Predictive Implications of Space Weather on Quantum Network Functionality

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Introduction

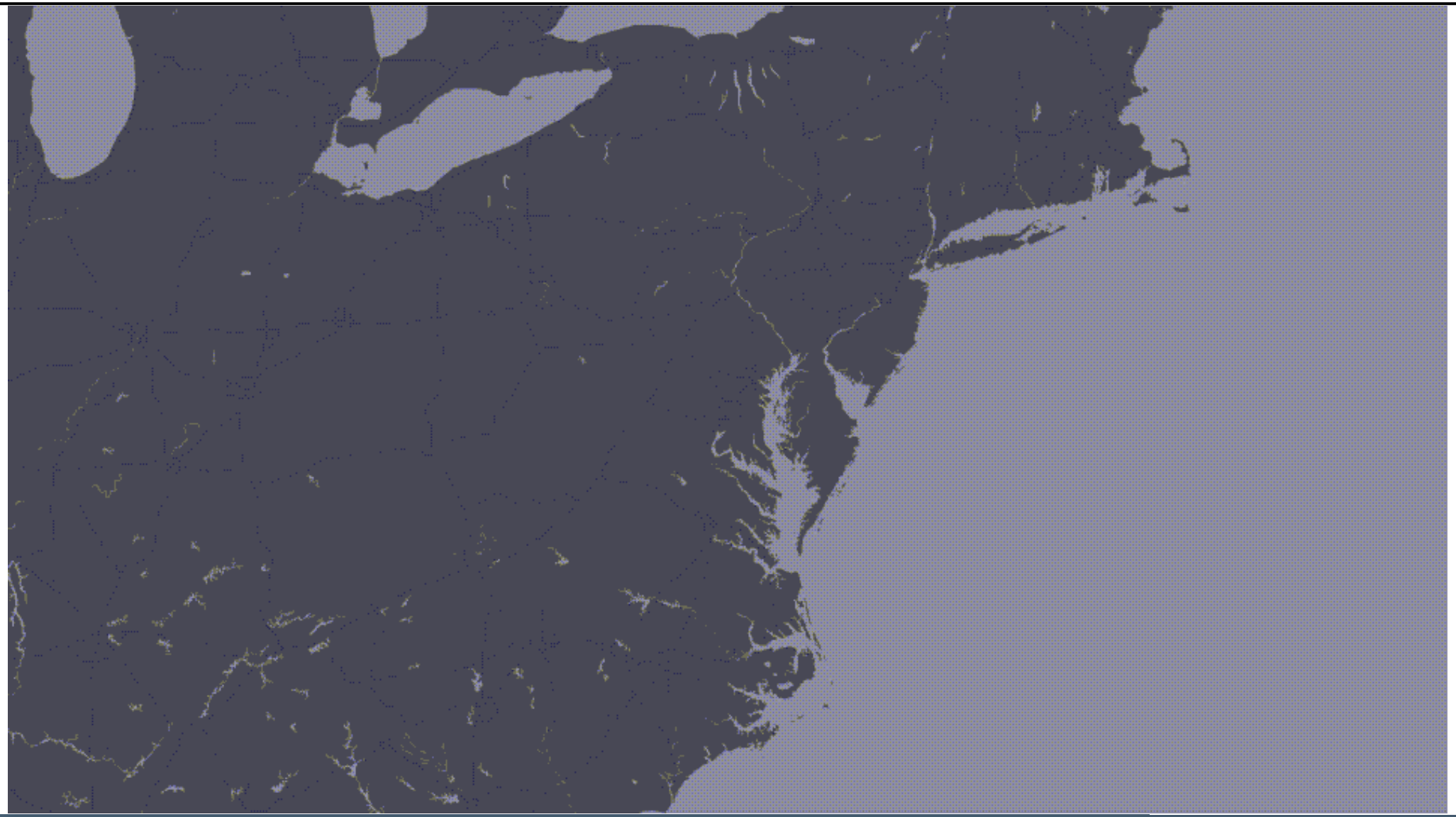
Quantum communication networks at a glance:

- Utilize quantum properties for ultra-secure communications and sensing
- Depend on precision timing and signal integrity
- Relies on maintaining strict synchronization and control over signal polarization
- Sensitive to external disturbances

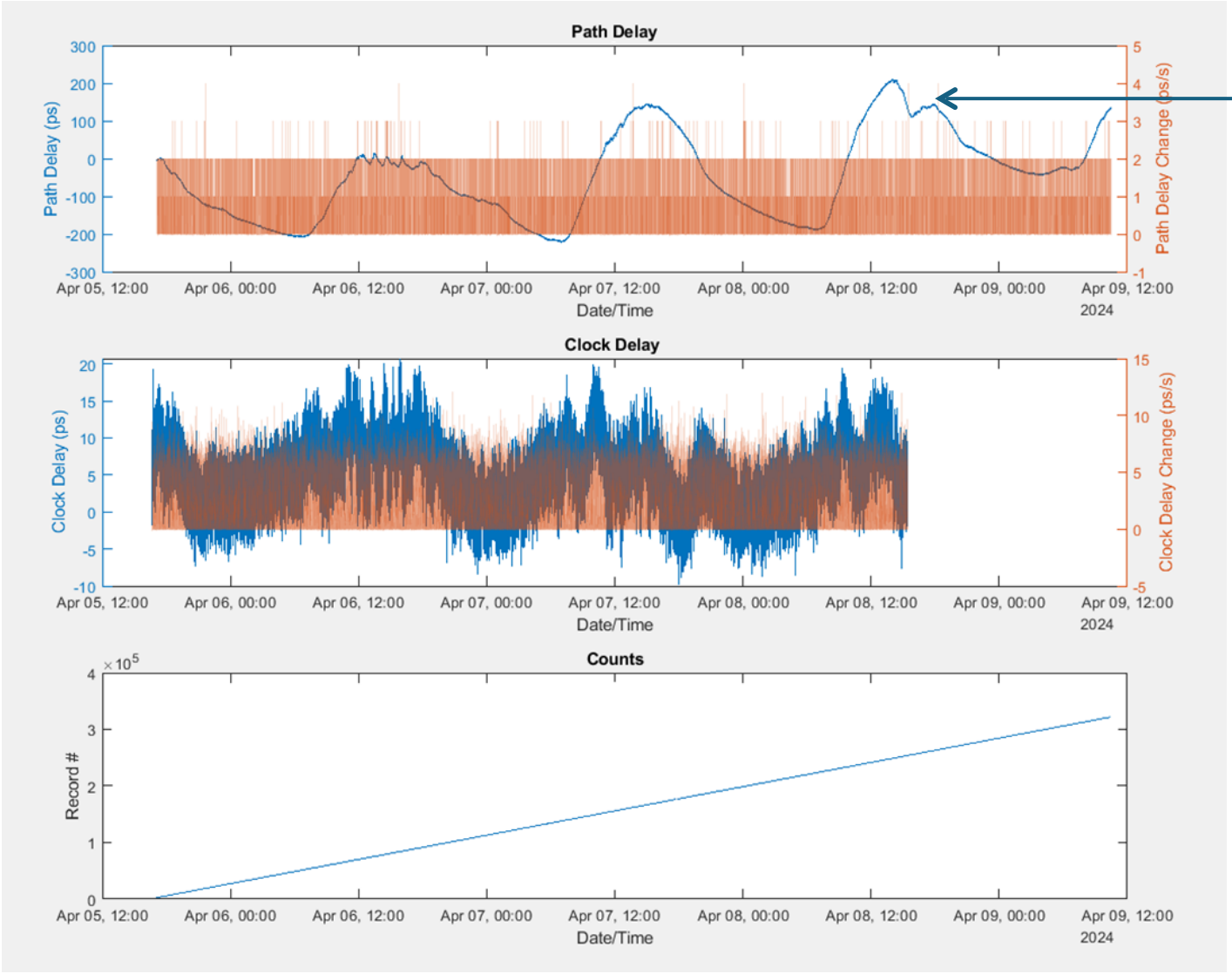
Previous Work:

- Coexistence of classical & quantum channels over single fiber [1]
- Metro traffic vibrations impacting fiber links [2]
- Weather effects on time synchronization error [3][4]

Background [5]



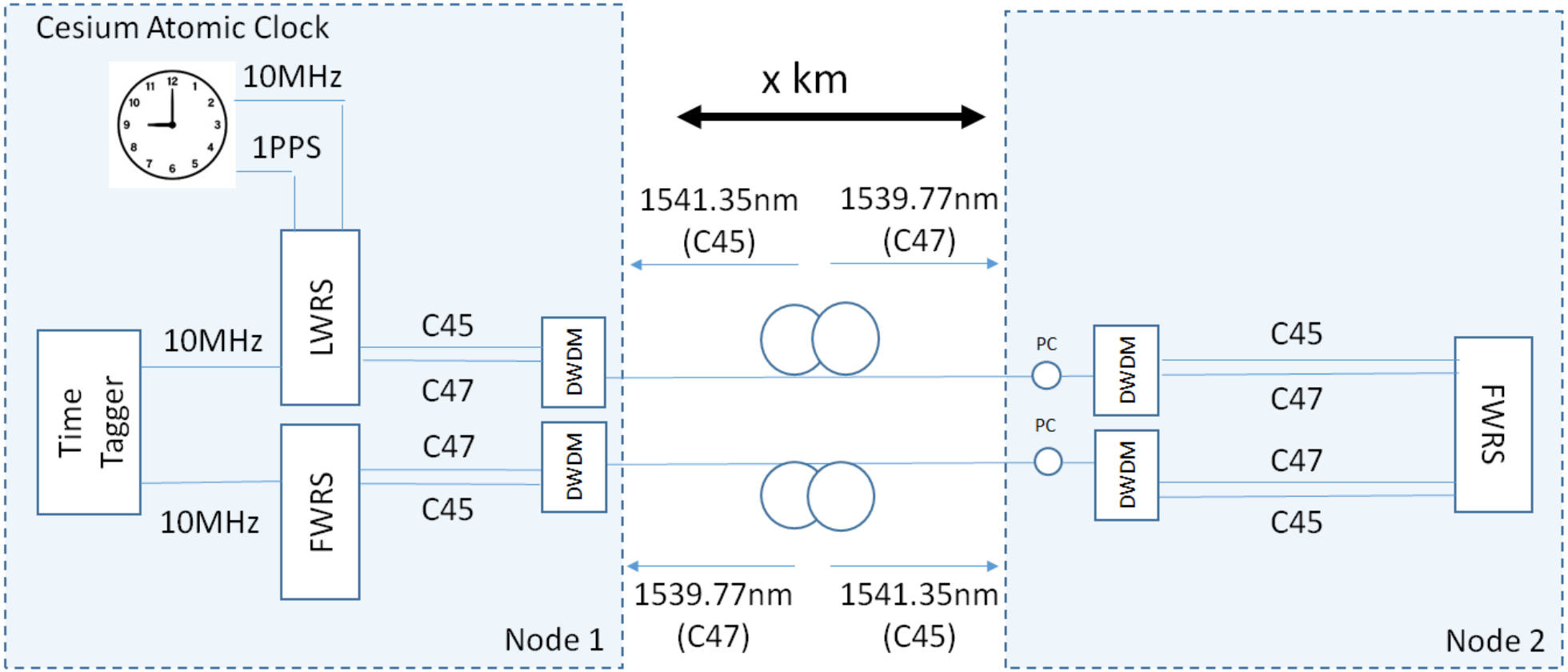
Motivation



8 APR 2024
Total Solar Eclipse

To what extent do space weather features contribute to explaining the variance in time synchronization errors?

Time Sync Experimental Setup



Dataset Sourcing

Ground-based observatory data (**SWPC**):

- **F10.7 Index** (10.7 cm radio flux) – solar radio emission measurements
- **SESC sunspot numbers** – aggregated daily counts of visible sunspots
- Daily observations

Space-based observations (**GOES-16**):

- **X-Ray flux** – solar X-ray emission measurements
- **Magnetometer** – ambient magnetic field measurements
- Second-by-second observations

Temporal Aggregation:

- **SWPC** data provided as daily observations; uses daily mean aggregate of **Time Sync Error**
- **GOES-16** hi-res data aggregated (mean) to match **Time Sync Error** 1 sec obs. rate

Methodology

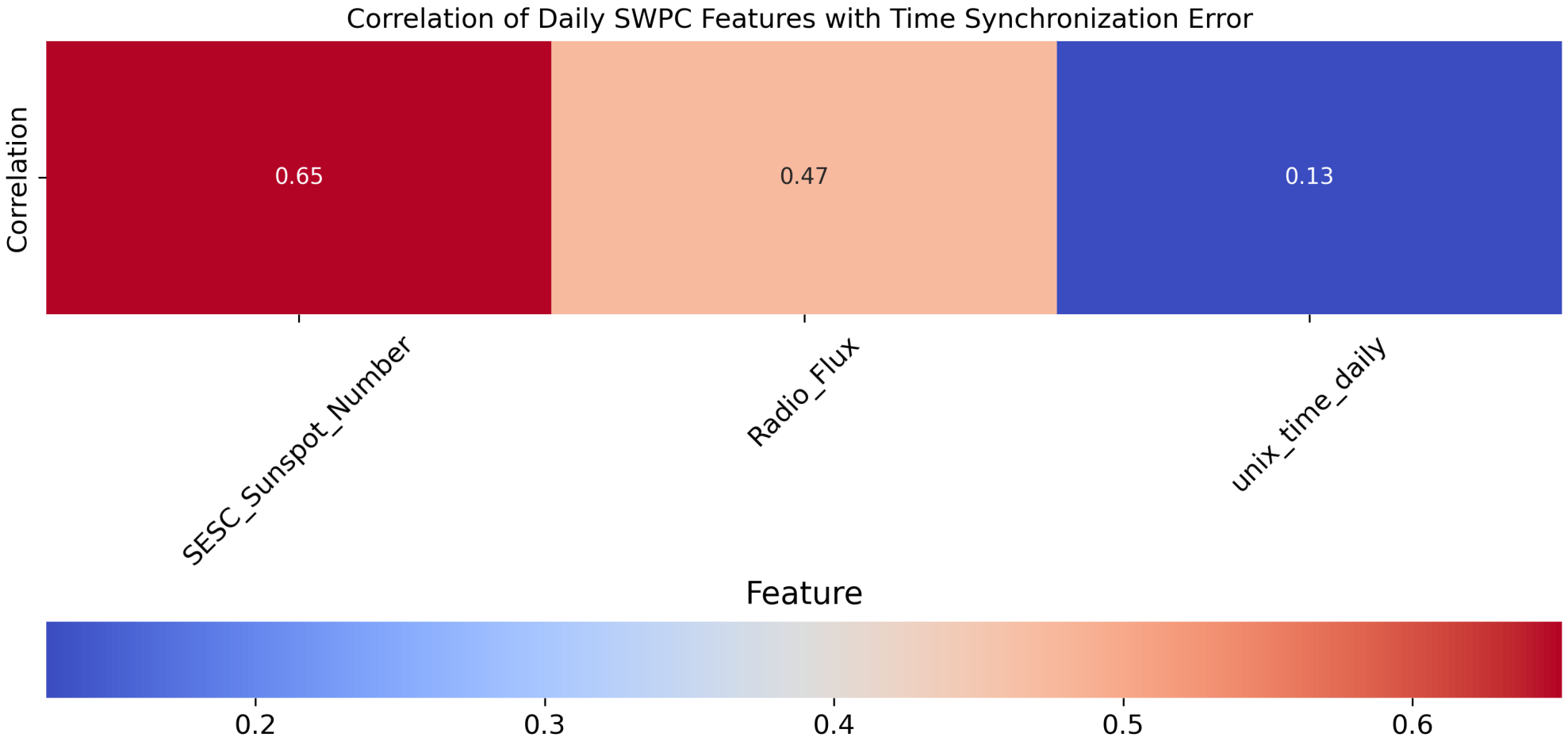
Analytical Strategy:

- Employ **correlation** and **regression** analyses
  - Explore potential connection between space weather and time sync error
  - Determine degree of time sync error variance explainability for each predictor
- Test **general linear models** against observed data
  - Apply data transforms to remediate violated model assumptions
- Account for curvilinear relationships
  - Include **polynomial expansion** of feature space with interaction terms

Model Evaluation:

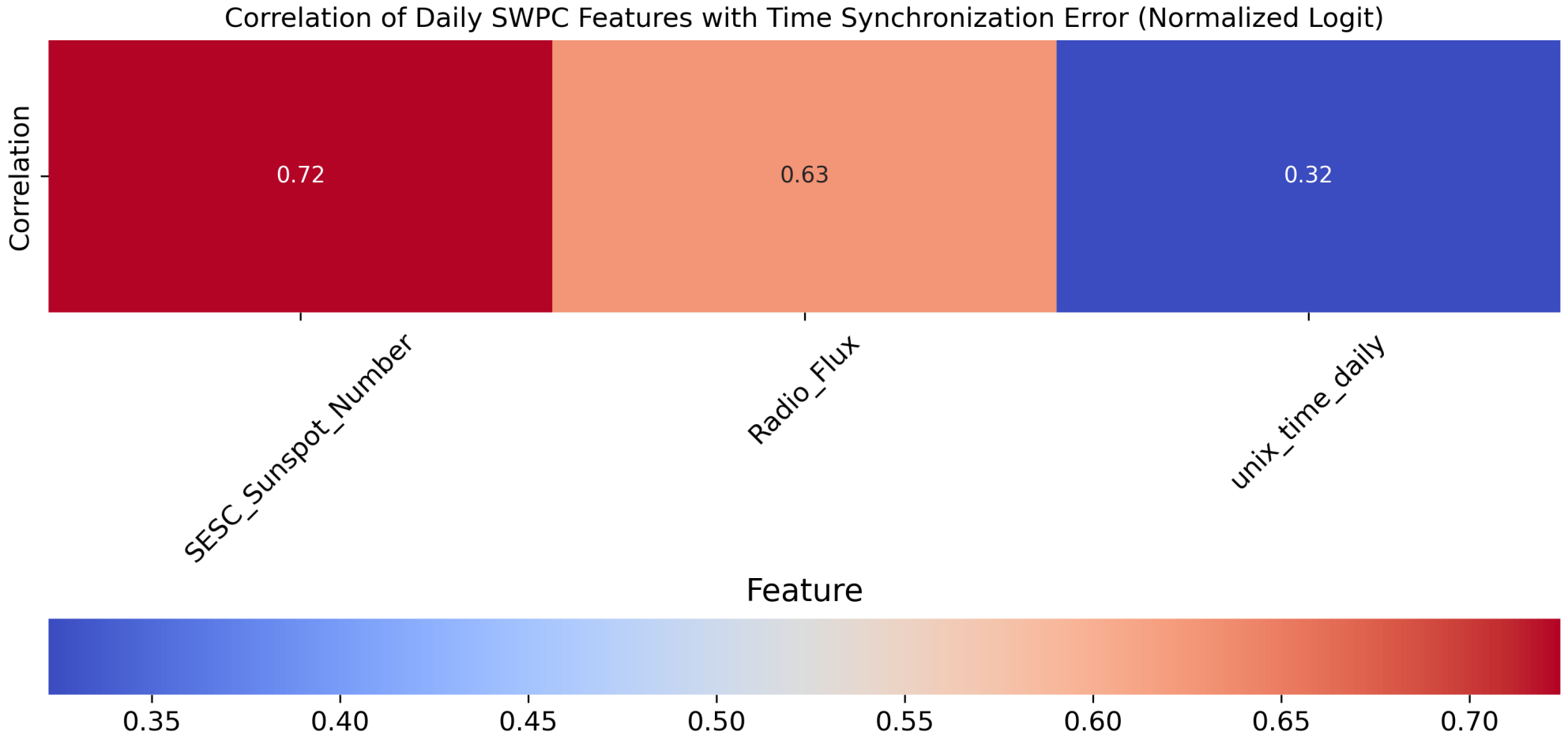
- Quantitative:
  - Coefficient of Determination, RMSE
- Qualitative:
  - Residual analysis
  - Examine suitability and limitations of regression model assumptions

Results (Correlation Analyses – Daily Aggregates)

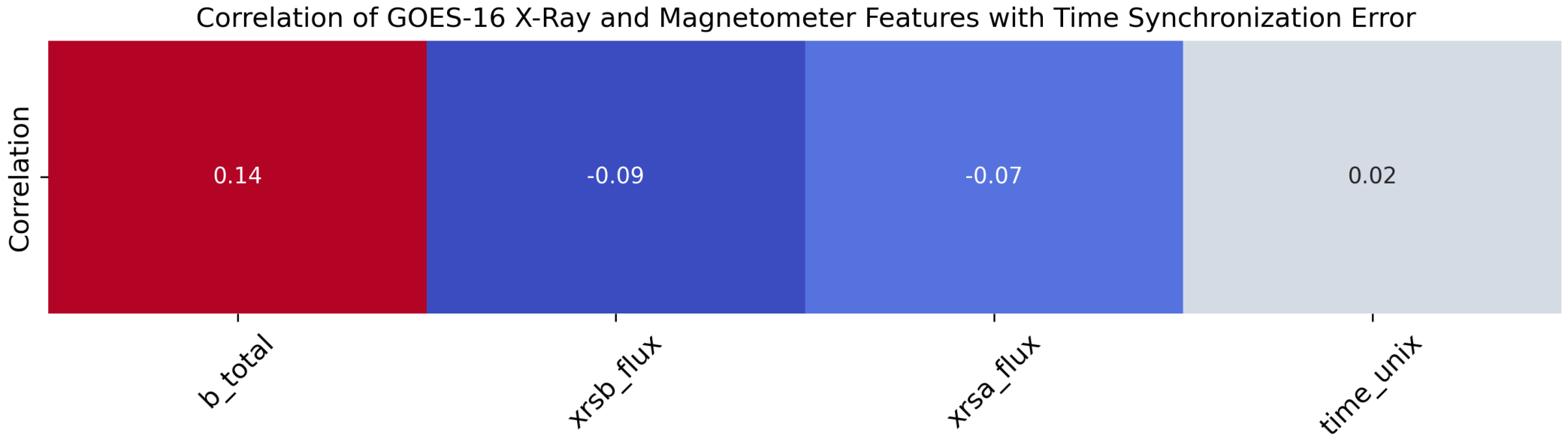


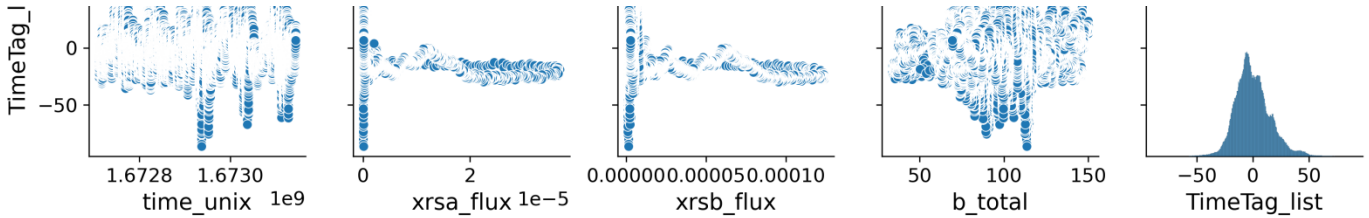
Results (Correlation Analyses – Daily Aggregates)

Post-transform on target variable (normalized logit)



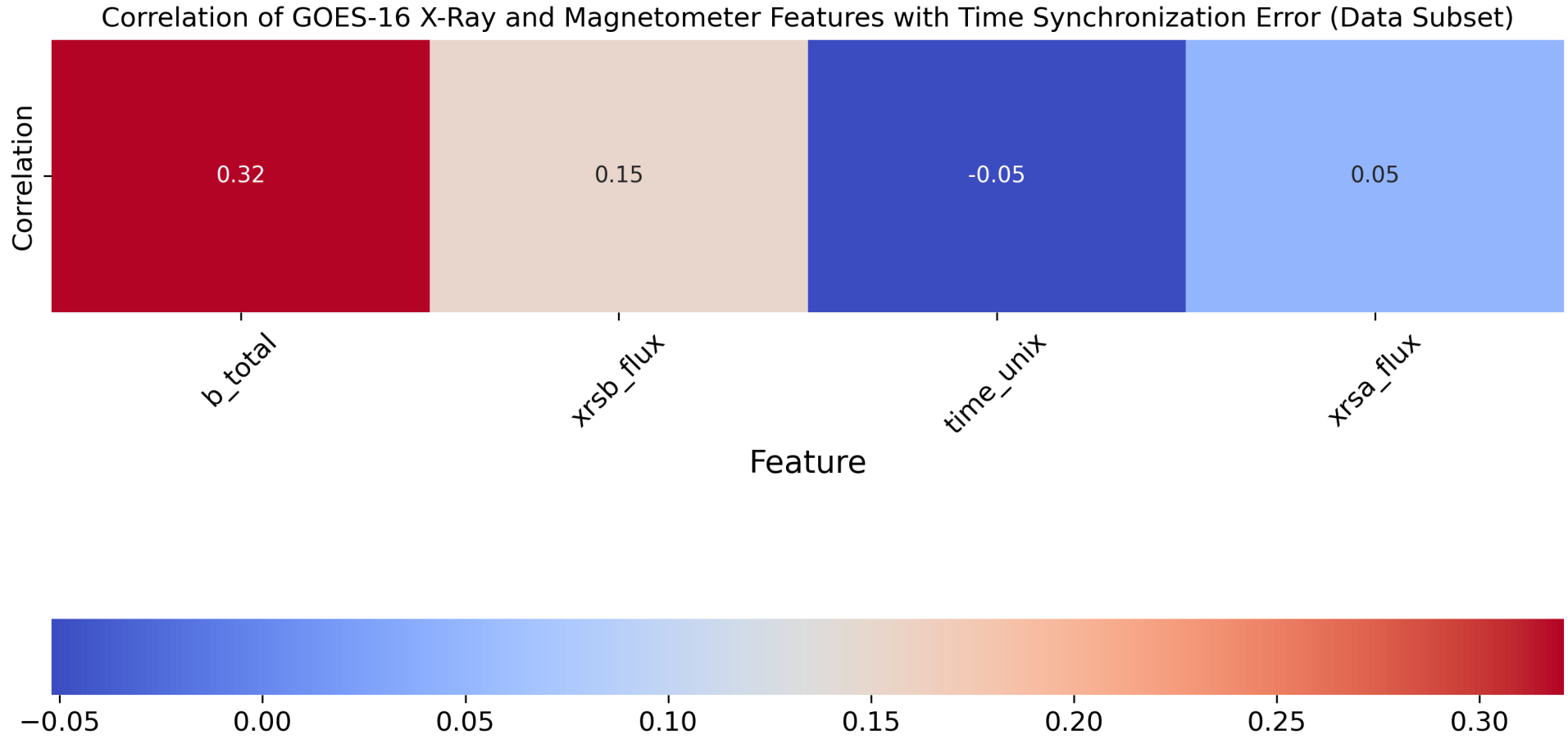
Results (Co a)



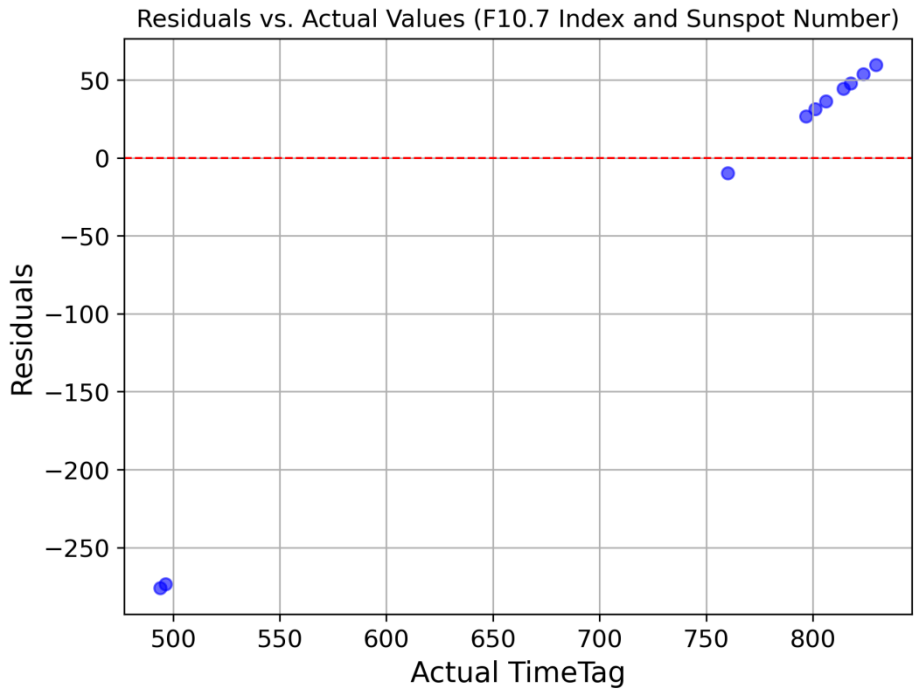


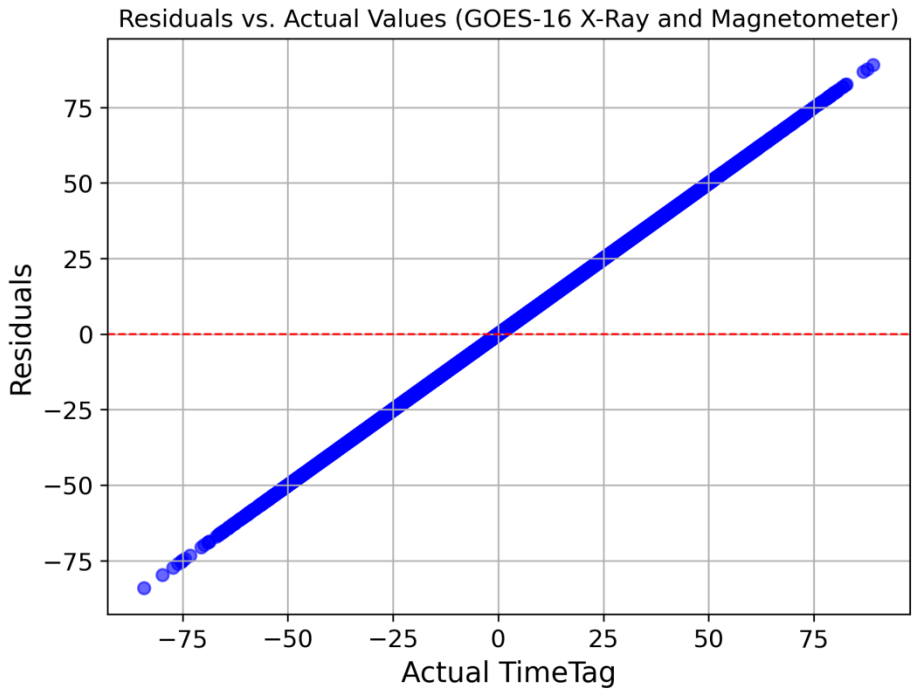
Results (Correlation Analyses – GOES-16 Data)

After selecting a subset of the combined data



Results (Regression Analyses – Baseline)

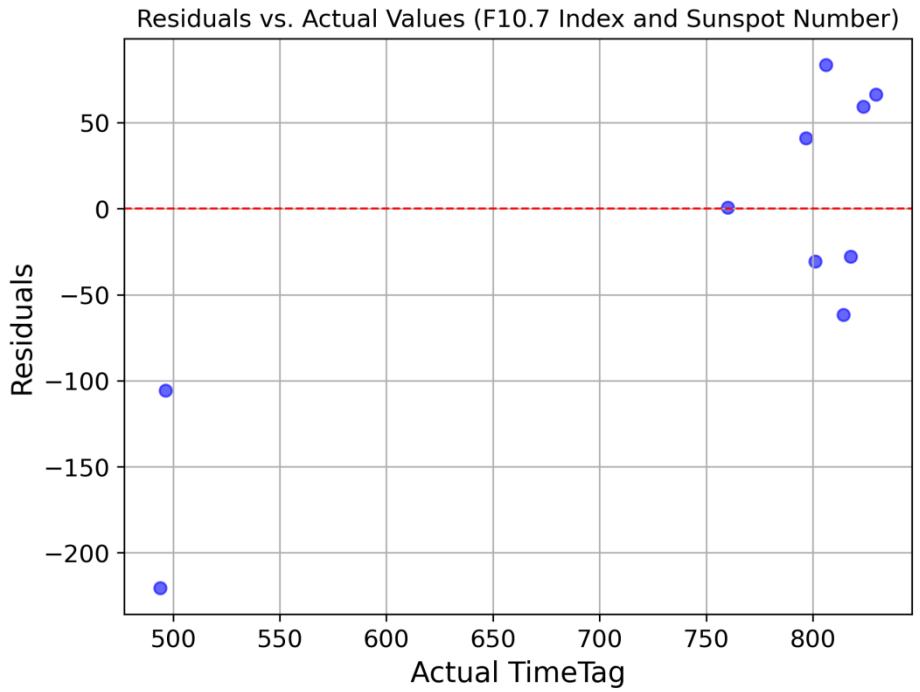


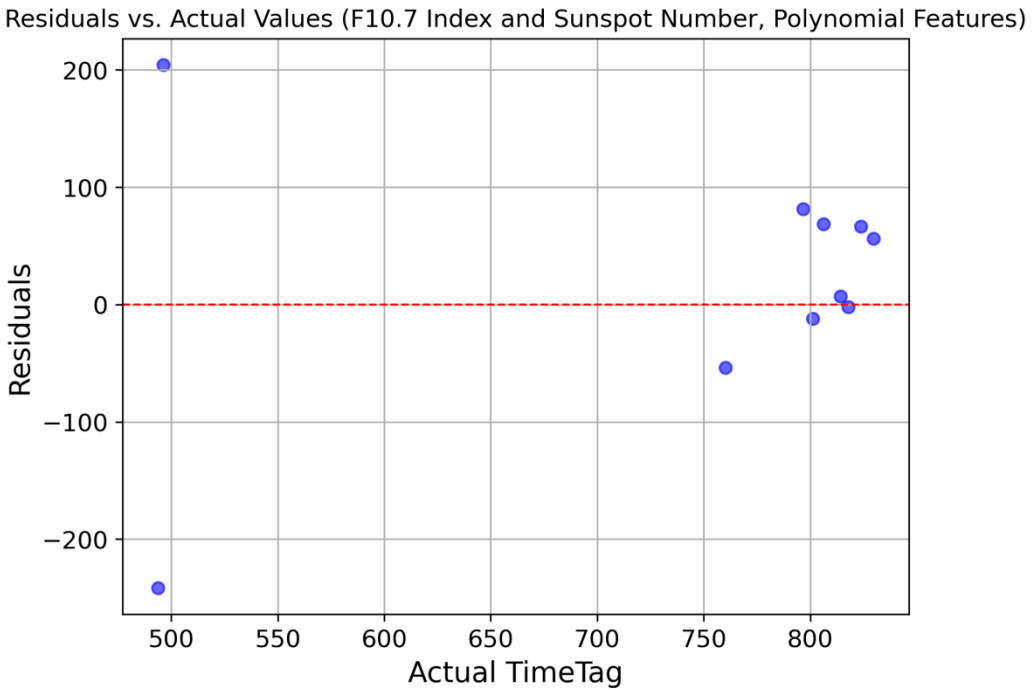


MSE	RMSE	R^2
16,485.845	128.397	-0.042

MSE	RMSE	R^2
251.522	15.860	0.000

Results (Regression Analyses – Daily Aggregates)



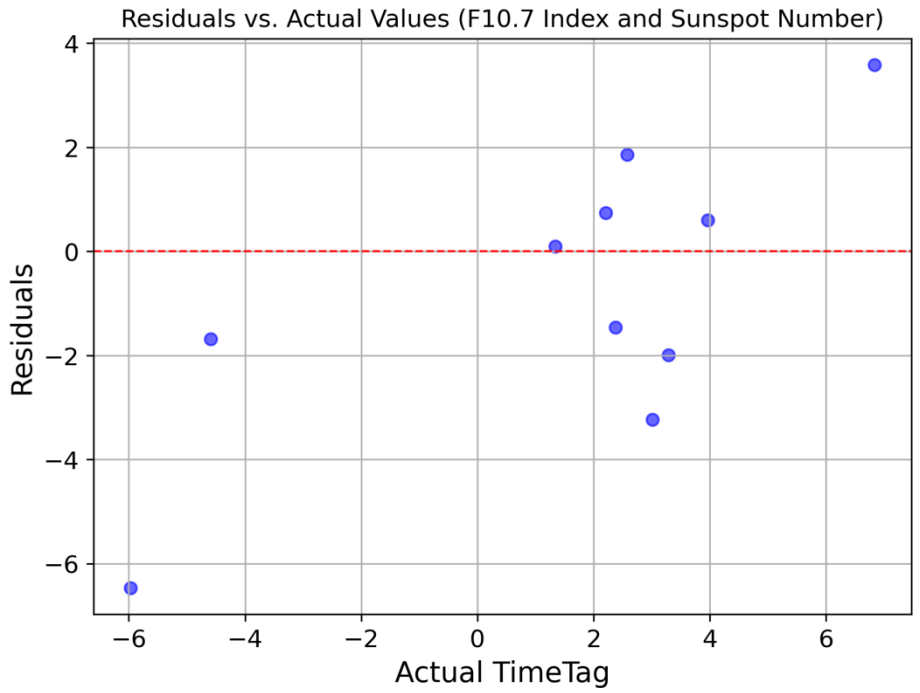


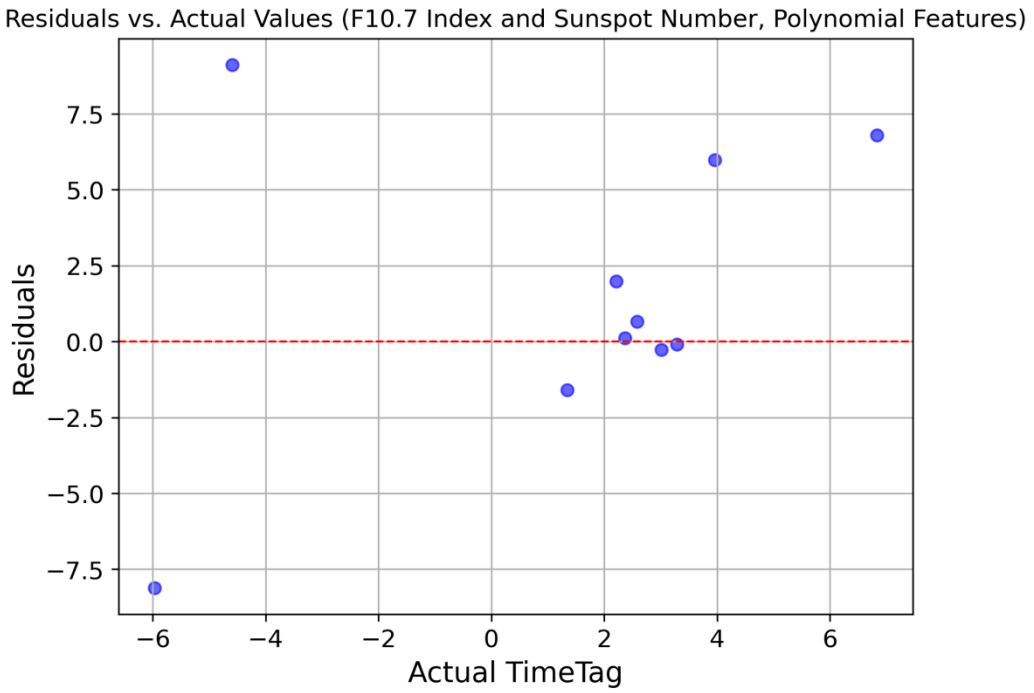
MSE	RMSE	R^2
8188.753	90.492	0.482

MSE	RMSE	R^2
12,216.808	110.530	0.228

Results (Regression Analyses – Daily Aggregates)

Post-transform on target variable (normalized logit)

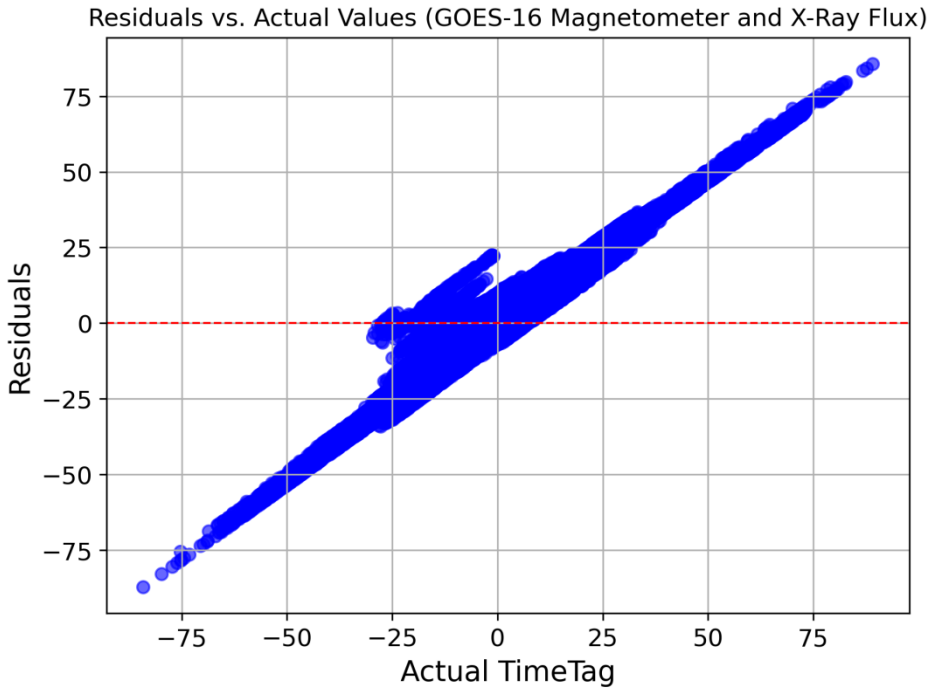


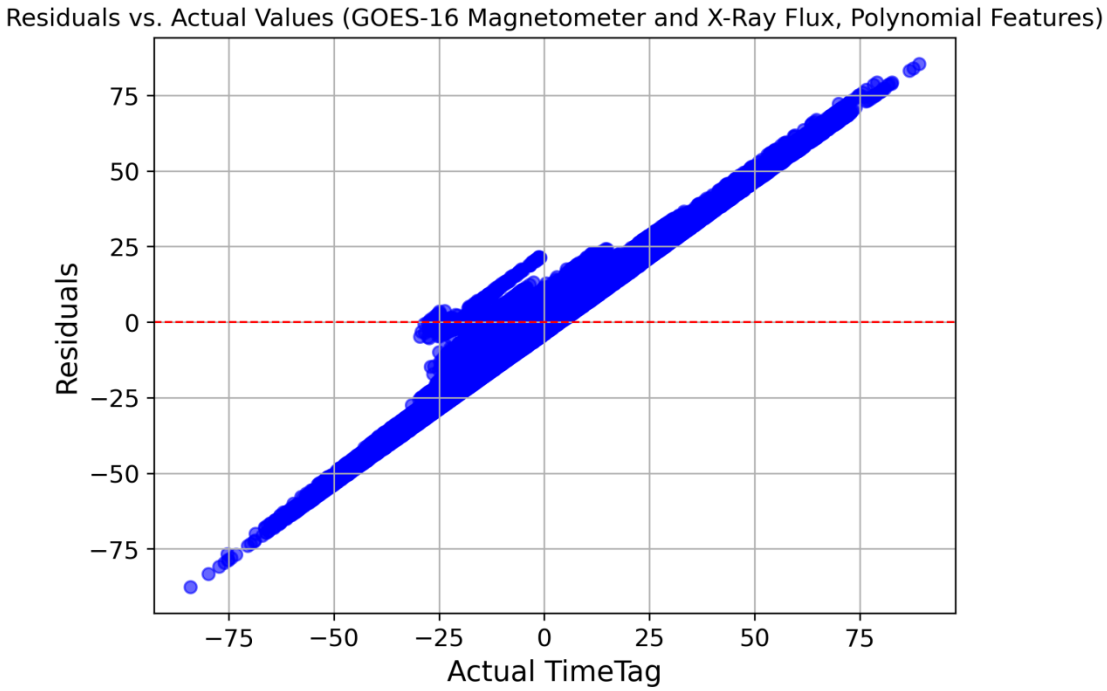


MSE	RMSE	R^2
7.852	2.802	0.420

MSE	RMSE	R^2
23.758	4.874	**-0.756**

Results (Regression Analyses – GOES-16 Data)



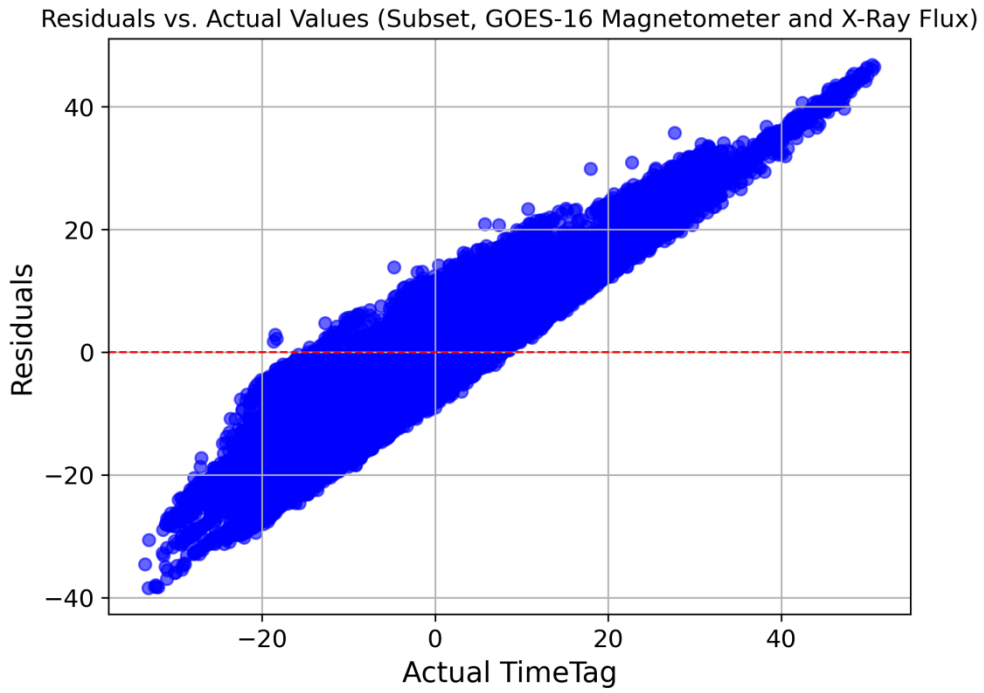


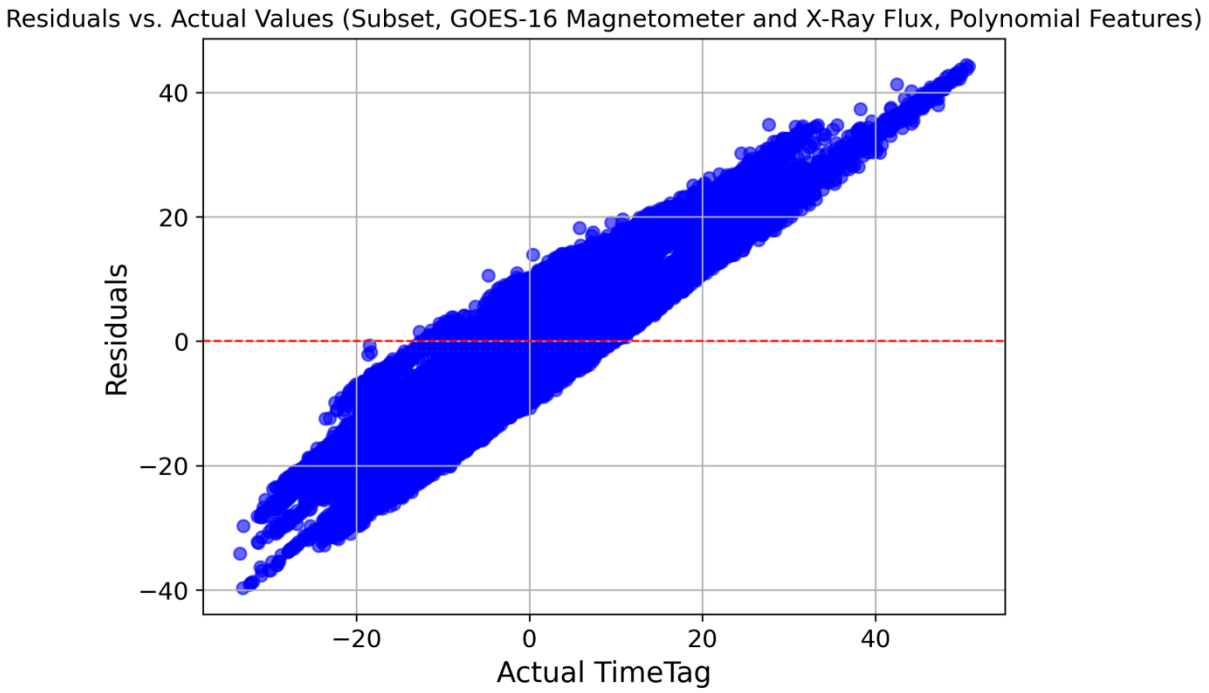
MSE	RMSE	R^2
243.839	15.615	0.031

MSE	RMSE	R^2
243.003	15.589	0.034

Results (Regression Analyses – GOES-16 Data)

Using data subset





MSE	RMSE	R^2
140.728	11.863	0.148

MSE	RMSE	R^2
139.217	11.800	0.158

Discussion

Cons:

- Limited Predictive Power
  - Space weather may not be as strong as **local** predictors
- Model Assumption Violations
  - Normality, homoscedasticity
- Non-Ideal Sample Size
  - Limits statistical power of predictive models
- Transform tradeoffs
  - Result in higher correlation, with reduced explainability
    - Does not translate to better performance on original scale

Pros:

- Select features may explain some time sync error variance
  - F10.7 index, sunspot number
  - Could offer insights WRT daily aggregates
- Informs future QNet modeling research

Summary

Key takeaways:

- Space weather may offer low to moderate explainability in variance of time synchronization error, but not for real-time applications
- Other confounding factors may be greater drivers for error (i.e. local weather)
- Space weather is far more likely to impact hardware systems supporting quantum networks (e.g. repeaters, White Rabbit switches) [6][7]

Concluding remarks:

- Space weather is likely not a significant predictor of discrete time synchronization errors
- Additional data and modeling necessary to conclusively separate effects of local vs. space weather factors on QNet timing performance

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Thank you!