The IRENE-AE9/AP9 Next Generation Radiation Specification Models—Progress Report

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Outline

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- Coverage and application
- ESA contributions
- Expanded team: Japan
- Industry Days
- V1.60/V1.70 overview
- Comments on usage and limitations
- Summary

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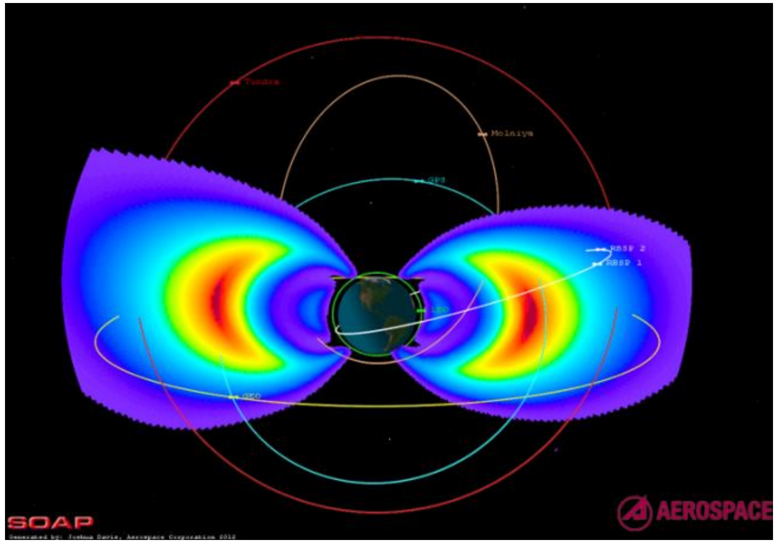
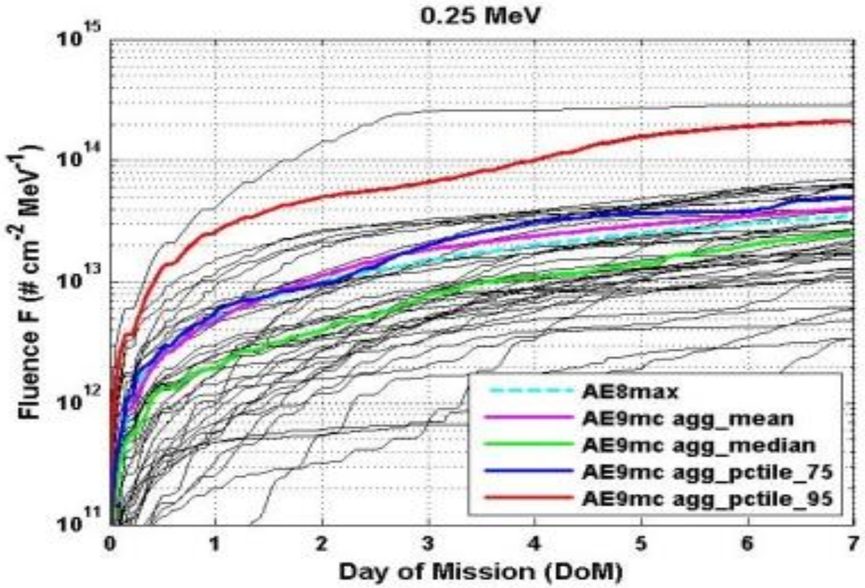
What is IRENE?

- IRENE-AE9/AP9 specifies the natural trapped radiation environment for satellite design and mission planning
  - IRENE = International Radiation Environment Near Earth
- It improves on legacy models to meet modern design community needs:
  - Uses 45 long duration, high quality data sets
  - Full energy and spatial coverage—plasma added
  - Introduces data-based uncertainties and statistics for design margins (e.g., 95th percentile)
  - Dynamic scenarios provide worst case estimates for hazards (e.g., SEEs)
  - Architecture supports routine updates, maintainability, third party applications
- V1.00 released in 2012, V1.50 in Dec 2017
- V1.58 released in March 2024



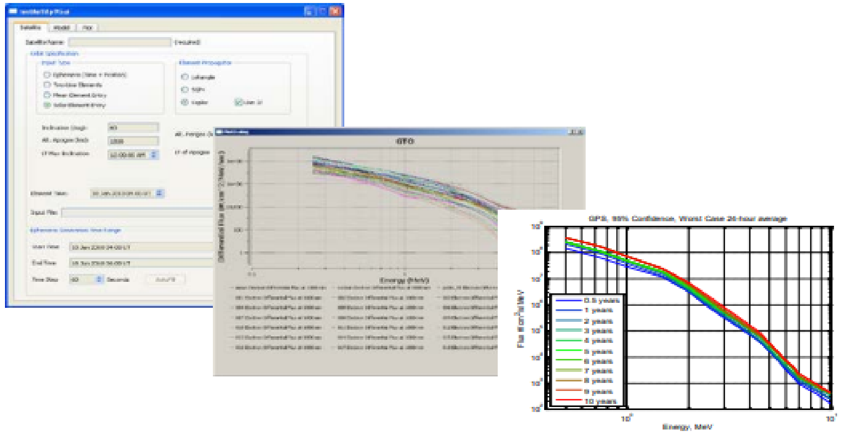


Coverage and application

- Energy coverage from keV plasma to GeV protons
- Spatial coverage for all orbit regimes, including tailored coverage for high resolution in LEO

Model	AE9	AP9	SPM
Species	e^-	H^+	e^-, H^+, He^+, O^+
Energies	40 keV—10 MeV	100 keV—2 GeV (V1.20)	1—40 keV (e^-); 1.15—164 keV (H^+, He^+, O^+)
Range in L	$0.98 < L^* < 12.4$	$0.98 < L^* < 12.4$	$2 < L_m < 10$

- Model provided with GUI and CmdLine access
- APIs available in C++, C, and Python
- Distribution as Windows binary
  - Source code package available on request from AFRL for other platforms (build instructions included)
- Documentation includes recommended modes for typical use cases and sample test cases

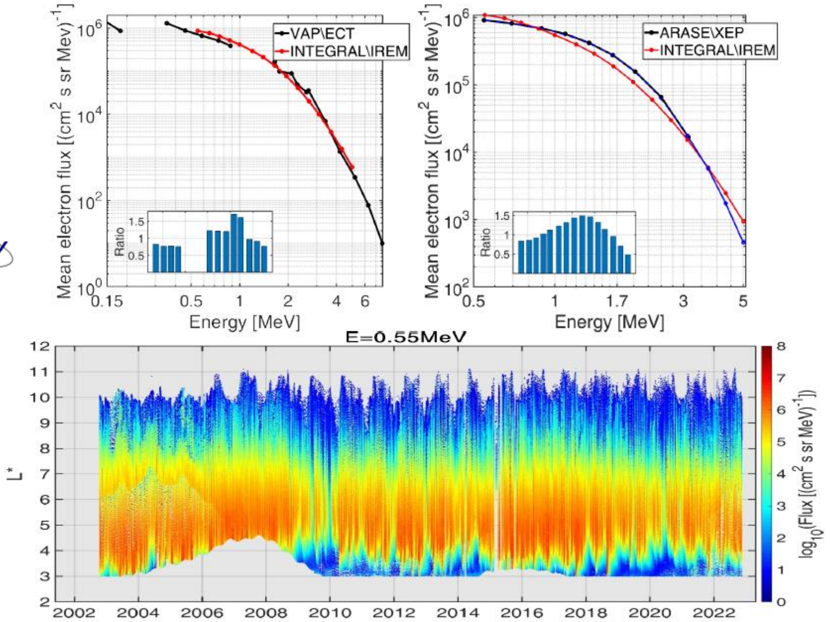


ESA Contributions

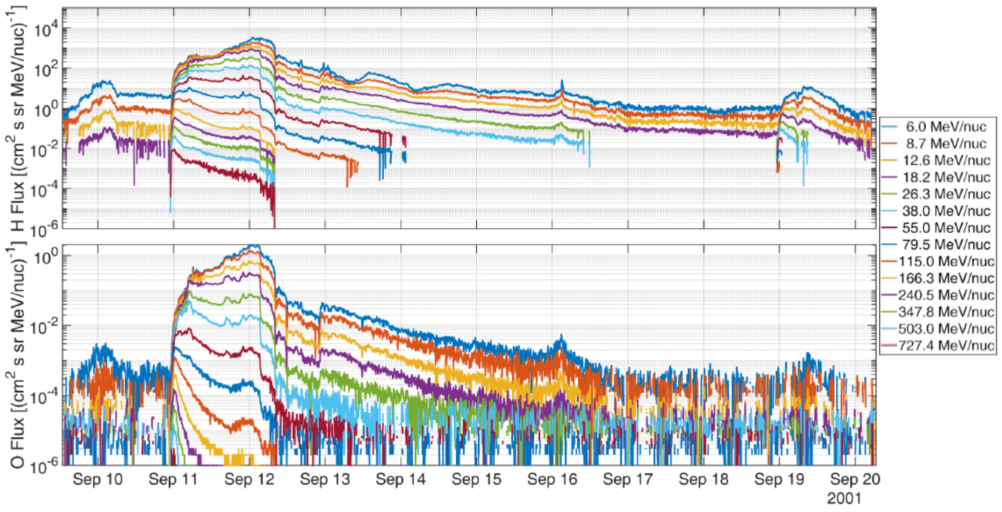
- SPARC-led, ESA-funded, European Contribution to IRENE (ecIRENE)
- Data sets from ESA and European missions:

  Giove-A, Integral, Proba-1, PAMELA
- Solar energetic particle model: SAPPHIRE-2S, including Monte Carlo scenario capability and geomagnetic shielding
- Trapped particle modeling – new statistical procedures, architectures and workflows
- Validation/verification and testing of IRENE models

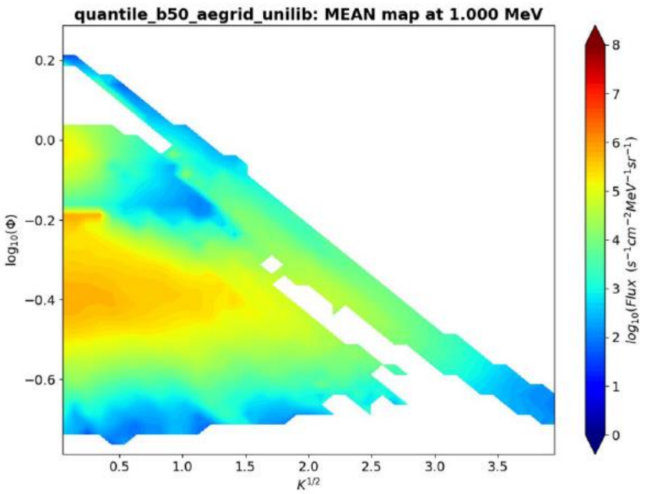
AI derivation of 20+ years of SREM electron fluxes



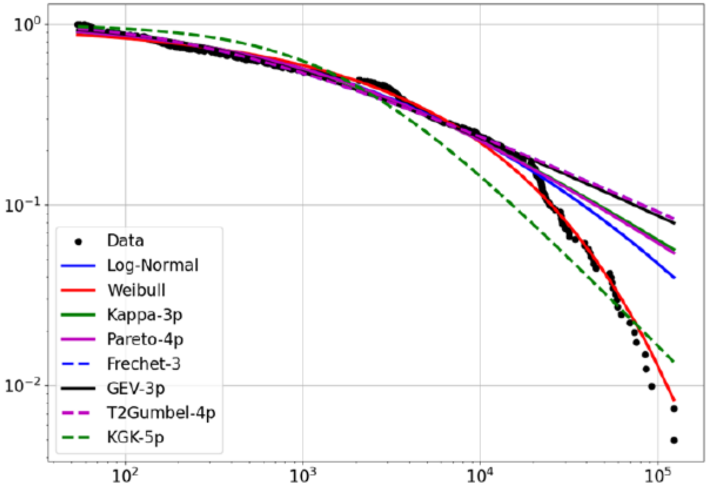
SAPPHIRE Virtual Solar Particle Events



Unified Framework for Rad Belt Modeling

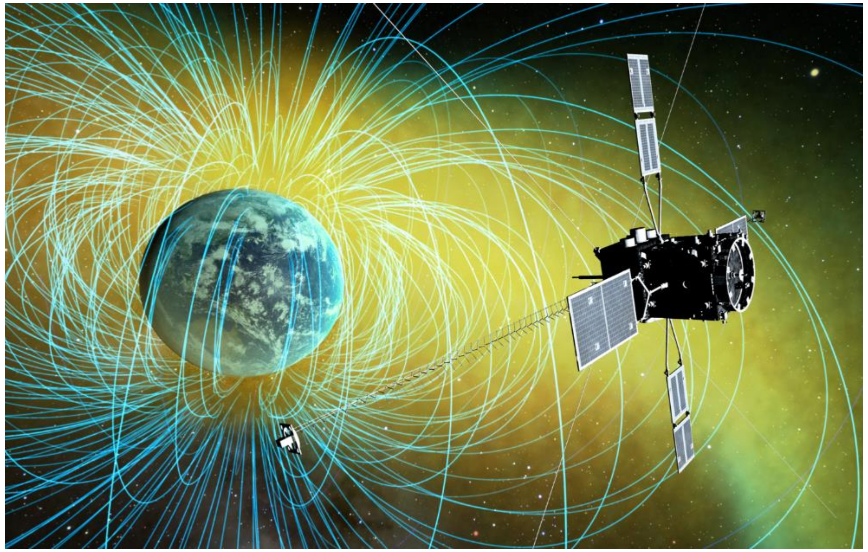


Modelling Methodology Studies



Expanded Team: Japan

- Japanese partners have joined the team: JAXA, NICT, ISEE/Nagoya
- New datasets: ARASE, Himawari, Akebono, GoSat…
- Modeling capabilities: IRENE has synergies with the ARASE modeling effort



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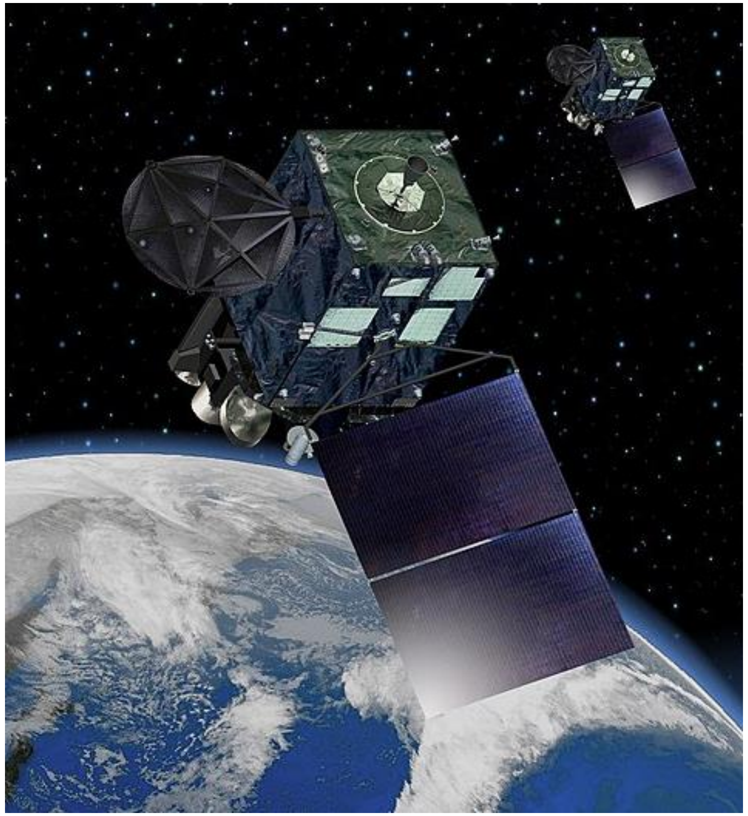

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Industry Days 2023

- Held 3 virtual industry days:
  - USA East / Europe Time Zone – 1 March 2023
  - USA West – 2 March 2023
  - Japan Time Zone – 15 May 2023
- Attended by more than 100 people representing more than 50 organizations
- Presentations available at https://www.vdl.afrl.af.mil/programs/ae9ap9/documents.php under “Presentations”
- Videos coming soon

Presentations:

- IRENE overview
- ESA perspective
- V1.57 feature changes
- Kernels
- V1.60 plans
- SAPPHIRE-2S solar protons
- V2.0 plans
- Q&A / Demo

V1.60, V1.70 Overview

- V1.60 release is planned for late 2025
  - Solar energetic particles (SAPPHIRE-2S)
- V1.70 release is planned for 2026
  - Will update trapped flux maps with additional data sets
- Minor feature updates also planned

New data sets

Data Set	Orbit	Time	Species/energies	Notes
Van Allen Probes/ HOPE, RBSPICE, MagEIS, REPT, RPS	GTO (600 x 22000 km, 10°)	2012-2019	electrons 20 keV->10 MeV protons 20 keV-2 GeV plasma <10 eV-50 keV	Final mission data sets; some MagEIS, REPT, RPS data used in V1.2
PROBA-V/EPT	LEO (820 km circ., 99°)	2013-2022	protons 9.5-300 MeV	
Resurs-DK1/PAMELA	LEO (350 x 600 km, 70°)	2006-2009	protons 80 MeV-4 GeV	
AMPTE-CCE/CHEM	HEO (1100 x 50000 km, 5°)	1984-1989	plasma 1.5-300 keV/e	
DSX/CEASE I, LEESA, LCI, HEPS	MEO (6000 x 12000 km, 42°)	2019-2021	electrons 80 keV-4 MeV protons 1-400 MeV GeV plasma 30 eV-30 keV	Initial data as available; final data sets will be added in V2.0
INTEGRAL/IREM	HEO (10000 x 153600 km, 72°)	2002-2022	electrons 0.5-5 MeV	
PROBA-1/SREM	LEO (570 x 670 km, 99°)	2001-2021	electrons 0.3-6 MeV	
GIOVE-A/Merlin/SURF	MEO (23300 km circ., 56°)	2006-2021	electrons 0.8-1.6 MeV	
Himawari-8,-9/SEDA	GEO	2014-	Electrons 0.2-5 MeV protons 20-100 MeV	Stretch goal
ARASE/XEP, HEP, MEP, LEP	MEO (460 x 32,000 km, 31°)	2016-	electrons 20 eV-6 MeV protons/ions 50 eV-180 keV	Stretch goal

These data sets are targeted to address several needs:

- More coverage for very high energy protons (0.4-4 GeV)
- Clean observations of inner zone electrons from Van Allen Probes
- Improved plasma coverage
- More data sets covering the last two solar cycles—modern climatology

Other updates

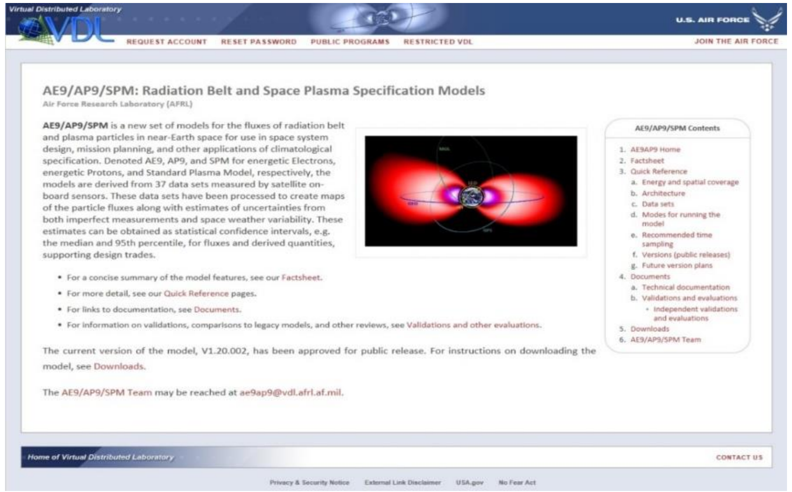
- V1.58 recent updates
  - Variable timestep ephemeris auto-generation (supports optimizing for high time resolution only where needed for accurate results, e.g., for eccentric orbits)
  - Simplified database specification parameter inputs
  - New option to separate bremsstrahlung contributions from direct electron ionization in dose calculations
  - API enhancements
  - Update source code to be compatible with C++17 standards
  - Additional input/output options (e.g., magnetic field output)
- Future feature updates
  - Update and improve neural net calculations of adiabatic invariants (for flux map querying)
  - High level Python interface (more "Pythonic")
  - Additional input/output options (e.g., YAML-format input)
- Update to use of IGRF 2020/2025 magnetic field model
  - V1.5X employs IGRF 2015 with extrapolation to 1/1/2020 and fixed internal field after that
  - V1.70 will employ IGRF 2025 with extrapolation to 1/1/2030, fixed after that
  - Note that IGRF 2015/2025 differences yield only small differences in IRENE results (less than other model uncertainties)
- Other minor feature updates as feasible and needed (**feedback welcome!**)

Comments

- Documentation in distribution package
  - Further documentation available on our web site **https://www.vdl.afrl.af.mil/programs/ae9ap9**
- Advice to users
  - User's guide provides recommendations for time steps, model mode and run duration for various objectives
  - See Aerospace report TOR-2022-00016, Best practices for generating space environment specifications with modern tools
- Current limitations
  - No solar protons *(forthcoming--see SAPPHIRE-2S)*
  - No explicit solar cycle variation *(forthcoming—V2.0)*
    - Statistics from Monte Carlo mode capture the range of expected fluxes over a solar cycle
  - Plasma model lacks local time dependence and Monte Carlo capability *(forthcoming—V2.0)*

Conclusion

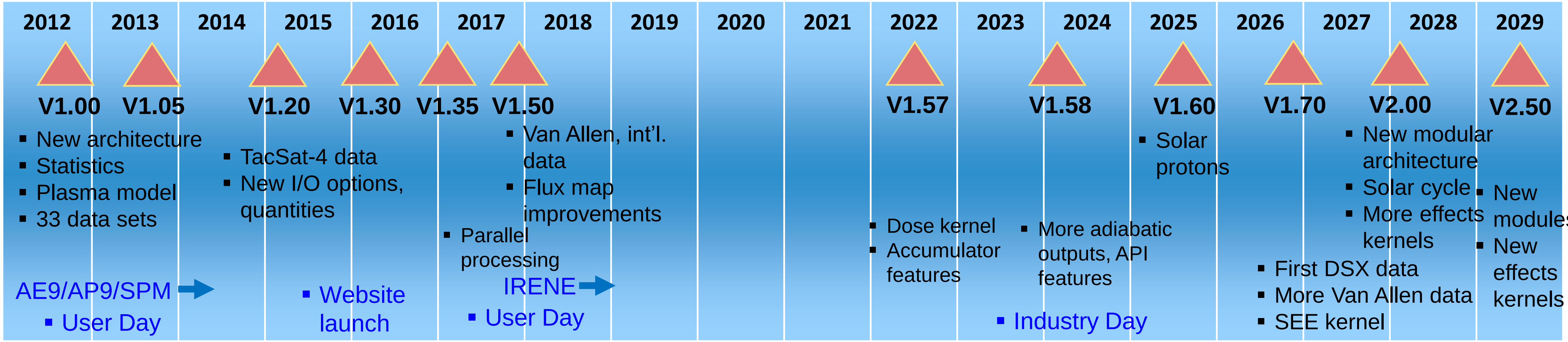
- IRENE-AE9/AP9 continues to be maintained and upgraded as a comprehensive radiation environment design standard
  - Future releases will include new data sets and new features, driven by user needs
  - We seek models and data from the community to further these improvements
- **Comments, questions, etc. are welcome and encouraged!**
- Please send questions, feedback, requests for model or documentation, etc., to (**copy all**):
  - Bob Johnston, Air Force Research Laboratory, AFRL.RVBXR.AE9.AP9.Org.Mbx@us.af.mil
  - Paul O’Brien, The Aerospace Corporation, paul.obrien@aero.org



- Current model downloads, documentation, news are available at AFRL’s Virtual Distributed Laboratory: **https://www.vdl.afrl.af.mil/programs/ae9ap9**

BACKUPS

IRENE-AE9/AP9 releases



Version numbering:

- **1**.00—1st digit change = new architecture
- 1.**5**0—2nd digit change = new flux maps
- 1.5**8**—3rd digit change = new features

Releases:

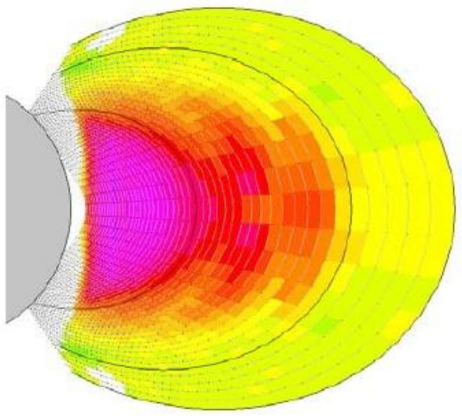
- AFRL conducts releases with public release slightly delayed from restricted release (no difference in versions)

Forthcoming:

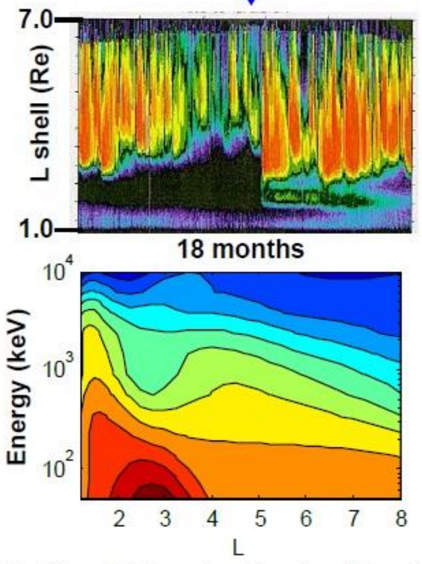
- V1.60—add solar proton module
- V1.70—flux map updates, IGRF 2025
- V2.00 development
  - Architecture overhaul—tailored modules, more hazard populations
  - Kernels for SEEs, internal charging
- V2.50—more modules, kernels

Architecture

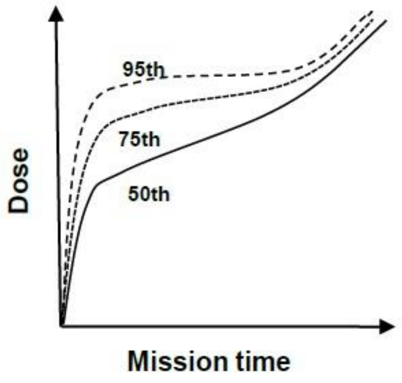
Satellite data



Satellite data & theory



User's orbit



Flux maps

- Derive from empirical data
  - Systematic data cleaning applied
- Create maps for median and 95th percentile of distribution function
  - Maps characterize nominal and extreme environments
- Include error maps with instrument uncertainty
- Apply interpolation algorithms to fill in the gaps

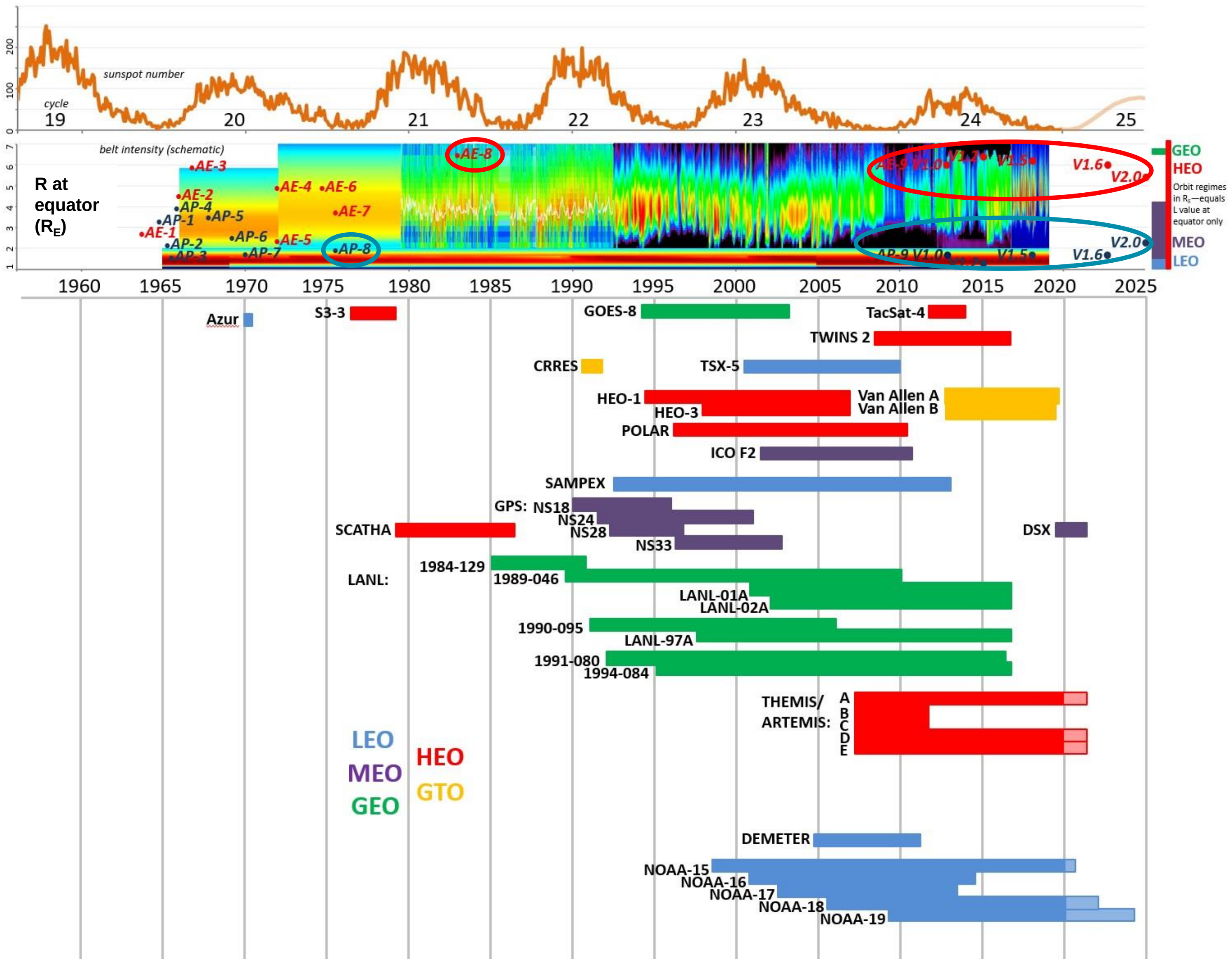
Statistical Monte-Carlo Model

- Compute spatial and temporal correlation as spatiotemporal covariance matrices
  - From data (V 1.0)
  - Use one-week (protons) and one-day (electrons) sampling time (V1.5)
- Set up Nth-order auto-regressive system to evolve perturbed maps in time
  - Covariance matrices give SWx dynamics
  - Flux maps perturbed with error estimate give instrument uncertainty

User application

- Runs statistical model N times with different random seeds to get N flux profiles
- Computes dose rate, dose or other desired quantity derivable from flux for each scenario
- Aggregates N scenarios to get median, 75th and 90th confidence levels on computed quantities

Data sets



Incorporates 45 data sets from 1969-2016

- Chosen for high quality and coverage

330+ instrument-years of data

- 10x more than AE8+AP8

All solar cycle phases sampled

- 16 sets >10 yrs
- 27 sets >5 yrs
- Long data sets yield statistics on variability

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