

SPACE ATLAS

Driver-resolved attribution and forecasting of voxel-level thermospheric density, with per-edge uncertainty and learned time-lag.

Heidi Bennett · Nervous Machine · space-atlas.nervousmachine.com

Problem

Operational thermospheric models (JB2008, NRLMSISE-00) estimate bulk density but do not resolve *which* driver — or at what lag — is responsible for a given perturbation. Without per-driver attribution and learned time-lag structure, there is no mechanism to forecast how a driver impulse propagates across orbital shells over hours to days.

Method

A causal-discovery pipeline ingests five space-weather indices — **Dst**, **IMF Bz**, **AE**, solar wind density, solar wind speed — and decomposes voxel-level density into per-driver contributions. Each causal edge carries a learned multiplier **m**, a time-lag distribution, and an evidence-weighted certainty **z**. Activity-weighted attribution and quiet-time baselines prevent confidence inflation during geomagnetic silence.

24 voxels · 104 causal edges · 460–510 km altitude band.

Validation

GRACE-FO accelerometer density (TU Delft TOLEOS v02c, 10-second raw averaged to hourly, 2024-12 → 2025-12): 3.41 M raw / 89.8 k processed observations.

Every driver recovered from near-noise TLE baseline. Four of five drivers cleared **z** > 0.91; all five cleared **z** > 0.80. Largest recovery: solar wind density Δ +0.74. Learned lag structure produced validated multi-day forecasts using held-out GRACE-FO as error signal.

Operational path forward

Live LEO GPS drag residuals already provide GRACE-FO-comparable cadence across the operational fleet but remain unexploited for thermospheric characterization. Ingesting these signals yields certainty-quantified, driver-resolved nowcasts and spatiotemporal perturbation forecasts without dedicated science missions. The same attribution + lag mechanism extends to seasonal-latitudinal variation and Joule-heating-driven density blooms.

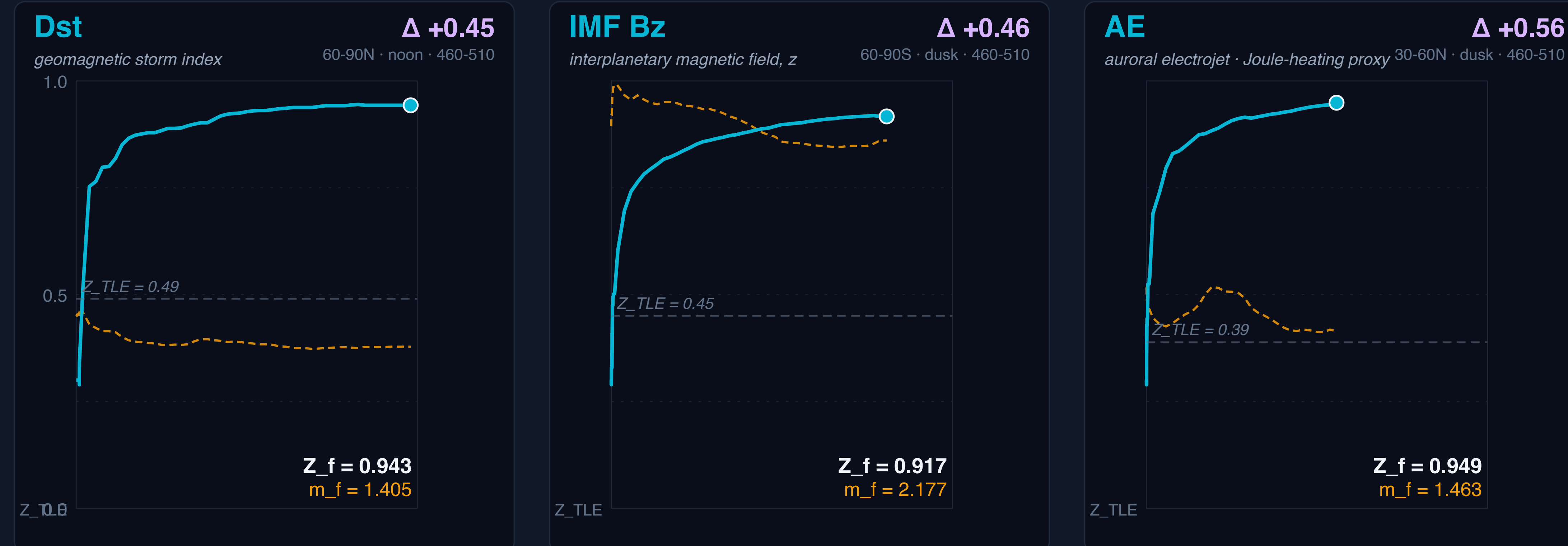
VOXEL CERTAINTY GRID · LATITUDE × ALTITUDE

GRACE-FO altitude band (460–510 km) converges to Very High Z; other shells await GPS-drag-residual data at comparable cadence. High cadence is the lever — at the altitude band where it exists today, the pipeline reaches $Z > 0.70$ across all latitudes and local times.



FIVE-DRIVER LEARNING TRAJECTORIES

One representative causal edge per driver · GRACE-FO TOLEOS v02c · 2024-12 → 2025-12
Z curve (cyan) · driver multiplier m (warm, dashed) · Δ certainty recovered vs TLE baseline



READING THE PANELS

- certainty Z on [0,1] left axis
- - - driver multiplier m (learned gain)
- - - TLE baseline Z for this driver
- final per-edge (Z_f , m_f)
- Δ $\Delta = Z_{GRACE-FO_avg} - Z_{TLE}$ across all edges

Each panel is one representative edge; Δ reports the driver-averaged recovery across all edges.

$\eta(Z) = 1 / (1 + e^{\{10(Z - 0.5)\}})$ learning rate contracts as certainty earns itself · obs count, 0 → 5,200 on shared scale · 24 voxels · 104 edges · 460–510 km · 89.8 k hourly obs

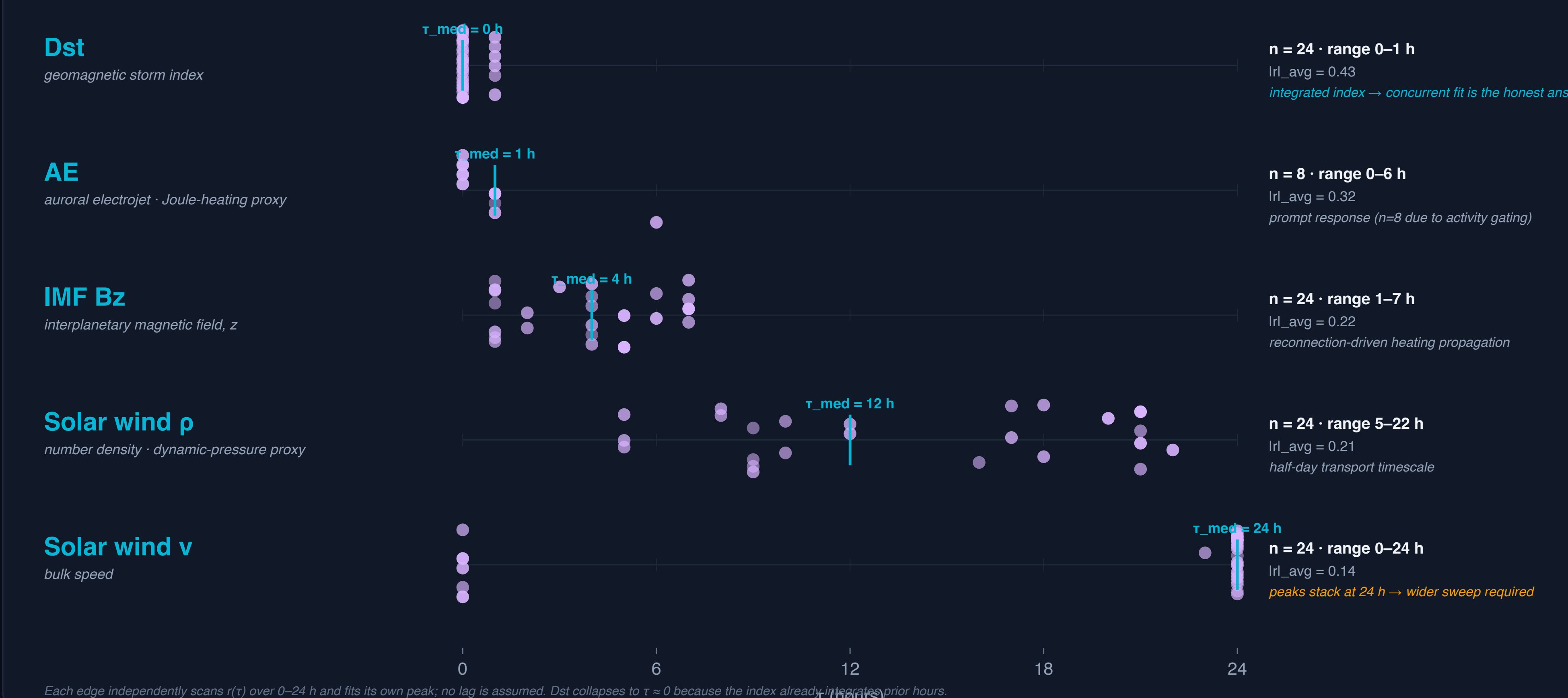
Driver attribution · GRACE-FO vs TLE baseline

DRIVER	Z_{TLE}	$Z_{GRACE-FO}$	Δ	M	EDGES
Dst <i>geomagnetic storm index</i>	0.49	0.940	+0.45	1.44	24
IMF Bz <i>interplanetary magnetic field, z</i>	0.45	0.912	+0.46	1.72	24
AE index <i>auroral electrojet · Joule-heating proxy</i>	0.39	0.949	+0.56	1.71	8
Solar wind ρ <i>number density · dynamic-pressure proxy</i>	0.20	0.937	+0.74	1.28	24
Solar wind v <i>bulk speed</i>	0.13	0.854	+0.72	1.08	24

TLE baseline certainties at top of pipeline metadata. GRACE-FO values are per-driver averages across all edges for that driver. Δ is the certainty recovered when cadence tightens from ~daily to sub-minute — the signal was there; the sampling wasn't.

PER-DRIVER LAG DISTRIBUTION

fitted τ across all 104 causal edges · 0–24 h search window · ordered by learned lag
Each edge scans τ and picks the peak of its own fit; dot opacity = fit, median marked in cyan.



Each edge independently scans $\tau(t)$ over 0–24 h and fits its own peak; no lag is assumed. Dot collapses to $\tau = 0$ because the index aligns with hours.