Validation of Trapped Proton Environment Models with EFT-1 Measurements

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Background & objective

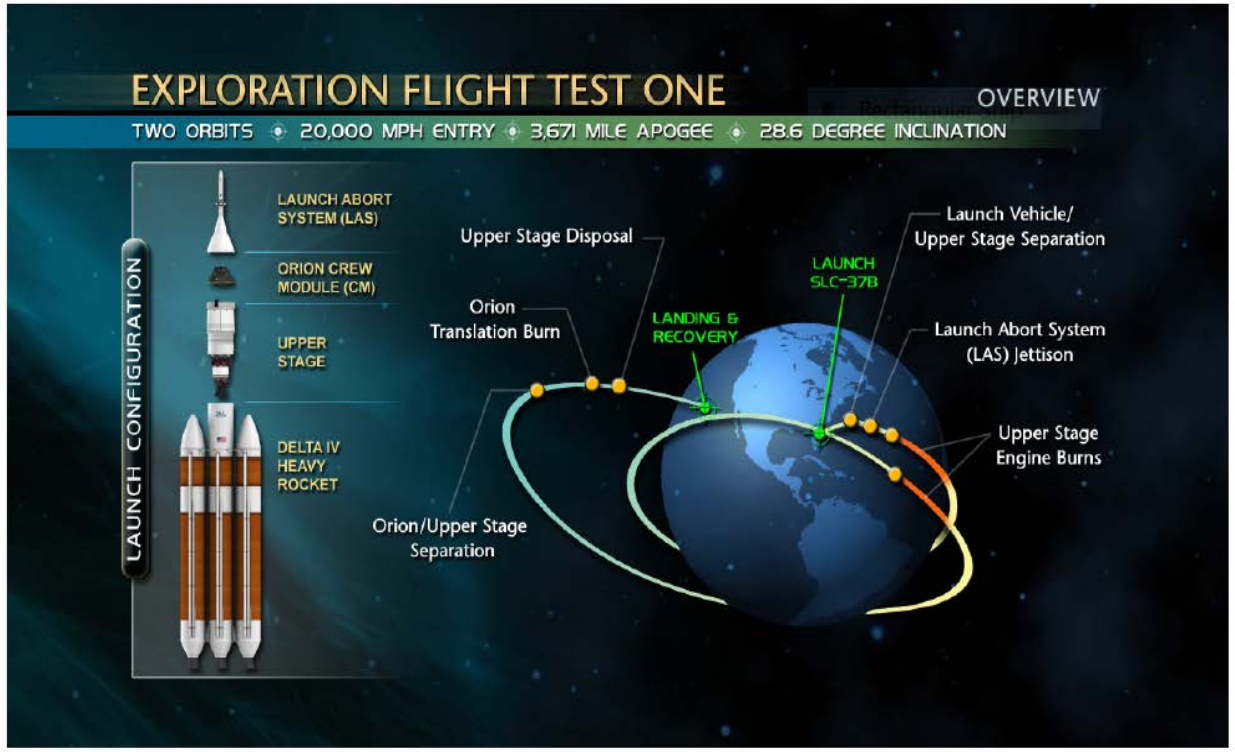
Subject: Inner Van Allen Belt

- A zone where the energetic protons were trapped by the Earth magnetic field.
- Most important radiation consideration in low Earth orbit

Models:

AP8 (and its variations) & AP9

Tools for space mission planning



https://www.nasa.gov/pdf/663703main_flighttest1_fs_051812.pdf

NASA EFT-1 Flight:

Dec. 5th, 2014

One low altitude and one eccentric orbit

Apogee: ~6000 km; Inclination: 28.6°

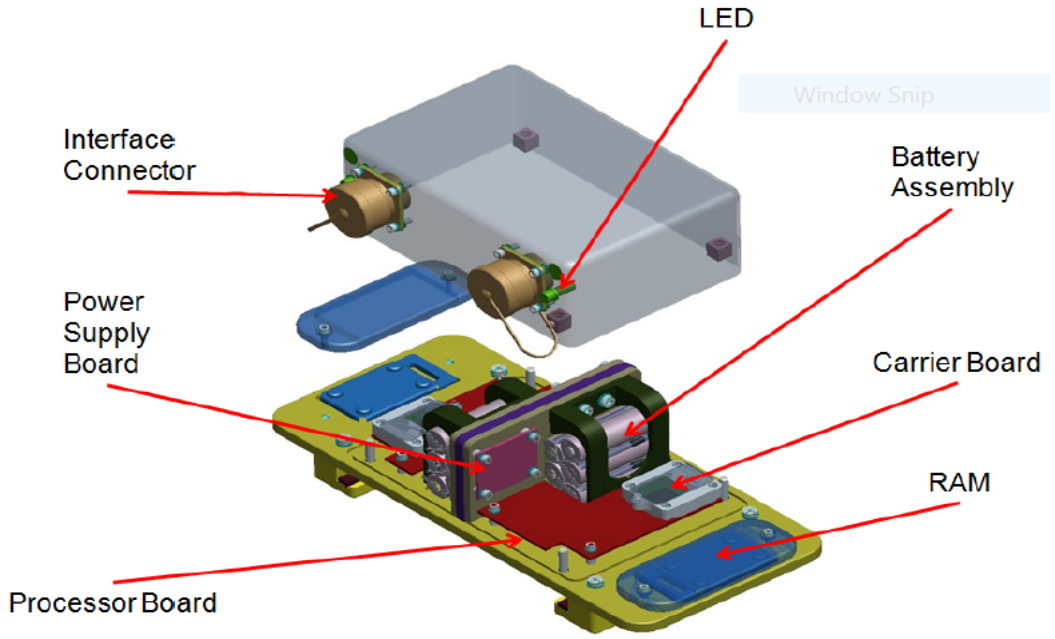
Objective:

Model evaluation for future mission planning

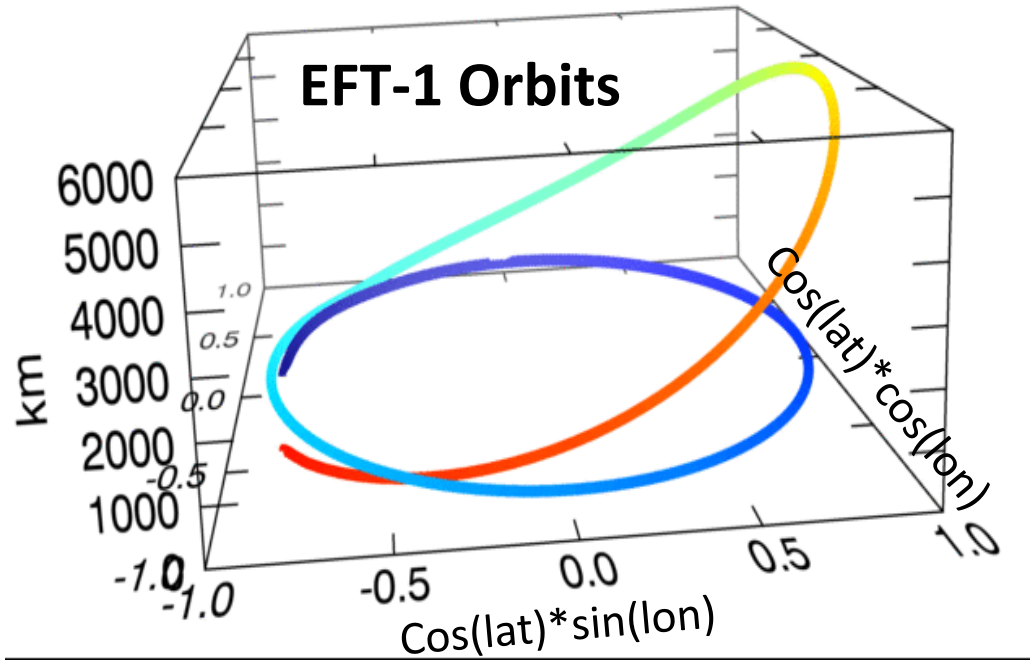
BIRD system and RAM sensors on EFT-1 mission

1. **Battery-operated Independent Radiation Detector (BIRD)**
   - two identical and isolated Timepix detectors with same mechanical enclosure
   - provides the dose for each frame associated with a location and time

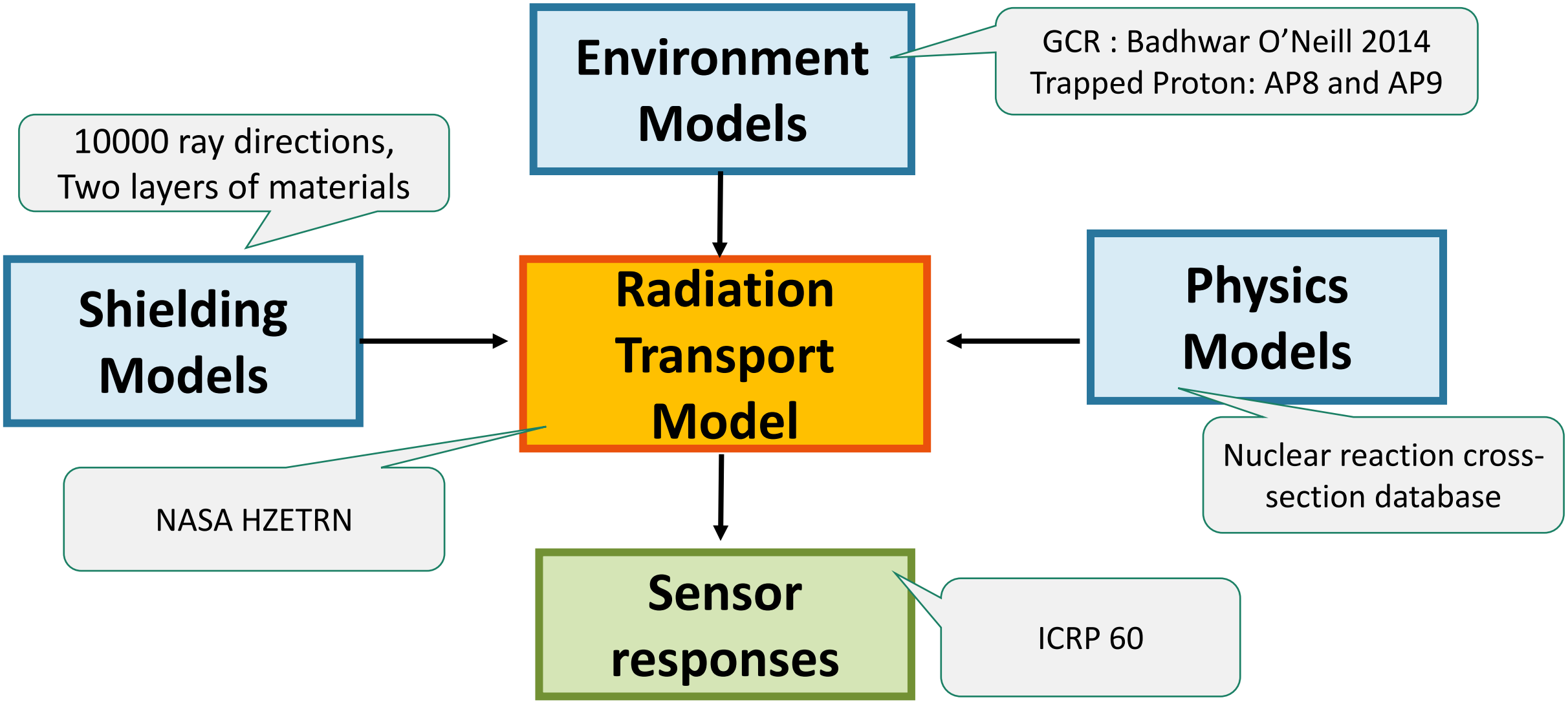
2. **RAM sensors: Radiation Area Monitor**
   - TL/OSL dosimeters provide the accumulated total mission dose



NASA/TP-2015-218575
https://ston.jsc.nasa.gov/collections/TRS/_techrep/TP-2015-218575.pdf



Calculation of space radiation inside a space vehicle



AP8 model and two variations

	AP8 Classic		AP8_DT (Design Tool)	AP8_SolMod (with Solar Modulation)
Flux database & coordinate	AP8MIN (L, B/B_{eq})	AP8MAX (L, B/B_{eq})	Inherited from AP8	Inherited from AP8
Magnetic Fields	JC-60	GSFC-12/66 extended to 1970	shifting of AP8's Magnetic Field (0.19° /yr W, 0.07°/yr N)	IGRF (main field and secular variation)
Solar Activity	solar minimum	solar maximum	Interpolated between SolMin and SolMax, according to its solar activity level	inherited from AP8_DT

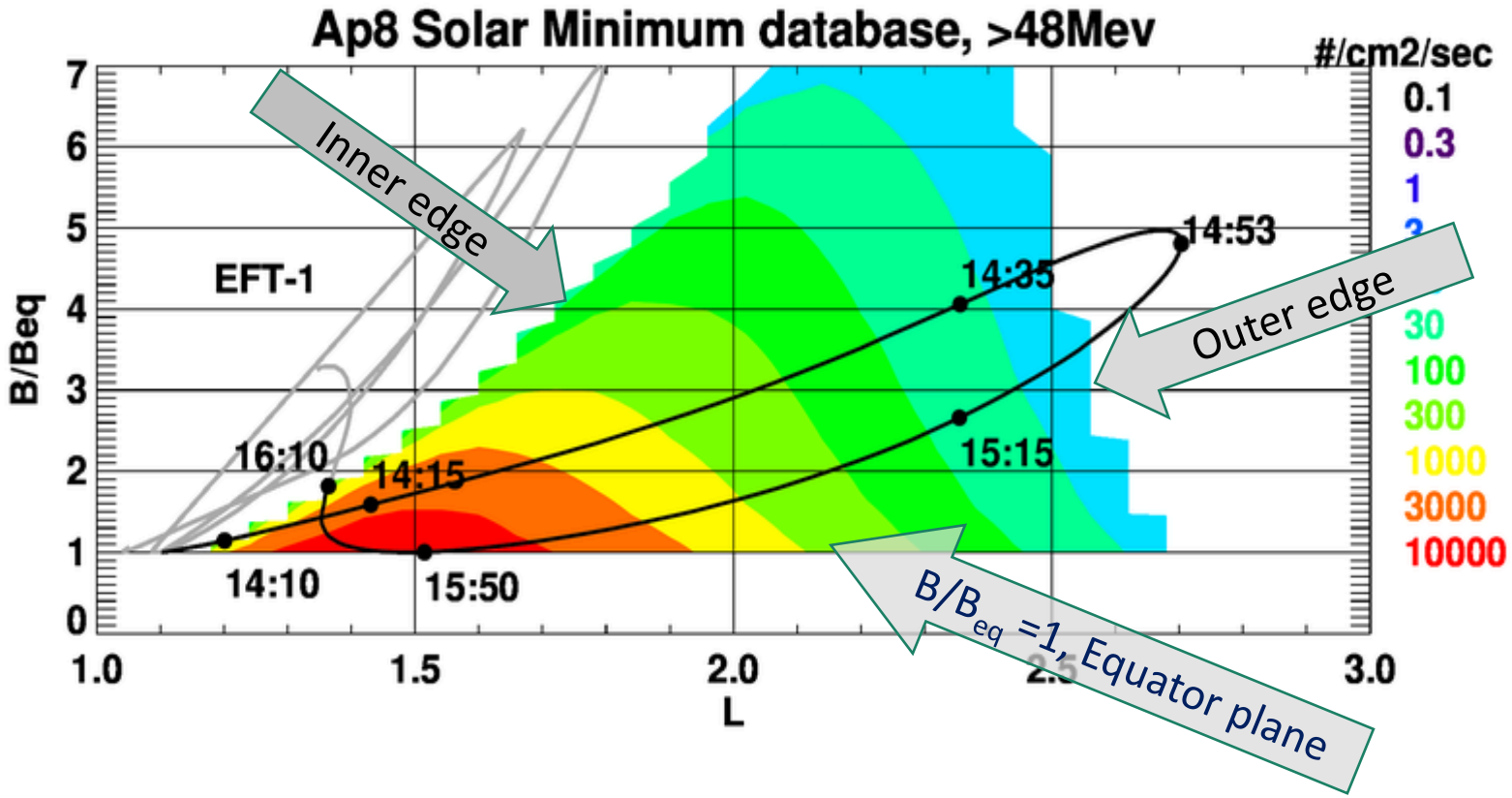
AP9 trapped proton model

	AP9 (version : 1.50.0001, Feb. 2019)
Flux database & coordinates	Global Static Model 1. Data collected from multiple missions and satellites over several decades 2. Adiabatic invariants as coordinates (K, Φ) for $H_{min} > 1000km$ (K, H_{min}) $H_{min} < 1000km$
Magnetic Fields	IGRF (internal magnetic field model) Olson-Pfizer Quiet model (OPQ77, external magnetic field model)
Solar Activity	No time-dependency with solar cycle

AP9 provides the percentile levels of flux occurrence

AP9 averaged proton fluxes were used in this work

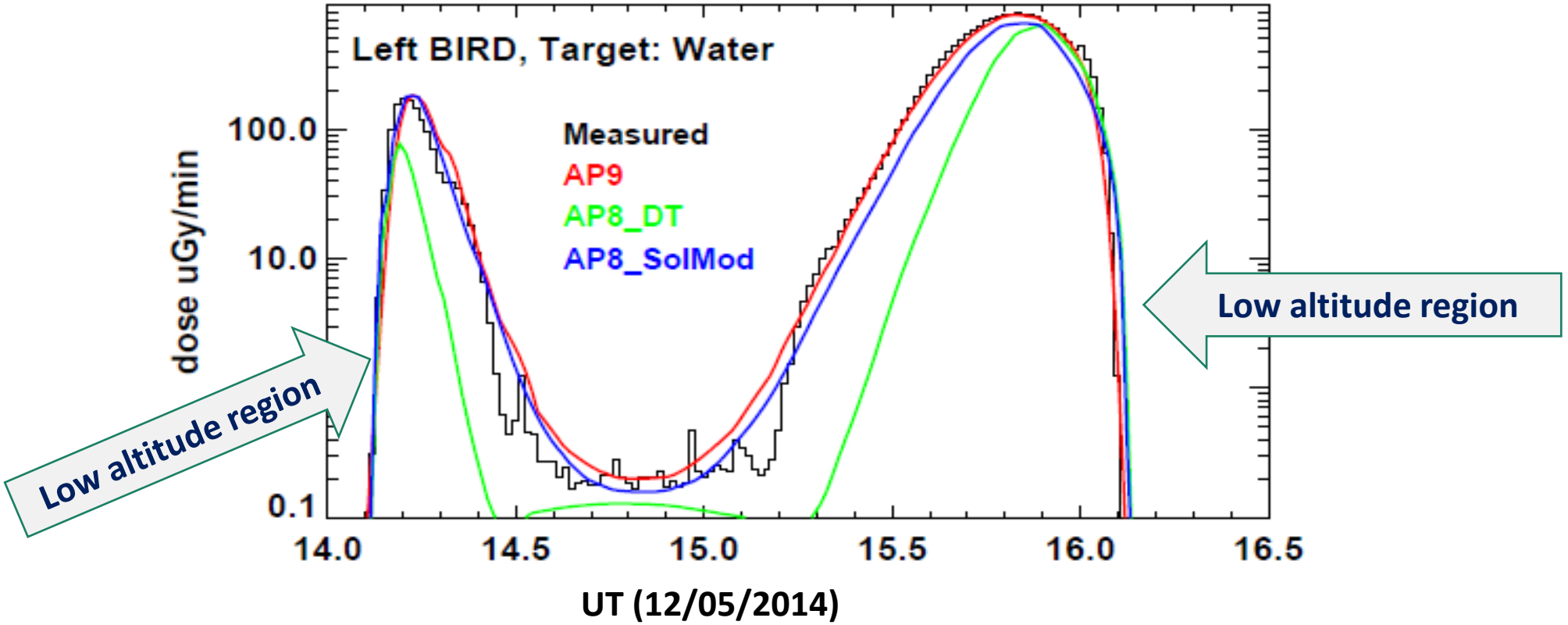
EFT-1 trajectory in geomagnetic system



Color-filled contour: location and intensity of inner Van Allen Belt

Black line: EFT-1 trajectory

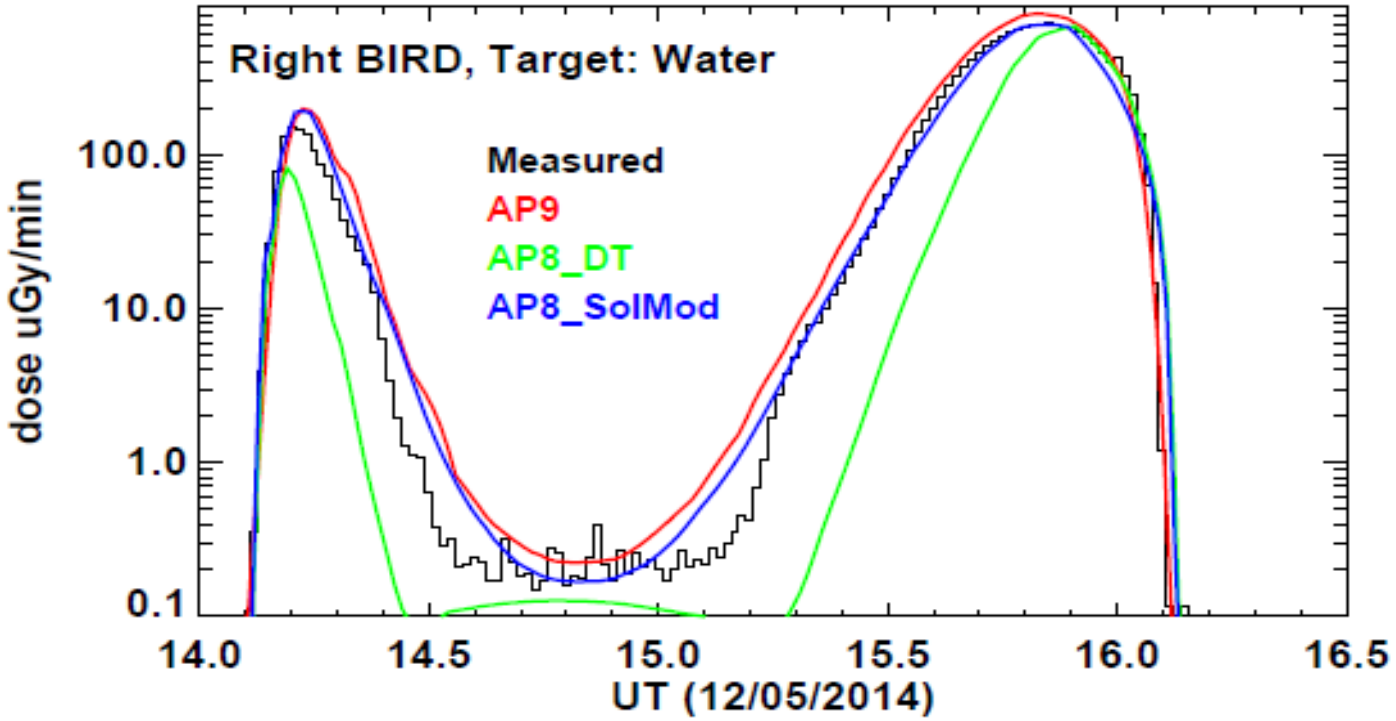
Model calculation and measurement comparison: Left BIRD

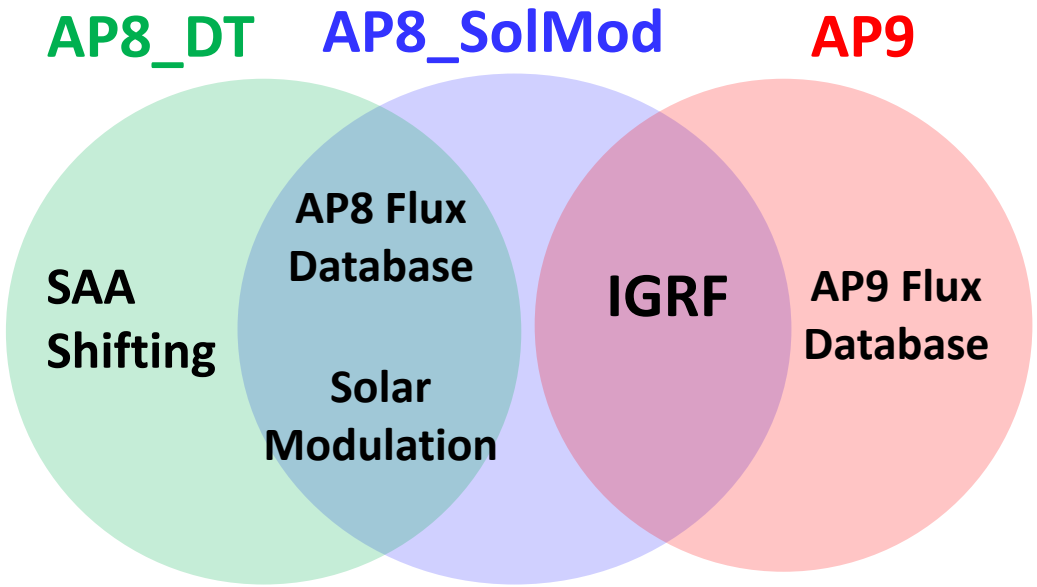


AP9 and **AP8_SolMod**: simulated the measurement variation **very well**

- **AP9**: the best simulation
- **AP8_SolMod**: slightly under-estimated
- **AP8_DT**: **agree well at low altitude** and **significantly under-estimate at high altitude** for EFT-1 trajectory

Model calculation and measurement comparison: Right BIRD





AP9 and **AP8_SolMod:** simulated the measurement variation **very well**

AP9: slightly over-estimated

AP8_SolMod: the best simulation

AP8_DT: **agree well at low altitude** and **significantly under-estimate at high altitude** for EFT-1 trajectory

Total mission dose: comparison between the sensors

A

mGy	L-BIRD	R-BIRD	L-RAM	R-RAM
Measured	17.9	15.7	15.1 +/-0.3	13.5 +/-0.2
AP9	16.9	18.2	21.1	19.0
AP8-SolMod	13.8	14.7	17.0	15.3

B

Difference	L-BIRD	R-BIRD	L-RAM	R-RAM
AP9	-5.8 %	15.7%	40.0%	40.4%
AP8-SolMod	-23.0%	-6.2%	12.3%	13.6%

1. AP9 is closer to the silicon-based Timepix BIRD sensors
2. AP8_SolMod is closer to TL/OSL RAM sensors

Model simulation at low altitude region - I

Simulating the proton flux near the inner edge of Van Allen Belt is challenging

- Proton flux changes rapidly with altitude in low altitude region. Small errors in location calculations can cause large errors in flux.
- Proton flux is modulated by solar activity level through the change in air density.
- Changes in geomagnetic field over years affect the shape and location of the inner edge of Van Allen belt.

These factors are intertwined by two coordinate systems affecting this region's proton flux. This makes it challenging for an individual static model to be suitable for all times.

Model simulation at low altitude region - II

With two coordinate systems involved, it is challenging for an individual static trapped environment model to be suitable for all times.

As an example:

Geomagnetic system (L=1.3, b/b_{eq}=1.4)

in IGRF (year 2013): H_{min} = ~450 km,

while in the JC-60 field: H_{min} = ~550 km

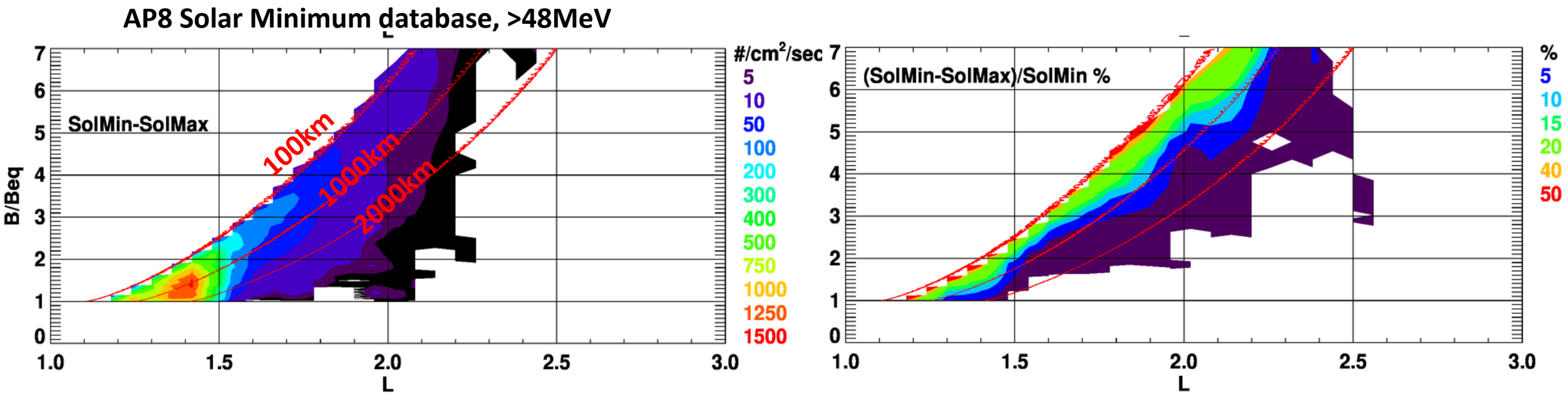
Geodetic (Gravity) system

An altitude where air density has large effects on proton flux, 100km difference results in very large flux change

Static trapped environment models need to be thoroughly evaluated in this region.

AP8_DT was evaluated with the time-dependent measurements from ISS and Space Transport System.

Trapped proton environment & future mission plan



- The difference between solar min and solar max helps to estimate the solar modulation
- Model selection for future mission planning depends on which region the mission trajectory will pass
- Flux in high altitude region is less time-dependent

Summary

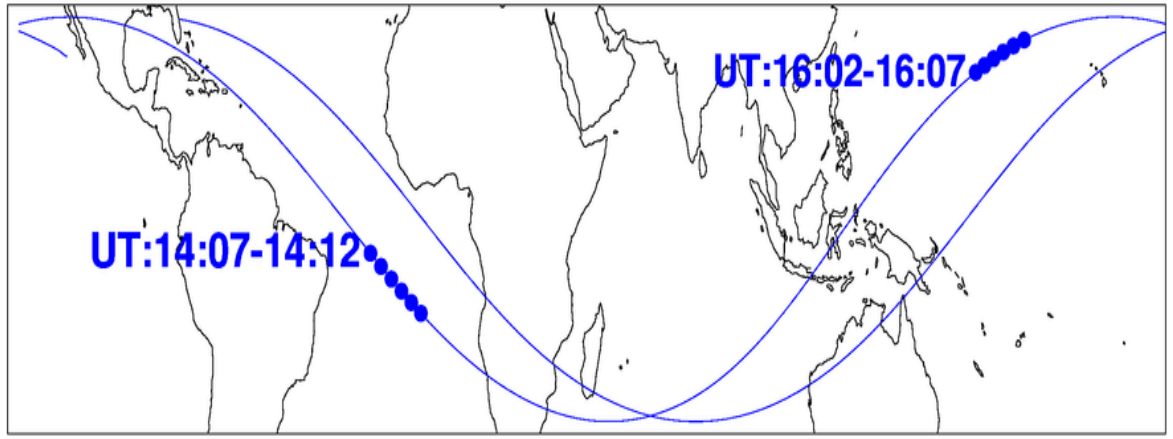
- EFT-1 BIRD measurements provided a great opportunity for trapped environment model evaluation
- AP9 and AP8_SolMod, both using IGRF field, show excellent agreement with EFT-1 measurements
- AP8_DT, using a time-dependent SAA shifting of AP8's geomagnetic fields, is capable of simulating low altitude region
- Good agreement between the measurements and simulations from AP9 and AP8_SolMod, which have different databases, confirms that the proton flux at the inner Van Allen Belt is relatively stable

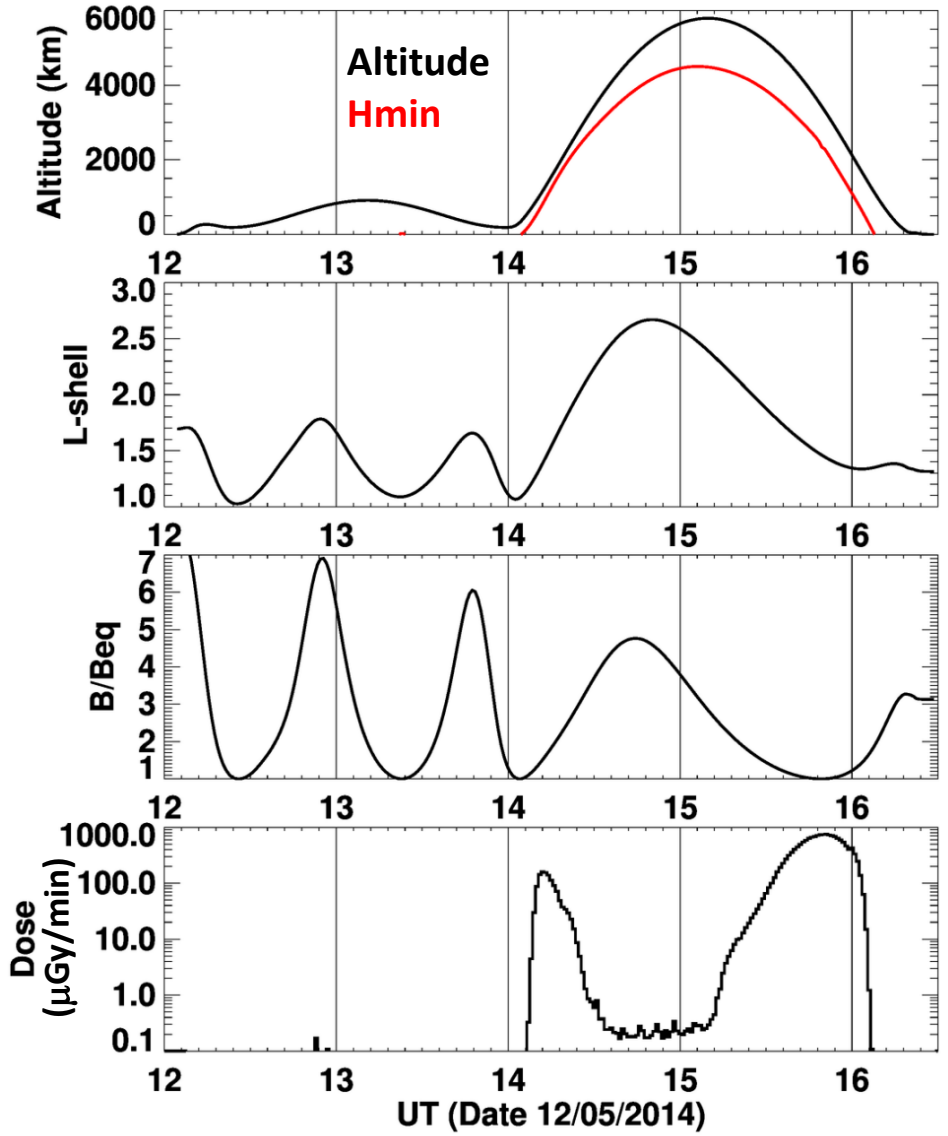
Recommendation for future missions

	AP8_DT	AP8_SolMod	AP9
High altitude region >1000km	X	✓	✓
Low altitude region <1000km	✓	Need to be evaluated	Need to be evaluated

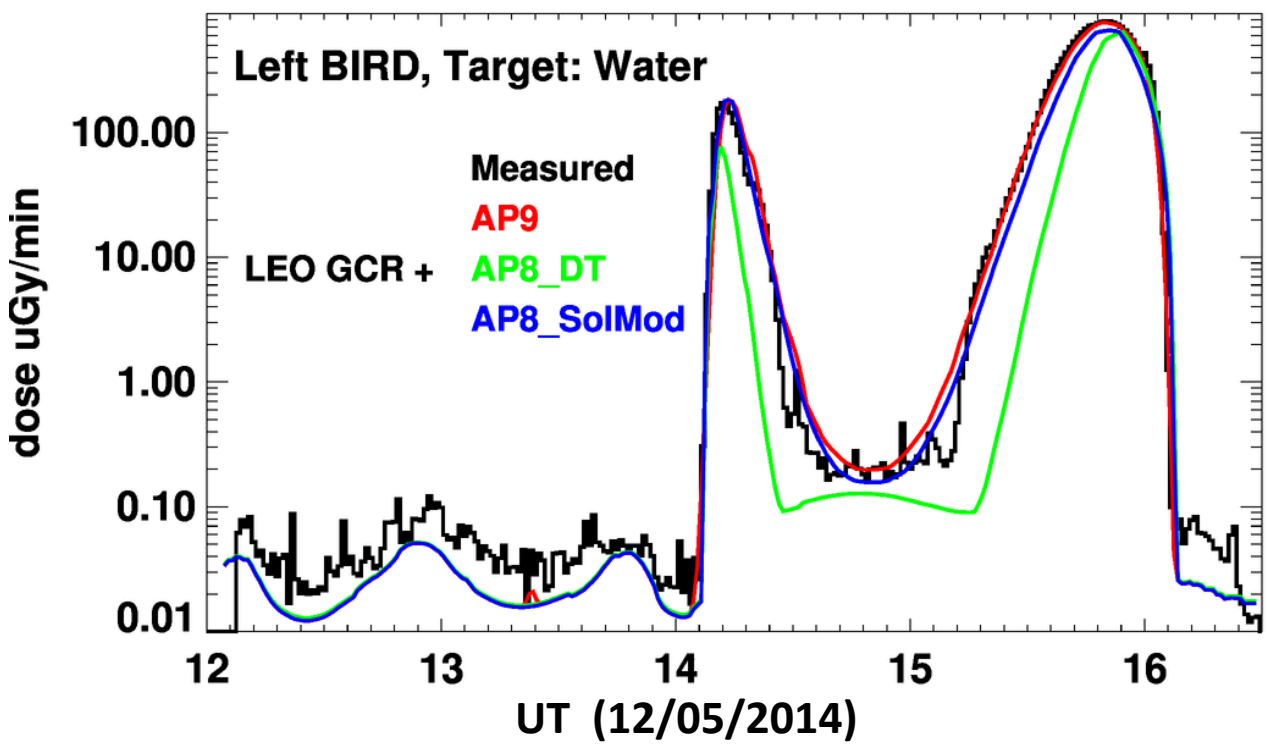
End

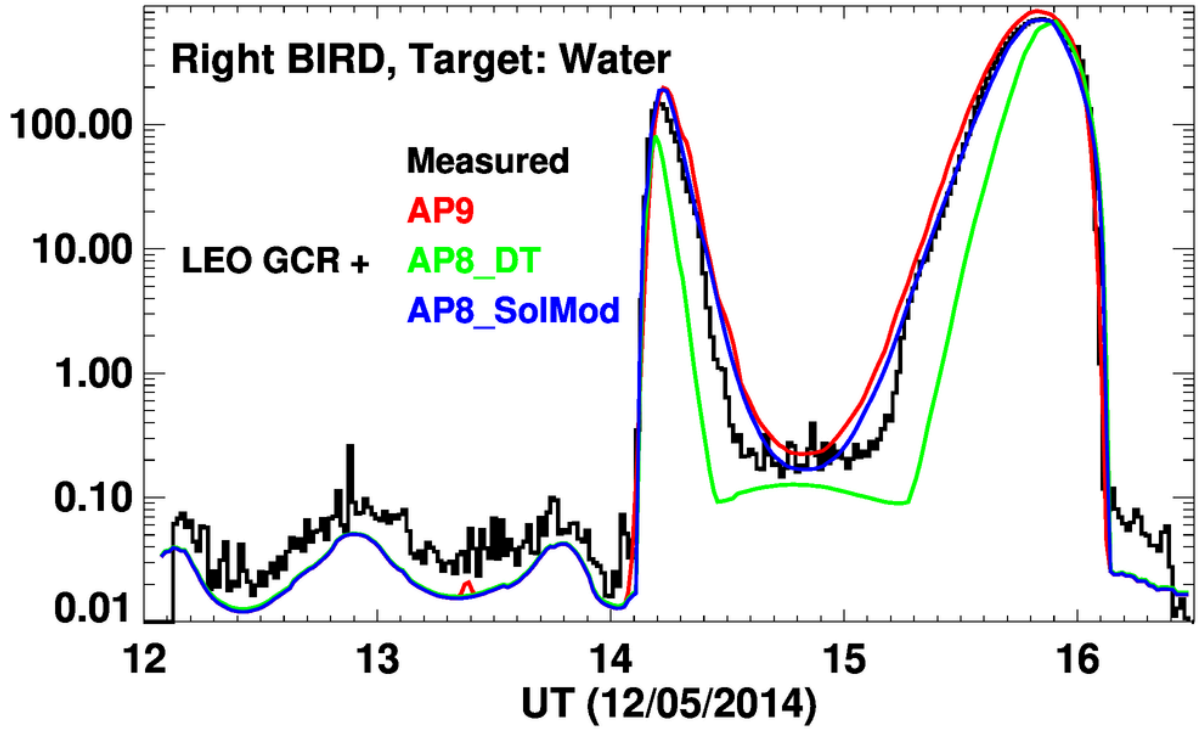
EFT-1 Trajectory and the important parameters



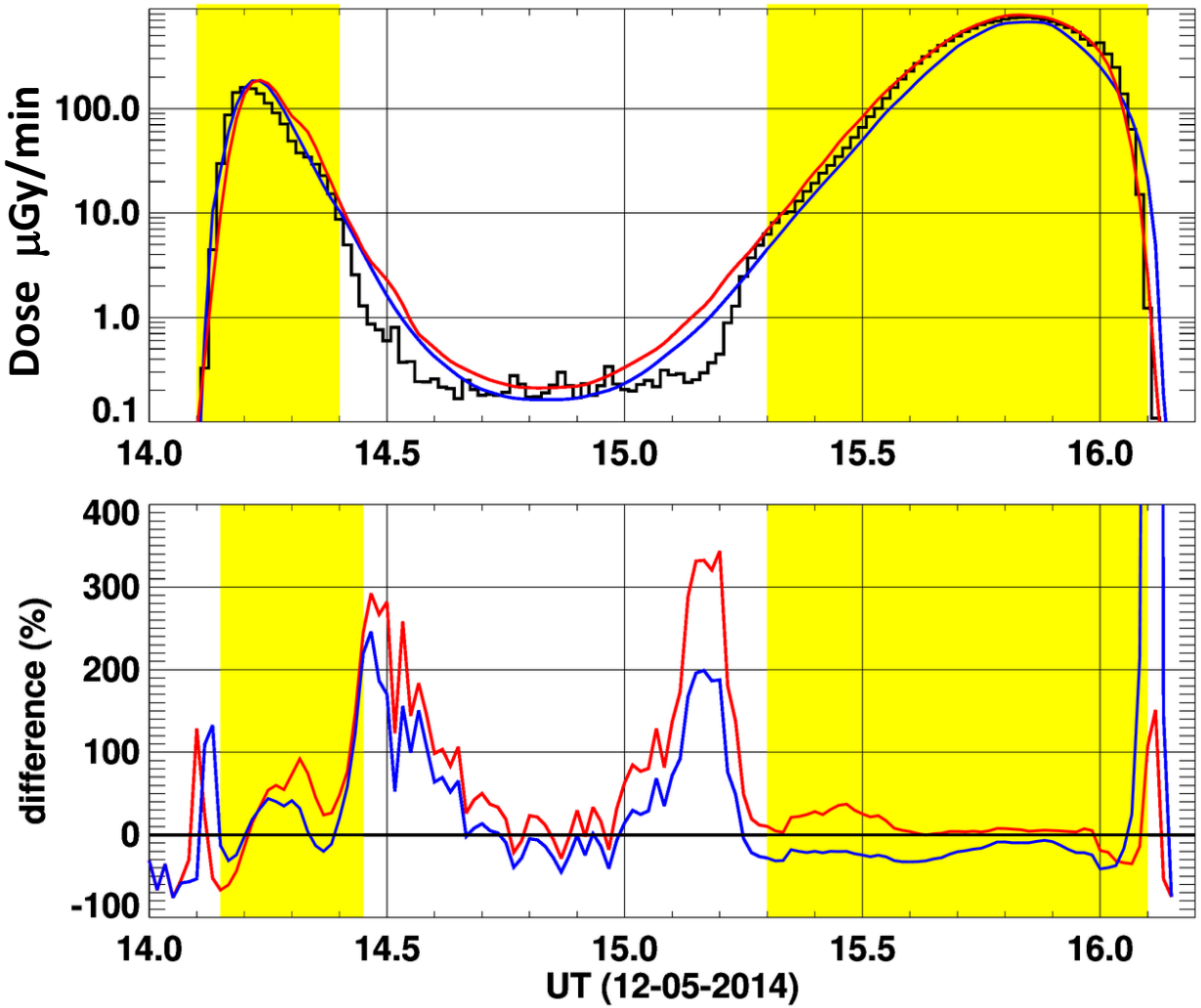


Model simulation and measurements





Averaged BIRD measurements vs. model simulation



- 1-minute BIRD system averaged data
- A point-to-point comparison between measurement and simulation is not recommended for a highly eccentric orbit with rapidly changing locations
- Good agreement between simulation and measurement is seen inside the Van Allen inner belt
- Large difference is seen at the transition area near the belt edges

Total mission dose: comparison between the sensors

A

mGy	L-BIRD	R-BIRD	L-RAM	R-RAM
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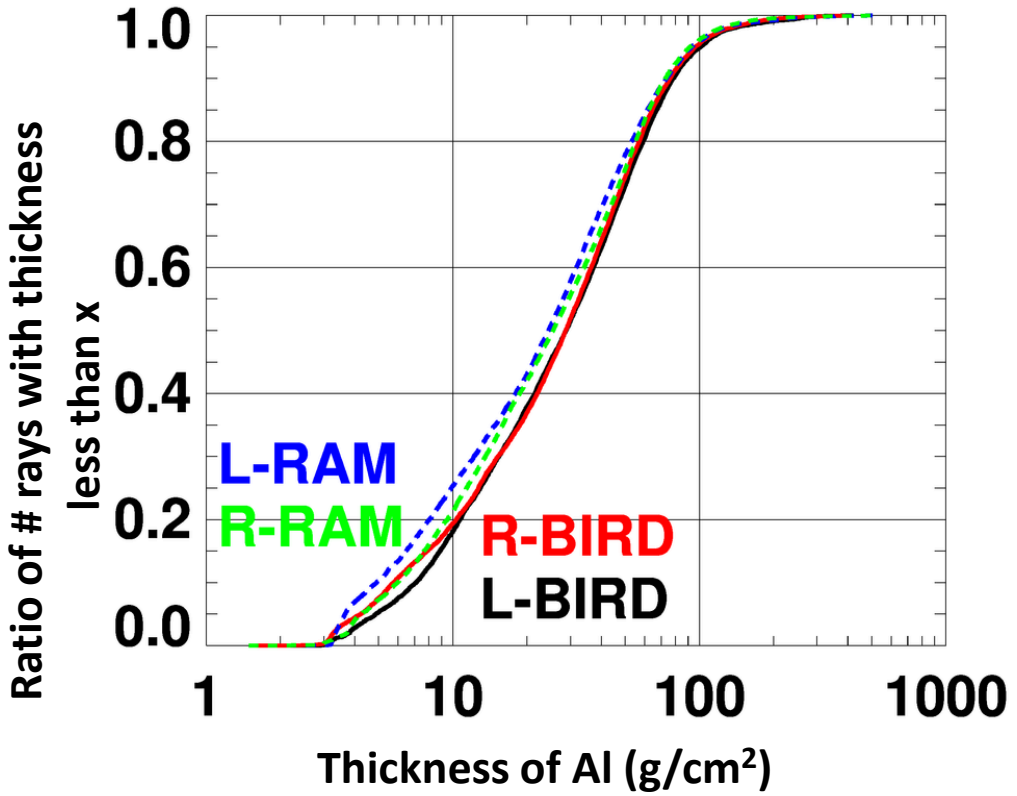

1. In model calculation, contribution from the thin directions largely effects the total dose a sensor receives
   Dose Simulation: (L-RAM > R-RAM) > (R-BIRD > L-BIRD)
   Dose Measurements: (L-RAM > R-RAM) < (L-BIRD < R-BIRD)
2. AP9 is closer to the silicon-based Timepix BIRD sensors
3. AP8_solmod is closer to TL/OSL RAM sensors

1. Difference of sensor response functions
2. Directionality of trapped environment
3. Precision of sensors' shielding definition

AP8_DT development and evaluation publications

1. F.F.Badavi, S.A.Walker, L.M.Santos Koos, “Low Earth orbit assessment of proton anisotropy using AP8 and AP9 trapped proton models”, Life Sci. in Space Res., vol. 5, pp. 21-30, 2015.

2. F.F.Badavi, J.E.Nealy, J.W.Wilson, “The Low Earth Orbit validation of a dynamic and anisotropic trapped radiation model through ISS measurements”, Advances in Space Research, vol. 48, no. 3, pp: 1441-1458, 2011.

3. F.F.Badavi, M.A.Xapsos, J.W.Wilson, “Description of a Generalized Analytical Model for a Micro-dosimeter Response”, Advances in Space Research, vol. 44, pp: 190-201, 2009.