NASA GDC Satellites as Sensors for Thermosphere Density and Drag Research

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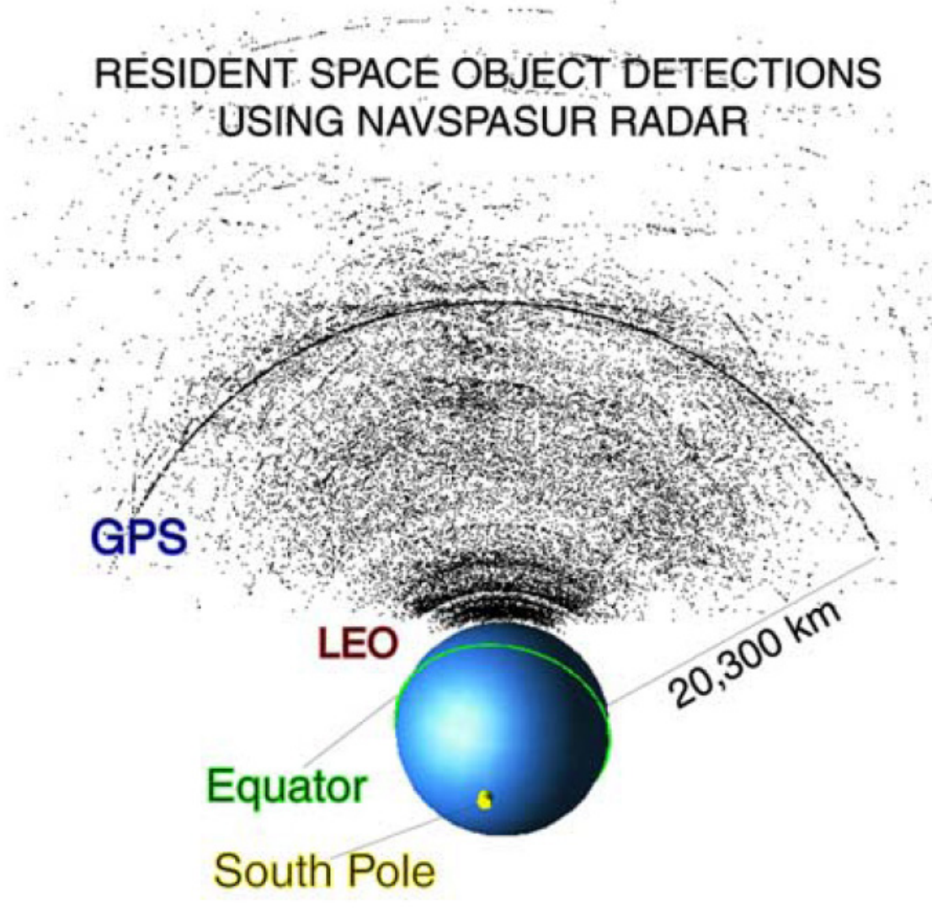
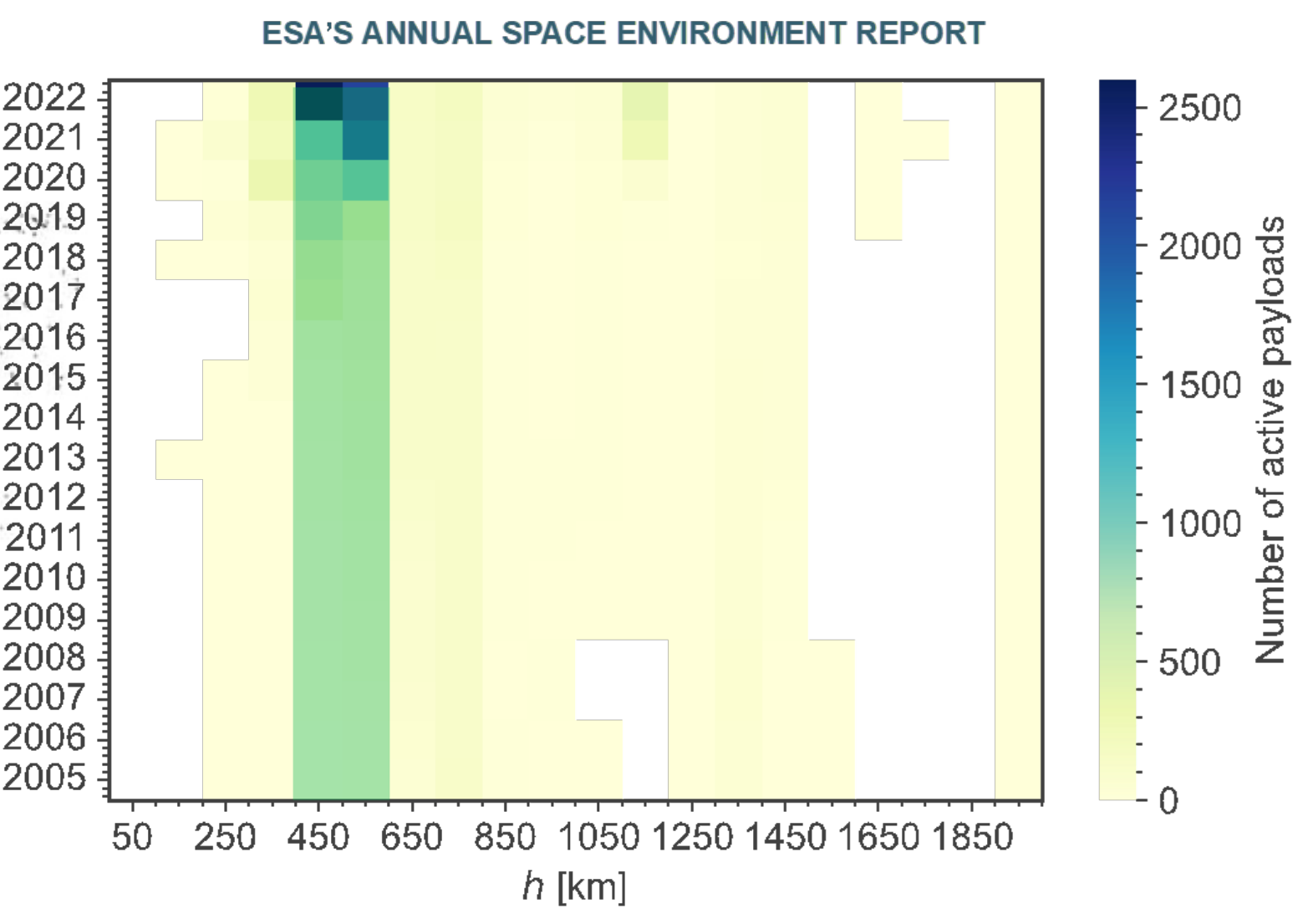
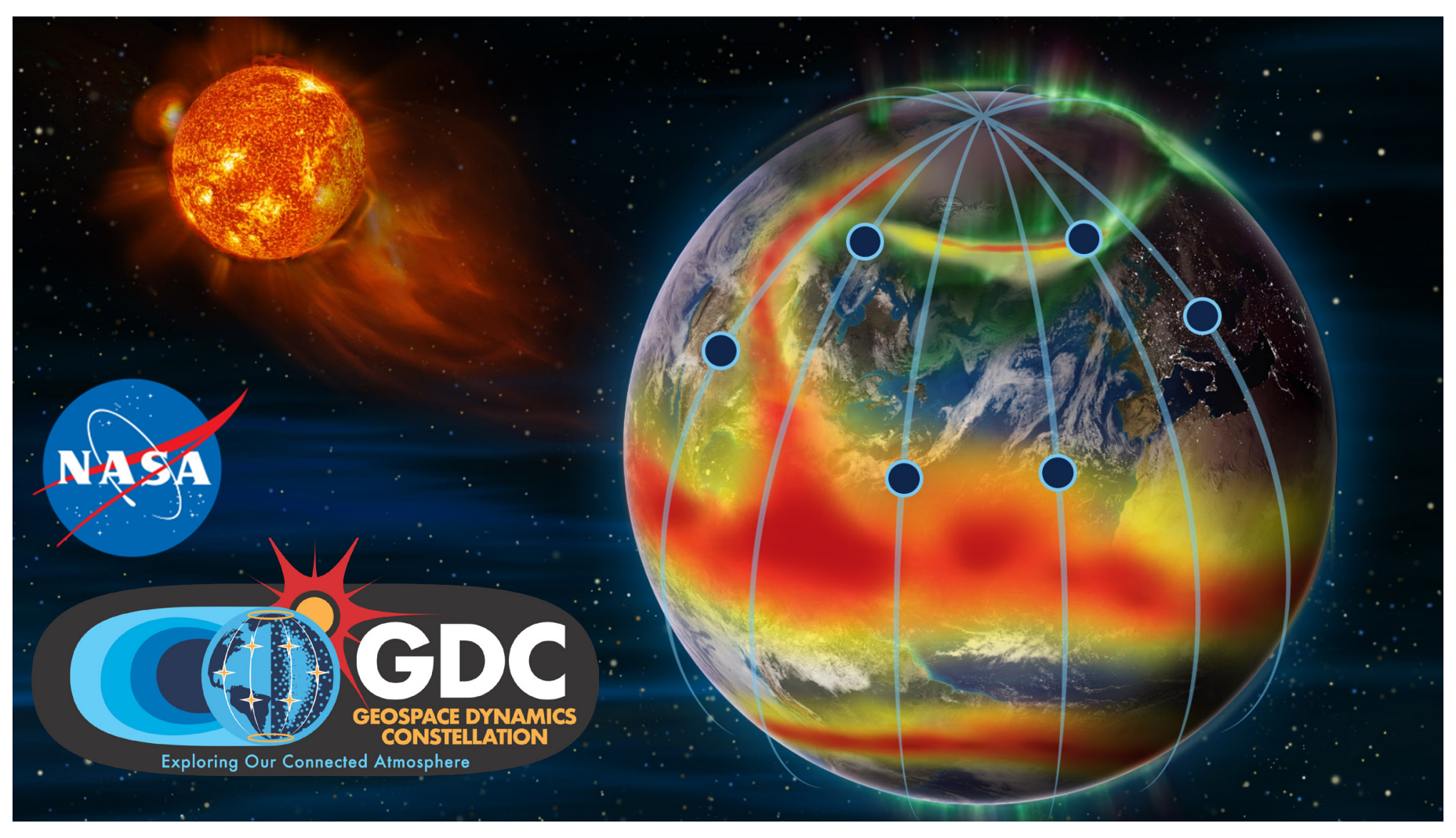
Society's Future in Space

- Societal expansion and economic growth will increasingly depend on how wisely low-earth orbit (LEO) is utilized.
- LEO space is big business with nearly $400 billion in annual revenue [1]. Furthermore, the recent shift from public to private priorities is pushing for a large-scale, largely self-sufficient space economy [2].
- LEO space environment science is lagging this rapid evolution and needs a coordinated, convergent effort to improve the fidelity of space environment forecasting to safeguard and advance operations in LEO.
- Thermospheric density variability causes the largest uncertainty in LEO drag. LEO satellite systems can be used to estimate thermospheric density globally and temporally for the betterment of space operations.



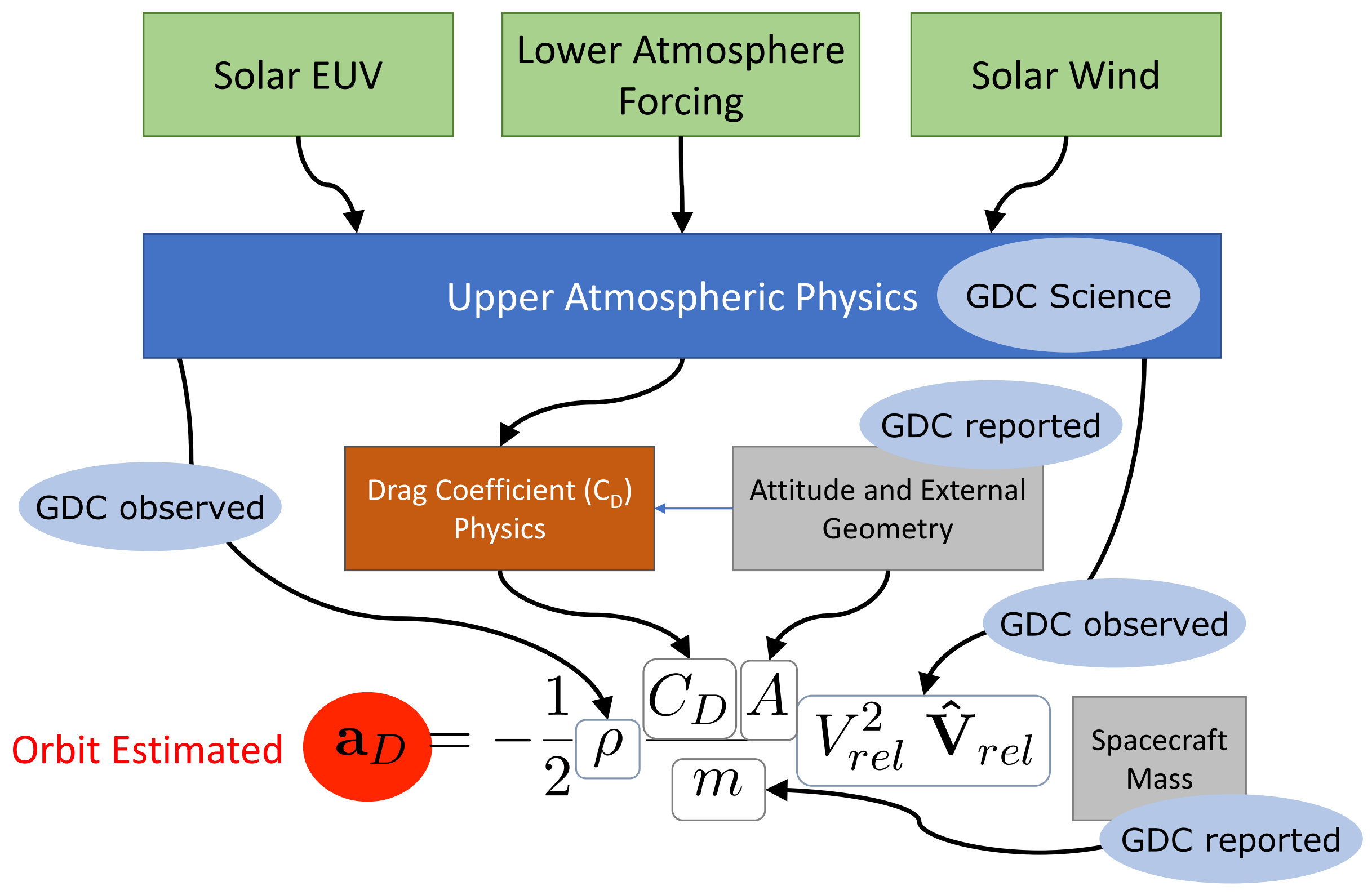


Objective: Understand LEO Environment



- **The Geospace Dynamics Constellation (GDC)** is a Decadal Survey-recommended Strategic LWS mission.
- GDC is a LEO (350-400 km, high inclination ~82 deg) constellation of satellites that will provide the first global picture of the upper atmosphere and its responses to forcing from the magnetosphere.
- Prime mission: 3 years. Carries propellant for 2 additional years. Launch expected early 2030s.
- The first global, systematic comprehensive in situ measurements in this region.
- Winds, temperature, composition, mass density, and GNSS-tracked satellite positions from all 6 spacecraft will provide unprecedented data for satellite drag research.
- Independently derived neutral density estimates from GNSS accelerometry will serve to validate the mass spectrometer (MoSAIC) throughout the mission.

LEO Spacecraft Drag Research



Solar EUV

Lower Atmosphere Forcing

Solar Wind

Upper Atmospheric Physics

GDC Science

GDC reported

GDC observed

Drag Coefficient (C_D) Physics

Attitude and External Geometry

GDC observed

Orbit Estimated

$$\mathbf{a}_D = -\frac{1}{2}\rho \frac{C_D A}{m} V_{rel}^2 \hat{\mathbf{V}}_{rel}$$

Spacecraft Mass

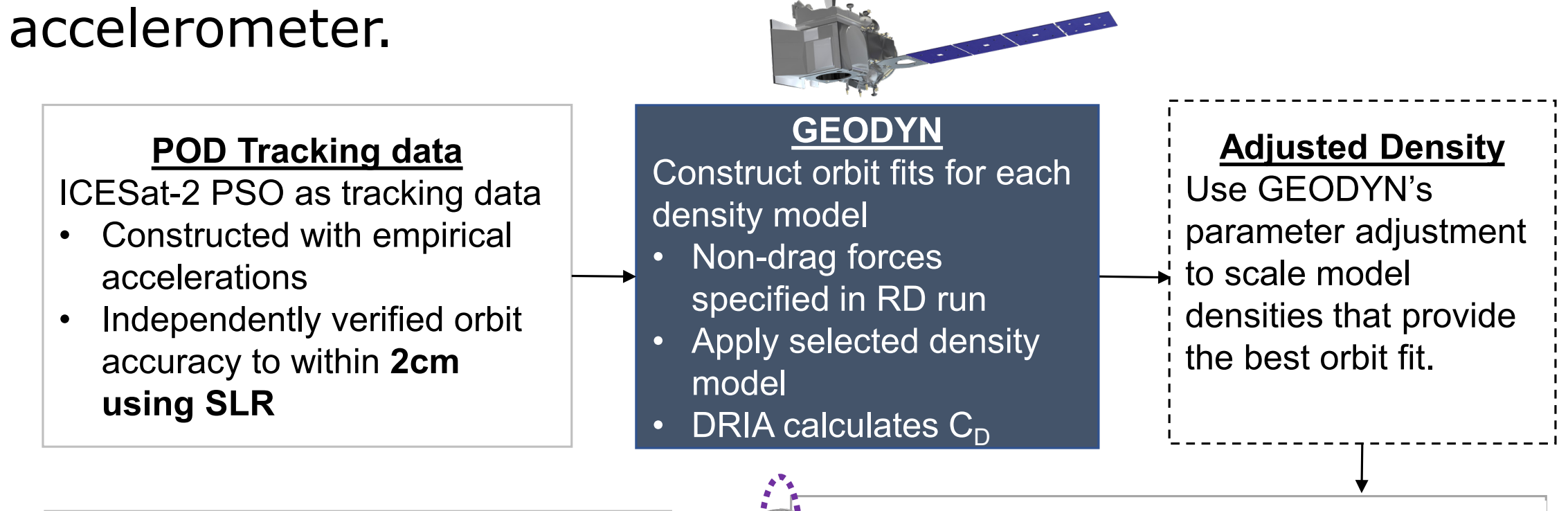
GDC reported

Drag accelerations provided by GNSS-derived orbital parameters can be used to extract mass density estimates along a GDC satellite orbit. Two methods are described below.

1. POD-Accelerometry: estimating density through model corrections as part of the POD scheme.
2. EDR: estimating density from orbital energy dissipation rate (EDR) calculations using post-processed position and velocity information.

POD Accelerometry Example

A Mass density-retrieval scheme has been developed using POD accelerometry by implementing a high-fidelity sophisticated orbital dynamics model (GEODYN-II) and a geodesy spacecraft (ICESat-2) with well-defined precise science orbits (PSO) [3]. The results are compared to the GRACE-FO mass density estimates from an electrostatic accelerometer.

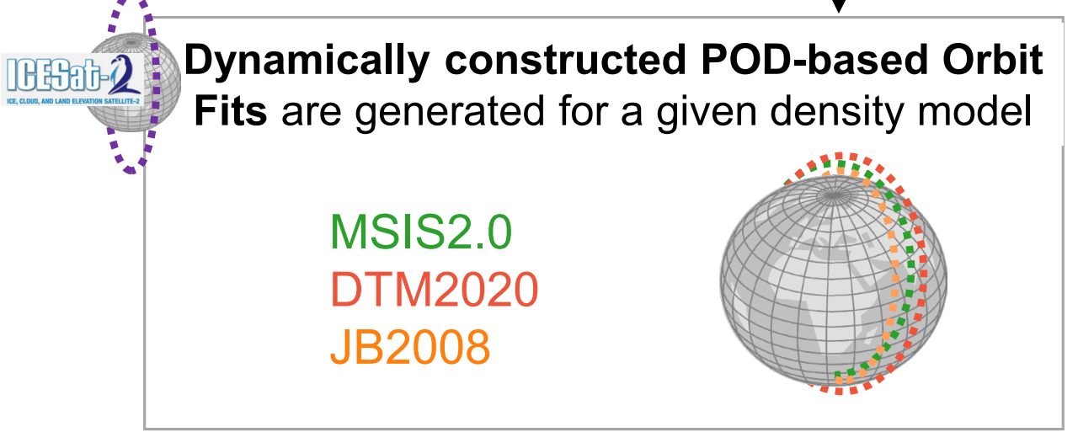


POD Tracking data
ICESat-2 PSO as tracking data
- Constructed with empirical accelerations
- Independently verified orbit accuracy to within **2cm using SLR**

GEODYN
Construct orbit fits for each density model
- Non-drag forces specified in RD run
- Apply selected density model
- DRIA calculates C_D

Adjusted Density
Use GEODYN's parameter adjustment to scale model densities that provide the best orbit fit.

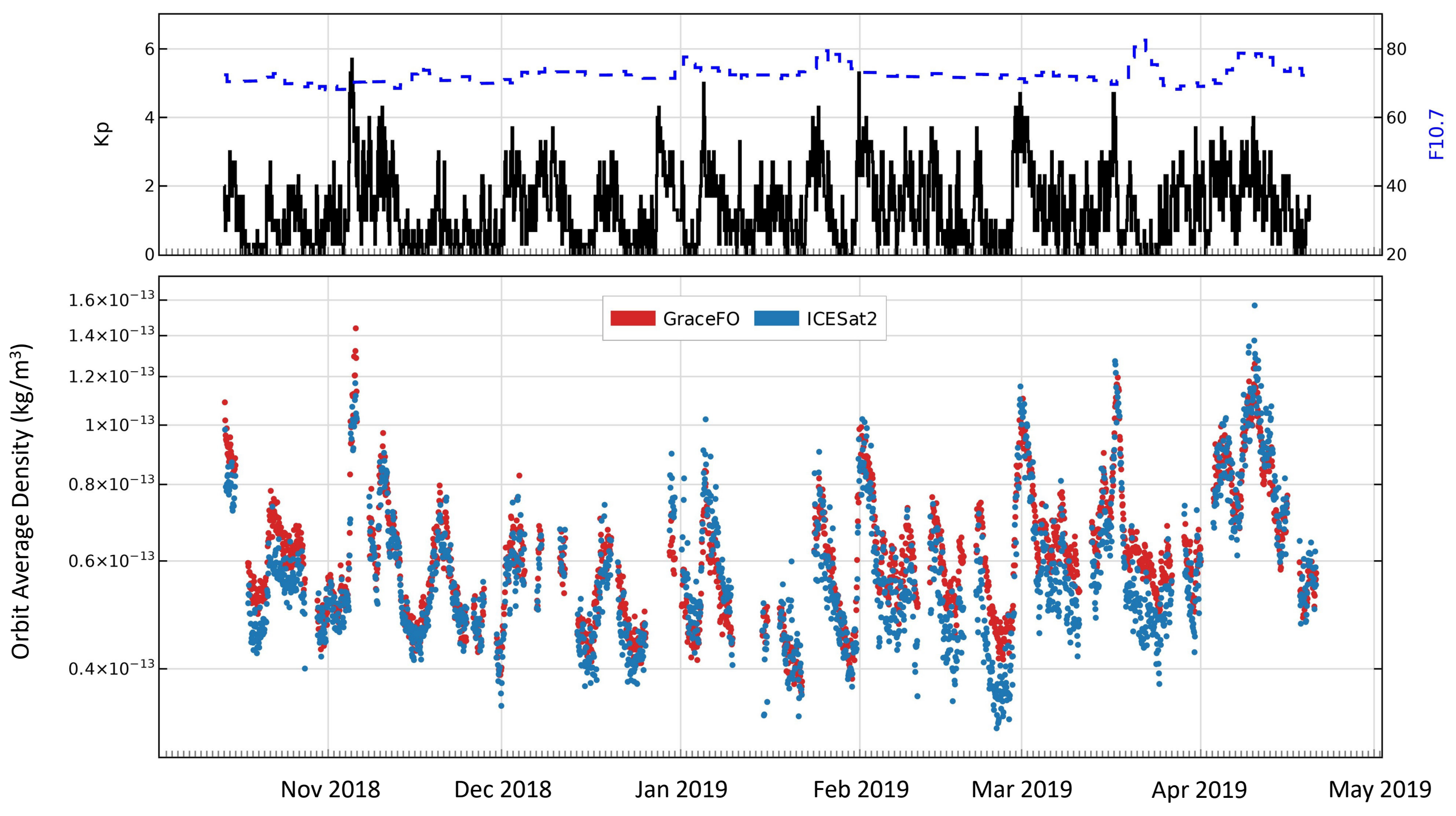
ICESat-2 Precise Science Orbit	
Altitude	$z = 496\ km$
Inclination	$i = 92°$
Eccentricity	$e = 0.001398$
Period	$P = 94.22\ mins$



Dynamically constructed POD-based Orbit Fits are generated for a given density model

MSIS2.0
DTM2020
JB2008

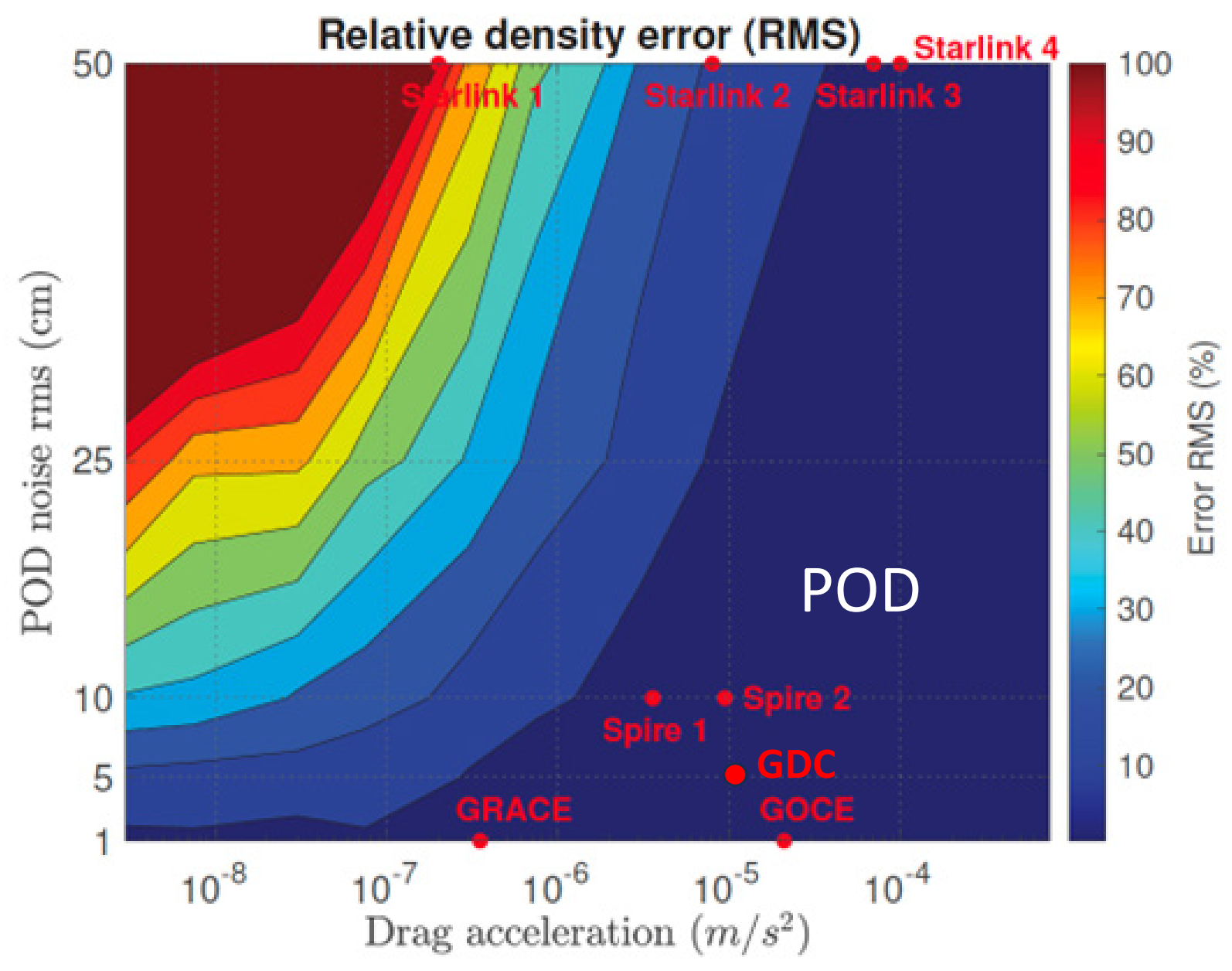
- A scaling factor is determined every 3 hours using a batch least squares fit to the precise science orbits.
- Modeled mass density estimates are adjusted by the determined scaling factor.
- The ensemble weighted average of the scaled densities is the estimated mass density extraction.



Orbit-averaged, mass-density estimates using POD accelerometry from ICESat-2 compares well with GRACE-FO mass-density estimates from electrostatic accelerometers. RMS differences better than 10%.

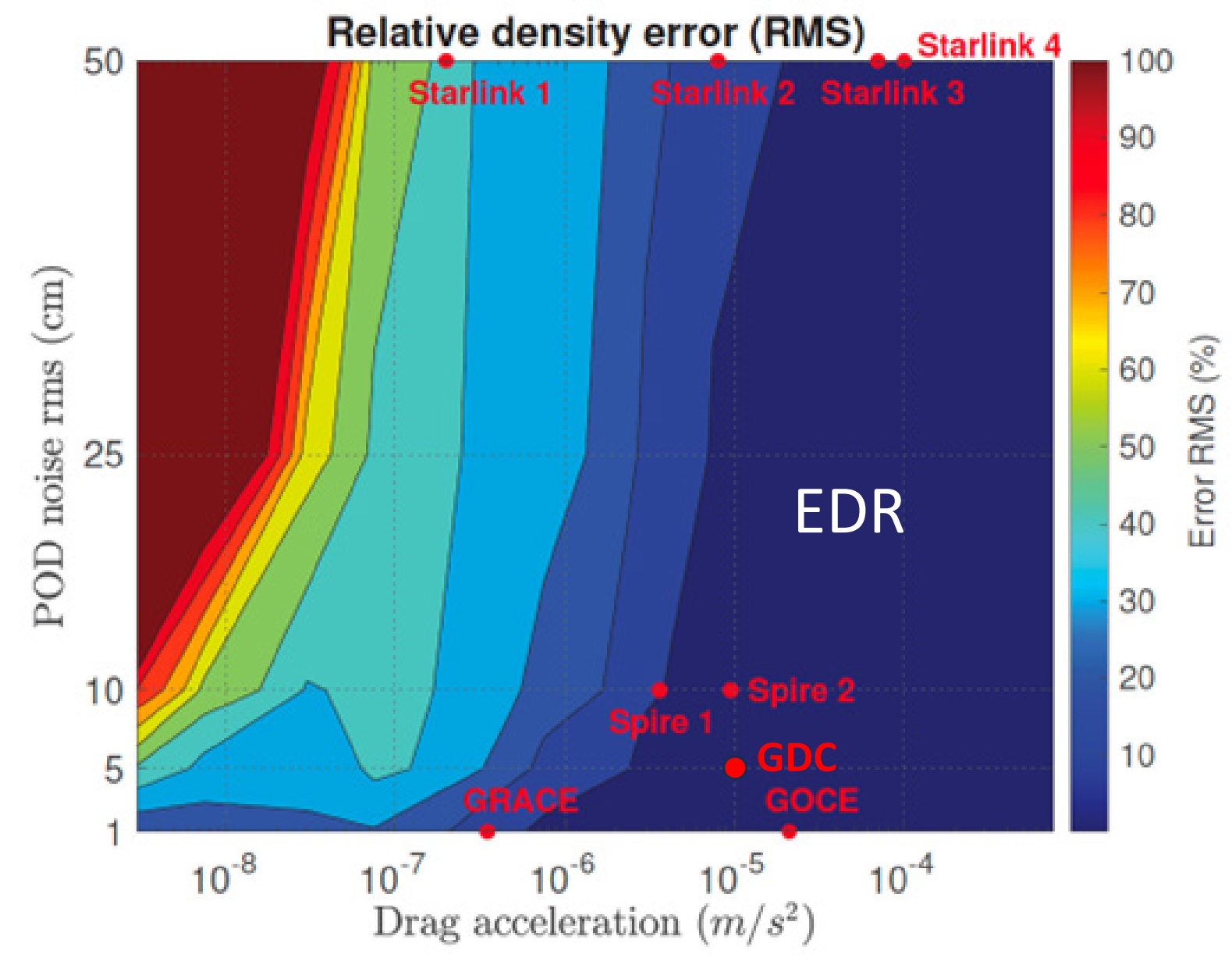
POD Accelerometry and EDR Simulations

Model simulations of RMS density error for varying drag regimes and POD noise levels using (a) POD accelerometry and (b) EDR methods [4]. The arc-length of the EDR method is chosen for each altitude such that the error RMS is minimized. The color scale is capped at 100%.



POD-Accel

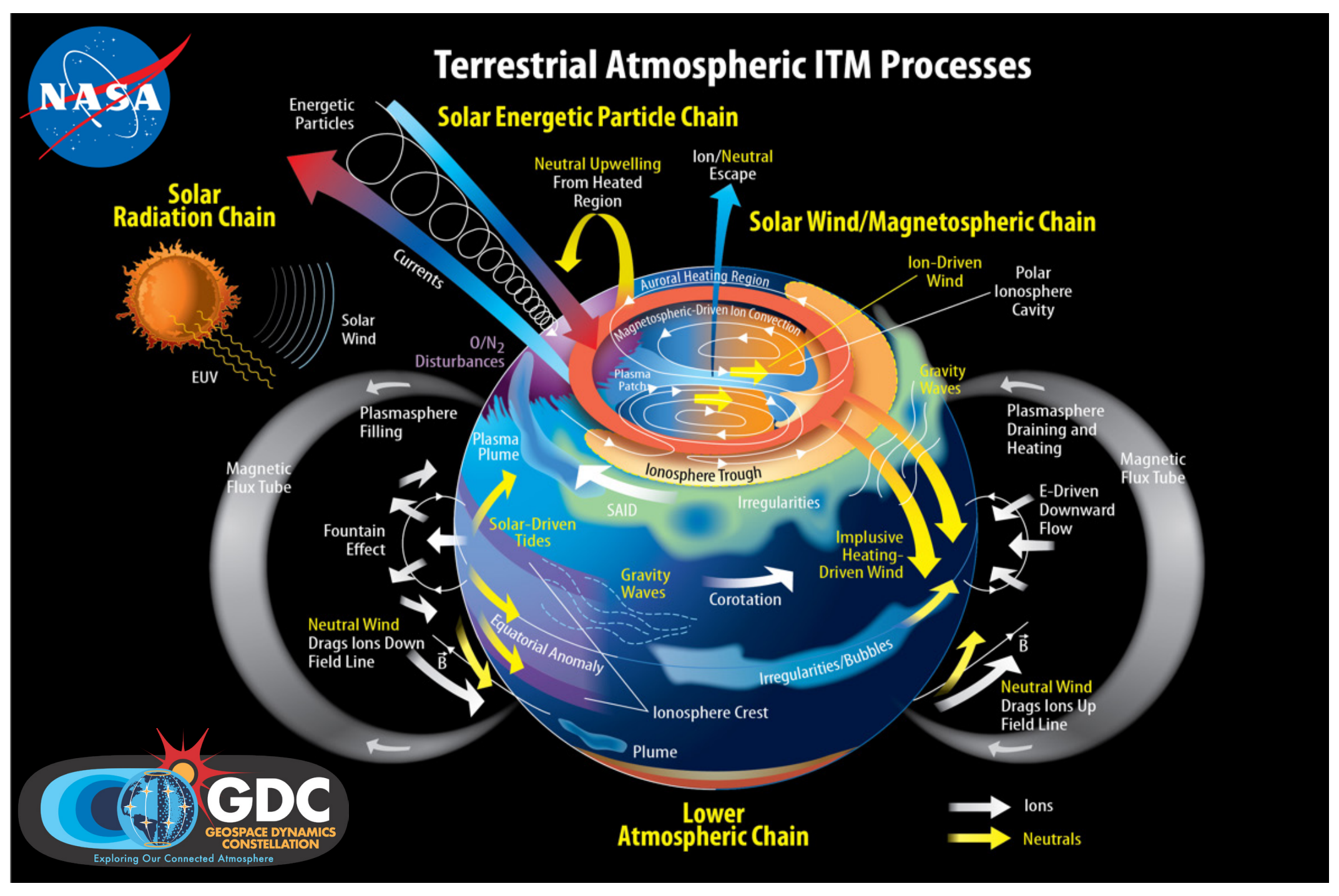
- Very low sensitivity to measurement noise.
- Beneficial for high-cadence, high accuracy retrieval of a density time-series.
- Requires calibration of tuning parameters for the orbital regime and space weather conditions.



EDR

- Computationally fast but susceptible to error sources.
- In high-drag environments (altitudes <500km – like GDC satellites), comparable to POD accelerometry.
- At higher altitudes (or lower drag accelerations), still suitable method but larger arc lengths.

Space Weather in the GDC Era



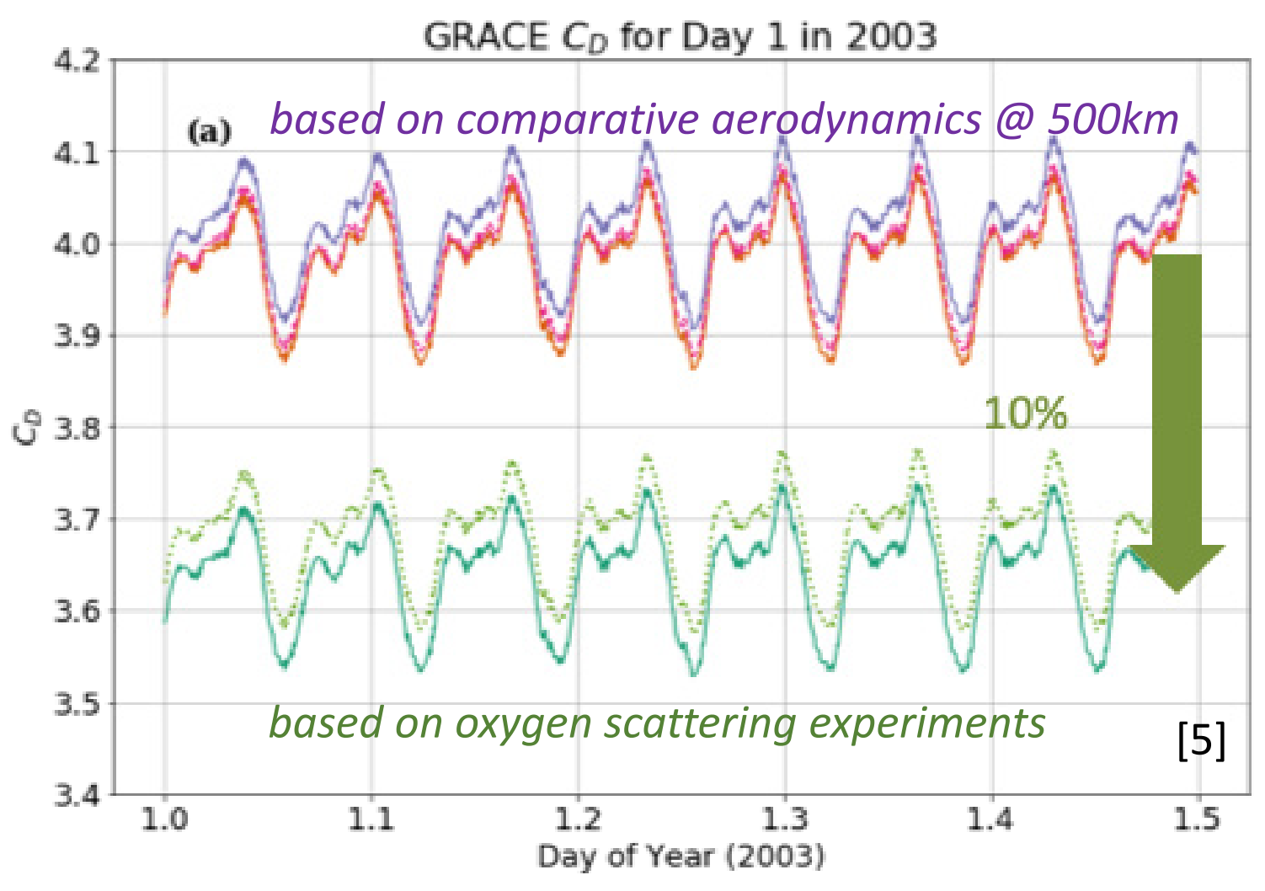
Goal 1: High latitude response to magnetospheric forcing.

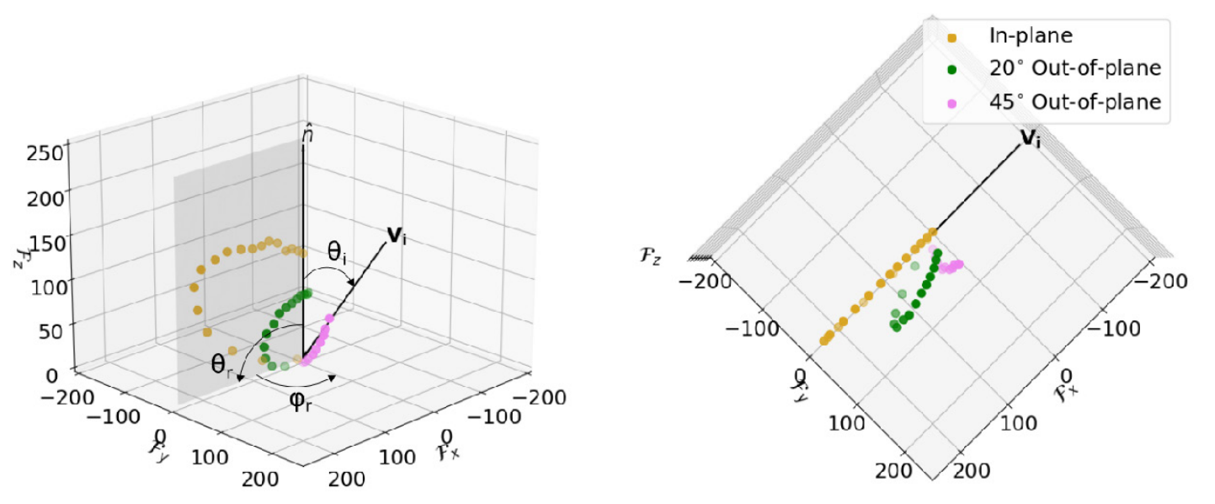
Goal 2: Internal processes that globally redistribute mass, momentum, and energy.

- Space weather predictions will involve a combination of data and physics-based models via data assimilation.
- The GDC mission will provide unprecedented coverage and data products that will rapidly accelerate space weather predictions.
- The GDC mission plans to provide a real-time data feed of primary properties to update predictions on a regular basis.

Drag Coefficient Research

Challenges in Drag Coefficient Research
- Quantification of helium scattering
- Out-of-plane scattering
  - Collection of experimental data
  - Scattering model development
- Surface roughness effects
  - ○ Laboratory experiments with various stages of Kapton erosion
- Adsorption effects
  - ○ Experiments that control for adsorbate (difficult)





In-plane and out-of-plane relative flux for a Teflon surface with an incident beam angle of 60°. The "in-plane" scattering plane is shaded grey. **Most drag-coefficient GSI models do not include out of plane scattering**.

Requirements:
- GPS and attitude measurement
  - fidelity and cadence, antenna positioning and orientation
- Satellite geometry information and surface properties
- Satellite mass and maneuver information
- MoSAIC mass spectrometer providing full definition of free-stream properties (Temperature, Wind, and Composition)

Conclusions

- NASA GDC mission is expected to provide thermosphere-ionosphere properties, geomagnetic drivers, satellite details, and high-fidelity GNSS-POD solutions to enable, for the first-time, a **direct** means to study the full effects of atmospheric drag on LEO satellites.
- The GDC satellites will be well-equipped to evaluate gas-surface interactions and drag coefficient physics.
- Many existing and future LEO satellites include GNSS receivers. Thus, the density-retrieval capability and associated GDC research can have wide-ranging impact on safeguarding LEO operations of the future.

Acknowledgements

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References:

[1] Space Foundation, (2018), The Space Report, available at: https://www.thespacereport.org .

[2] Weinzierl, M. (2018), Space, the Final Economic Frontier, Journal of Economic Perspectives, volume 32, no. 2, pp. 173–192.

[3] Waldron, Z. C., Garcia-Sage, K., Thayer, J. P., Sutton, E. K., Ray, V., Rowlands, D. D., et al. (2024). Assessing Thermospheric Neutral Density Models Using GEODYN's Precision Orbit Determination. Space Weather, 22(2), e2023SW003603. https://doi.org/10.1029/2023SW003603.

[4] Error analysis of thermospheric mass density retrieval methods using Precision Orbit Determination (POD) by Ray, V., J. P. Thayer, E. K. Sutton, and Z. C. Waldron, submitted to space weather journal, May 2023.

[5] Bernstein, V., & Pilinski, M. (2022). Drag coefficient constraints for space weather observations in the upper thermosphere. Space Weather, 20, e2021SW002977. https://doi.org/10.1029/2021SW002977

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