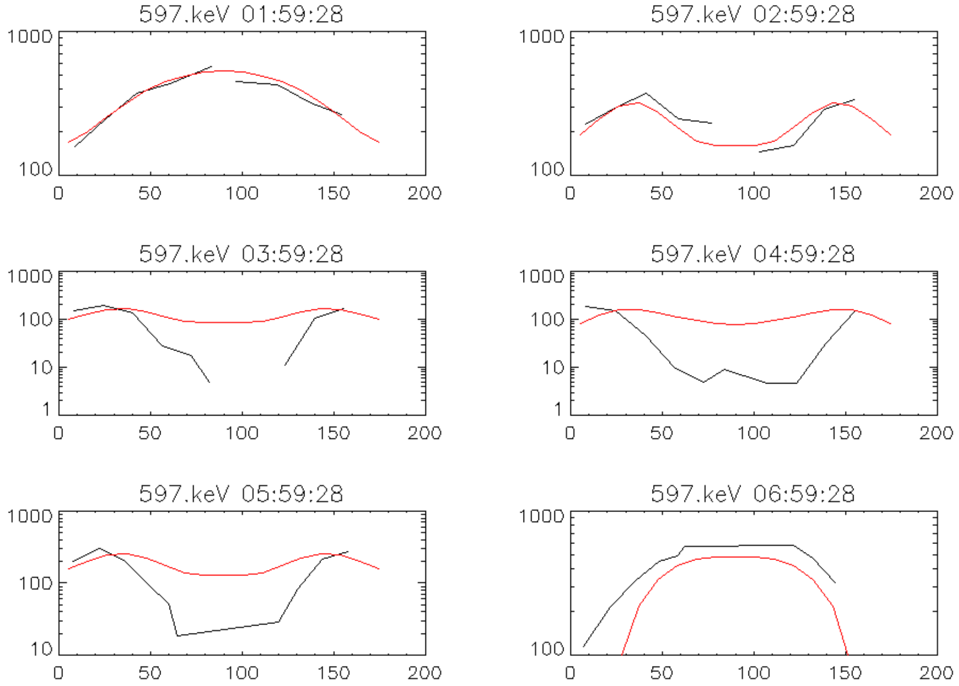
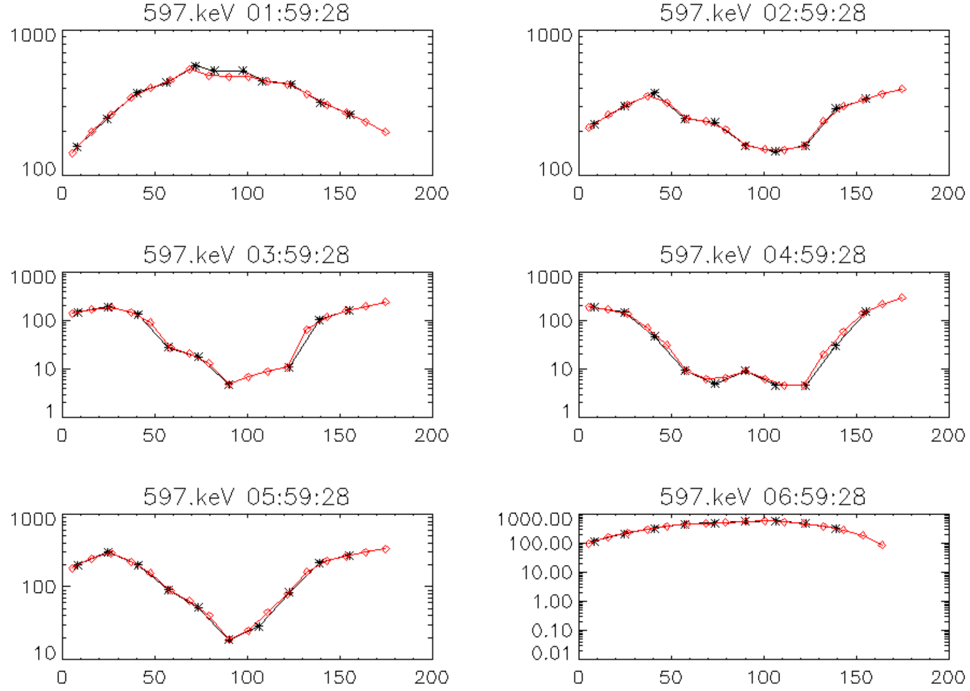


Data interpolates + Sine Function

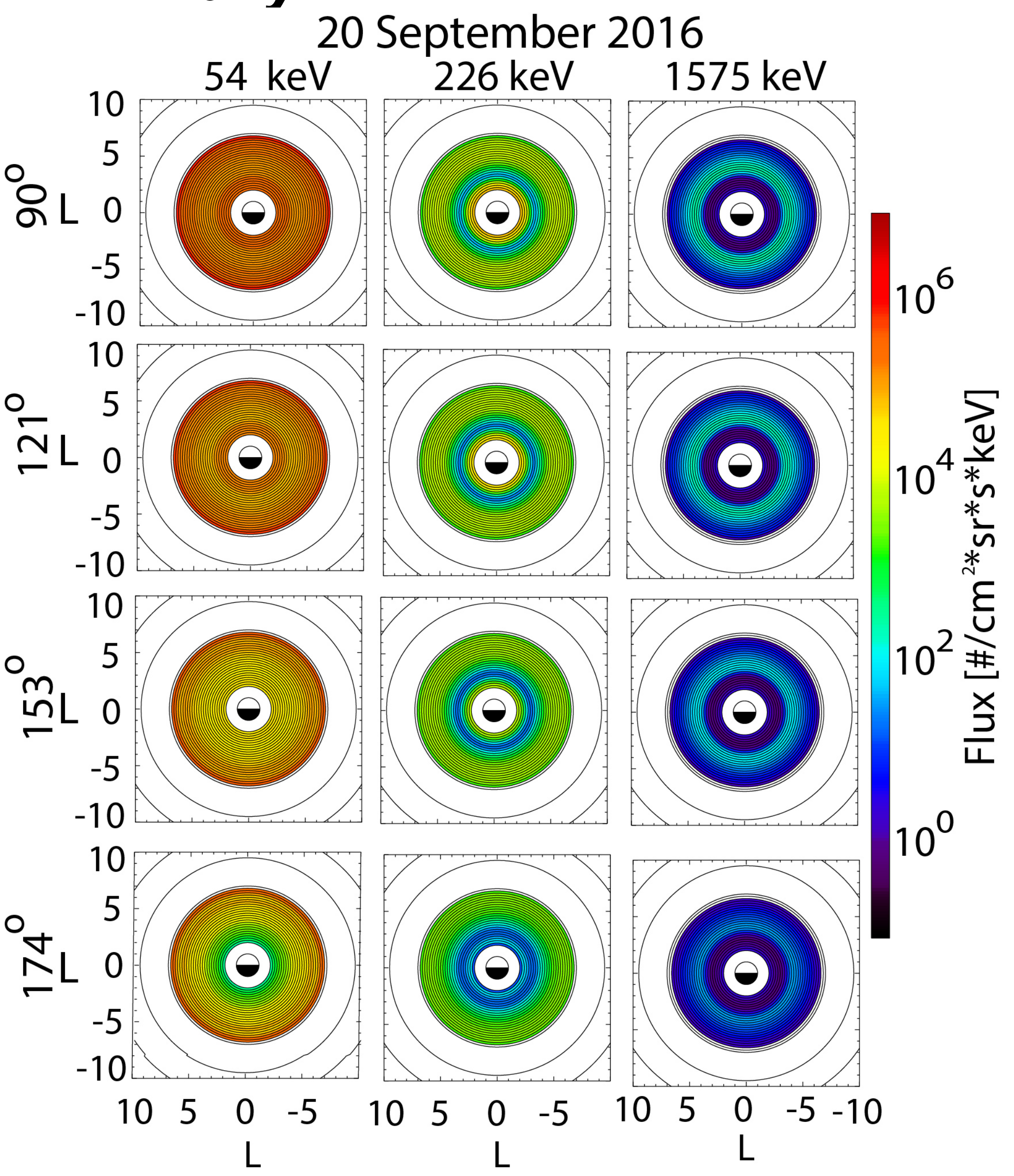


Legendre Polynomial fitting may be good for statistics (e.g. Chen et al., 2014), but we want actual daily fluences

Radiation Belt Daily Electron Flux Model: RB-Daily-E

Matrix: 0.2 R_E L shell (from 2-7 R_E) x 17 pitch angle

- 1440 minutes per day x 17 pitch angles x 25 energy bins are saved.
- Bin fluxes into 0.2 R_E L shell bins by summing total fluxes and normalizing by time spent in each bin that day.
  - Allows us to change L shell bin width without reprocessing.



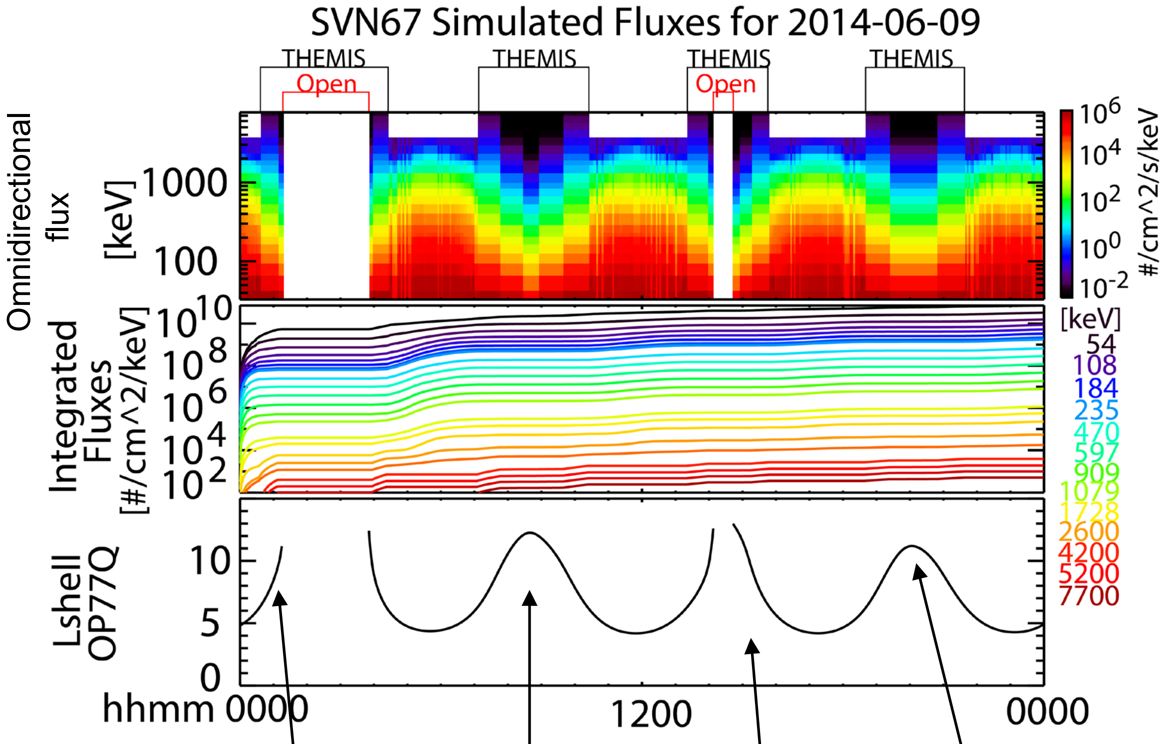
Right: Example of 54, 226, and 1574 keV fluxes at 90, 121, 153, and 174 deg equatorial pitch angles. Must assume MLT symmetry.

GPS Fluxes from RB-Daily-E

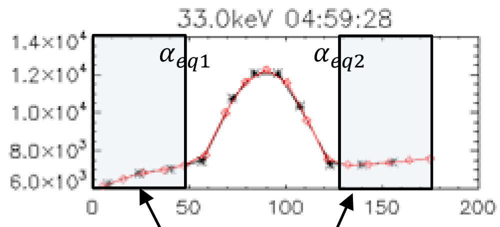
Fly hypothetical GPS through model each minute by:

1) Mapping GPS location to equator (OP77Q field model) to get L bin.
2) Integrate fluxes within pitch angle range of particles that reach GPS to get omnidirectional flux. (e.g. Local 0-180 at GPS may map to equatorial pitch angles of 0-60 and 120-180: see insert.)
3) Integrate omnidirectional flux over time to obtain a daily fluence as input to degradation models.

Open=open field lines according to OP77Q

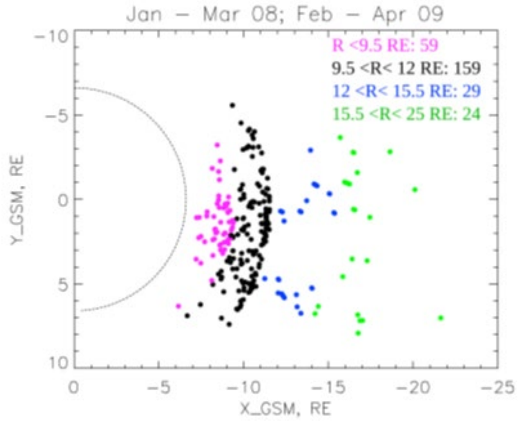


When GPS maps to L shells > 7 (Van Allen equatorial apogee), use THEMIS statistics (4 R bins spanning <9.5-25 R_E). *Runov et al.*, AGU JGR, 2015.



Hypothetical example of fluxes GPS actually sees (blue).

Interpolate the equatorial fluxes from RBSP to get the exact flux at α_{eq1} and α_{eq2}.

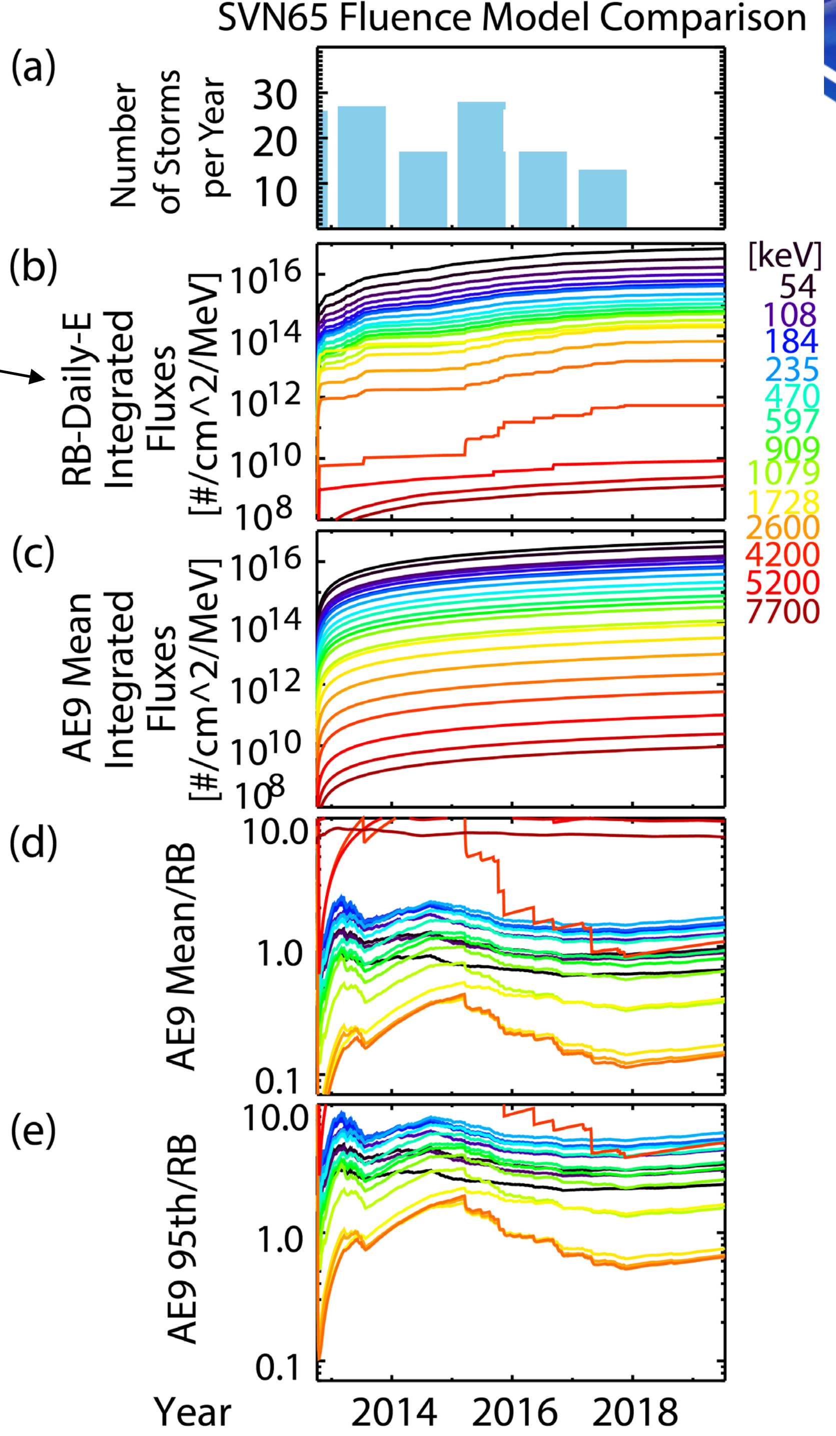


GPS Fluxes from RB-Daily-E

Integrated Fluxes over Mission Lifetime

Plot fluences (time integrated fluxes)

These are inputs to solar cell degradation models



GPS Fluxes from RB-Daily-E

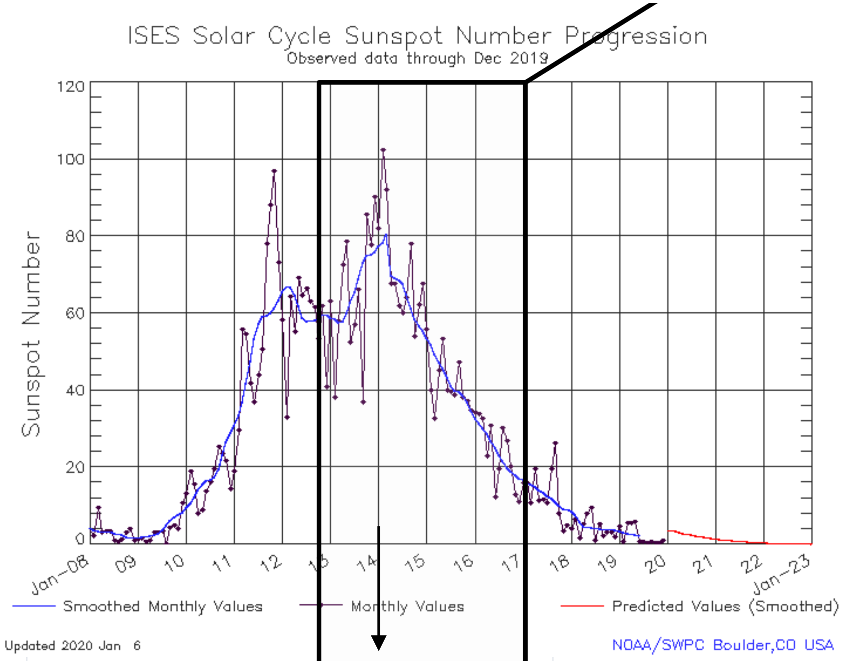
Integrated Fluxes over Mission Lifetime

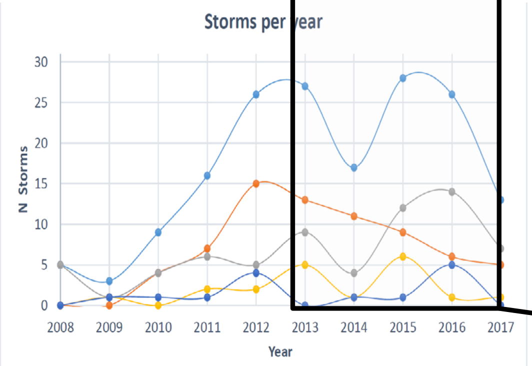
Plot fluences (time integrated fluxes)

These are inputs to solar cell degradation models

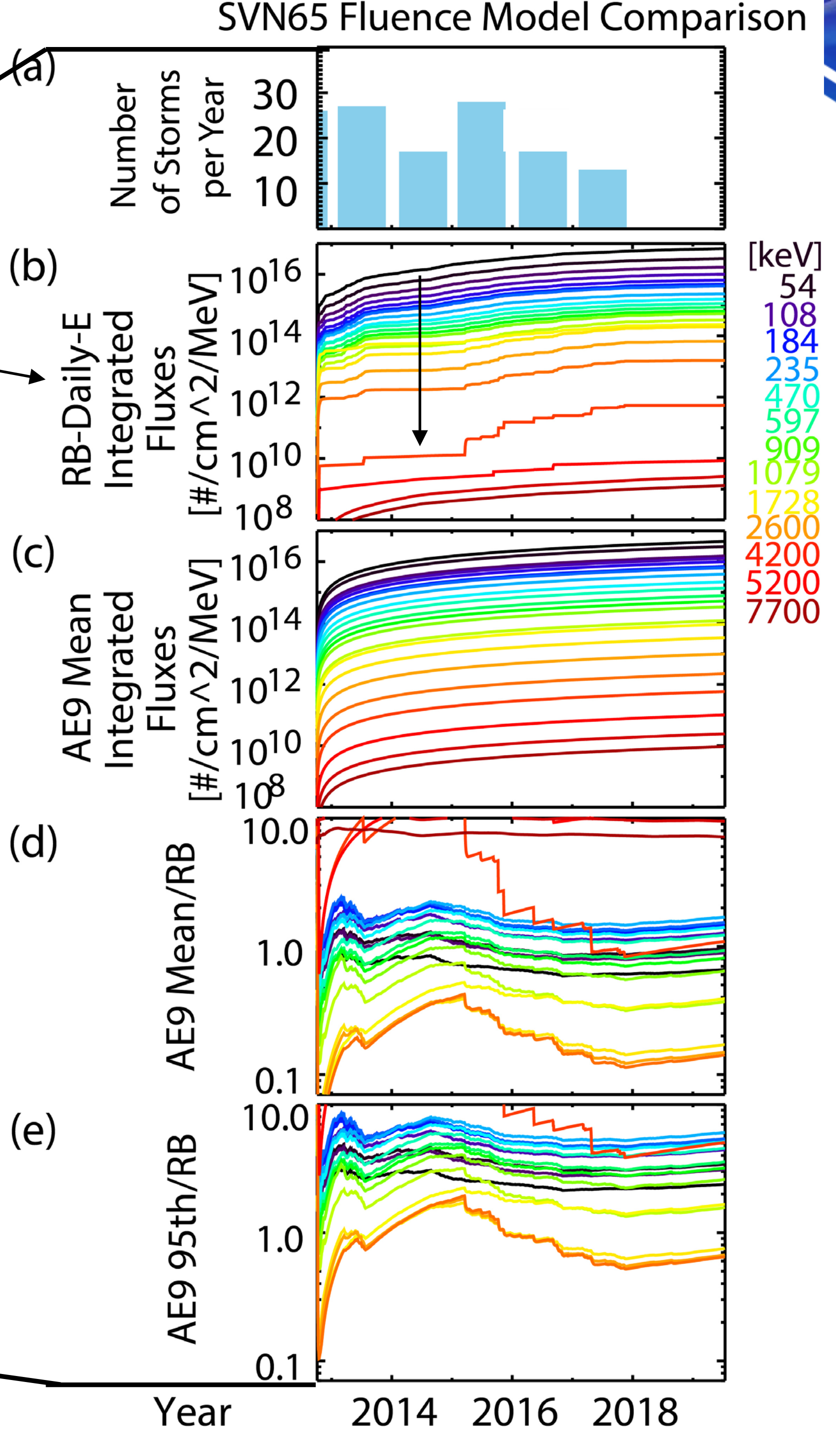
Fewer storms in 2014
→Integrated fluxes stagnate

More High Speed Stream storms occur during the declining solar cycle (*Mursula & Zieger*, 1996; *Gabrielse et al.*, 2019).
→2015 integrated fluxes sharply increase





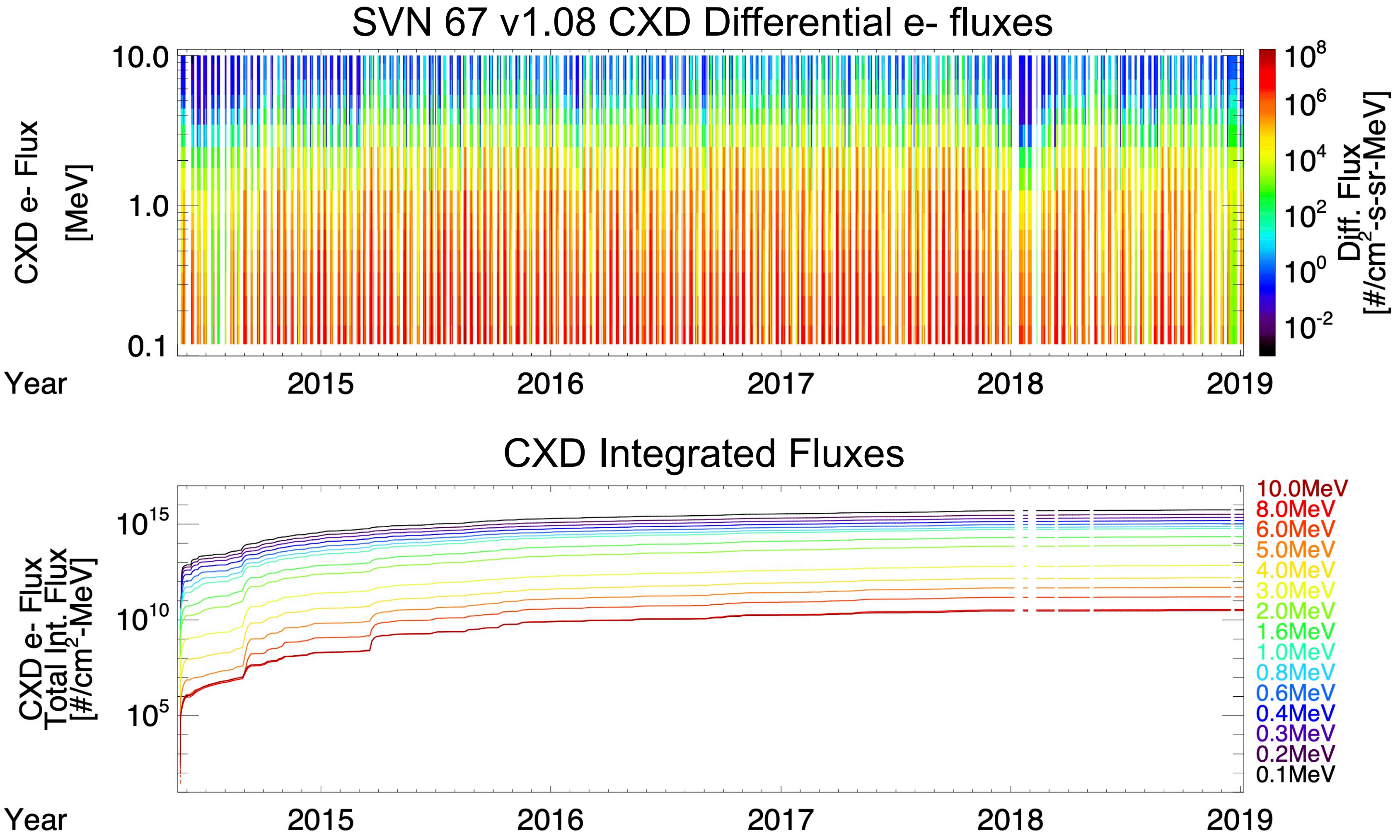
Gabrielse et al., AGU GRL, 2019



Comparison of RB-Daily-E to GPS IIF CXD Data

Example from SVN 67

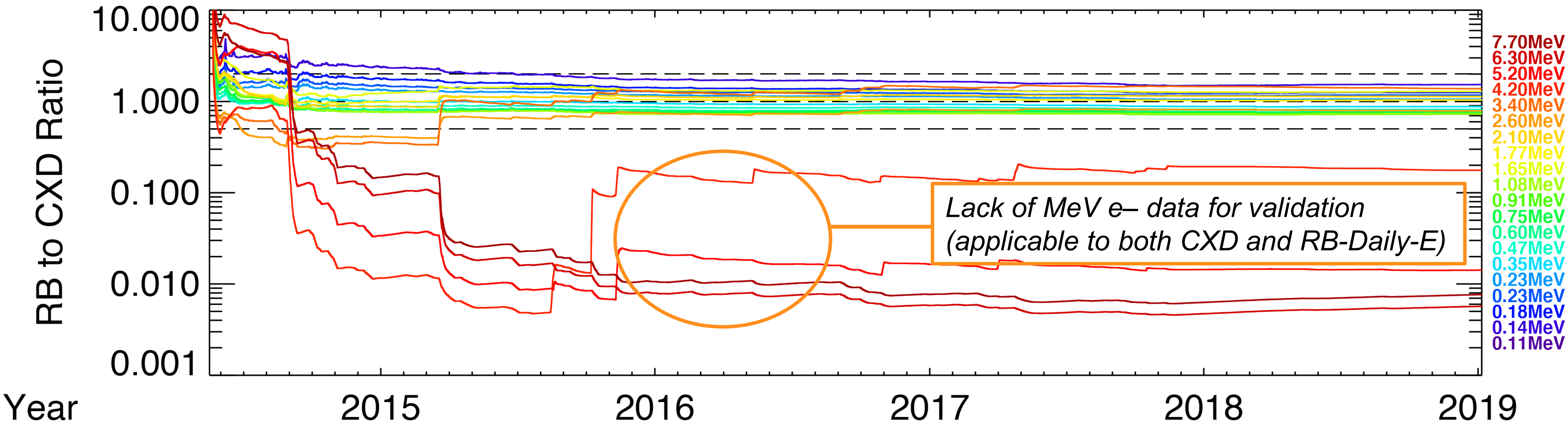
- Each IIF SVN carries a Combined X-ray Dosimeter (CXD) that provides monitoring of the space environment
- CXD v1.08 data publicly released under OSTP call for space weather data and archived on public NOAA data server (cf. Morley et al. 2017)
- Data span beginning of SVN operations until Jan 2019.
- Effort undertaken to compare RB-Daily-E predictions to CXD fluxes for same SVN



CXD electron flux data availability enabled comparisons to fluxes predicted by the RB-Daily-E model.

Comparison of integrated fluxes at GPS IIF SVN 67

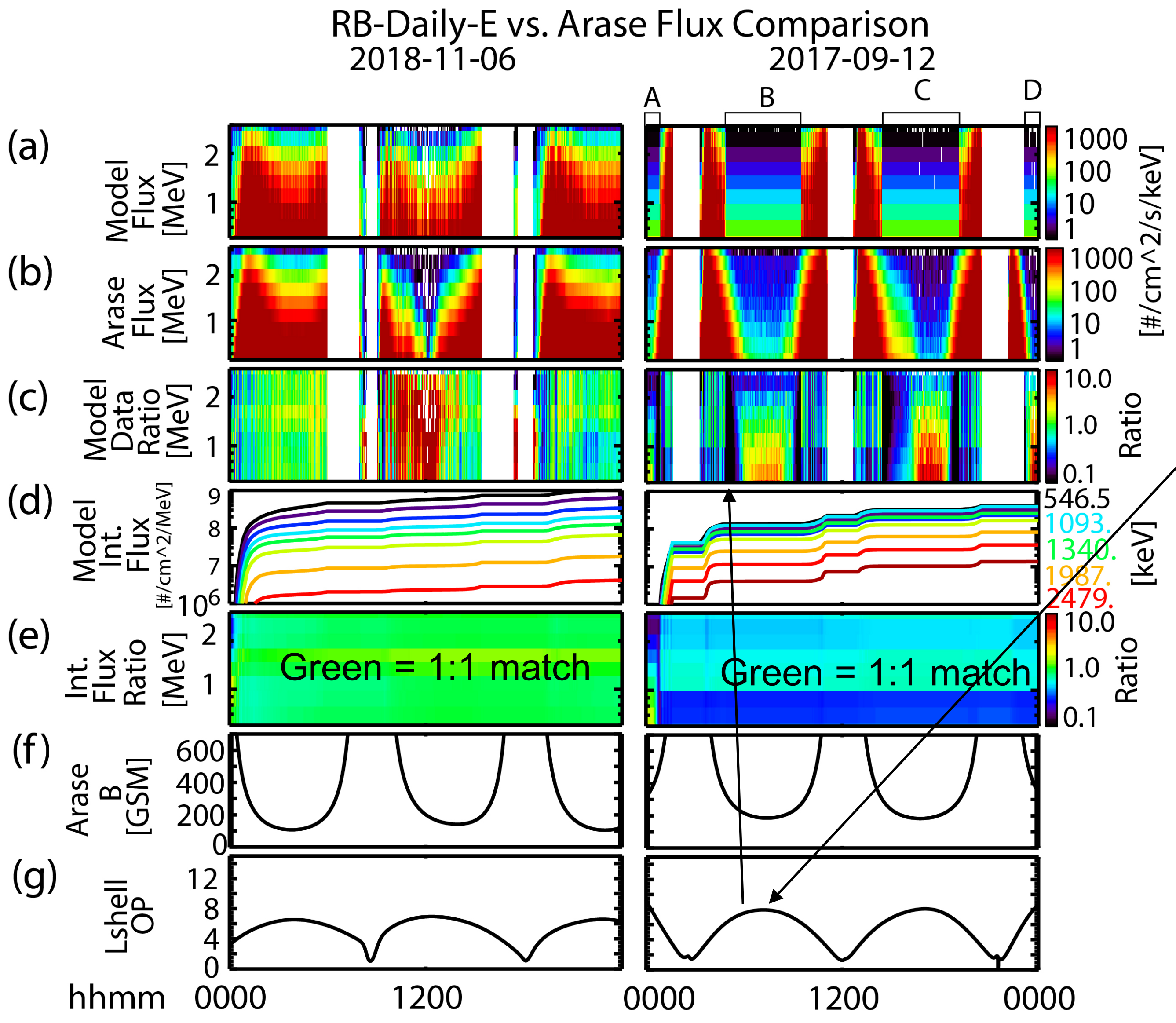
Following time and energy interpolation of the integrated fluxes to support direct comparison



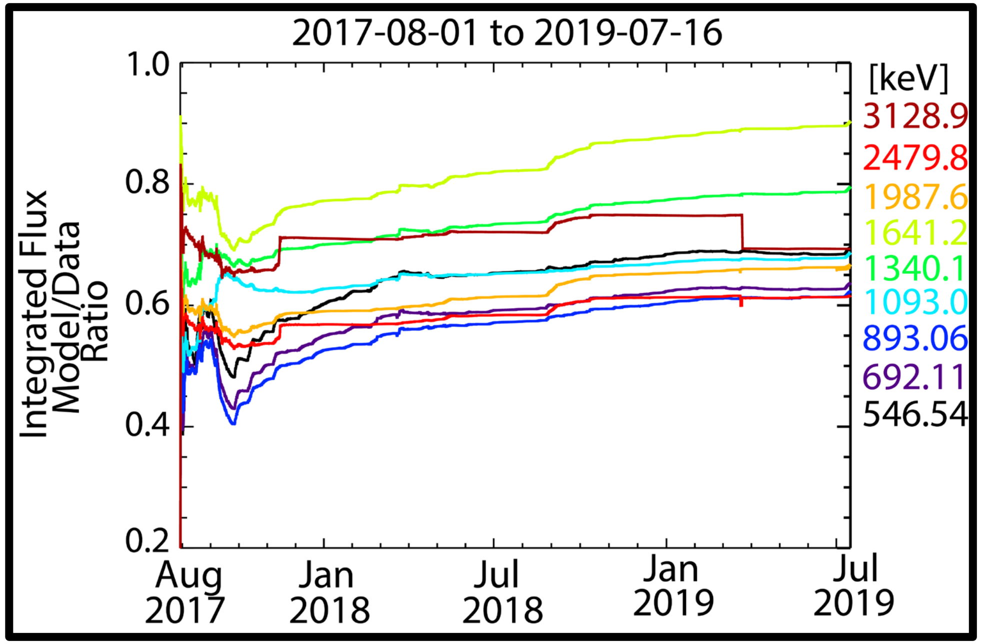
- Dashed lines are at 0.5, 1.0, and 2.0. Majority of RB-Daily-E predictions settle and remain within 2x of CXD-derived fluxes for majority of time period
- Some larger differences at MeV energies (>4 MeV), consistent with uncertainties of measuring electrons at these energies
- <0.1 MeV electrons not considered since CXD does not monitor these electron energies

Comparison results show physics-based predictions provided by the RB-Daily-E model are promising and likely applicable to supporting studies involving the GPS satellites.

Compare RB-Daily-E with Arase XEP Data

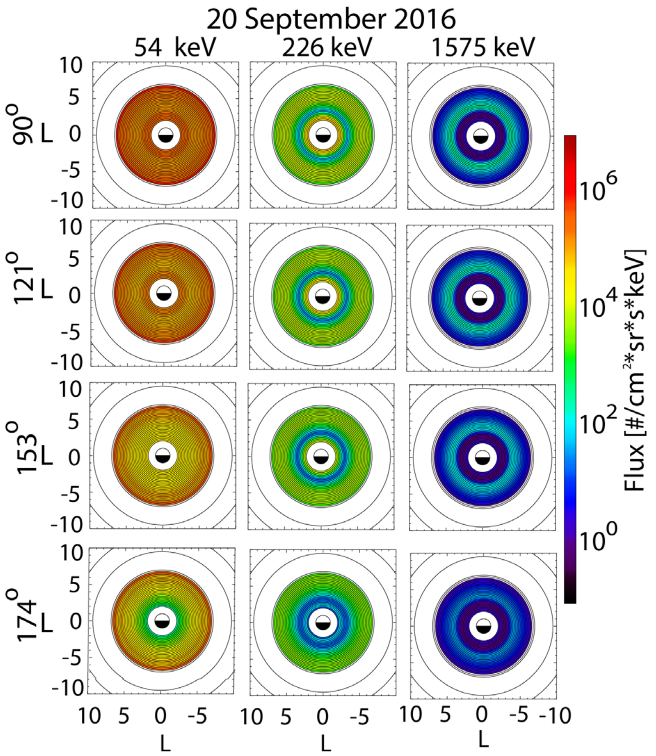


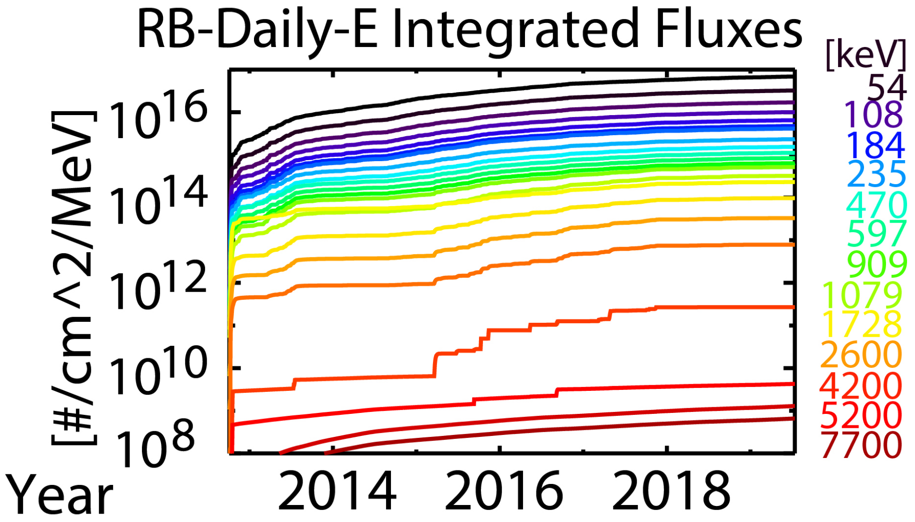
- Decent comparison between RB-Daily-E and Arase XEP fluxes (*Higashio et al.*, 2018)
  - Within a factor of 2, but **for most energies after a year within a factor of ~<1.67.**
- "A-D": Times we relied on THEMIS statistics.
  - THEMIS was only fit up to ~293 keV (Arase XEP lower energy is ~600 keV).
  - Arase spends a lot of time just beyond RBSP L shells. THEMIS is a bin up to 9 RE, which seems to underestimate Arase at L>7 .



RB-Daily-E Summary

- We built a daily average electron flux model based on 7 years of Van Allen Probe (RBSP) data.
  - *L shell x Pitch angle x Energy*
  - *2 to 7, > 7R_E supplement with THEMIS statistics*
  - *33 keV to 7.7 MeV*
- RB-Daily-E provides daily average fluences for a given satellite providing ephemeris and date range as input.
- RB-Daily-E and GPS SVN67 fluences agree for relevant energies within a factor of ~1.4 after a few years (or within a factor of 2 more immediately).
- RB-Daily-E accurately predicted Arase fluences within a factor of ~1.6 after one year
  - *Care should be taken if much of the orbit sits just outside an L shell of 7*
- RB-Daily-E performs more precisely than AE9 Mean or 95th percentile.
- Practical application: RB-Daily-E outputs can be used in solar cell degradation models.





Modeling on-orbit degradation of space solar cells

- Jet Propulsion Lab Equivalent Flux (JPL EQFLUX) [Anspaugh 1996] semi-empirical method for modeling on-orbit degradation of space solar cells
- Method relies on ground qualification irradiation test data at specific proton and electron irradiation energies
  - *Solar cell current-voltage data acquired before and following each round of irradiation at the specific particle energies*
    - EQFLUX relates all irradiation test data to 1 MeV electron equivalent fluence curve
- Space radiation from AE8/AP8 or AE9/AP9 or other radiation environment models can be convolved using EQFLUX method to derive respective 1 MeV e– equivalent fluence, then applied to solve for remaining factor based on the 1 MeV e– curve derived from solar cell vendor's irradiation test data
  - *Model can predict on-orbit degradation of standard solar cell parameters: open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), voltage at max power (V_{max}), current at max power (I_{max}), max power (P_{max})*
- Also plans to use the Solar Cell Radiation Environment Analysis Model (SCREAM or DDD method)

Semi-empirical methods based on ground irradiation test data and charged particle radiation spectra inputs are applied to predict or interpret on-orbit solar cell degradation.

Monitoring GPS solar array electrical performance

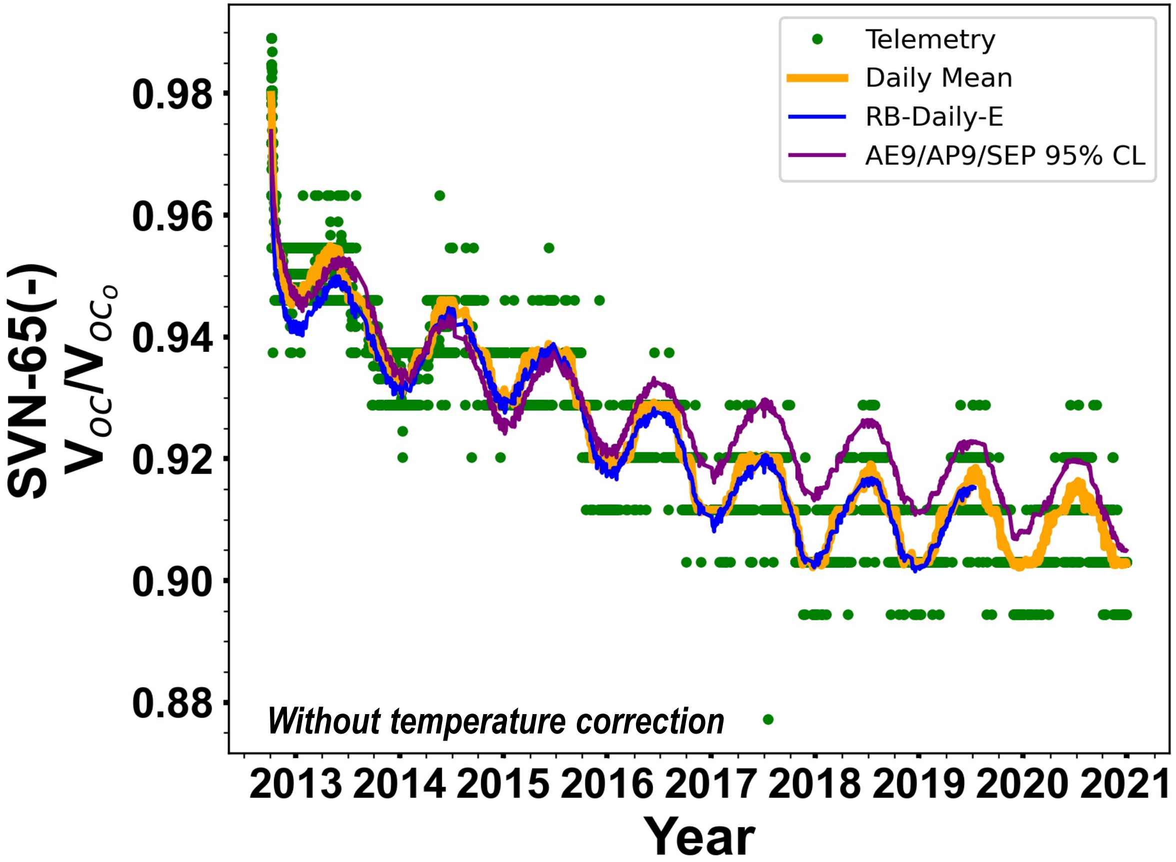
Different methods are used to monitor on-orbit GPS solar arrays on different blocks

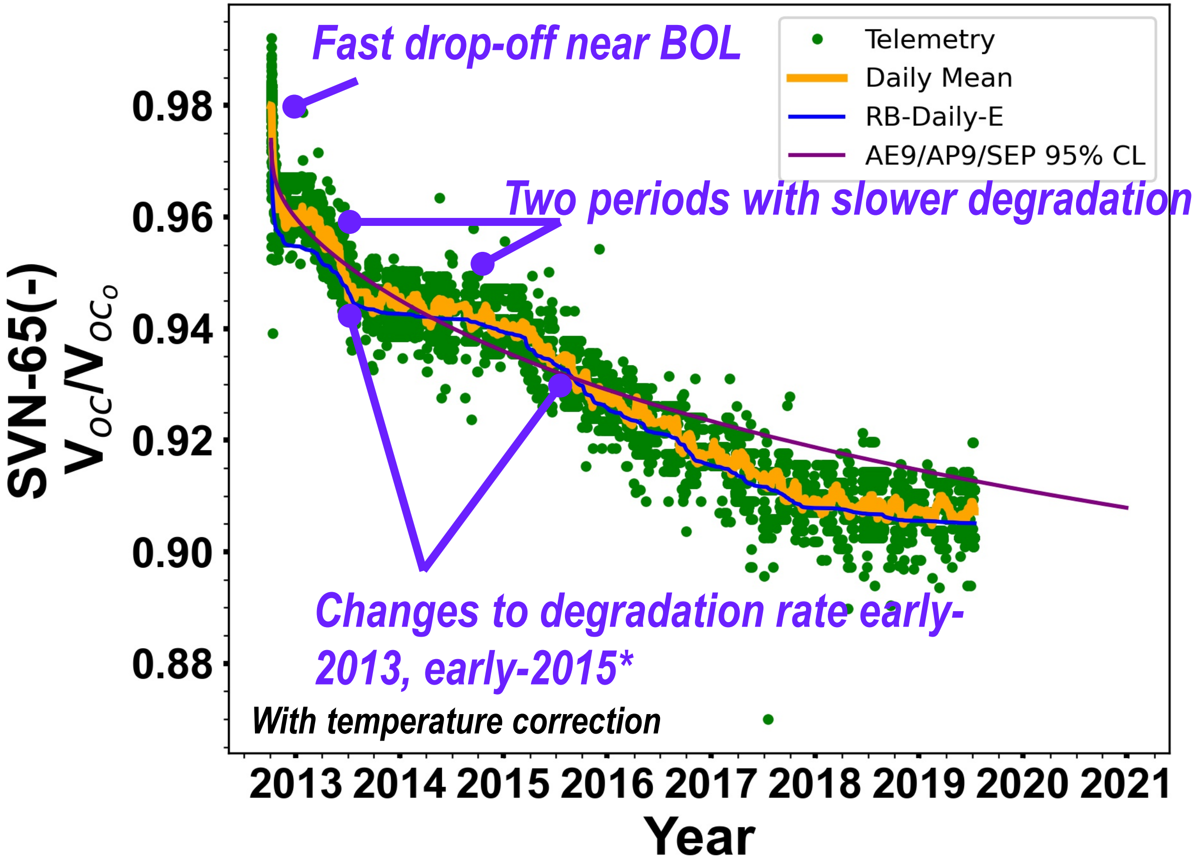
- GPS IIR/IIRM solar array telemetry consists of on-orbit measurements of solar array string current under load
  - *On-orbit currents monitor combined effects degradation to the solar array that are due to decreased quality of solar illumination to the solar cell AND radiation damage to the solar cell*
    - Radiation damage to the solar cells making up the array
    - Cover glass darkening and contamination
    - Adhesive darkening
  - *Open question on cause of "anomalous" solar array degradation*
- GPS IIF vehicles carry additional solar array monitoring instrumentation on two wings
  - *String monitors that measure current near short-circuit (I_{SC})*
    - Measurements enable trending of I_{SC}
    - I_{SC} measurements still reflect combined effects degradation by the space environment (cf. IIR/IIRM current measurements)
  - *Cell monitors that measure voltage near open-circuit (V_{OC})*
    - Fundamental properties of solar cells tell us V_{OC} is substantially less affected by changes to quality of illumination and therefore provides a strong tracer of radiation damage to the solar cell
    - V_{OC} trends should therefore indicate how much the array is degrading due to radiation

More recent GPS blocks carry additional solar array monitoring instrumentation.

GPS IIF SVN 65 processed and normalized on-orbit V_{OC} monitor data

Data filtered, corrected to common temperature of 66°C, and normalized to ground reference data



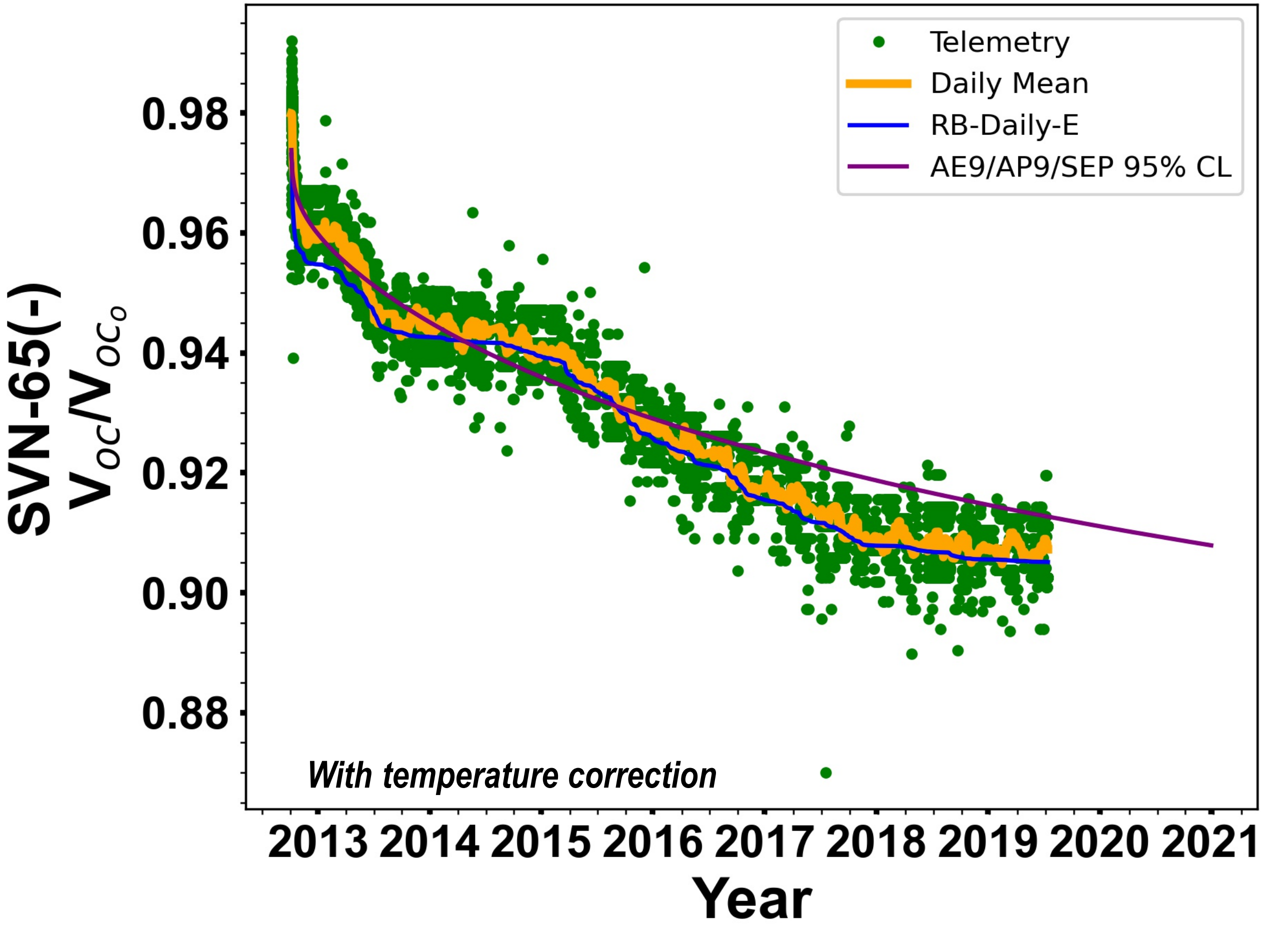


- *V_{OC} data filtered based on standard deviation method to exclude most outliers.*
- *Temperature data filtered using similar method and interpolated to match the time resolution of the V_{OC} data for temperature correction.*
- *Because of the left plot we can derive radiation dependent temperature-coefficients to correct for any variation in temperature whenever we have RB-Daily-E fluences.*
- **see Chart 11 for further context on the space environment and geomagnetic storms*

Note to OTR/Management/Customer Reviewer: Only data associated with the green dots and orange traces on both plots will show on the slide that will be presented. Color coding may change.

GPS IIF SVN 65 processed on-orbit V_{OC} data alongside AX9 predicts

AX9 and Solar Energetic Particle 95th Confidence Level fluxes used as inputs into EQFLUX

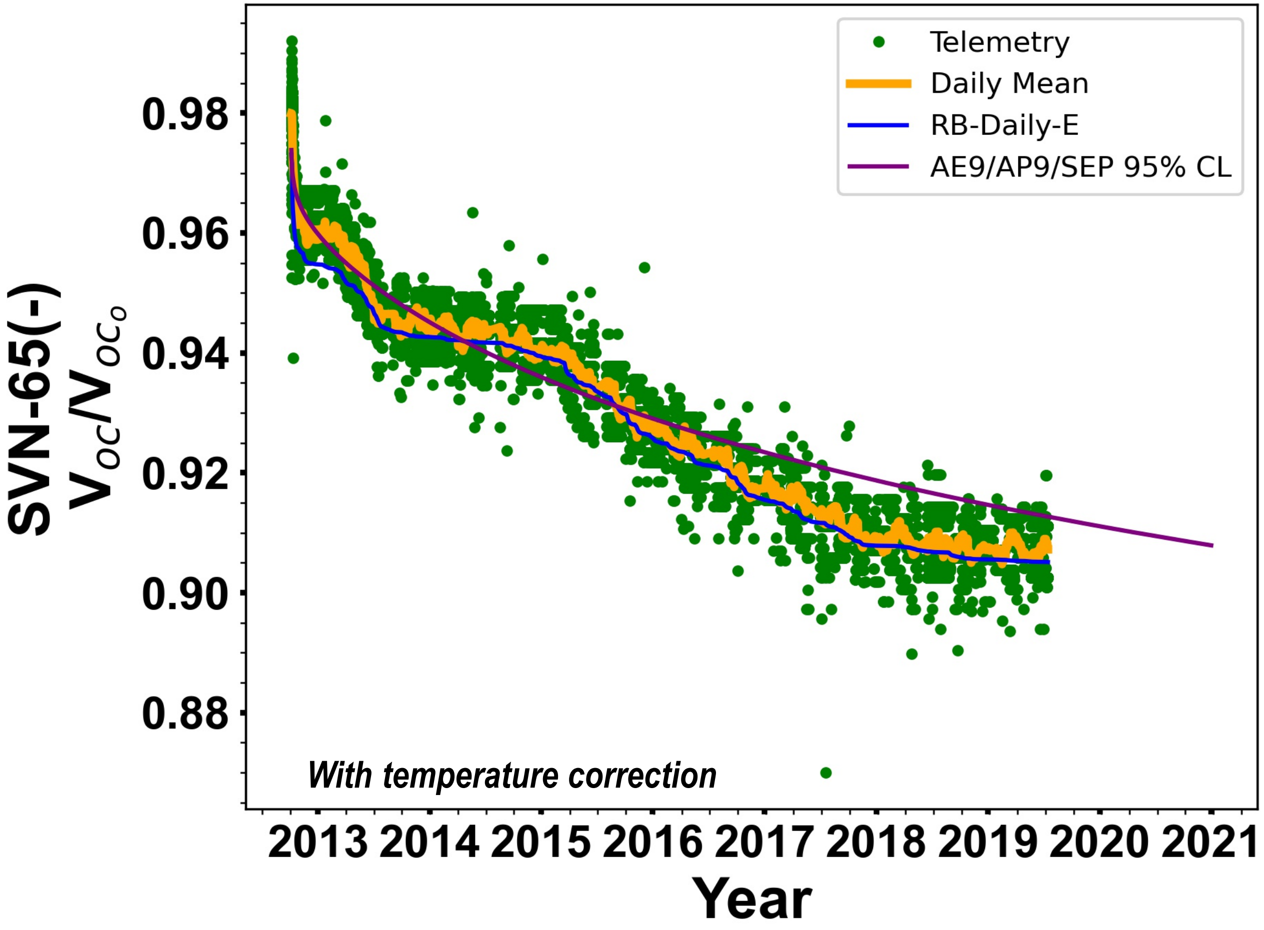


Note to OTR/Management/Customer Reviewer: Only data associated with the purple trace, green dots, and orange trace will show on the slide that will be presented. Color coding may change.

- *V_{OC} data compared to EQFLUX results using AX9-derived (v1.50.001) and solar particle (ESP/PSYCHIC 95% confidence level; e.g. Xapsos et al. 2004) fluxes shows that it is unable to capture the time-varying shifts in the data trends*
- *AX9-derived predict either under- or overestimates the degradation indicated in the data trends*

GPS IIF SVN 65 processed on-orbit V_{OC} data alongside RB-Daily-E predict

RB-Daily-E electrons used as input into EQFLUX



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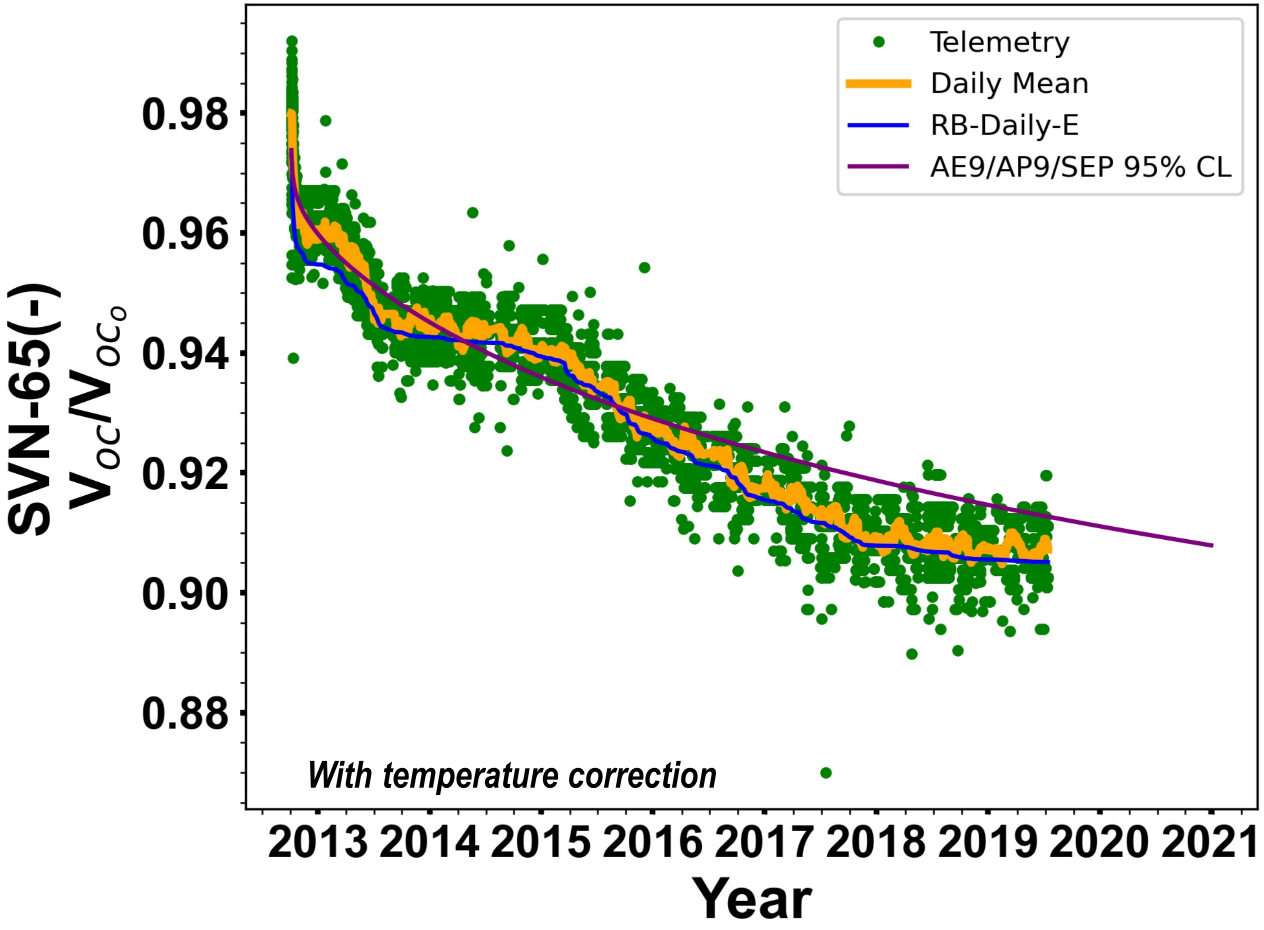
- *RB-Daily-E normalized remaining factor predict shows close correspondence to on-orbit V_{OC} data trends.*
- *RB-Daily-E model captures the variability of radiation incident on SVN65 solar arrays*

GPS IIF SVN 65 processed on-orbit V_{OC} data alongside all predicts

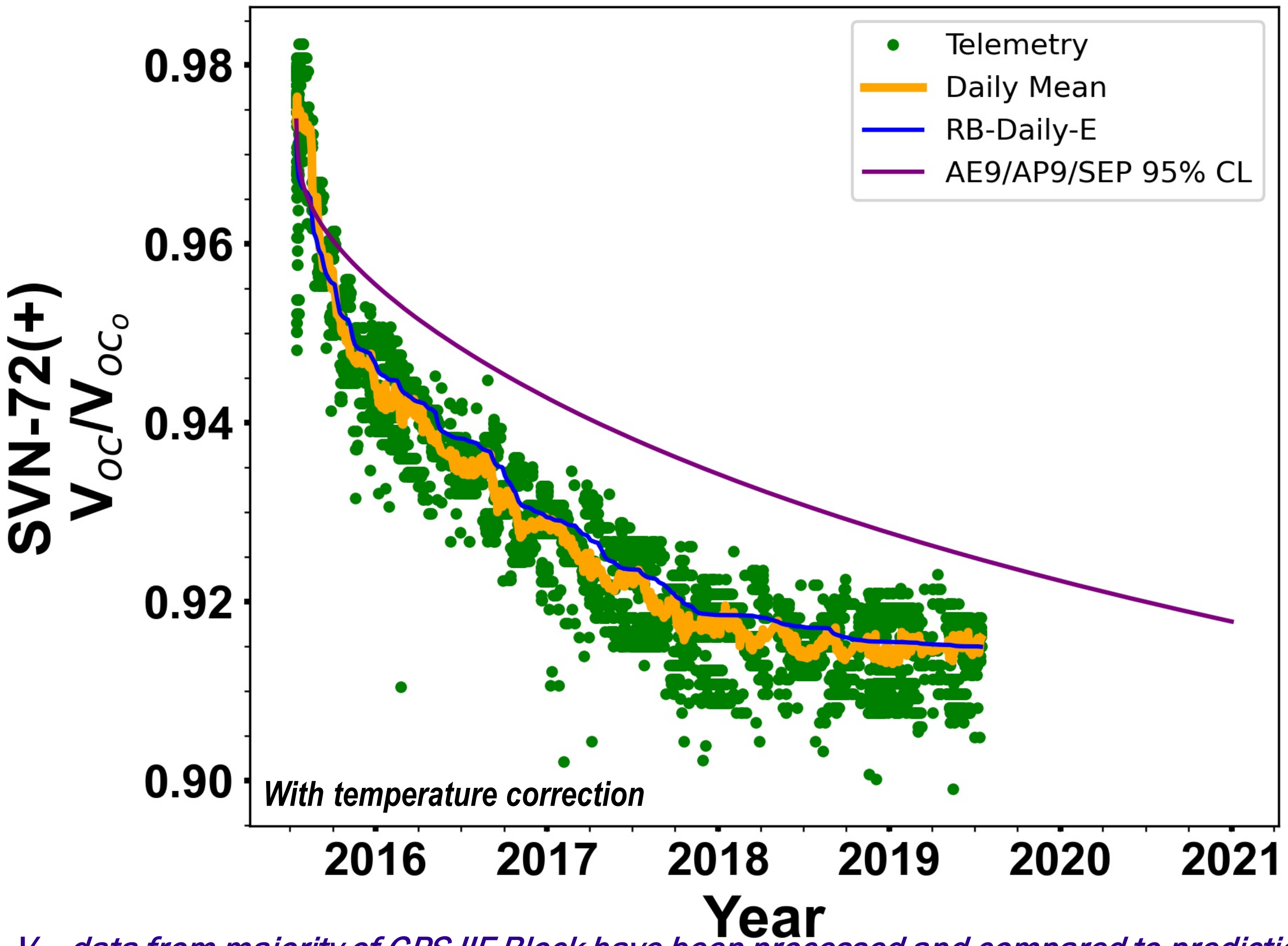


Note to OTR/Management/Customer Reviewer: Color coding may change.

- *Comparison of AX9 and RB-Daily-E predicts to show how the modeling compares to the trends all on the same chart*

GPS IIF SVN 72 V_{OC} data alongside RB-Daily-E and AX9+SEP predicts

Similar success observed for other SVNs that could be modeled using RB-Daily-E



Note to OTR/Management/Customer Reviewer: Color coding may change.

- *V_{OC} data from majority of GPS IIF Block have been processed and compared to predictions using the RB-Daily-E & AP9 fluxes*
- *Similar success observed across all SVNs*
- *Degradation rates differ depending on when the SVN was injected into orbit*

Improving understanding of I_{SC} degradation

Analysis of on-orbit I_{SC} trends is in progress

- Analysis of data provided by GPS IIF string monitors of current near short-circuit (I_{SC}) is in progress
  - *Measurements enable trending of I_{SC} from BOL to present*
  - *I_{SC} measurements reflect combined effects degradation by the space environment (cf. IIR/IIRM current measurements; Messenger et al. 2011)*
- Close correspondence between observed and RB-Daily-E modeled V_{OC} degradation provides new confidence in quantitative estimate of radiation at each vehicle and how much that radiation contributes to solar cell degradation
- Application of RB-Daily-E radiation fluxes to I_{SC} degradation analysis enabling separation of radiation degradation to the cell from other combined effects degradation (cover glass/adhesive darkening, contamination)

We may soon be able to constrain I_{SC} degradation caused by radiation damage to the cell and estimate the contribution of additional combined effects degradation.

Future Work

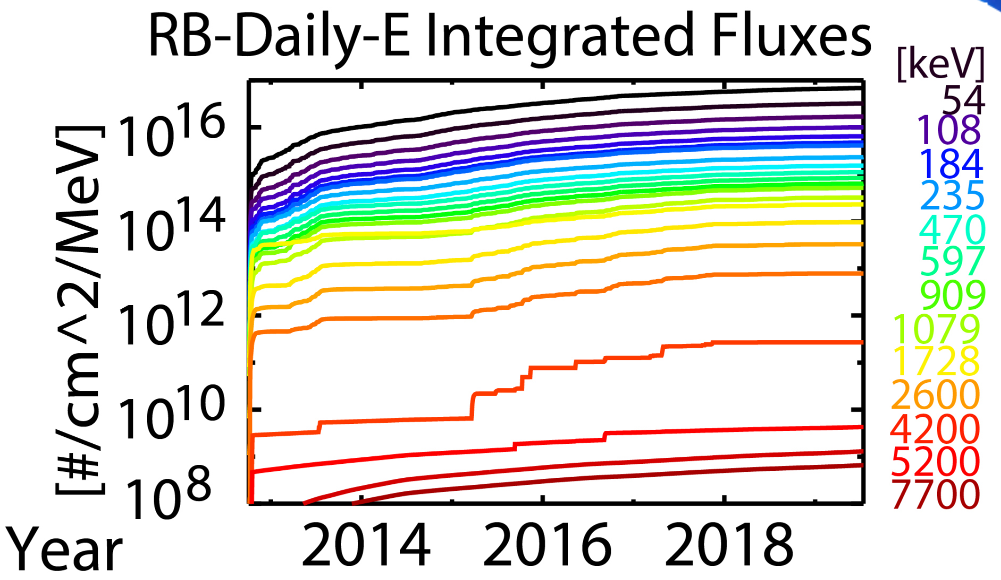
- Additional V_{OC} degradation modeling of other GPS IIF SVNs has been performed, showing similar success to results presented
- Close correspondence between observed V_{OC} degradation trends and those modeled using RB-Daily-E
  - *Enabling further investigation of how much radiation contributes to I_{SC} degradation*
    - Radiation can be separated from other combined effects degradation affecting solar array currents
- Work in progress to understand whether cover glass contamination/darkening and adhesive darkening rates are consistent with additional I_{SC} degradation trends observed
- Efforts demonstrate importance of solar array telemetry, particularly accurate voltage telemetry, and on-orbit radiation sensors for quantifying measured solar array degradation trends
  - *V_{OC} voltage telemetry enables—for the first time for GPS vehicles—investigations of radiation degradation that are difficult to isolate using solar array current telemetry*
- RB-Daily-E model could also be applied to interpret other space environment effects such as time-dependent charge buildup and discharge in dielectric materials in the absence of radiation sensors on relevant host vehicle

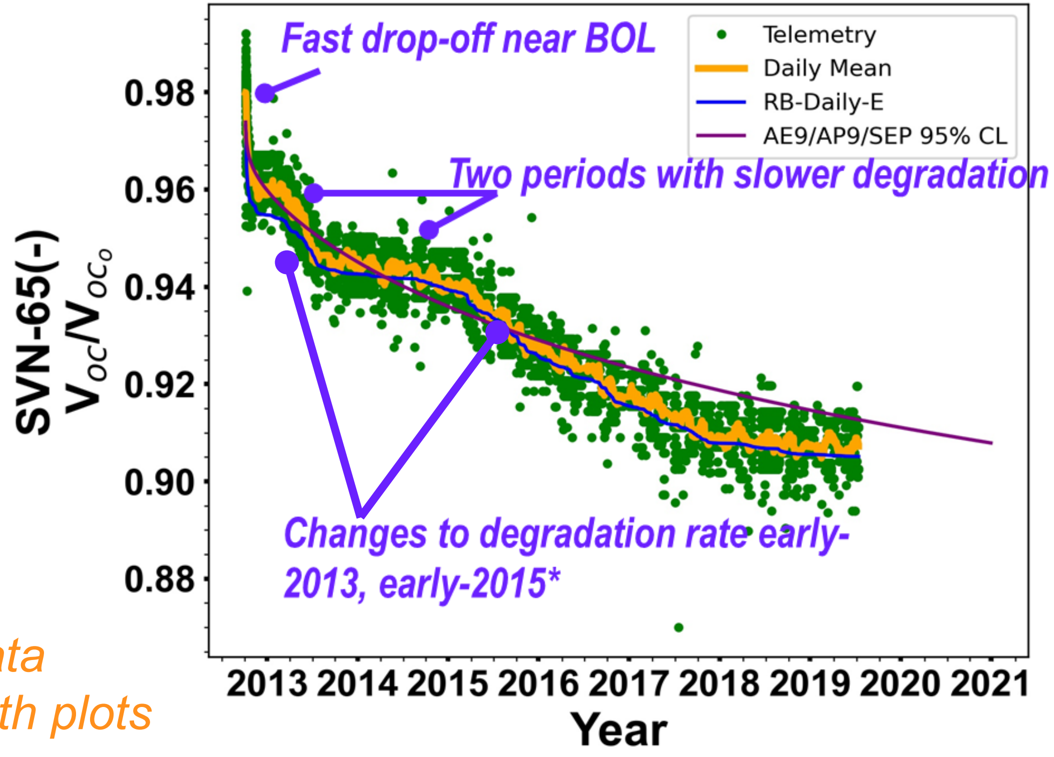
Analysis and modeling methods could improve accuracy of GPS IIF SVN solar array lifetime predicts and could be applied to other space programs.

Summary and Conclusions

RB-Daily-E Applied to Voltage Degradation

- We built a new radiation environment model based on 7 years of Van Allen Probe (RBSP) data supplemented by THEMIS data.
- RB-Daily-E provides daily average electron fluxes or fluences for a given satellite providing ephemeris and date range as input.
- Using those fluences as EQFLUX model inputs, we have demonstrated the application of RB-Daily-E to investigating the on-orbit voltage degradation of GPS IIF solar arrays.
- **The voltage degradation is occurring consistent with the radiation environment, helping explain a long-standing open question about the cause of the degradation rates.**





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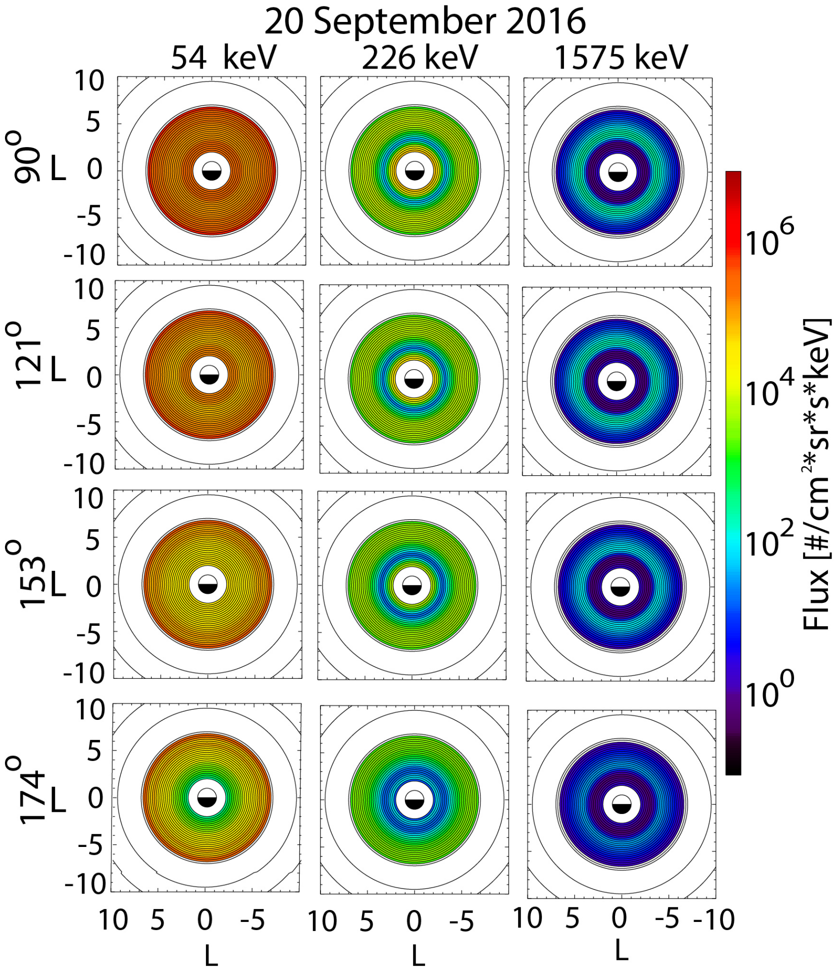
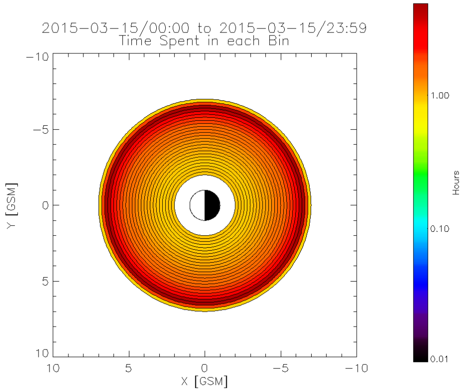
Backup

Methodology Overview

Pitch Angle Distributions at the Equator

- Obtain equatorial pitch angle distributions (PADs) from Van Allen Probe data
  - Map Van Allen Probe satellites to equator
  - Determine equatorial PAD from local PAD
- Create daily flux averages for each L shell bin (2-7 RE with 0.2 RE increments), energy bin, and pitch angle bin.
- Fly GPS through the model to obtain daily fluences
  - Use GPS ephemeris to map GPS to equator
  - Determine which portion of the equatorial PAD will reach GPS
  - Integrate to obtain omnidirectional flux at GPS
  - Collect flux estimate every minute, and integrate over the day
- Use daily integrated fluxes as input to degradation models

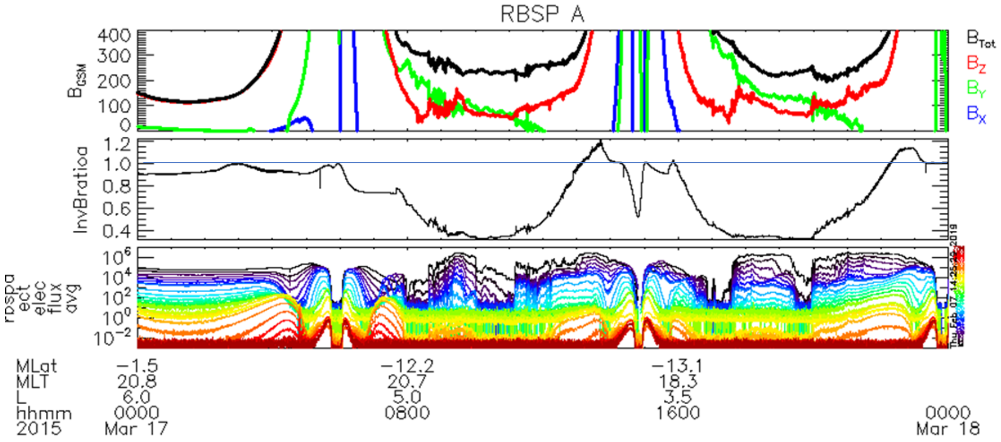


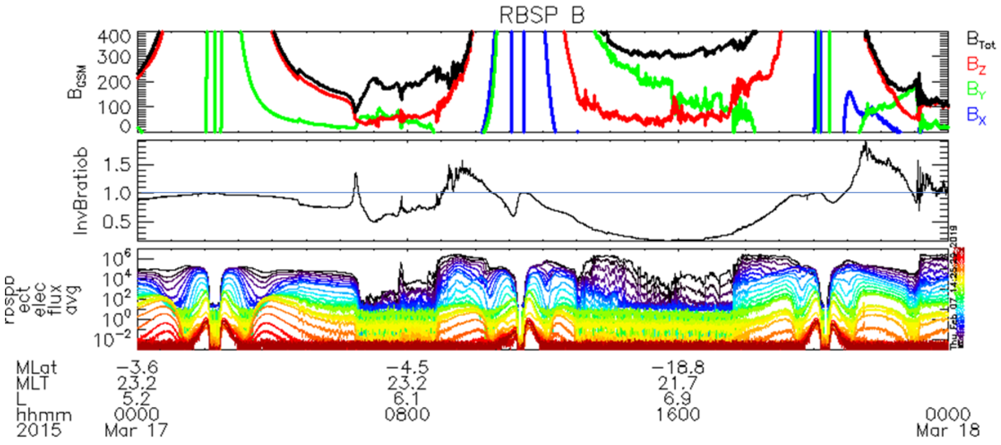


Methodology

Mapping various pitch angles

- Because GPS could be at the equator when Van Allen Probes is far from the equator, we need to fill in the populations that Van Allen Probes did not see.
- Step 1: Convert local pitch angles to equatorial pitch angles.
  - Use the L shell and Beq data provided with the MagEIS product. Use REPT
  - Use MagEIS data without background correction.





$$\alpha_{eq} = sin^{-1}\sqrt{\frac{B_{eq}}{B_{sc}} sin^2(\alpha_{sc})}$$

InvBratio= $\frac{B_{eq}}{B_{sc}}$

There are some points when Beq > Bsc, so InvBratio >1.

This doesn't really mean anything, it must result from the data not following the model. (For example, dipolarization could mean observed B is larger than modeled B at the equator. Or a compression of the Magnetosphere could increase observed B.)

Because asin(1.5)=NaN, the mapped pitch angles are stored as NaNs when Beq>Bsc. They are interpolated over.

Treated α_{sc} as α_{eq}.

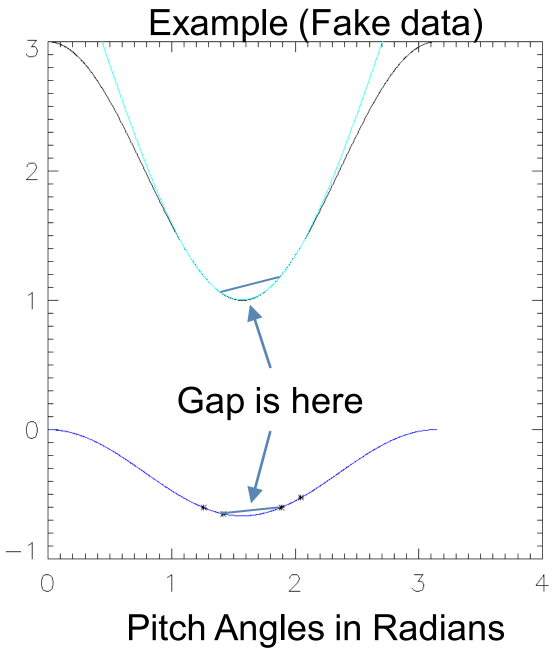
Methodology

Pitch angle model

To fill the gap, I use the four data points surrounding the gap and treat them as part of a sine function of the following form:

$$flux = A * \sin(B\,\alpha + \frac{\pi}{2} - B\,\frac{\pi}{2})$$

MPFIT uses the Levenberg-Marquardt technique to solve the least-squares problem.



Black: "the data" to fit
Navy: Normalized data
4 dots: the 4 normalized data points to fit
Cyan: Fitted sine function.

Remember: Only need to fit the gap, the wings do not matter.

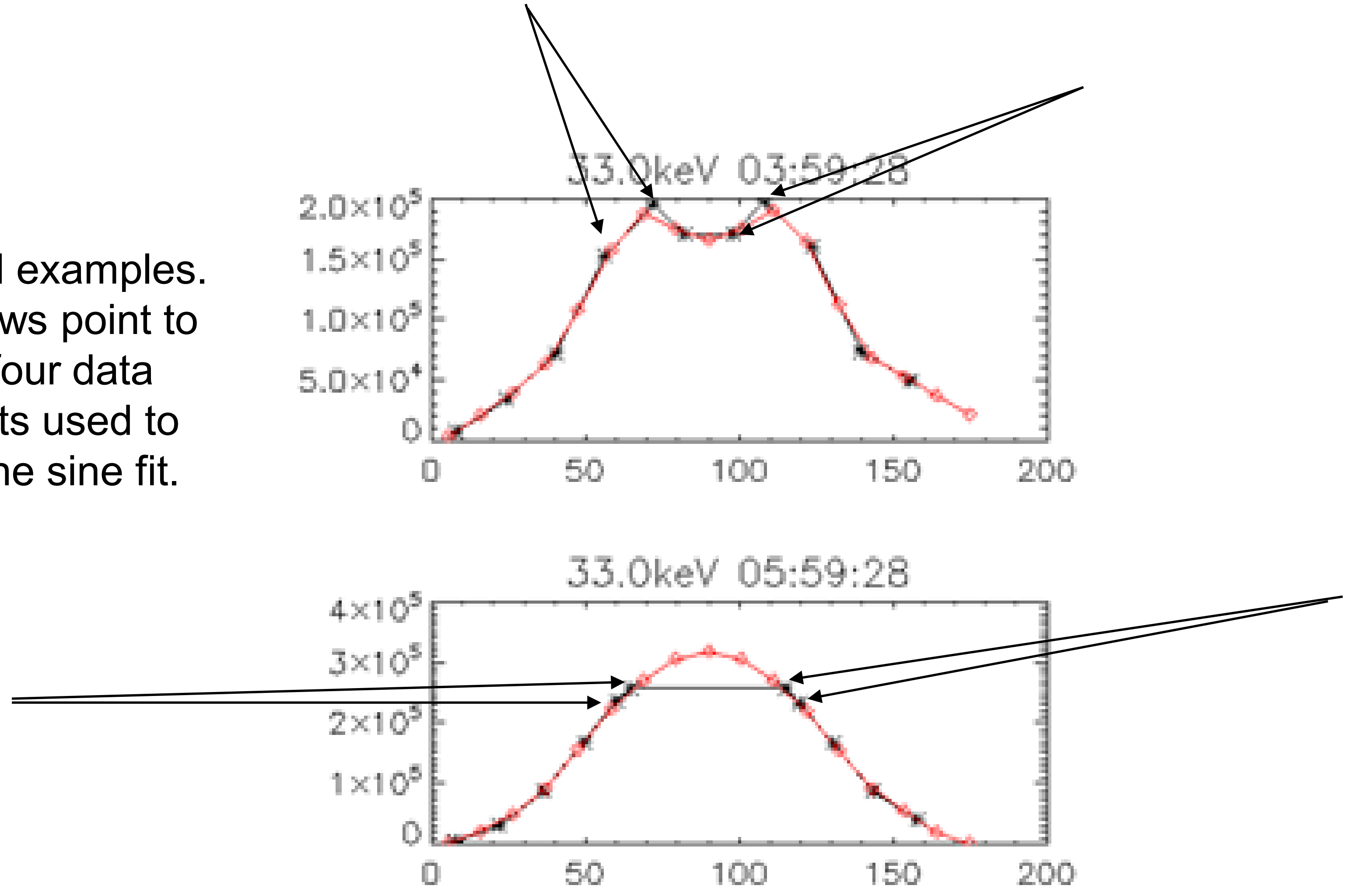
Method to fill the gap:

1. Normalize the PAD by the maximum flux at that time and energy channel (so flux ranges from 0 to 1).
2. Determine if there is a decrease or an increase at 90 based on the four surrounding data points.
   - If there is a decrease,
     - Subtract the PAD by 1 (see example). Always want 0 and 180 to be near 0.
     - Set initial A parameter to -0.5. (Helps the fitting routine know where to start.)
   - If there is an increase,
     - Set initial A parameter to 1. (Helps the fitting routine know where to start.)
3. Run fitting routine, which fits sine function to 4 data points near gap.
   - Outputs: A and B.
4. Use A and B in Flux eqn to calculate flux for 80, 90, and 100 deg equatorial pitch angle.
5. Multiply by the maximum flux to "un-normalize" the mapped data.
6. Use real mapped data & values calculated in step 4. Interpolate to the 17 pitch angle values in REPT to get consistent equatorial pitch angle outputs.

Methodology

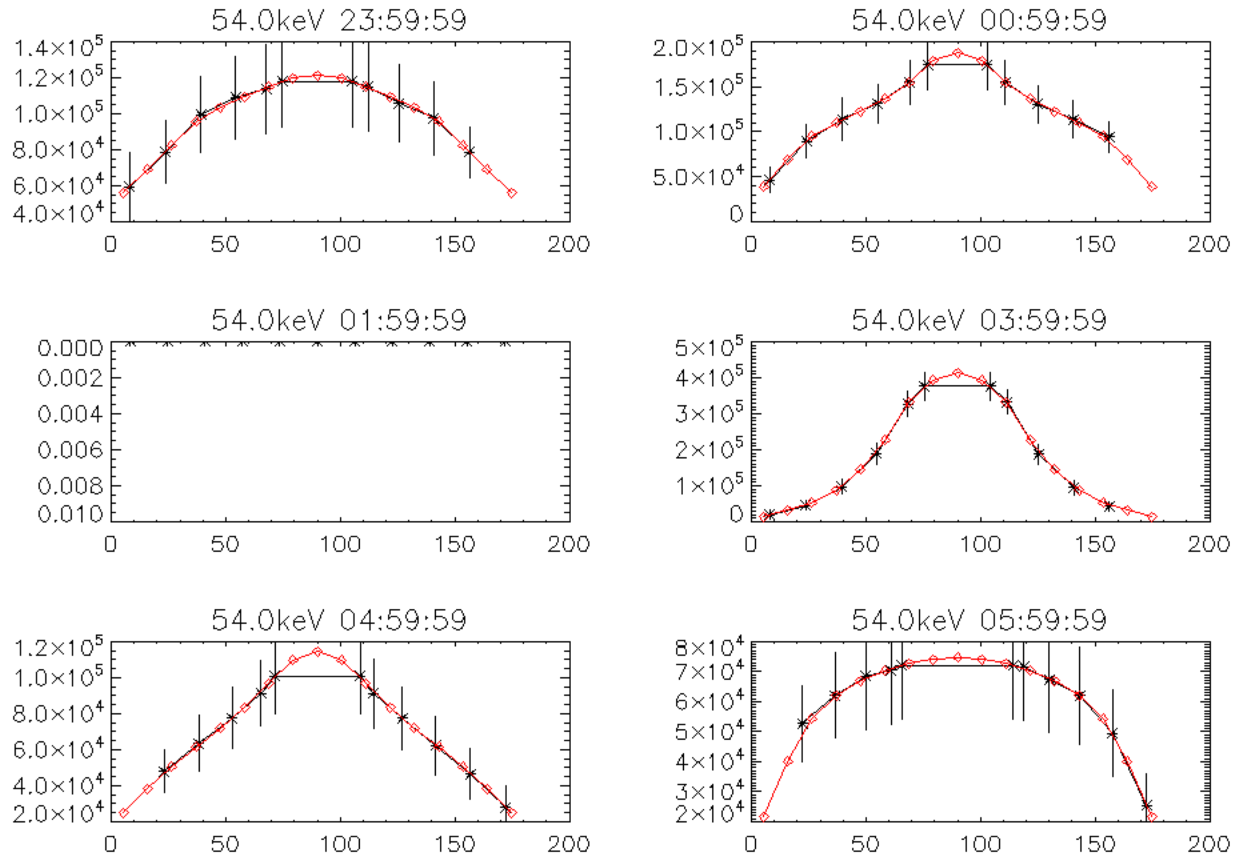
Pitch angle model

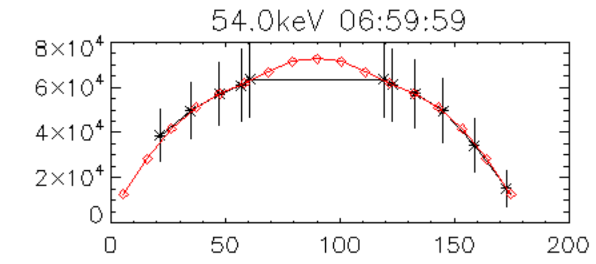
Real examples. Arrows point to the four data points used to do the sine fit.



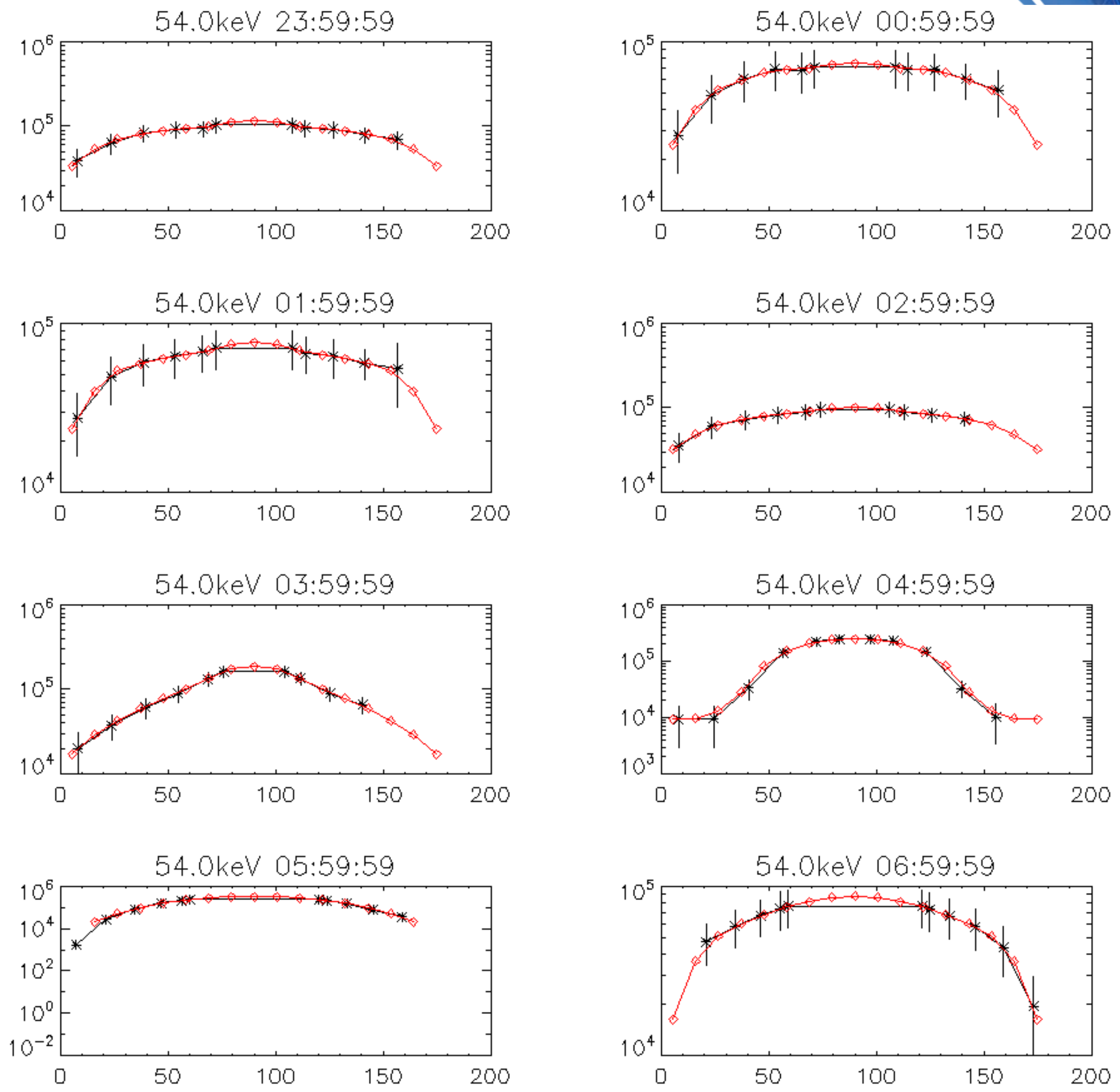
$$flux = A * \sin(B\,\alpha + \frac{\pi}{2} - \mathrm{B}\,\frac{\pi}{2})$$

54 keV fits to fluxes on 2015-03-26 for RBSP-A (left) and RBSP-B (right)





Fitting was very good.



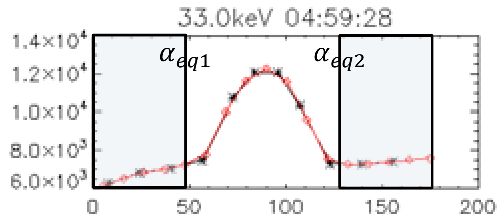
Applied Product (Results)

GPS daily flux counts over time, separated by energy

Knowing the equatorial fluxes, we fly a virtual GPS through the flux map to determine what fluences GPS observed.

1. Map GPS to equator to obtain its L shell and Beq. Initially use IGRF. (Now using T89)
2. Using Beq and Bsc, calculate maximum equatorial pitch angle that GPS observed.

$$\alpha_{eq1} = sin^{-1}\sqrt{\frac{B_{eq}}{B_{sc}} sin^2(90°)} \qquad \alpha_{eq2} = 180 - \alpha_{eq1}$$



Example of fluxes GPS actually sees (blue).

3. Integrate fluxes for all observed pitch angles:

$$j_{omni}(E) = \frac{\int_0^{\pi} j(\alpha, E)\sin\alpha\, d\alpha}{\int_0^{\pi} \sin\alpha\, d\alpha}$$

I interpolated the equatorial fluxes from RBSP to get the exact flux at α_{eq1} and α_{eq2}.

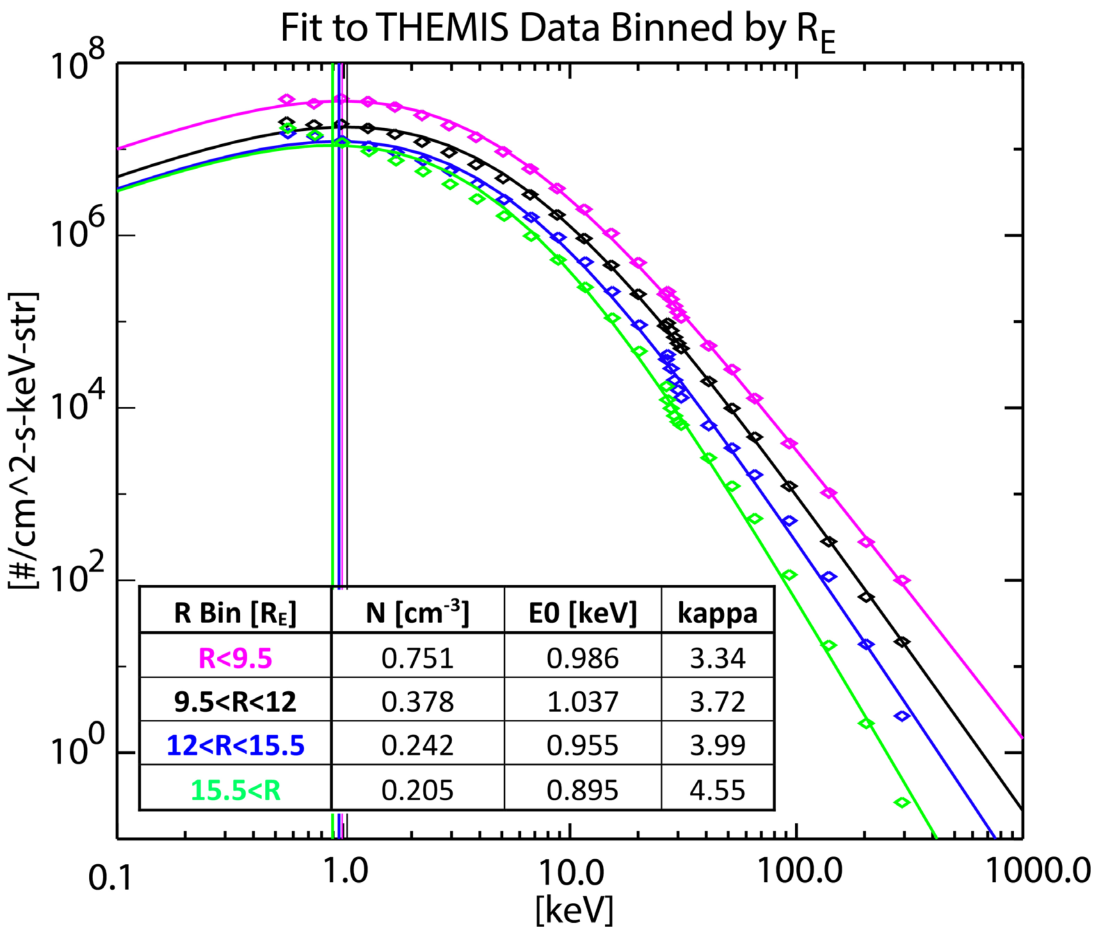
$$\text{J(omni)=} \frac{\left(\int_0^{\alpha_{eq1}} flux(t,W,\alpha)\sin(\alpha)d\alpha + \int_{\alpha_{eq2}}^{180} flux(t,W,\alpha)\sin(\alpha)d\alpha\right)}{\left(\int_0^{\alpha_{eq1}} \sin(\alpha)d\alpha + \int_{\alpha_{eq2}}^{180} \sin(\alpha)d\alpha\right)}$$

[#/cm^2/s/str/keV]

Where flux is a function of time (t), energy (W), and pitch angle (α).

Runov et al. 2015 Results

Four R-bins from THEMIS statistics in the plasma sheet extends our flux model out to 25 R_E.



R Bin [R_E]	N [cm^{-3}]	E0 [keV]	kappa
R<9.5	0.751	0.986	3.34
9.5<R<12	0.378	1.037	3.72
12<R<15.5	0.242	0.955	3.99
15.5<R	0.205	0.895	4.55

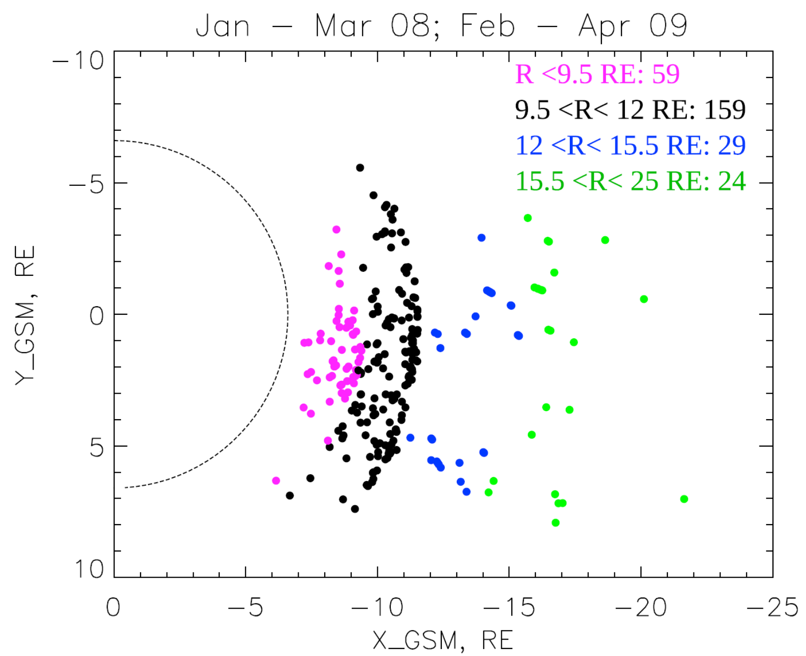


Figure 1. XY_{GSM} distribution of DFB/bubble events detected during the 2008 and 2009 THEMIS tail seasons. Colors indicate geocentric distance (magenta: $R < 9.5\ R_E$, black: $9.5 \geq R < 12\ R_E$, blue: $12 \geq R < 15.5\ R_E$, and green: $15.5 \geq R < 25\ R_E$).

Runov et al., AGU JGR, 2015

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Slide 4 Figure source: https://www.nasa.gov/mission_pages/sunearth/news/gallery/20130228-radiationbelts.html

Slide 11 NOAA data: https://www.swpc.noaa.gov/products/solar-cycle-progression