Innovative Global Mapping Techniques for Navigating Space Weather Hazards in Low Earth Orbit

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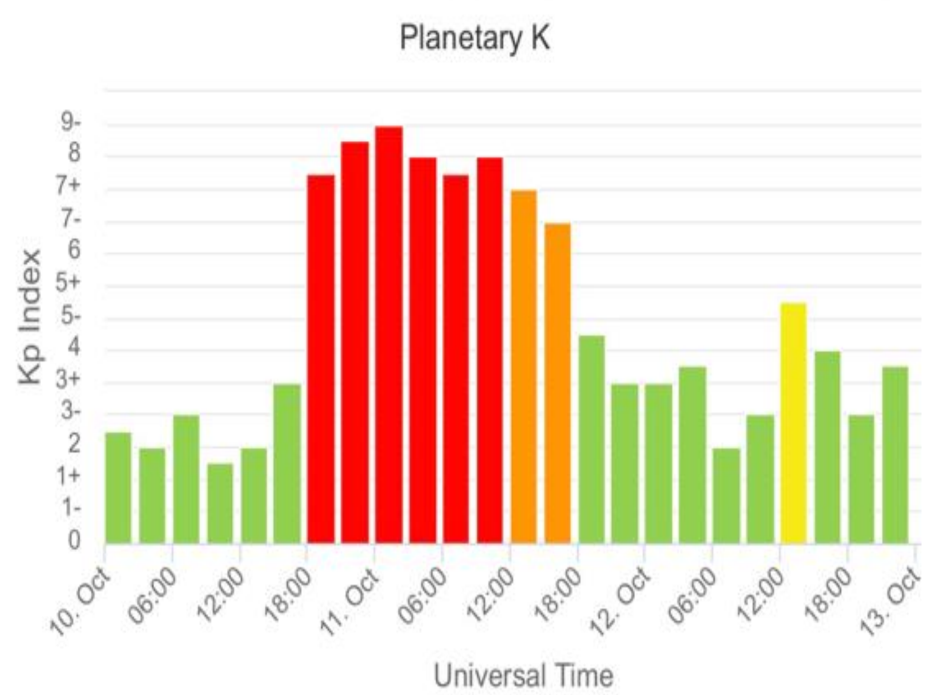
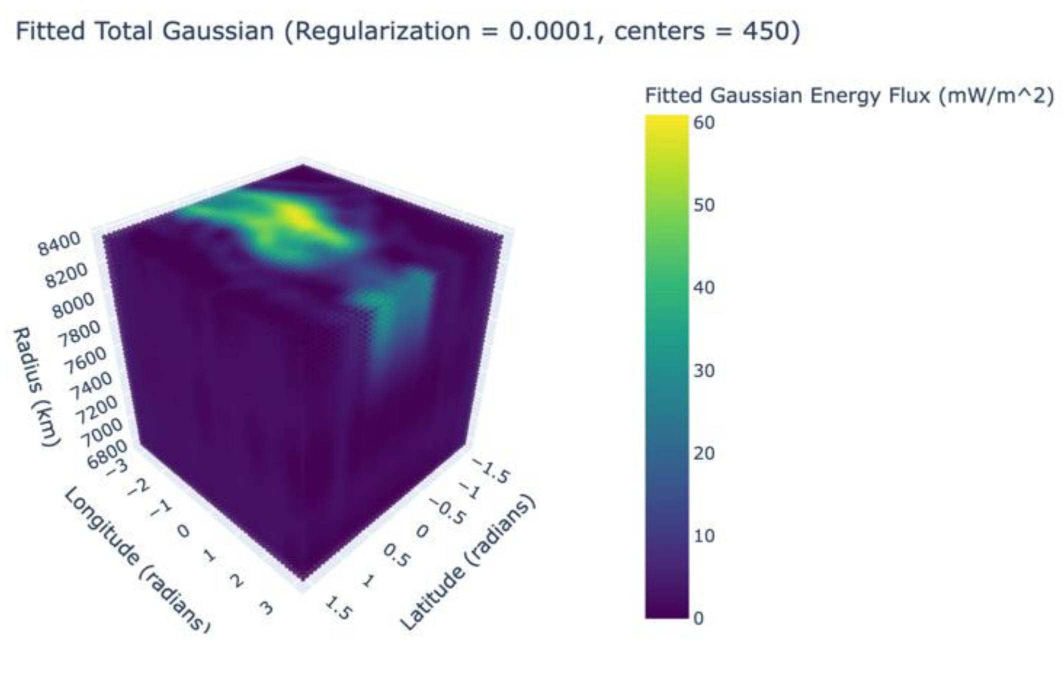
Abstract

Spacecraft are particularly vulnerable to space weather events; solar energetic particles (SEPs) discharge large amounts of energy to spacecraft electronics, degrading system performance, causing malfunctioning software, and physically damaging hardware. Astronauts face health risks from radiation exposure in space. To protect high-value assets and human lives, we present a methodology for creating global space radiation risk maps for spacecraft guidance, navigation, and control (GNC). We aim to improve operational spacecraft GNC and onboard autonomous capabilities for mitigating the effects of space weather through global space environment risk mapping for use in navigating space weather hazards.

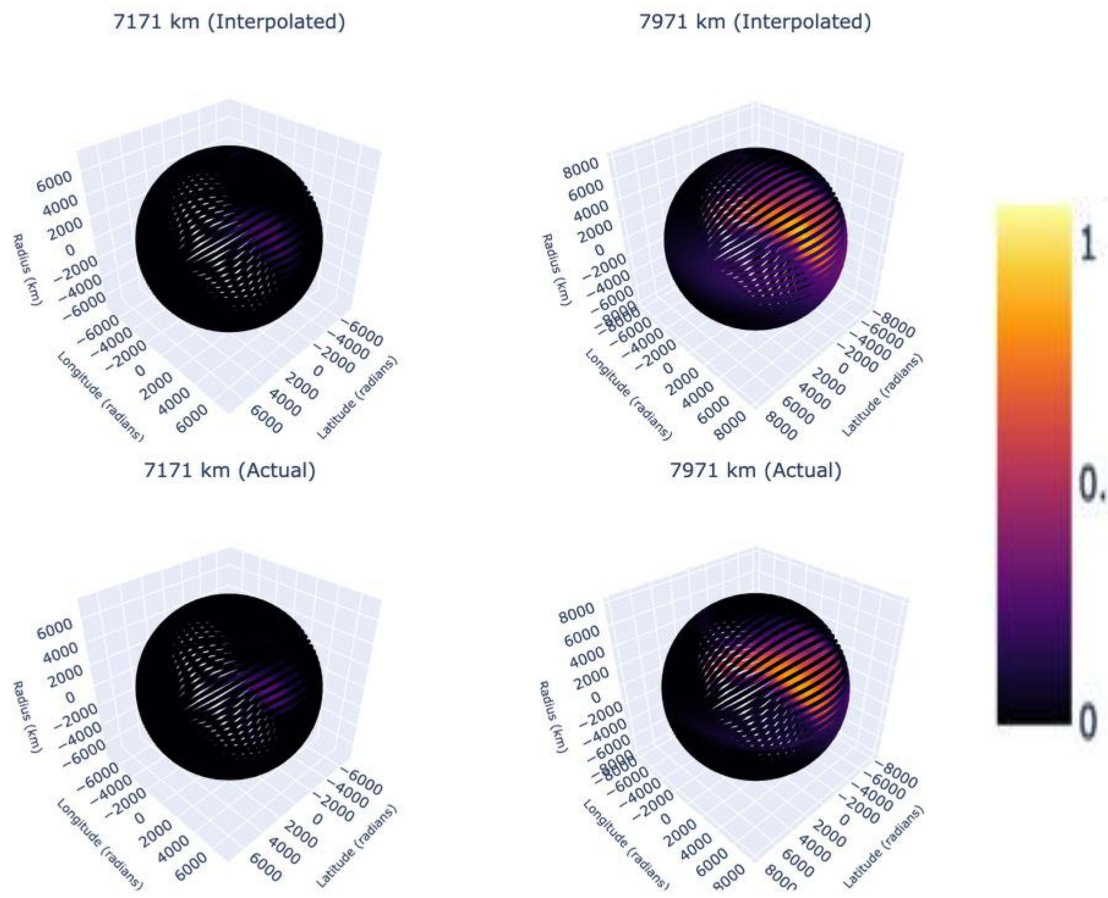


Kp Storm Index: G4-rated geomagnetic storm on October 10th and 11th, 2024. (1)

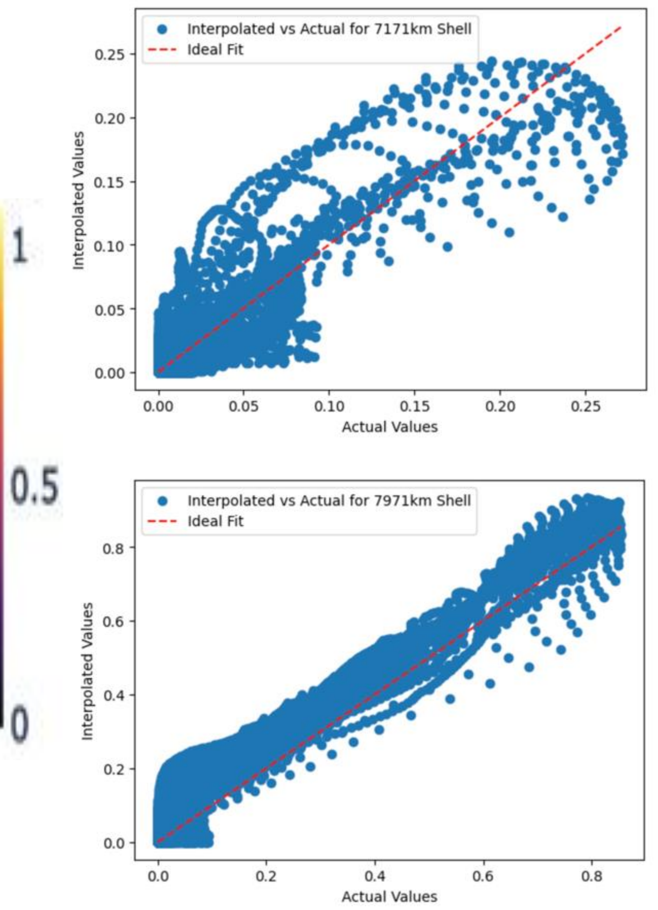


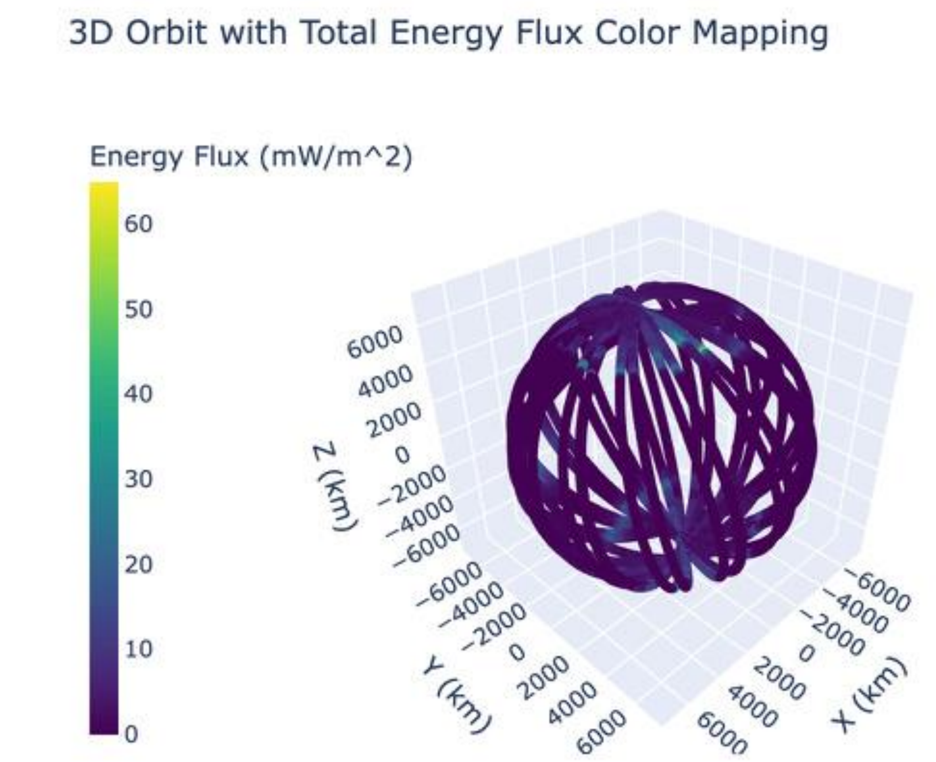
Radiation risk map: Created using runs from the IRENE radiation belt model at 11:00 UTC on October 10th, 2024. (2)

Verification and Validation



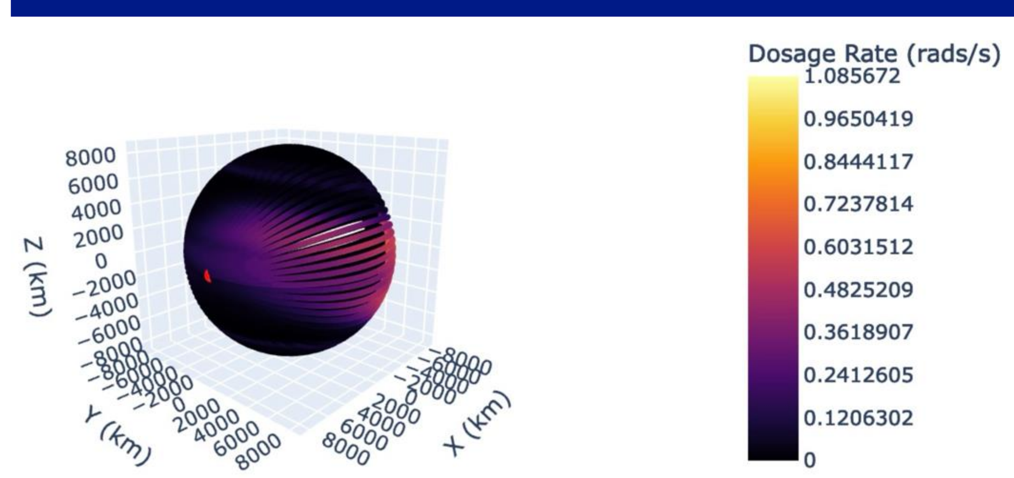
Verification: Comparison of IRENE data and the interpolated IRENE data from the same region. The associated R-squared plots are shown on the right for both tested altitudes. They are 0.809 and 0.894. (2)



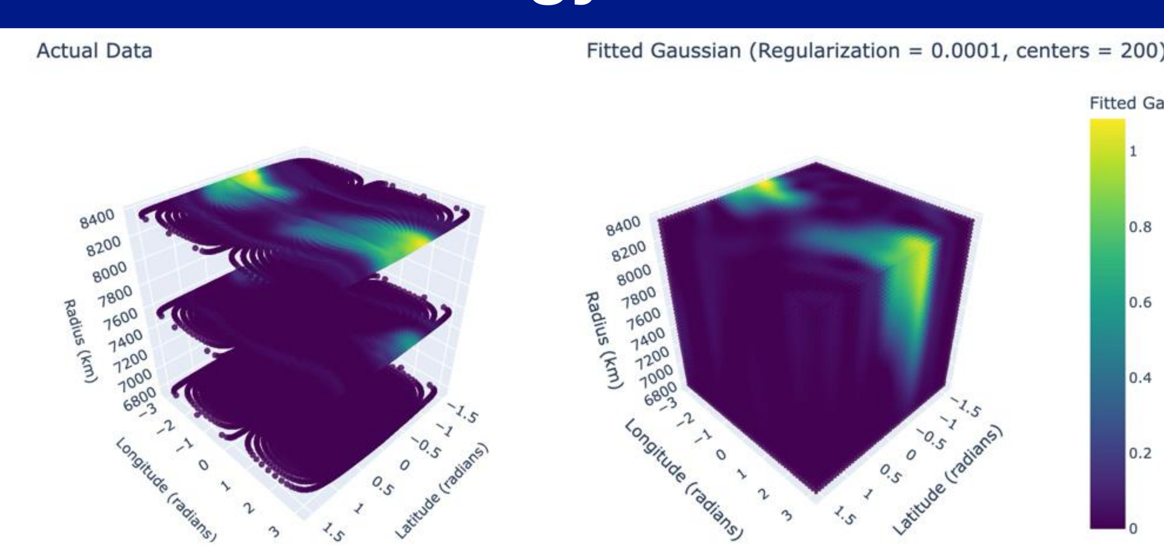


POES: Proton and electron observational satellite data. We use this to compare to our interpolated radiation risk maps. 11:00 - 23:00 UTC Oct. 10th. (2)

Methodology



Step 1: Gather values from the AE9 model in GDZ coordinates. This figure shows the predicted dosage rates for three altitudes: 6771, 7571, and 8371 km. Dosage rates are subsequently used as input for interpolating regions between those altitudes. (2)



Step 2: Take **Step 1** IRENE values and interpolate to get 3-dimensional energy flux that can be used in spacecraft GNC. This figure is specifically from the AE9 portion of the model and focuses on electron particle contributions. (2)

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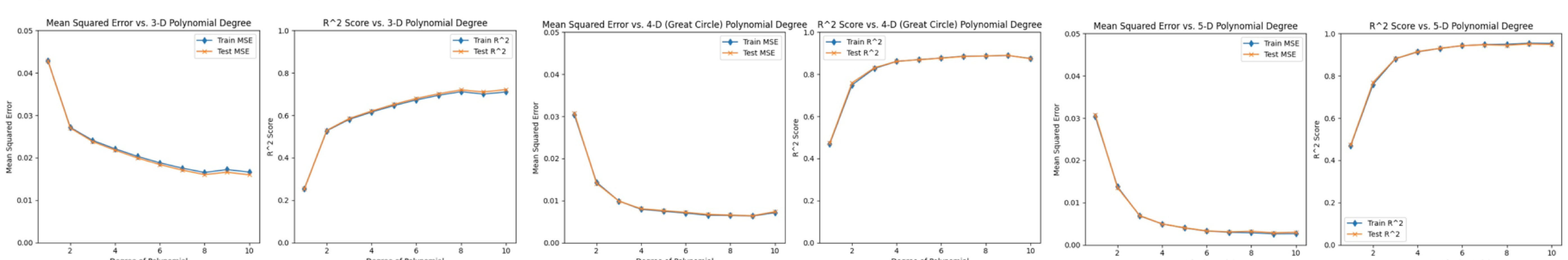
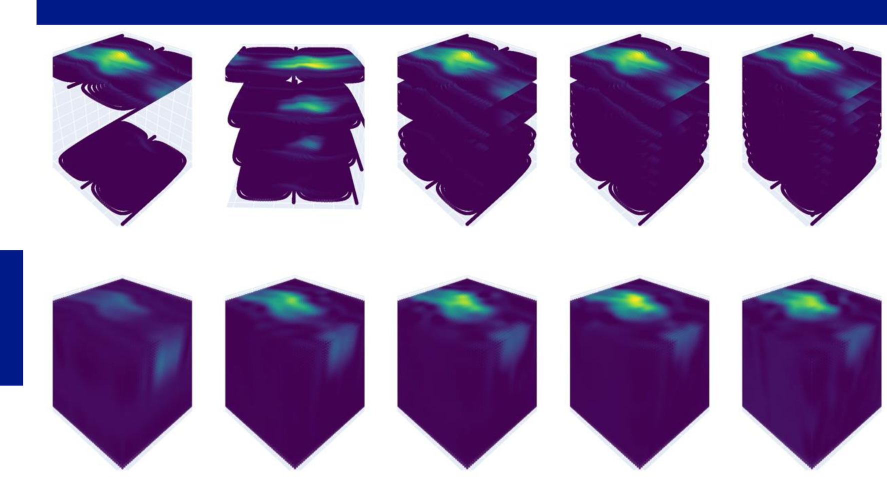
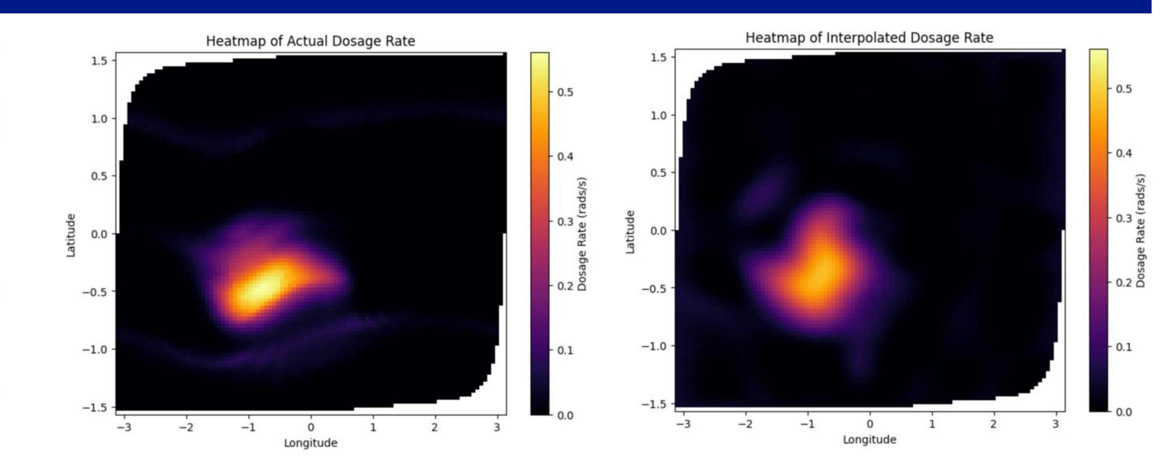


Comparison of Interpolation Variables: R-squared scores for 3, 4, and 5 spatial variable polynomial interpolations. These variables are latitude, longitude, radial distance, haversine distance, and the multiplication of the first three variables. The interpolation for each variable combination is compared to the AE9 test set data at those points and is given a corresponding R-squared score. (0.722, 0.874, and 0.949 respectively) (2)

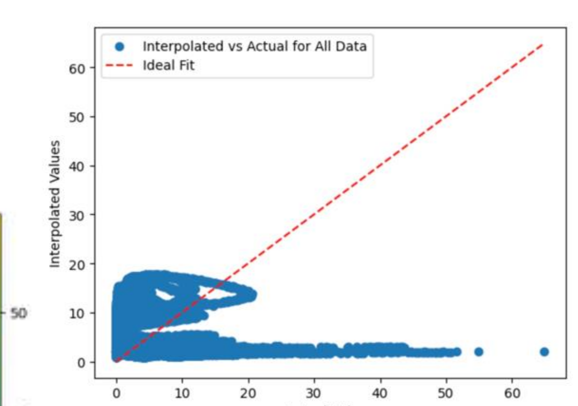
Results and Conclusion



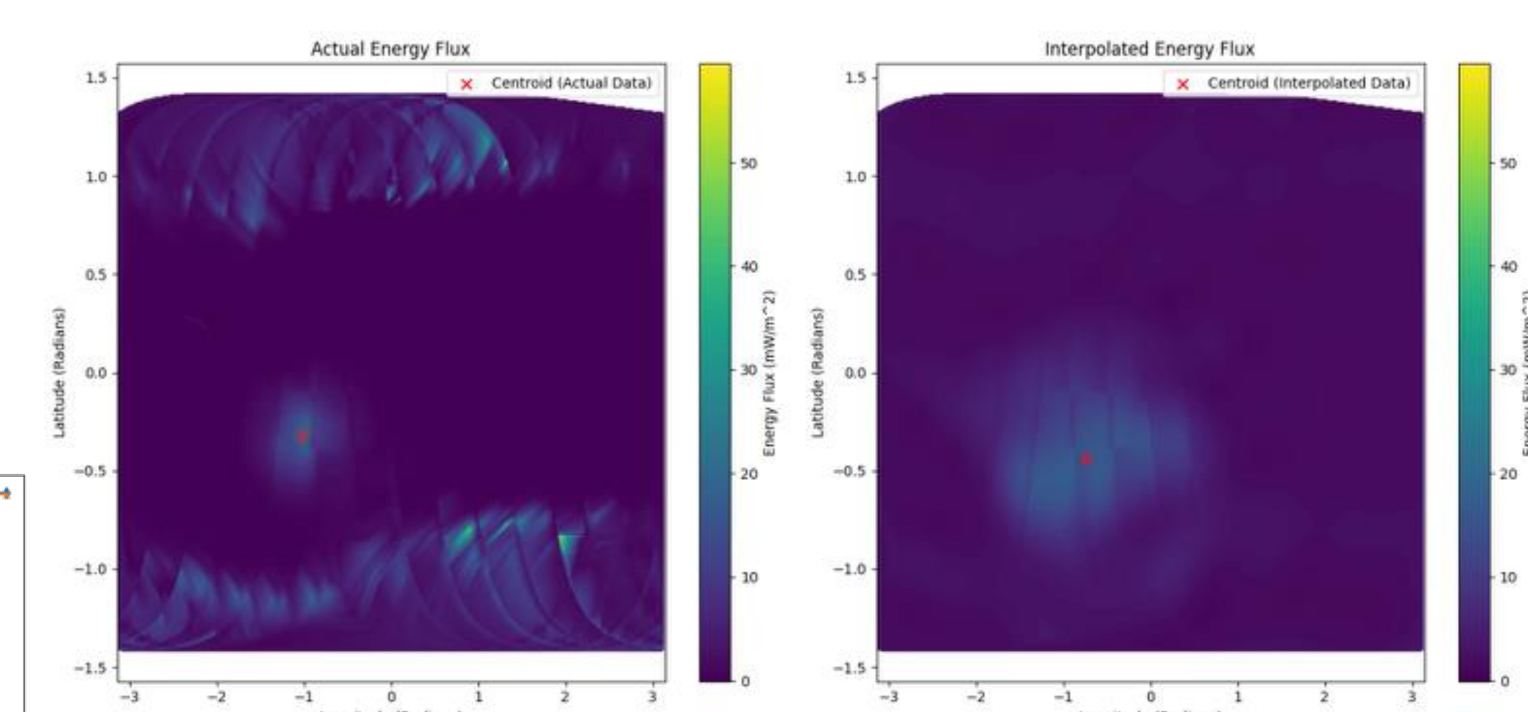


Shell Comparison: Experimenting if adding more layers increases performance. The lower graphs compare actual IRENE data to interpolated IRENE data for the 10-shell case. Below is a table showing the values for the R-squared scores for varying grid refinements(2)

	2 Shells	4 Shells	6 Shells	8 Shells	10 Shells
R-Squared Score	0.179	0.798	0.672	0.768	0.810



Validation: R-squared comparison between POES and interpolated IRENE data. The overall R-squared score is -.381. We attribute this disparity to several errors. (2)



Results: Comparison of POES data to interpolated IRENE data. The red crosses represent the anticipated centroid of radiation. The centroids are 1951 km away, with an error of 9.74%. (2)

Conclusions and Future Work:

- Our interpolation method sufficiently describes space weather behavior for GNC uses
- With future work, these maps will be more accurate and can be applied in other environments
- Utilize other models and satellite observations in our interpolative methodology
- Incorporate a unique SEP transport model using DECAPODES (discrete exterior calculus)
- Enable real-time nowcasting by optimizing our process further and integrating the SEP model

References:

(1) L. f. Atmospheric and S. P. (LASP), "Kp Indices for Space Weather Storm Analysis," 2024. Data accessed through the LASP Space Weather Data Portal, analyzed January 3, 2025.
(2) Furioso, N., Abed Azad, F., Petersen, C., Petersen, A. (in press). "Innovative Global Mapping Techniques for Navigating Space Weather Hazards in Low Earth Orbit," 2025. In Proceedings of the AAS/AIAA Spaceflight Mechanics Meeting.

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