Satellite Orbital Decay and Solar Wind Interactions: A Data Driven Case Study of May 2024 Space Weather Events

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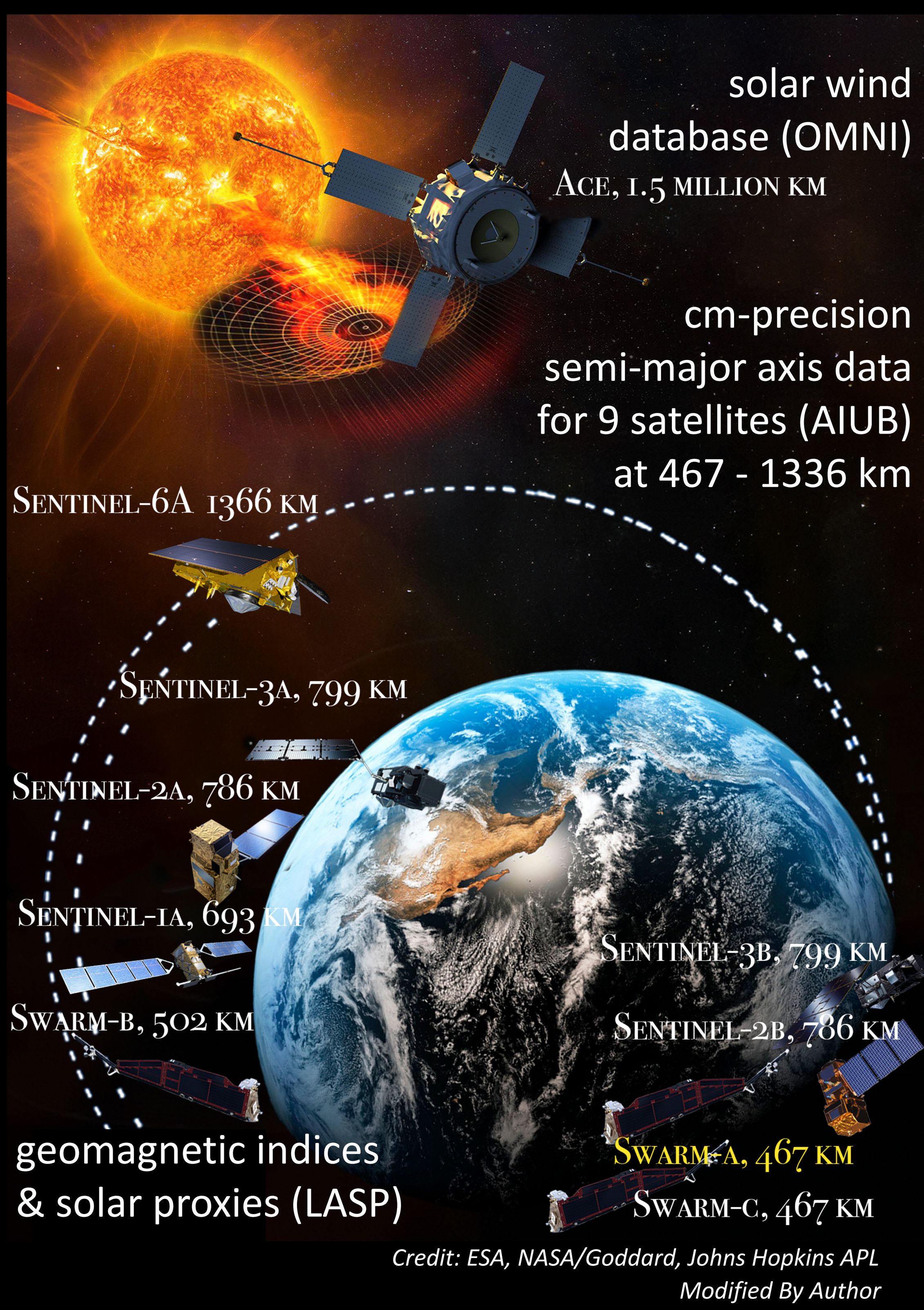
1. Introduction I Data and Motivation



Credit: ESA, NASA/Goddard, Johns Hopkins APL Modified By Author

10+ X-class flares were observed by GOES in May 2024. Several **Coronal Mass Ejections** (CME) launched **towards Earth.**

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High cadence & precision orbit data allows for a clearer analysis of space weather effects.

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Which parameters drive orbital decay at different altitudes?

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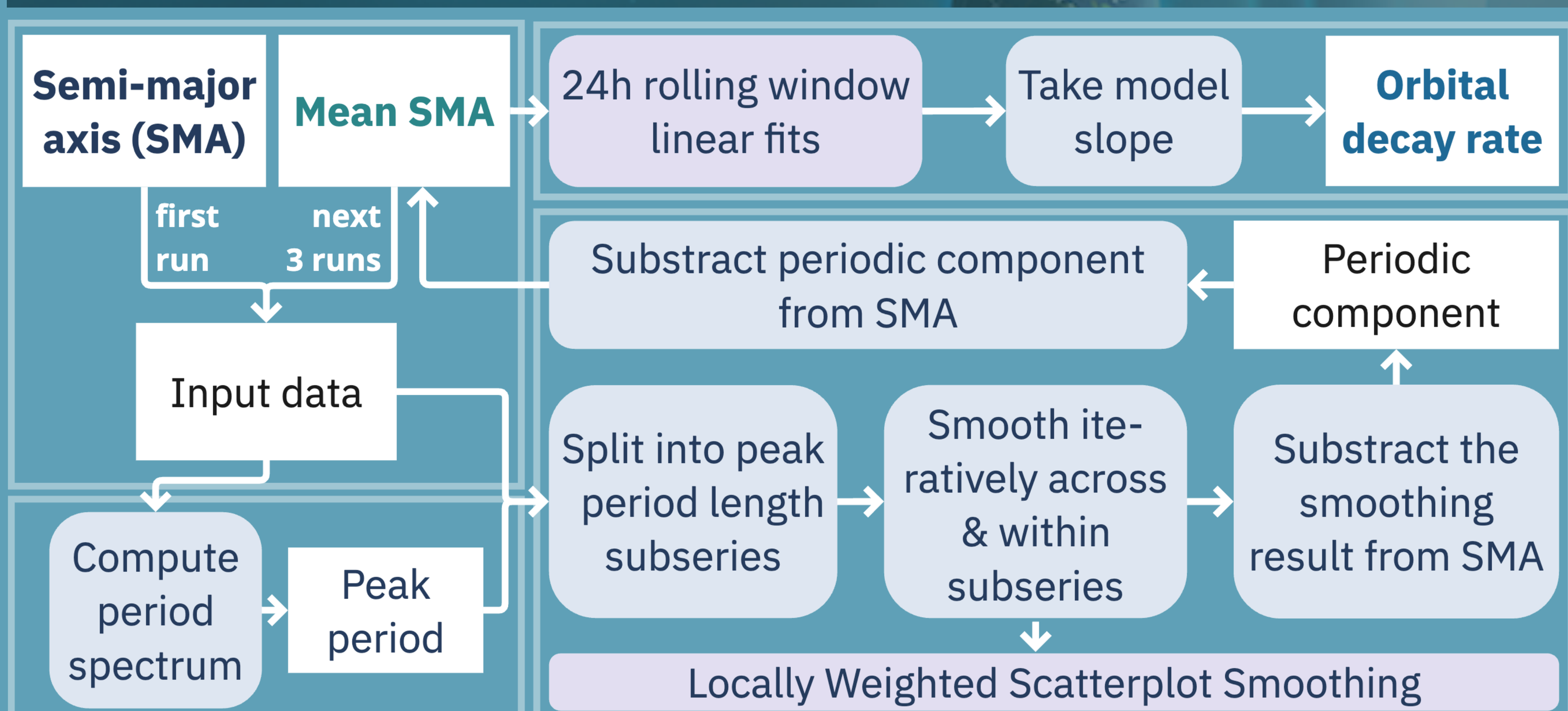
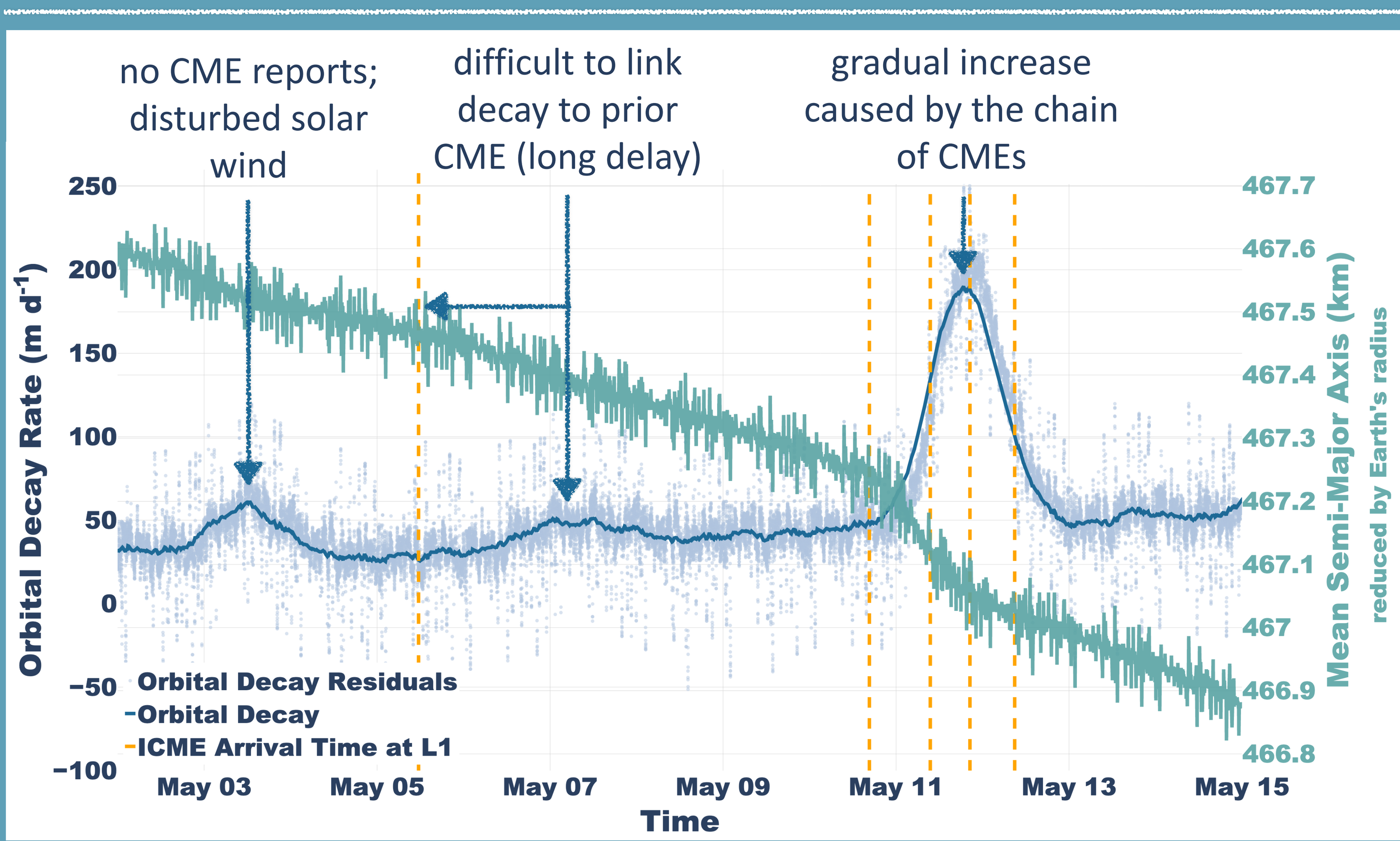
Is there potential for decay forecasting?

2. Methodology I Preprocessing



Workflow for orbital decay rate computation from semi-major axis data.



Orbital decay rate for **Swarm A** (467 km), CME arrivals (dashed lines) and mean semi-major axis. Different parametrizations can affect the computed decay rate. Decay rates of up to **190 m per day** are observed.

Flare	CME	L1 Arrival Time (UTC)
X1.6 Flare	faint CME	May 5th 2024 11:30
M3.5, X1.0 Flares	full halo CME	May 10th 2024 16:36
X1.0, M9.8 Flares	full halo CME	May 11th 2024 09:30
X1.1 Flare	partial halo CME	May 11th 2024 20:30
X3.9 Flare	asymmetric halo CME	May 12th 2024 08:55

List of solar events that were reported at 1 AU based on L1 satellite data.

Credit: CCMC/CME Scoreboard

3. Methodology I Modeling

Compile a data-set of relevant observations for atmospheric changes.

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Observe time lags between L1 and orbit disturbances.

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Model future decay as a linear combination of current inputs & coefficients β.

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Predict decay rates with a **15-hour lead time** at different altitudes.

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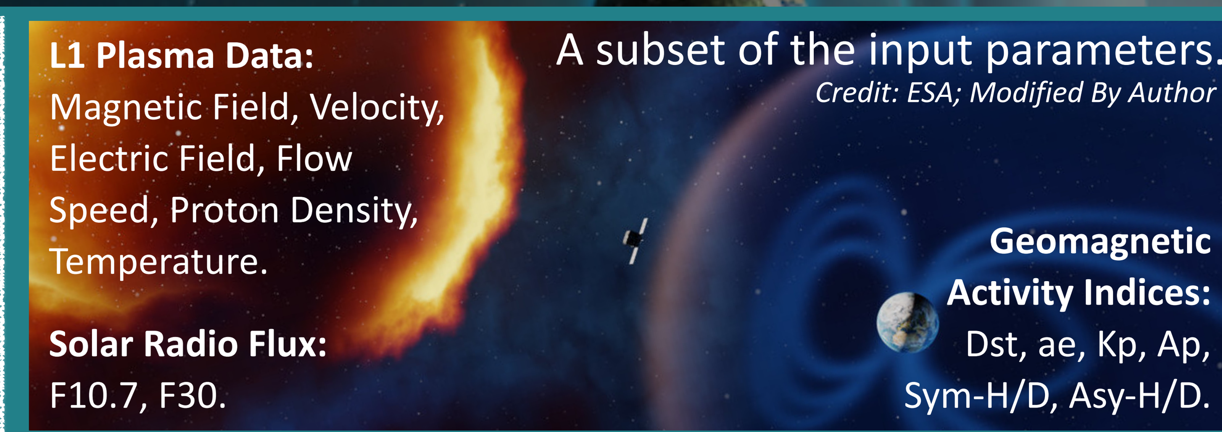
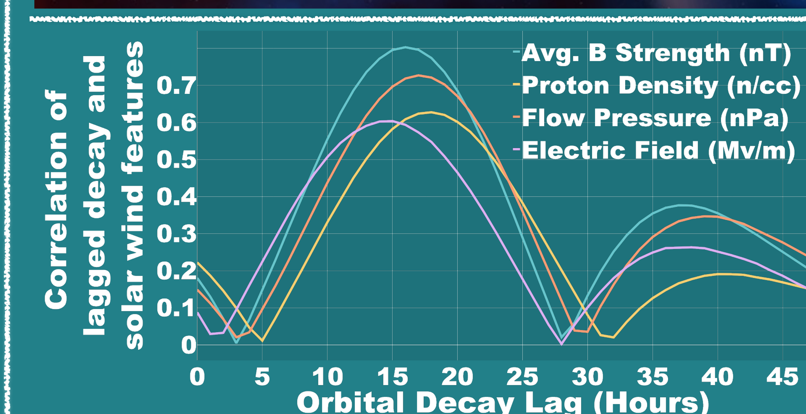
Assess behavior at CME arrival.



Credit: ESA; Modified By Author



The lag with the highest correlation is an estimator for how long L1 events take to affect our atmosphere.

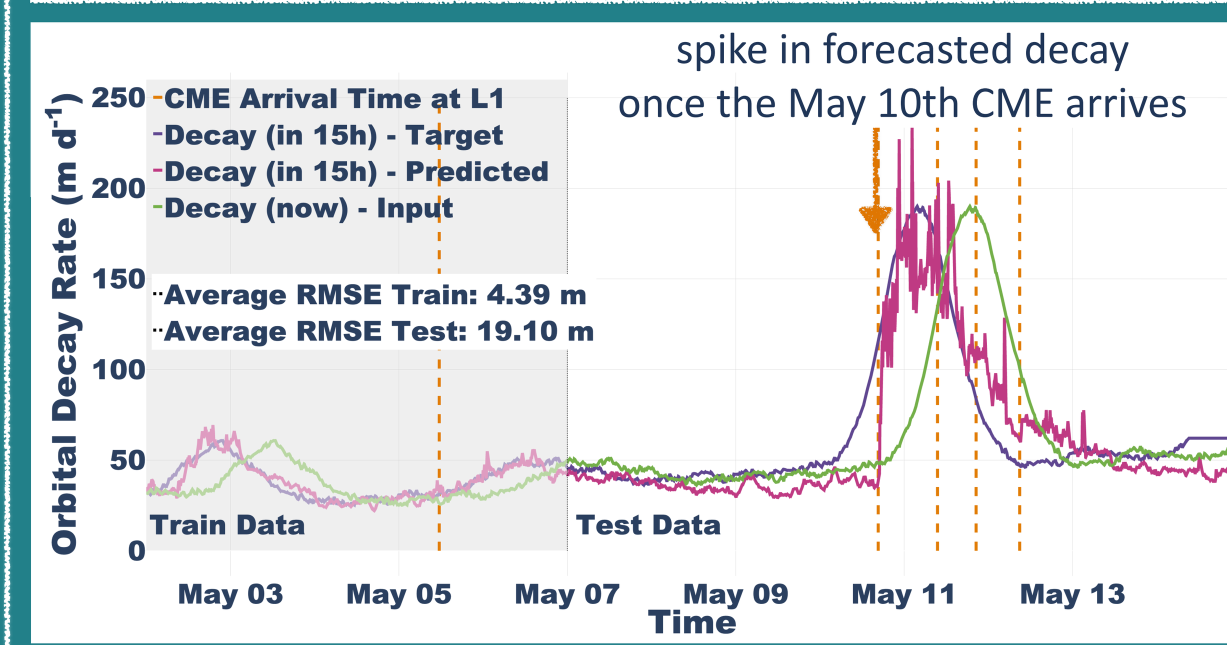
$x(t_i)$ - solar wind, proxy and geomagnetic parameters at t_i

$d(t_i)$ - orbital decay at t_i

LASSO regularization

$$\hat{d}(t_i+N) = f(x(t_i), d(t_i); \beta) = \begin{bmatrix} x(t_i) \\ d(t_i) \end{bmatrix} \beta, N = 15h$$

$$\hat{\beta} = \arg\min_{\beta} \left(\sum_{i=1}^{m} \left(d(t_i+N) - \hat{d}(t_i+N) \right)^2 + \lambda \sum_{j=1}^{p} |\beta_j| \right)$$



Swarm A orbital decay at 467 km (forecast, future, present).

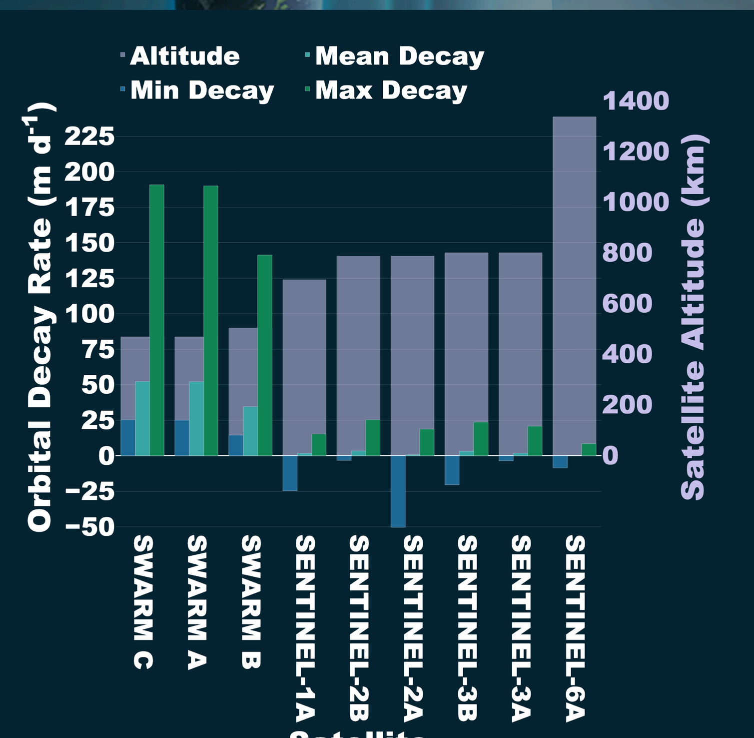
4. Challenges

Satellite **maneuvers obscure effects** in the thermosphere.

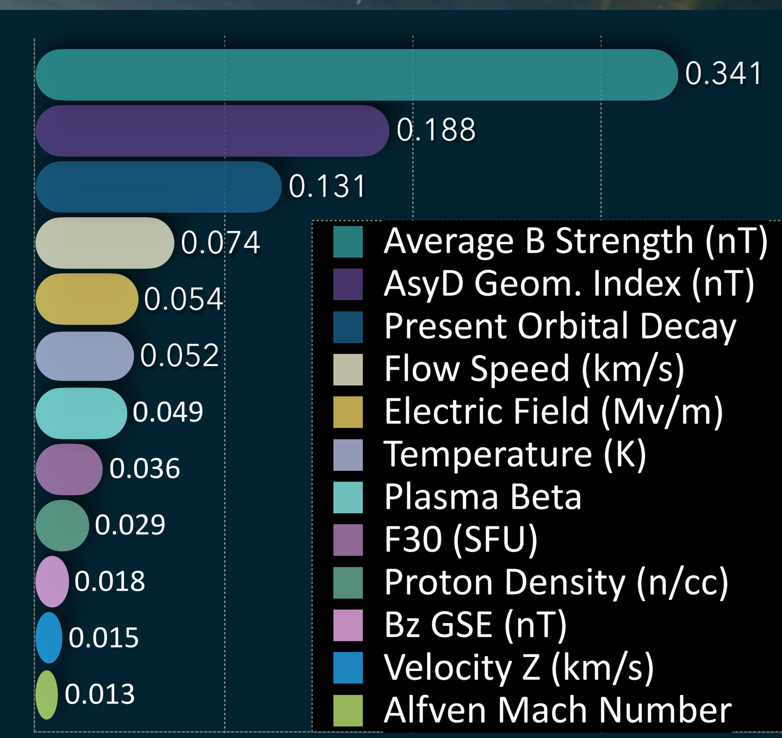
Time lag for atmosphere changes after L1 events **varies.**

Increased decay **without prior CMEs** is difficult to explain.

5. Findings



Decay statistics per altitude (min, mean, max). Negative values correspond to maneuvers. Computed decay rate increase ratios: 3-4x at low altitude, 7-12x at high altitude.



Parameter impact on the model (normalized non-zero coefficients) for an altitude of 467 km. Similar results can be obtained from alternate collinear parameters.

6. Future Work

Refine and apply the forecasting pipeline to data from Jan 2023 to May 2024.

Develop an estimator to determine L1-to-orbit event propagation times.

Extend parameters and integrate findings into an atmospheric model.

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