THE AEROSPACE CORPORATION

Impact of Radiation Environment and Solar Array Uncertainty on Achieving Mission Power Requirements

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Why do we care about solar cell and array degradation

- Solar cell degradation from trapped radiation is a primary factor in the reduction of solar array power.
- Mitigating radiation degradation has driven advancements in solar cell and array technology:
  - Transition from silicon to gallium arsenide (GaAs) and multijunction designs.
  - Development of large, lightweight, flexible arrays.
- Predicting solar array power output is critical for mission planning, impacting:
  - Solar cell selection.
  - Array design.
  - Pointing requirements.
  - Spacecraft design.
- Accurate solar cell degradation and trapped radiation environment models support decisions on operational duration and potential replacements.

Radiation degradation performance is a key driver of advancements in space photovoltaic and array.

Trapped Radiation Environment Models

- Radiation effects influence spacecraft design, with radiation requirements typically based on trapped radiation models.
- Since 1964, models for predicting solar cell degradation and space radiation have evolved[1]:
  - Ae8/Ap8 model introduced in 1991.
  - Ae9/Ap9 model developed to provide more accurate predictions for the spacecraft development community.
    - v1.0 released in 2012
- Ae9/Ap9 offers a probabilistic assessment of the trapped radiation and plasma environment.
- Ongoing learning is necessary to effectively leverage the outputs of the Ae9/Ap9 model.
- We demonstrate the use of statistics to manage uncertainty in predicting the likelihood that an array design will meet mission objectives.

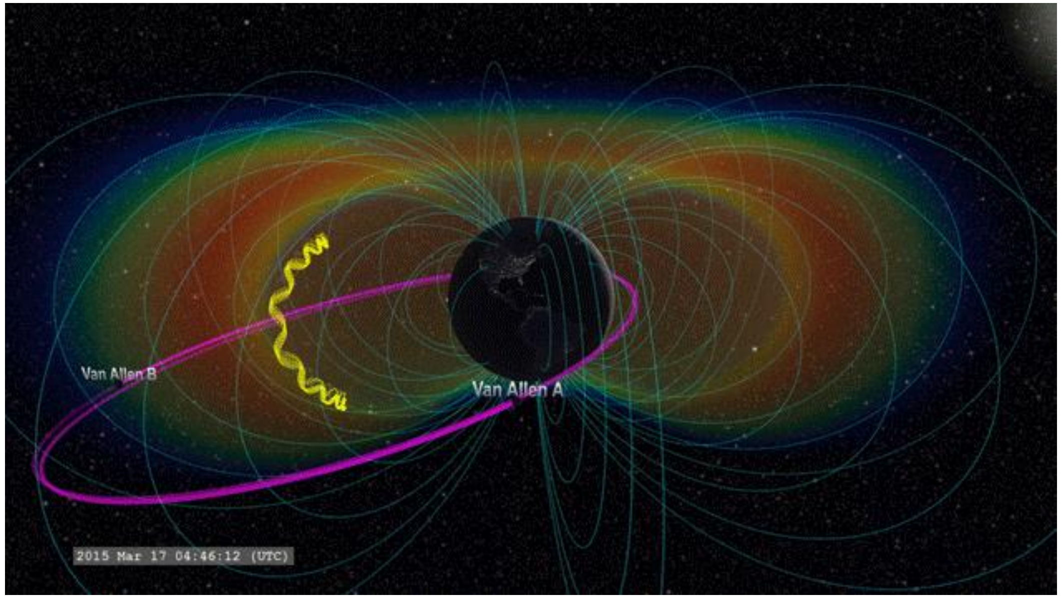


Image by NASA

1. J. I. Vette, “The NASA/National Space Science Data Center Trapped Radiation Environment Model Program (1964-1991),” Technical Memorandum NSSDC/WDC-A-R&S 91-29, Nov. 1991.
2. G. P. Ginet *et al.*, “AE9, AP9 and SPM: New Models for Specifying the Trapped Energetic Particle and Space Plasma Environment,” *Space Sci Rev*, vol. 179, no. 1–4, pp. 579–615, Nov. 2013, doi: 10.1007/s11214-013-9964-y.

Understanding Ae9/Ap9

Probabilistic model

- AE9/AP9-IRENE is a “consensus” model.
  - Takes estimates of the radiation environment from many different sensors and at different times and attempts to synthesize the particle fluxes.
  - Not all datasets agree with each other, sometimes for good reasons (e.g., taken at different phase of solar cycle)
  - Disagreements are retained in the model as uncertainty
    - Uncertainties from sensors, natural space environment variability, etc.
  - Other datasets can differ from the model mean or model statistics. This does not make the model or the new conflicting dataset wrong, just another voter in a consensus model.
  - With more unique datasets included in the AE9/AP9-IRENE model architecture, the model output will approach the true distribution of the environment with a shrinking uncertainty.

Satellite/Sensor	Orbit	Temporal range	Energy range (MeV)	Version introduced
Protons (energy in MeV)				
CRRES/PROTEL	350 × 33000 km, 18°	1990–1991	2.0–80	V1.00
S3-3/Telescope	236 × 8048 km, 97.5°	1976–1979	0.1– 2.0	V1.00
HEO-F1/Dosimeter	500 × 39000 km, 63°	1994–2011	10–400	V1.00
HEO-F3/Dosimeter	500 × 39000 km, 63°	1997–2011	10–400	V1.00
ICO/Dosimeter	10000 circular, 45°	2001–2009	10–400	V1.00
TSX5/CEASE	410 × 1710 km, 69°	2001–2006	10–400	V1.00
POLAR/IPS	5100 × 51000 km, 86°	1996–2008	0.1–1.0	V1.00
POLAR/HISTp	5100 × 51000 km, 86°	1996–2008	6.0–15.0	V1.00
TacSat-4/CEASE	700 × 12050 km, 63°	2011-2013	1-80	V1.20
Van Allen Probe A/RPS/REPT	800 x 30600 km, 10°	2012-2016	20-2000	V1.50
Van Allen Probe B/RPS/REPT	800 x 30600 km, 10°	2012-2016	20-2000	V1.50
Azur/EI-88	380 x 2140 km, 103°	1969-1970	1.5-104	V1.50
TWINS 2/HiLET	1000 x 39500 km, 63°	2008-2016	5-30	V1.50
Electrons (energy in MeV)				
CRRES/MEA/HEEF	350 × 33000 km, 18°	1990–1991	0.1–7.0	V1.00
SCATHA/SC3	28000 × 43000 km, 7.8°	1979–1991	0.25–4.5	V1.00
HEO-F1/Dos/Tel	500 × 39000 km, 63°	1994–2011	1.5–10.0	V1.00
HEO-F3/Dos/Tel	500 × 39000 km, 63°	1997–2011	0.5–5.0	V1.00
ICO/Dosimeter	10000 km circular, 45°	2001–2009	1.0–7.0	V1.00
TSX5/CEASE	410 × 1710 km, 69°	2001–2006	0.07–3.0	V1.00
SAMPEX/PET	550 × 675 km, 82°	1992–2004	2.0–3.5	V1.00
POLAR/HISTe	5100 × 51000 km, 86°	1996–2008	1.0–6.0	V1.00
GPS/BDDII ns18	20200 km circular, 55°	1990–1994	0.25–1.0	V1.00
GPS/BDDII ns24	20200 km circular, 55°	1991–2000	0.25–1.0	V1.00
GPS/BDDII ns28	20200 km circular, 55°	1992–1996	0.25–1.0	V1.00
GPS/BDDII ns33	20200 km circular, 55°	1996–2004	0.25–1.0	V1.00
LANL-GEO/SOPA 1989-046	36000 km circular, 0°	1989–2008	0.05–1.5	V1.00
LANL-GEO/SOPA 1990-095	36000 km circular, 0°	1990–2005	0.05–1.5	V1.00
LANL-GEO/SOPA LANL-97A	36000 km circular, 0°	1997–2008	0.05–1.5	V1.00
LANL-GEO/SOPA LANL-02A	36000 km circular, 0°	2002–2008	0.05–1.5	V1.00
Van Allen Probe A/MagEIS	800 x 30600 km, 10°	2012–2016	0.04–0.9	V1.50
Van Allen Probe B/MagEIS	800 x 30600 km, 10°	2012–2016	0.04–0.9	V1.50
Plasma (energy in keV)				
POLAR/CAMMICE/MICS	5100 × 51000 km, 86°	1997–1999	1.0–164.0	V1.00
POLAR/HYDRA	5100 × 51000 km, 86°	1997–1999	1.0–40.0	V1.00
LANL-GEO/MPA 1990-095	36000 km circular, 0°	1990–2005	1.0–63.0	V1.00
LANL-GEO/MPA 1991-080	36000 km circular, 0°	1991–2004	1.0–63.0	V1.00
LANL-GEO/MPA 1994-084	36000 km circular, 0°	1994–2008	1.0–63.0	V1.00
LANL-GEO/MPA LANL-97A	36000 km circular, 0°	1997–2008	1.0–63.0	V1.00
THEMIS A/ESA	440 × 92000 km, 16°	2007-2013	1-30	V1.20
THEMIS B/ESA	440 × 92000 km, 16°	2007-2010	1-30	V1.20
THEMIS C/ESA	440 × 92000 km, 16°	2007-2010	1-30	V1.20
THEMIS D/ESA	440 × 92000 km, 16°	2007-2013	1-30	V1.20
THEMIS E/ESA	440 × 92000 km, 16°	2007-2013	1-30	V1.20

Table from https://www.vdl.afrl.af.mil/programs/ae9ap9/datasets.php

Modes for Running IRENE

- **Mean**
  - Uses mean flux maps with no variance statistics

- **Probabilistic Modes**
  - Flux values in each coordinate bin along an orbit are determined by randomly varying the mean flux within its variance.
  - Users select the number of scenarios or orbits to simulate, creating multiple possible environment spectra. The following modes dictate which uncertainties are included to generate these scenarios:

  - **Monte-Carlo**
    - Accounts for uncertainties from measurement, natural environment variation, gap filling, and dynamic variations due to space weather processes (e.g., solar cycle).
    - Captures worst-case fluxes and should be run for the entire mission duration to encapsulate the solar cycle.
  - **Perturbed Mean**
    - Considers uncertainties from measurement, natural environment variation, and gap filling.
    - Ideal for long-duration missions where fluence/total dose is crucial, as space weather variability averages out over time.
  - From these modes, we can calculate statistics such as confidence levels and reliability.

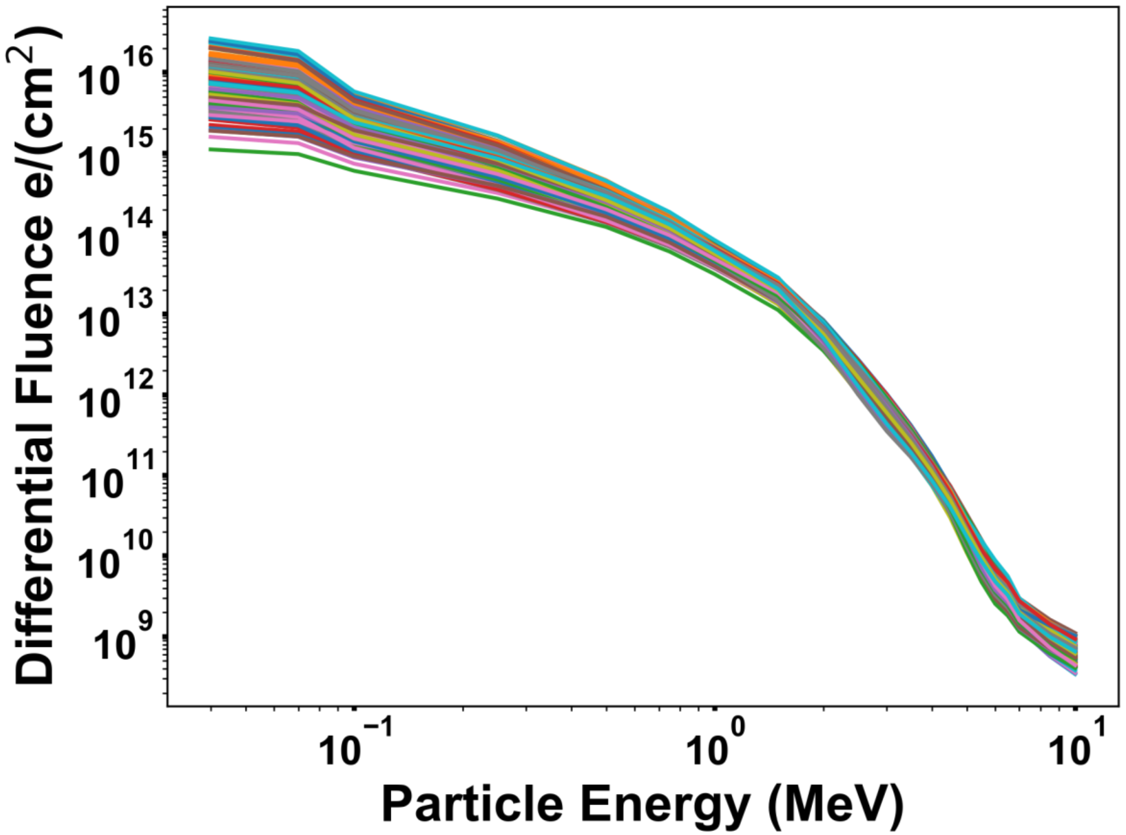
Scenarios

Possible Mean Environments for a 10-year GPS mission

- Differential electron fluence spectra from 200 scenarios output from an Irene (Ae9/Ap9) perturbed mean simulation of a 10 year GPS orbit

- Each scenario plotted represents the 10-year differential electron fluence of a GPS orbit

- If you look closely, you can see that some of the spectra overlap



Scenarios can overlap

Scenarios

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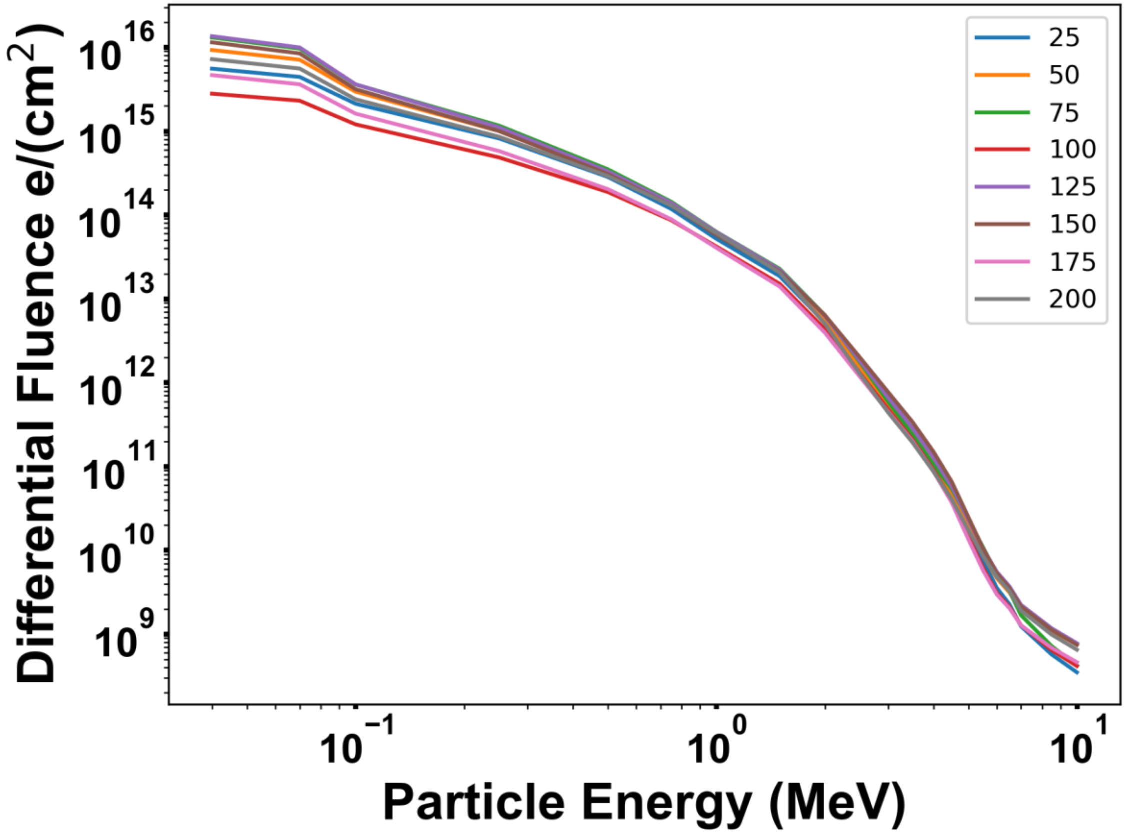
- If you look closely, you can see that some of the spectra overlap
- Removing some of the scenarios we can see this a little better



Scenarios can overlap

Scenarios

Possible Mean Environments for a 10-year GPS mission

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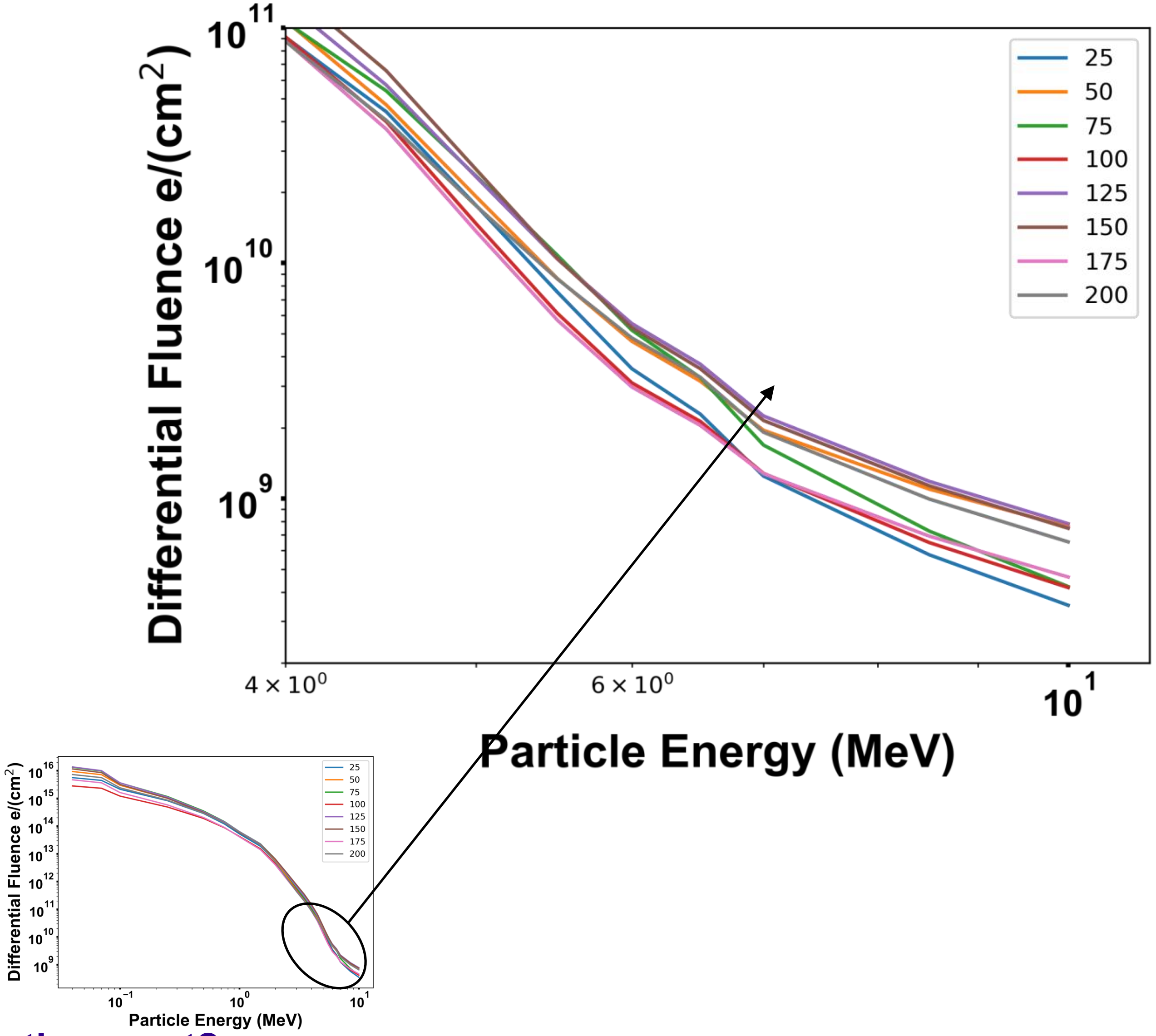
- Each scenario plotted represents the 10-year differential electron fluence of a GPS orbit

- If you look closely, you can see that some of the spectra overlap

- Removing some of the scenarios we can see this a little better

- Zooming in we can see where the spectra criss-cross



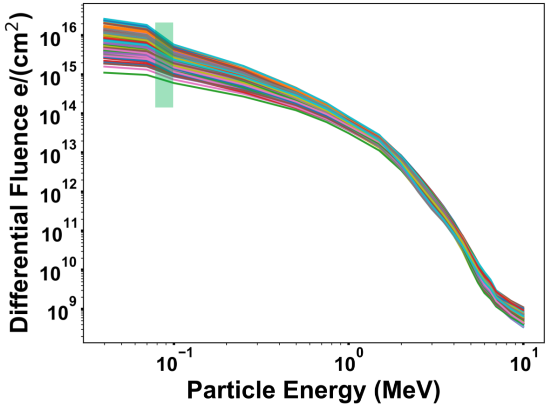
Scenarios can overlap….How do we determine which is the worst?

Ranking Scenarios

How we've been doing it

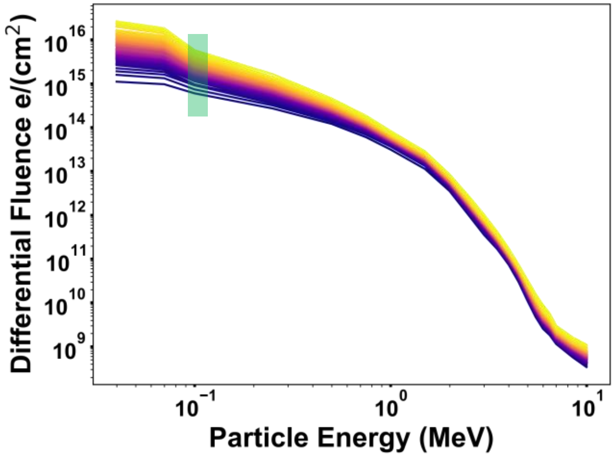
- Generation of Radiation Environment Spectra:
  - Use Irene Ae9/Ap9 in perturbed mean mode to generate spectra.
  - Obtain multiple possible mean environment spectra based on selected scenarios.
- Conversion to Confidence Levels:
  - Convert scenario spectra into spectra at confidence levels ranging from 1% to 99%.
  - Use the NIST percentile method to order fluence values in each particle energy bin.
- Resulting Spectra:
  - Obtain aggregate spectra for each confidence level.
  - These spectra are statistical aggregates, not specific real-world scenarios.
- Purpose and Use:
  - Provide a statistical representation of the environment.
  - Aid in risk assessment and planning by illustrating the range of possible environments and associated confidence levels.
    - The fluences at each particle energy indicate the probability a fluence is less than or equal to the fluence at the given confidence level for any potential scenario

Yields Aggregate Environment Spectra



0.1 MeV	
$\Phi_{scenarios}$	Φ_{CL}
2e15	8e13
5e15	1e14
3e15	2e15
1e16	3e15
4e15	4e15
1e14	5e15
8e13	1e16

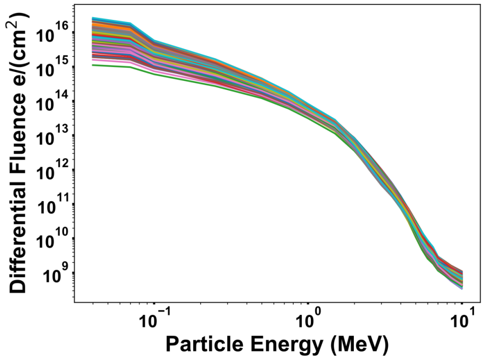
Complete for each particle Energy



Calculate 1 MeV Fluence/DDD/Dose then Determine Confidence Levels

How we should be doing it

- Recommended Approach:
  - Calculate 1 MeV/DDD/Dose for each scenario.
  - Derive probabilities and statistics from these calculations.
- Issue with Current Method:
  - Calculating 1 MeV/DDD/Dose with aggregated confidence levels can lead to exaggerated values.
- Correct Statistical Approach:
  - "To get the statistics right, we must combine the proton and electron to 1MeV/DDD/Dose before we compute percentiles. That is because percentiles do not add; a percentile is a nonlinear statistic. For example, the sum of the 95th percentile electron dose and the 95th percentile proton dose is not the 95th percentile of the combined electron-plus-proton dose."[1]
    - O'Brien, T. P., "AE9/AP9 Guidance for Third-Party Developers", Aerospace Report No. TOR-2014-01204



→ Compute 1MeV/DDD/Dose for each Scenario →

1 MeV Fluence	
Scenario	**Φ**
1	2e14
2	4e14
3	6e14
4	2e15
5	3e14
………	………
200	2e13

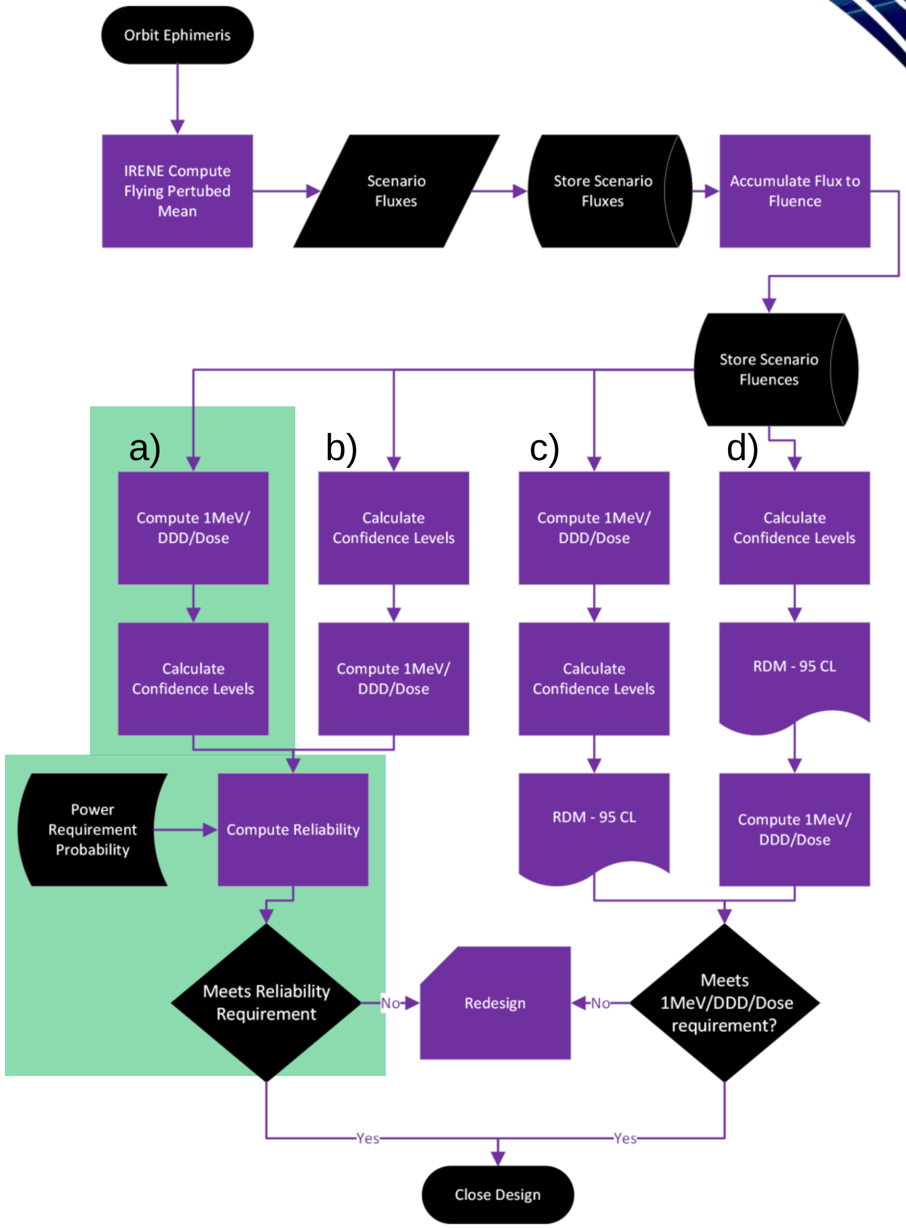
→ Calculate Confidence Levels →

1 MeV Fluence	
CL	**Φ**
1	2e13
2	2e14
3	3e14
4	4e14
5	6e14
………	………
99	2e15

Meeting Array Power Requirements

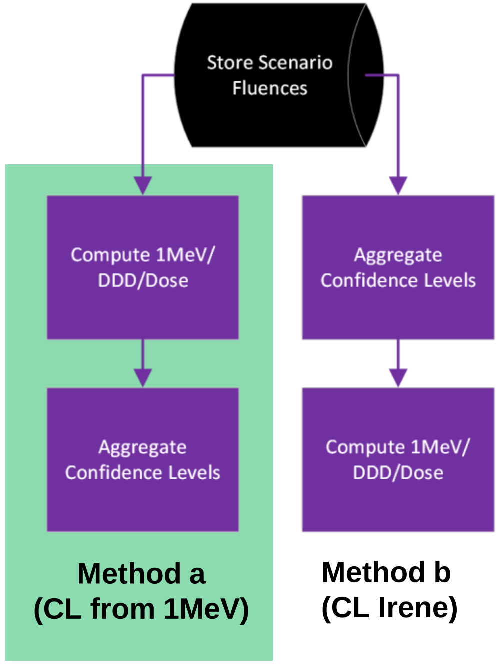
Data Pipeline and Aggregation Infrastructure

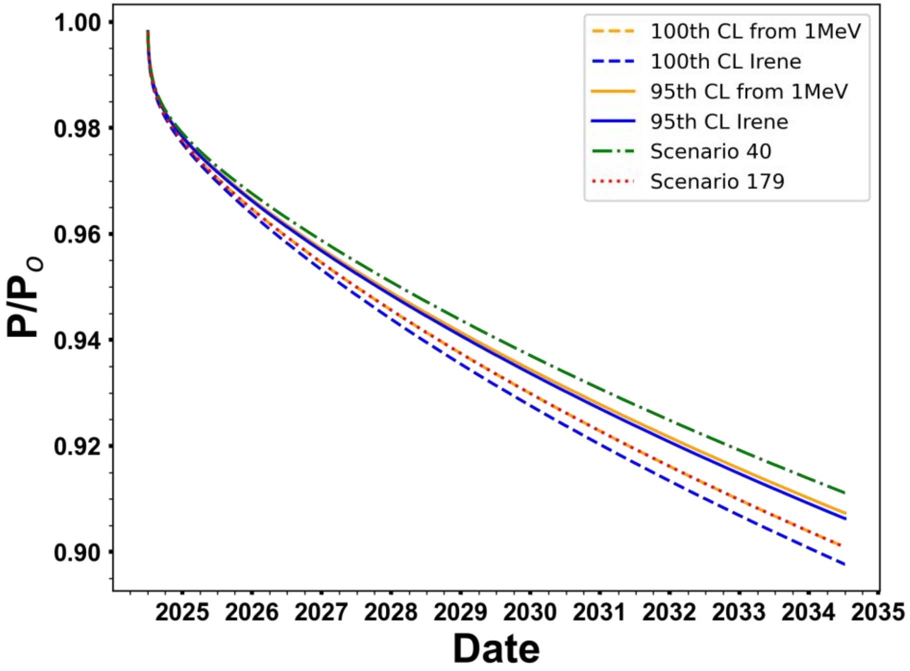
1. Mission Orbit Profile Generated
   - Any orbit generation software or code can be used such as IRENE, astropy, etc.
2. Compute Perturbed Mean using IRENE
   - 200 scenarios is the recommended starting point for enough scenarios to calculate confidence levels
3. Collect scenario flux outputs
4. Store scenario flux outputs into time series mongoDB (python)
5. Accumulate flux to fluence (python)
6. Methods to determine if array design closes
   a) Reliability from probability of environment as determined by using 1MeV/DDD/Dose and probability of array power
   b) Reliability from probability of environment as determined by using aggregate CL and probability of array power
   c) Meets RDM of 95CL from 1MeV/DDD/Dose
   d) Meets RDM of 95CL from aggregate CL

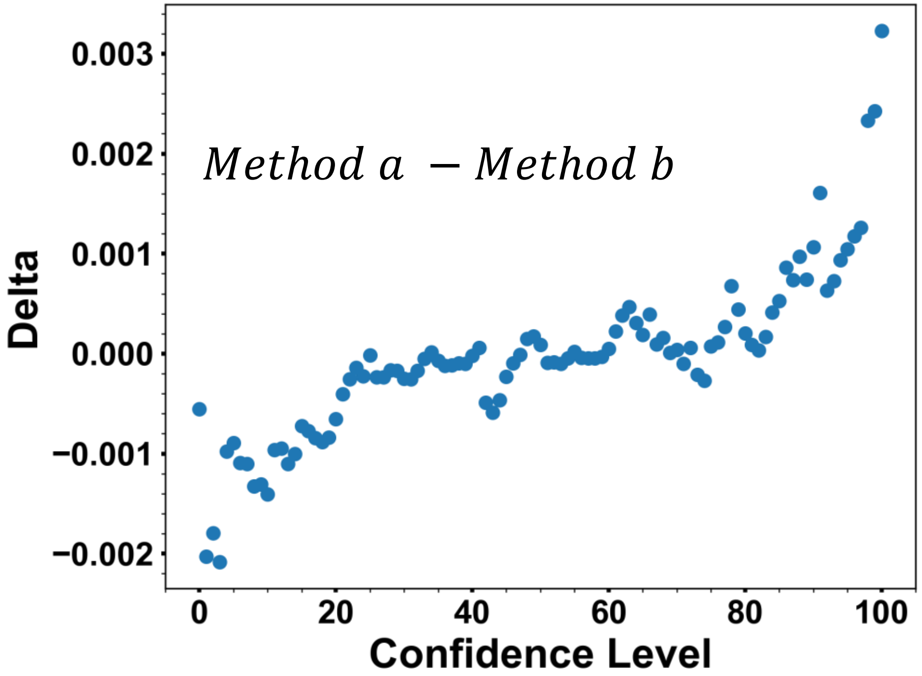


Comparing degradation using aggregate CLs vs from Scenarios

How we should do it…how its recommended

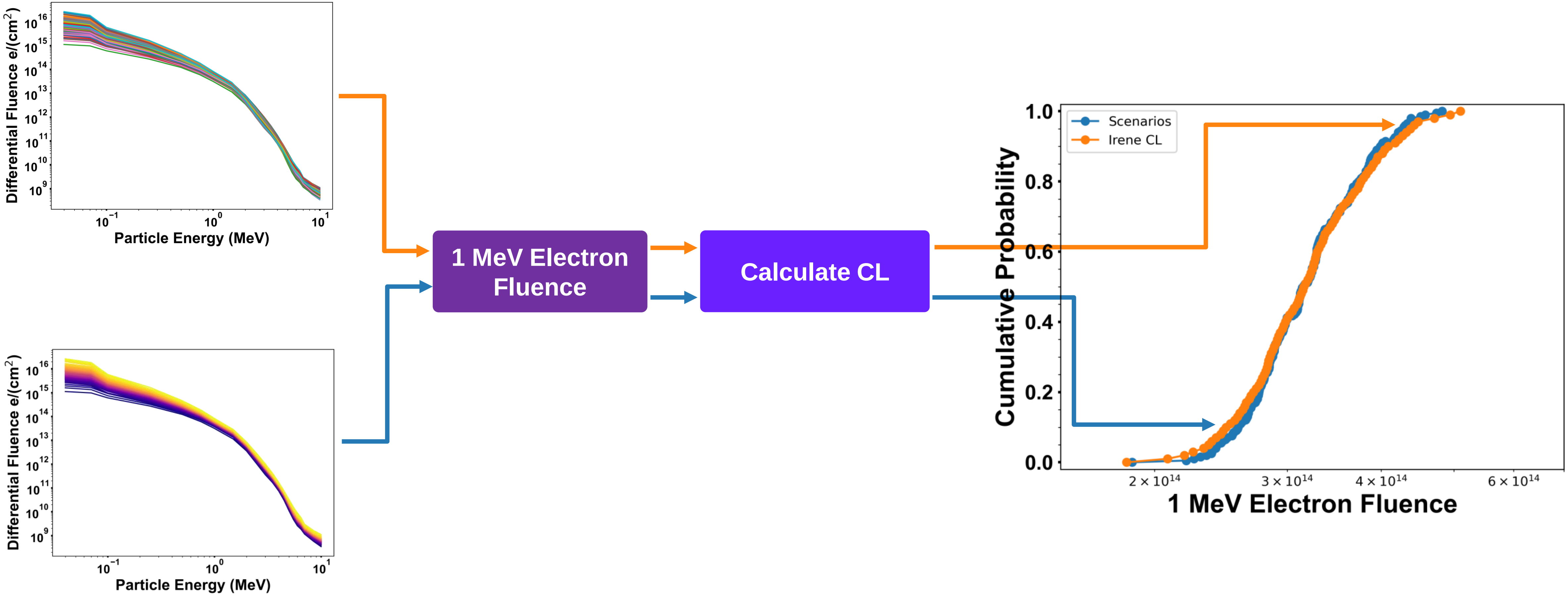






- When calculating the power remaining factor (P/P_o) from the aggregated CL from IRENE (method b) vs calculating the 1MeV electron fluence first then aggregating the CL (method a), the differences in power remaining at the 95^{th} and 100^{th} CL (worst case scenario) are exaggerated for method b vs method a

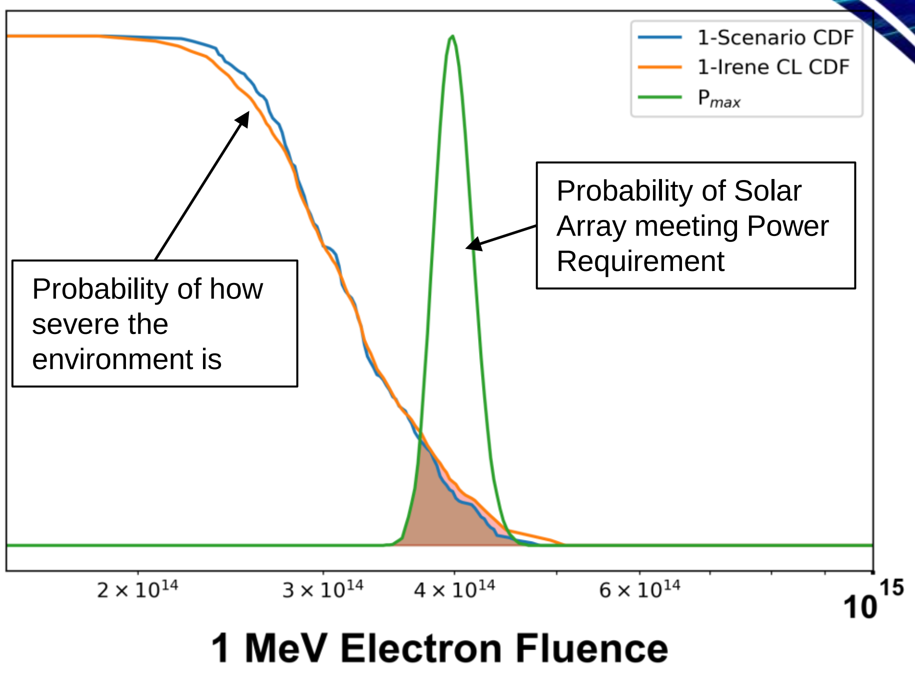
Deriving Cumulative Probabilities from 1MeV Electron Fluences



How do we leverage all these statistics?

$$R = 1 - P_{fail},\ P_{fail} = \int 1 - H(\theta) g(\theta) d\theta$$

- For solar array power prediction, we have two probabilities
  - Solar array power
    - Probability that solar array design can achieve a specified power at a particular 1MeV fluence, DDD, or Dose
    - Variability in the radiation degradation performance of solar cells, cover glass, measurement error, etc. Drives the probability of power production
  - Trapped radiation environment
    - Probability that an environment will experience fluence of various particle energies
    - Uncertainty in the model from various data sets and natural randomness of the environment
- We can use a static stress-strength analysis where probability of failure is based on the probability of stress exceeding strength[1,2].
  - For solar arrays this stressor would be the probability of the radiation environment vs the dose
  - The strength is the probability the solar array will not make power as a function of dose
- Reliability is $1\text{-}P_{fail}$



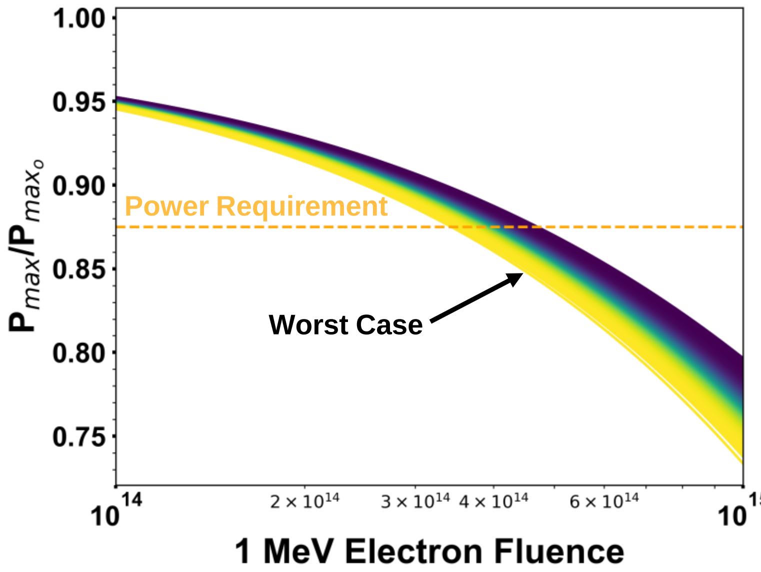
$$P_{fail} = \int 1 - H(\theta) g(\theta) d\theta$$

- *H(θ)* represents the probabilities of the space environment
- *g(θ)* is the probability of the solar array not making enough power

1. Xapsos, M.A., Ladbury, R.L., “Inclusion of Radiation Environment Variability in Total Dose Hardness Assurance Methodology”, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 1, JANUARY 2017
2. E. A. Amerasekera and F. N. Najm, "Static stress-strength analysis" in Failure Mechanisms in Semiconductor Devices, New York, NY, USA:Wiley, vol. 11, pp. 249, 1997.

Solar Cell/Array Power Degradation Uncertainty

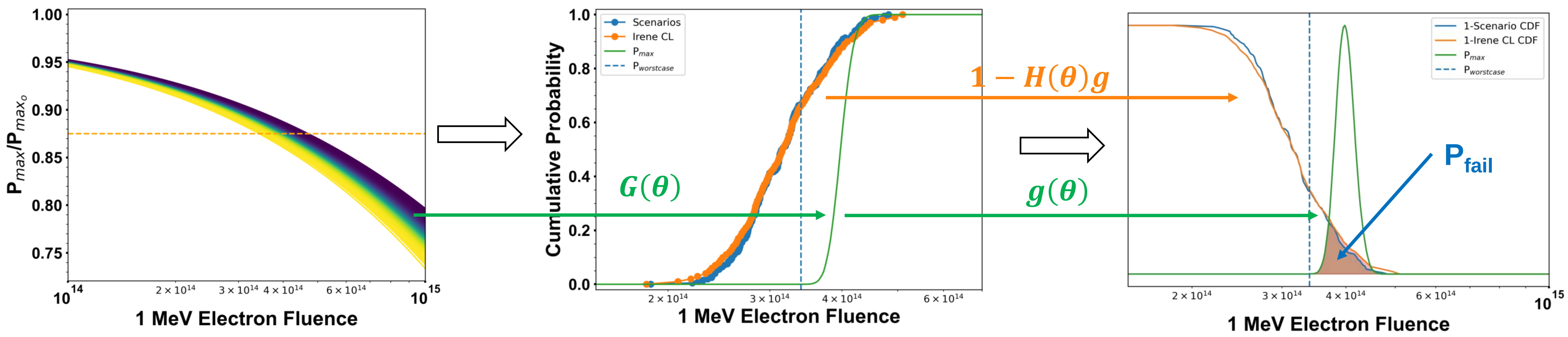
- Loss factors for current grouped into 3 Groups
  - *Static*
    - Factors that are not affected by time varying components
    - These factors remain constant from the start of the mission
  - *Time Dependent*
    - Factors that change over time
    - Considered linear in the simplest case, but are more than likely nonlinear
  - *Uncertainties*
    - Uncertainties are treated as 1 sigma
- Totals
  - *Calculated total loss factors at end-of-life (EOL), but could also be applied at any given point in time*
  - *Static losses are multiplied to arrive at a total static lost factor*
  - *Time dependent total losses are also multiplied, and the aphelion was used as the "worst case" EOL time dependent loss factor*
  - *Uncertainties are treated as uncorrelated, thereby we propagated the error by taking the square root of the sum of squares.*
    - With PSIM, uncertainties can be applied at the cell level or an array.
    - For this work we applied the uncertainty across the array



Loss Factor	Type of Loss	%Loss
Static Loss	**Installation Losses**	0.98
	Off Pointing	0.995
Time Dependent	**Earth Sun Distance**	0.967-1.033
	Coverglass Darkening	1-0.95
	Adhesive Darkening	1-0.99
	Contamination	1-0.95
	Micrometeoroid	1-0.999
Uncertainties	**Cell Measurements**	±0.05
	Coverglass Darkening	±0.02
	Adhesive Darkening	±0.001
	Contamination	±0.05
	Micrometeoroid	0
Totals	**Static (EOL)**	0.975
	Time Dependent (EOL)	0.863
	Uncertainty	0.073
	Total Loss Factors (EOL)	0.841±0.073

Example P_{fail} Calculation

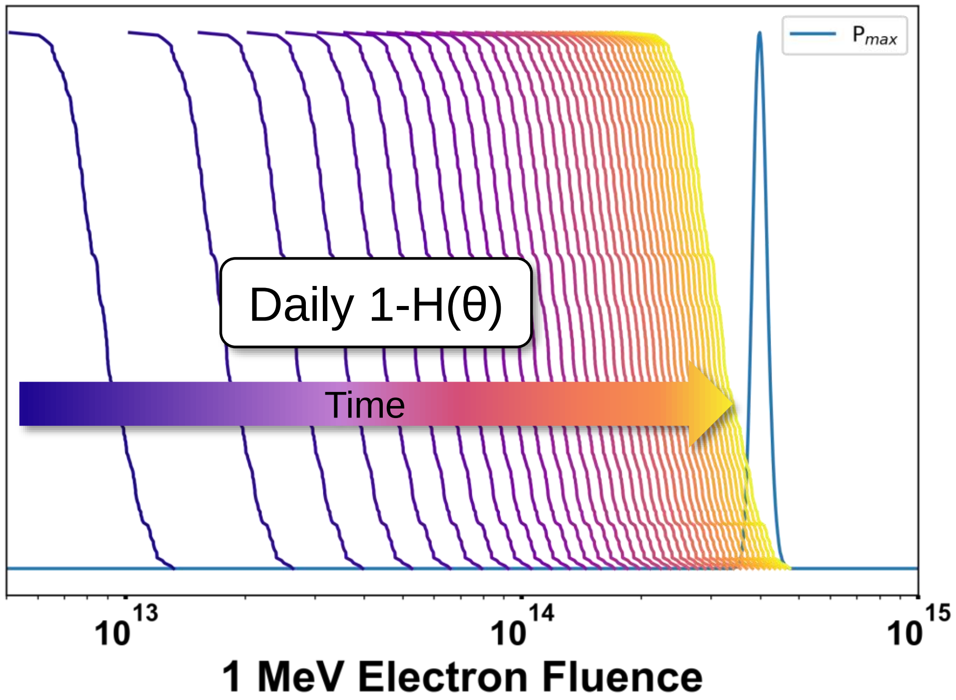
$$R = 1 - P_{fail},\ P_{fail} = \int 1 - H(\theta)g(\theta)d\theta$$

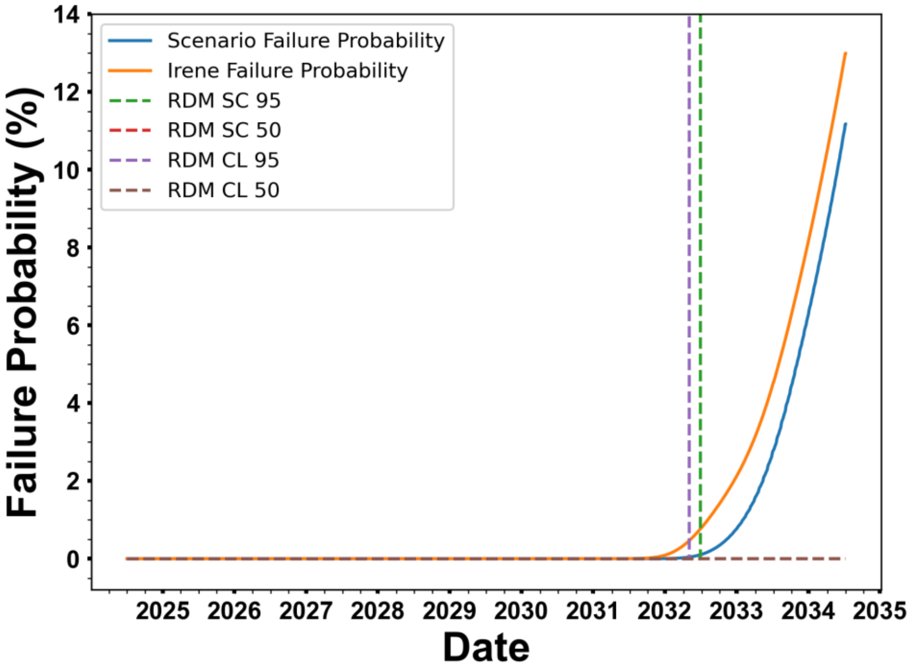


- Determine the cumulative distribution function (CDF) of failure of the solar array, which is the cumulative probability the solar array falls below the power requirement as a function of 1MeV fluence and we call this *G(θ)*
- 1 – H(θ) is the probability a particle will experience a fluence greater than the 1MeV fluence at the prescribed confidence level
  - H(θ) is the CDF of the 1MeV electron fluence of the trapped space environment
- G(θ) is then transformed to its probability distribution function *g(θ)* and multiplied by *1- H(θ)*
- The integral of the above result yields the probably of failure or probability of not meeting the mission power requirement.
  - *1-* P_{fail} (probability of failure) is equivalent to reliability (R) which can be carried over into other reliability calculations

Meeting Mission Life

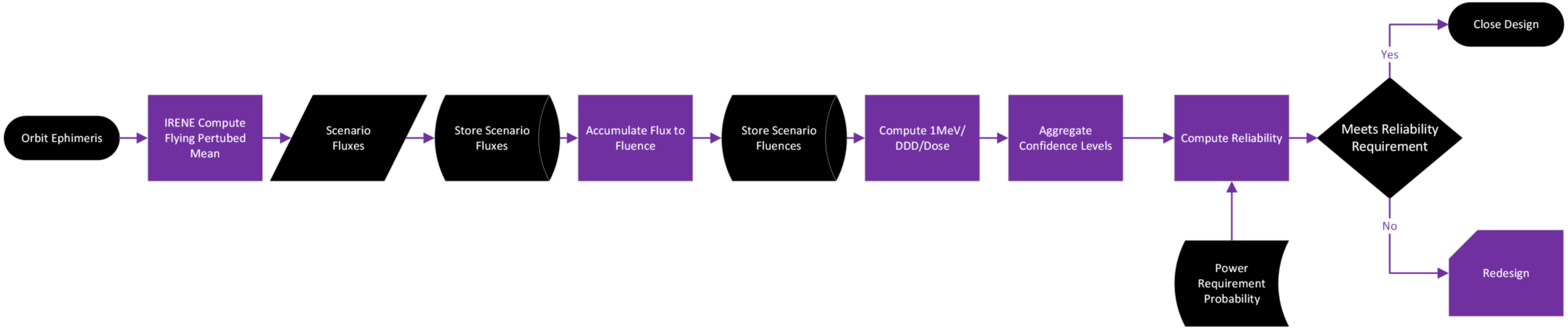
10 Year GPS Mission





- Since we have *H(θ,t)* we can calculate the probability of failure or reliability over time
- This enables us to calculate mean life estimates as matter of statistics/probability
- For a 10 year GPS mission of this array design one would have 11.1% P_{fail}.
- If using the aggregated CLs from Irene the P_{fail} would be 13%.
- When using the RDM method, with the worst case solar array design, the design doesn't close
  - Using 95th CL from calculating the 1MeV electron fluence from the scenarios gives you a more life than when using aggregate CLs from Irene
  - Using the 50th CL indicates the array would never fail and this is statistical not true

Recommendations



- The proposed method above leverages all the uncertainty in both the solar array and radiation environment
- It can give back margin as we are not designing to the worst/least likely cases
- It can only get better with more data…..this is a case where more data has the potential to save costs on array design. For example,
  - More radiation environment data would reduce model uncertainty which would increase reliability
  - More on orbit data could better capture array uncertainties, further increasing reliability
  - Increasing reliability ultimately yields smaller arrays and better power predictions

What do you do with this information

- Gain back some reliability
  - Reduce uncertainty of Irene
    - This is not something a program could do at the moment but more data from the environment would reduce P_{fail}
    - Perhaps other statistical approaches that takin into account the current behavior of the space environment could reduce probability distribution of the future expected environment
  - Reduce uncertainty of Solar Array Power Model
    - More testing of the solar array components and data about on orbit solar array performance could reduce the uncertainty of the power model
    - For example, reducing uncertainty in coverglass darkening, adhesive darkening, sun pointing, etc. could reduce P_{fail} by bringing in the tails of the solar array power pdf
- Reduce Testing
  - If an array design is qualified and its performance is well understood, a change in solar cells or material can be quantified as an effect on the array's reliability.
    - For example, if a qualified array is going to be upgrade with more efficient cells one would expect the reliability to go up because of the extra power but could be reduced again by how much one knows about the reliability of the parts. One can decide how many parts to test and to what levels to determine if the current design meets the reliability of the mission
      - The trade off here then becomes between reliability vs cost of more power, or reliability vs cost of more testing
  - Depending on the classification of the mission as A, B, C, etc. a more, or less reliable array can be used. Meaning the qualification test can be tailored to fit the reliability of the power or vice versa one could add more power to meet the reliability

More options to meet mission

References

- O’Brien, T. P., “AE9/AP9 Guidance for Third-Party Developers”, Aerospace Report No. TOR-2014-01204
- Guild T. B., Davis S. C., Boyd A. J., O’Brien T. P., et. al., “Best Practices for Generating Space Environment Specifications with Modern Tools”, Aerospace Report No. TOR-2022-00016
- Xapsos, M.A., Ladbury, R.L., “Inclusion of Radiation Environment Variability in Total Dose Hardness Assurance Methodology”, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 1, JANUARY 2017
- E. A. Amerasekera and F. N. Najm, "Static stress-strength analysis" in Failure Mechanisms in Semiconductor Devices, New York, NY, USA:Wiley, vol. 11, pp. 249, 1997.