

# Climatology of Orbital Propagation Error in LEO



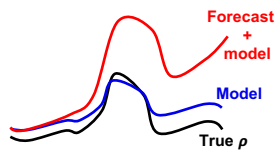
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## Motivation

Drag is the largest source of propagation error for spacecraft in LEO. As orbits become increasingly congested, operators rely on collision avoidance (COLA) maneuvers, executing hundreds of thousands of such maneuvers per year. Suddenly, predicting accurate satellite trajectories is essential for space safety, but bad predictions are still very common.

### Where do errors come from?

1. **Models** specifying neutral density
2. **Forecasts** of the drivers that feed the models
3. Poorly characterized satellites



**Question: Do models or forecasts contribute more to satellite propagation error?**

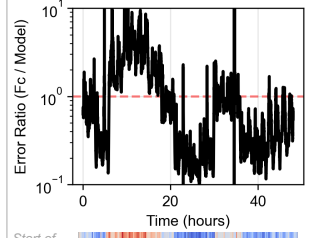
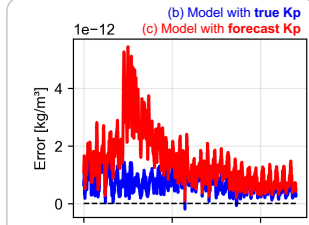
## Forecast vs. Model

### Which contributes more to satellite propagation error?

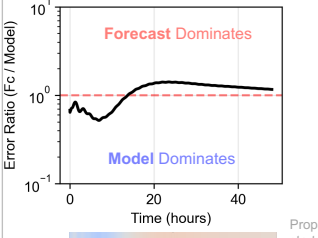
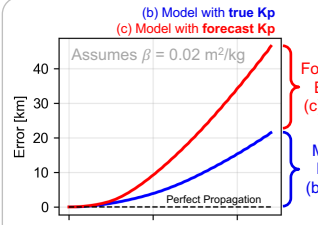
There is a need to compare model and forecast performance in the same units – km of satellite propagation error. To isolate each contribution, propagate a satellite trajectory under different density knowledge assumptions from the same initial condition.

- (a) Trajectory using Swarm-A **accelerometer-derived density**
- (b) Trajectory using **modeled** (MSIS 2.0) density with **true Kp**
- (c) Trajectory using **modeled** (MSIS 2.0) density using **forecasted Kp** (SWPC).

### Density Error Analysis



### Propagation Error Analysis

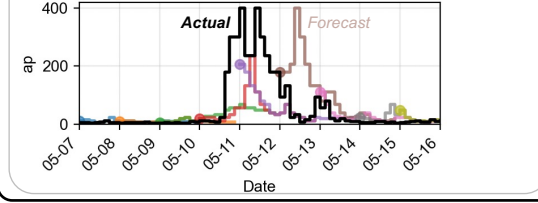
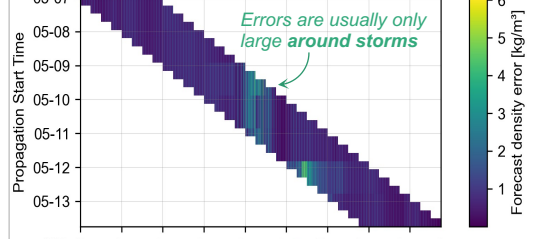
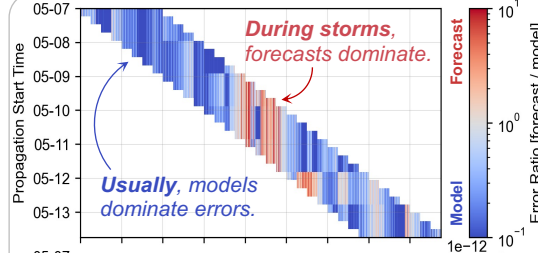


At each timestep, which error source dominates?

## Example Period

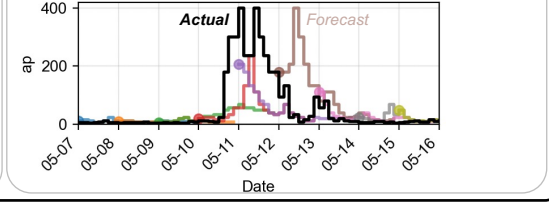
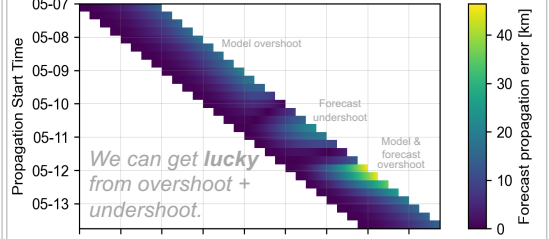
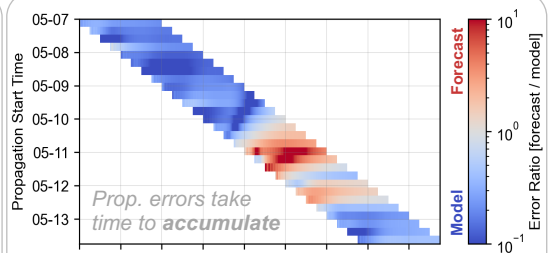
### Gannon Storm (May 2024)

#### Density Error Analysis



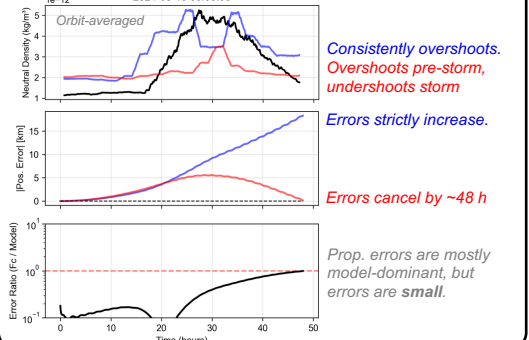
Top panel shows stacked error ratios for 48-hour windows every 6 hours.  
Middle panel shows forecast error magnitude (c) – (a).  
Bottom panel shows ap, including actual and SWPC forecasts.

#### Propagation Error Analysis



## Luck

Overshooting/undershooting can cancel out propagation error.



## Conclusions

**Models are more impactful more of the time, but forecasts are usually more impactful during the times that the propagation errors are large enough to matter to a satellite operator.**

We need to communicate model/forecast performance and impact in units that are interpretable to users. Kp/ap or neutral density errors are **not** an informative way to measure drag impacts for satellite operators.

### Ongoing Pursuits

- How much modeling fidelity (time/length/height scales) is necessary before we hit diminishing returns in propagation performance?
- How do uncertainty-aware forecasts and models change operator decision-making?