Sources of Uncertainty in Atmospheric Drag: The Drag Coefficient

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Abstract

Atmospheric drag describes the main perturbing force of the atmosphere on the orbital trajectories of near-Earth orbiting satellites. The ability to accurately model atmospheric drag is critical for precise satellite orbit determination and collision avoidance. Assuming we know atmospheric winds and satellite velocity, area and mass, the primary sources of uncertainty in atmospheric drag include mass density of the space environment and the spacecraft drag coefficient, CD. Historically, much of the focus has been on physically or empirically estimating mass density, while CD is treated as a fitting parameter or fixed value. Presently, CD can be physically modeled through energy and momentum exchange processes between the atmospheric gas particles and the satellite surface. However, physical CD models rely on assumptions regarding the scattering and adsorption of atmospheric particles, and these responses are driven by atmospheric composition and temperature. Modifications to these assumptions can cause CD to change by up to ˜40%. The nature and magnitude of these changes also depend on the shape of the spacecraft. We can check the consistency of the CD model assumptions by comparing densities derived from satellite drag measurements and computed CD values for satellites of different shapes orbiting in the same space environment. Since all of the satellites should see the same density, offsets in the derived densities should be attributable to inconsistencies in the CD model. Adjusting the CD model scattering assumptions can improve derived density consistency among the different satellites and inform the physics behind CD modeling. In turn, these efforts will help to reduce uncertainty in CD, leading to improved atmospheric drag estimates.

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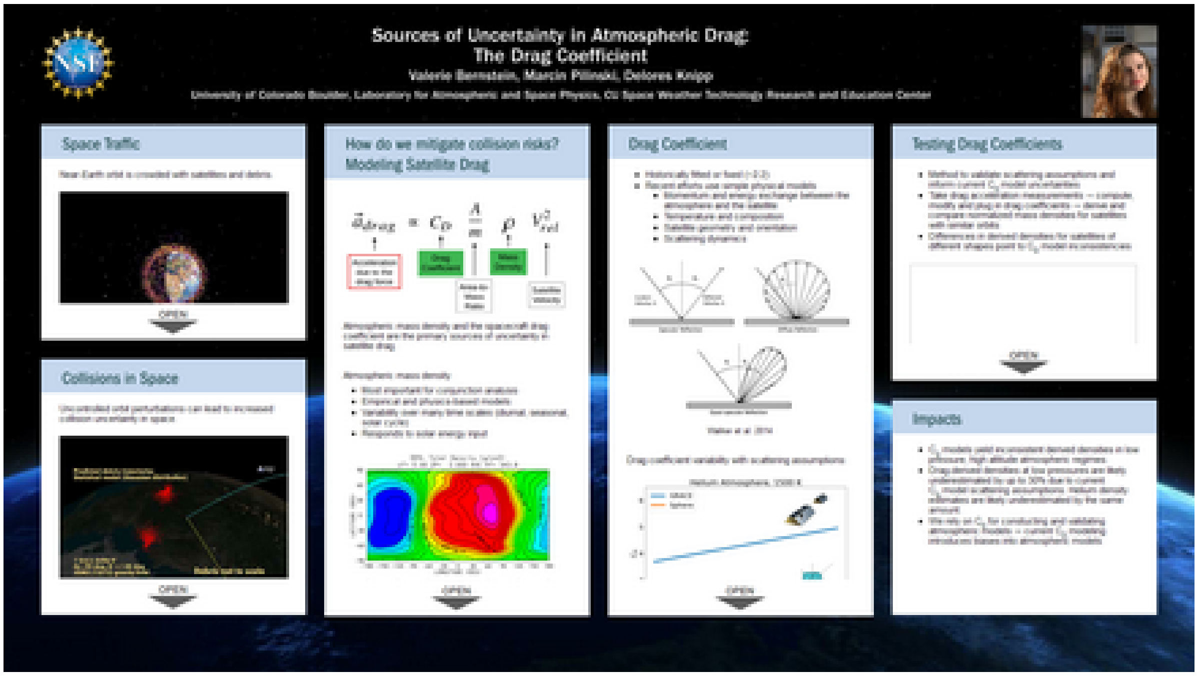

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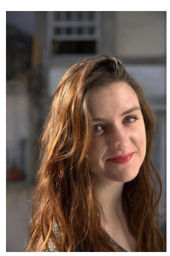


PRESENTED AT:

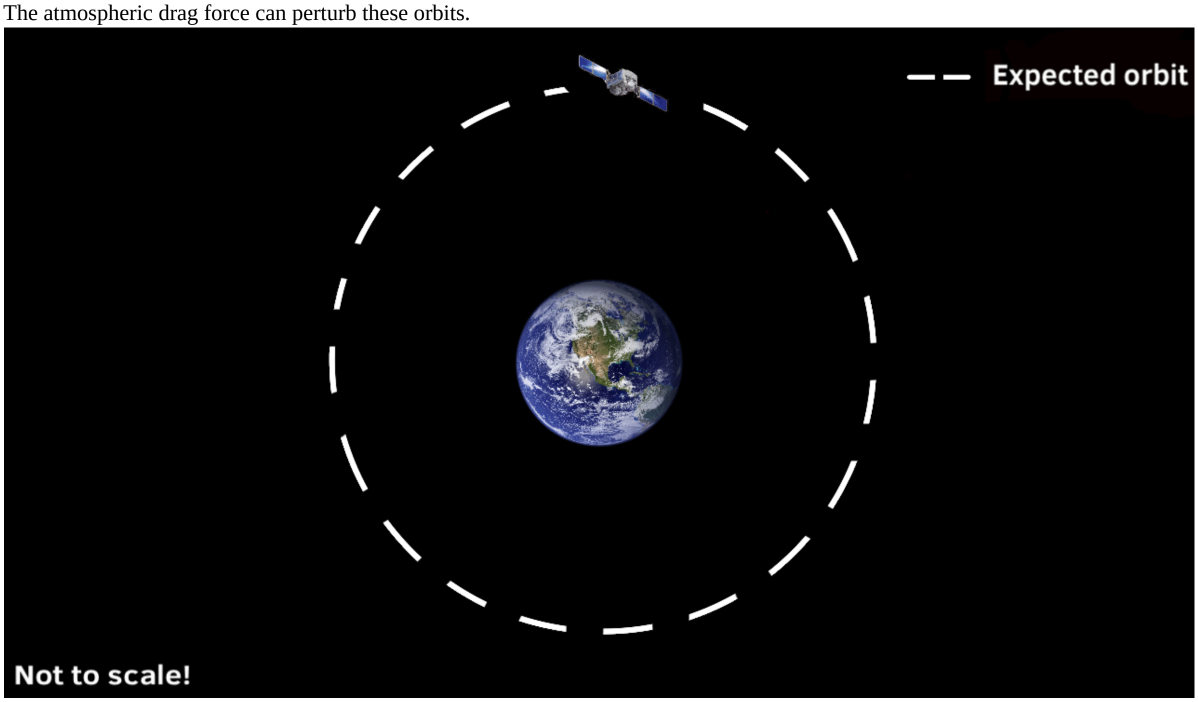
SPACE TRAFFIC

Near-Earth orbit is crowded with satellites and debris.

[VIDEO] https://www.youtube.com/embed/O64KM4GuRPk?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0
Video credit: Dr. Stuart Grey at University College London

- 1,700+ operational satellites
- 19,400+ debris objects larger that 10 cm orbiting Earth
- 0.5 million debris objects between 1 and 10 cm

The atmospheric drag force can perturb these orbits.



COLLISIONS IN SPACE

Uncontrolled orbit perturbations can lead to increased collision uncertainty in space.

[VIDEO] https://www.youtube.com/embed/_o7EKlqCE20?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0

- In 2009, Iridium 33 and Cosmos 2251 unexpectedly collided at 12 km/s at 800 km altitude
- Collision generated 2100+ debris objects in space
- The number of orbital debris objects is increasing fast

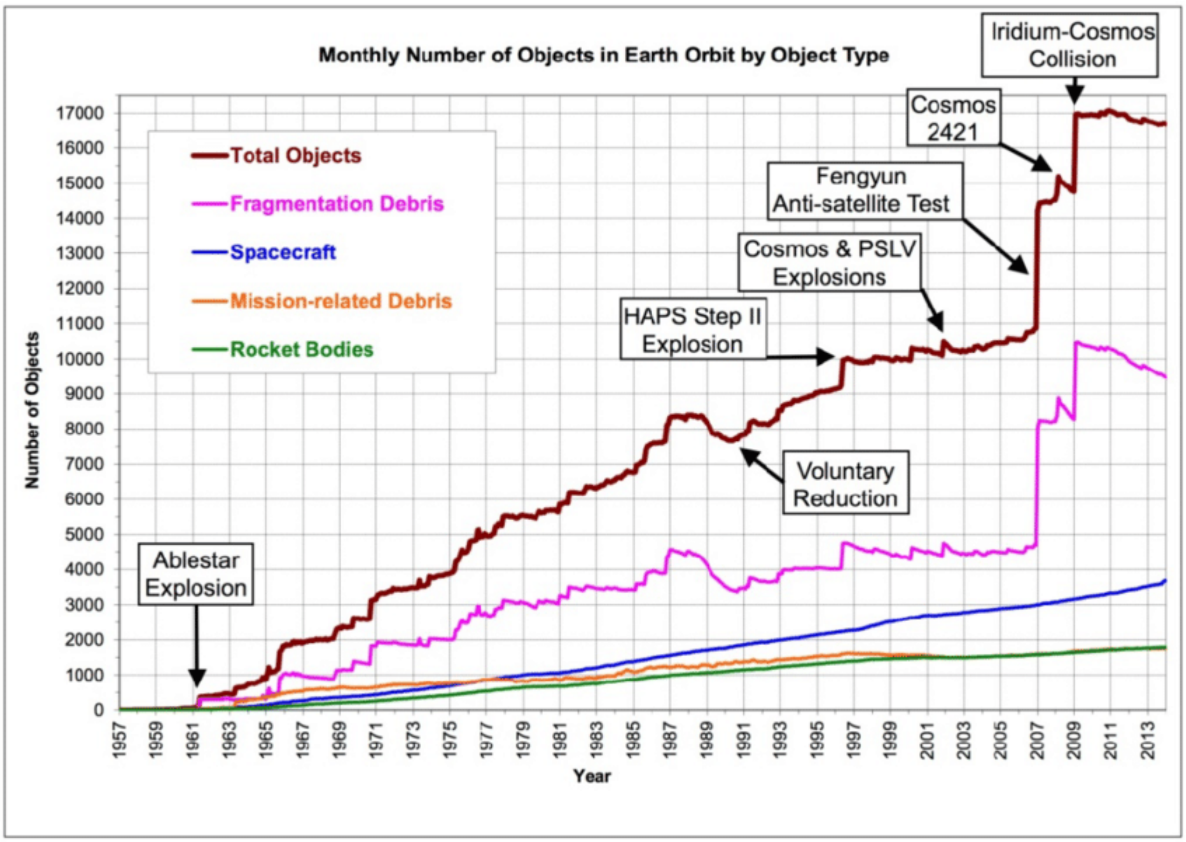


Image credit: NASA Orbital Debris Program (2014), annotated by Mika McKinnon

HOW DO WE MITIGATE COLLISION RISKS?
MODELING SATELLITE DRAG

$$\vec{a}_{drag} \propto C_D \frac{A}{m} \rho V_{rel}^2$$

Acceleration due to the drag force

Drag Coefficient

Area-to-Mass Ratio

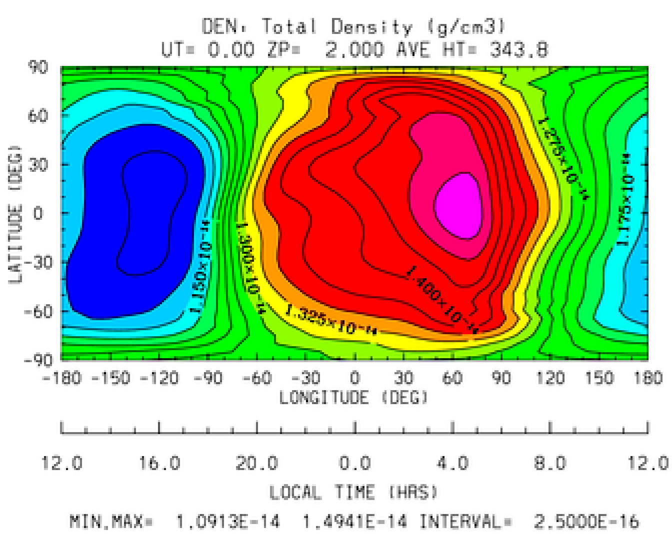
Mass Density

Satellite Velocity

Atmospheric mass density and the spacecraft drag coefficient are the primary sources of uncertainty in satellite drag.

Atmospheric mass density

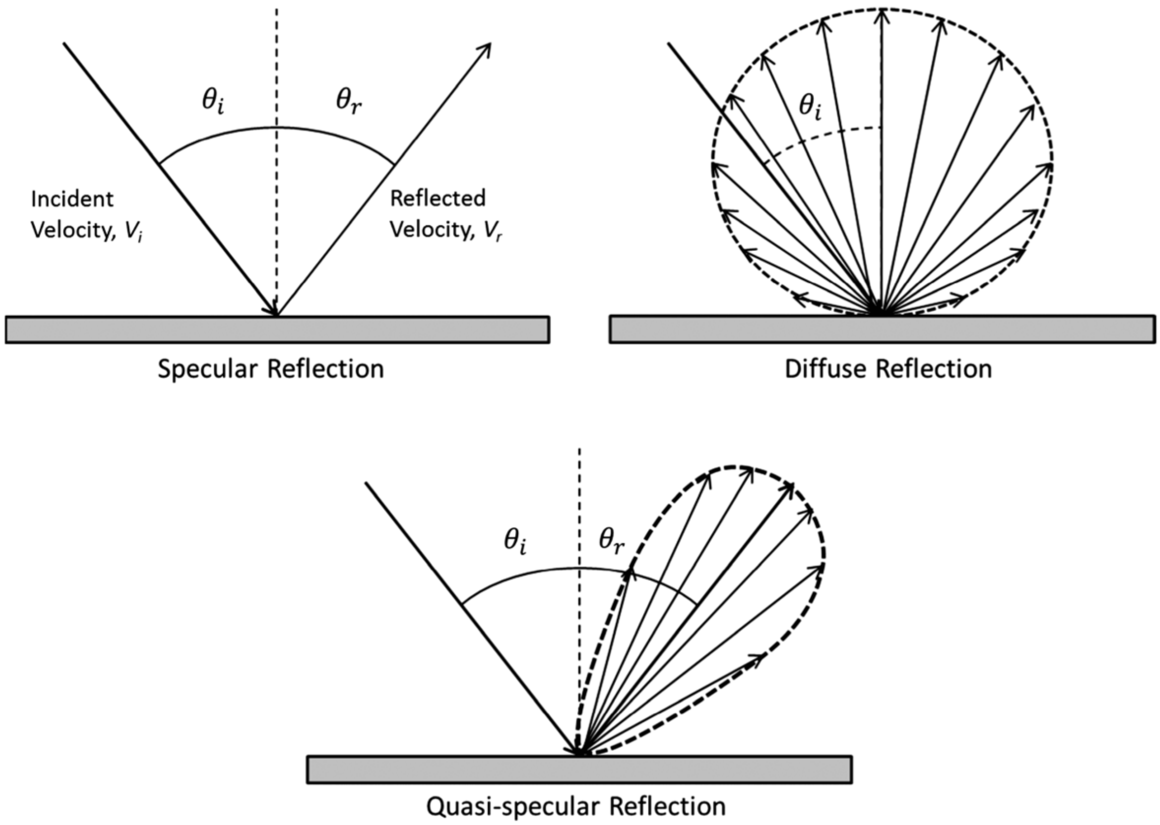
- Most important for conjunction analysis
- Empirical and physics-based models
- Variability over many time scales (diurnal, seasonal, solar cycle)
- Responds to solar energy input



TIE-GCM model density - a global map at 344 km

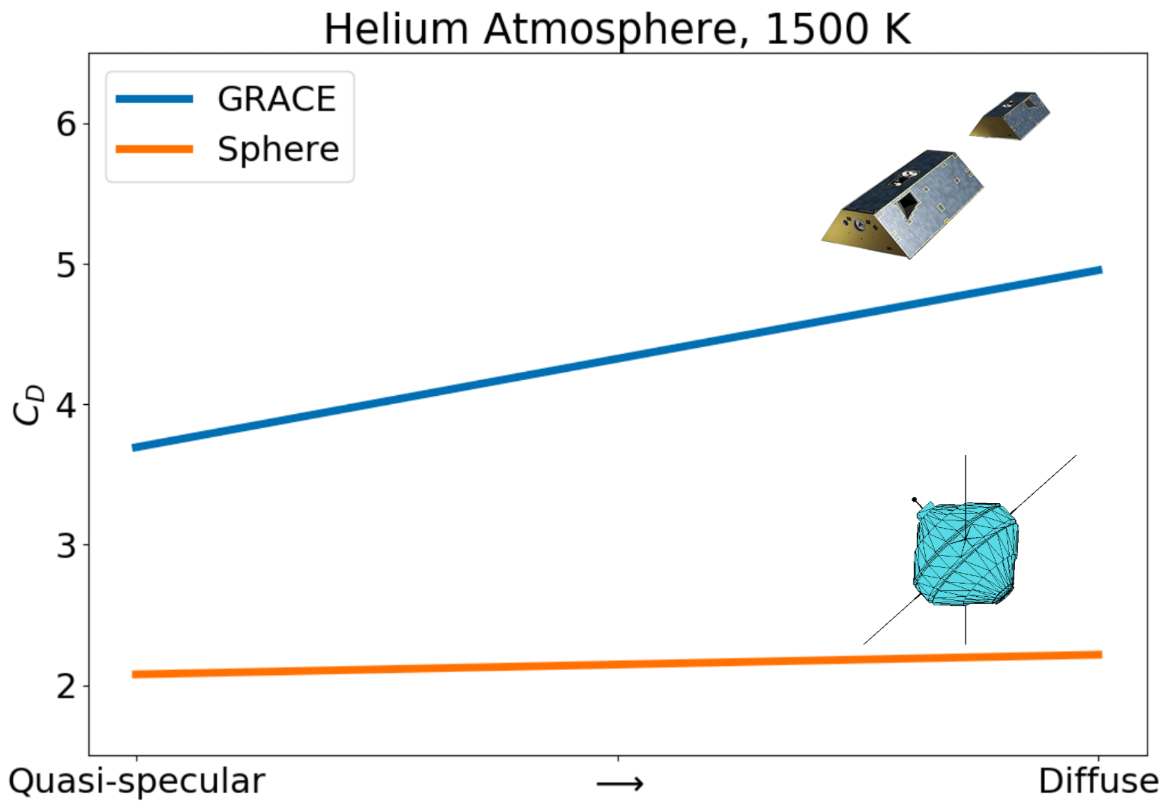
DRAG COEFFICIENT

- Historically fitted or fixed (~2.2)
- Recent efforts use simple physical models
  - Momentum and energy exchange between the atmosphere and the satellite
  - Temperature and composition
  - Satellite geometry and orientation
  - Scattering dynamics



Walker et al. 2014

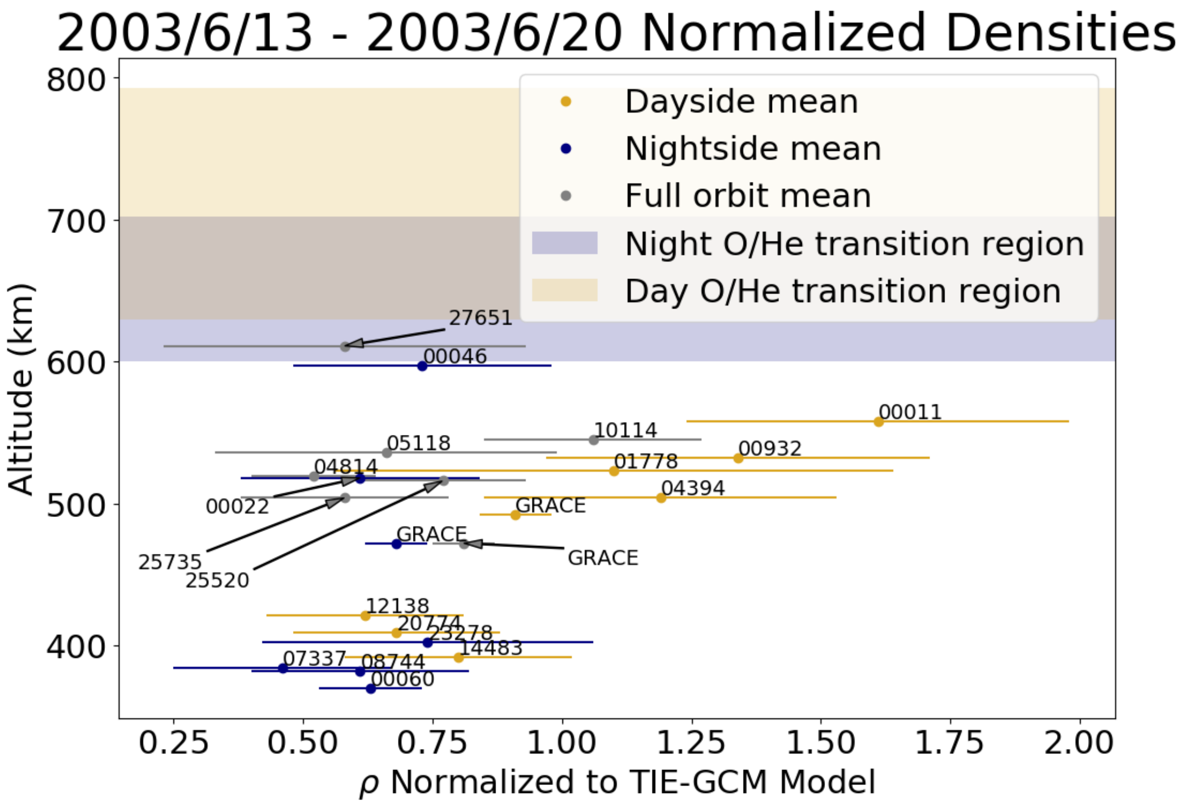
Drag coefficient variability with scattering assumptions:



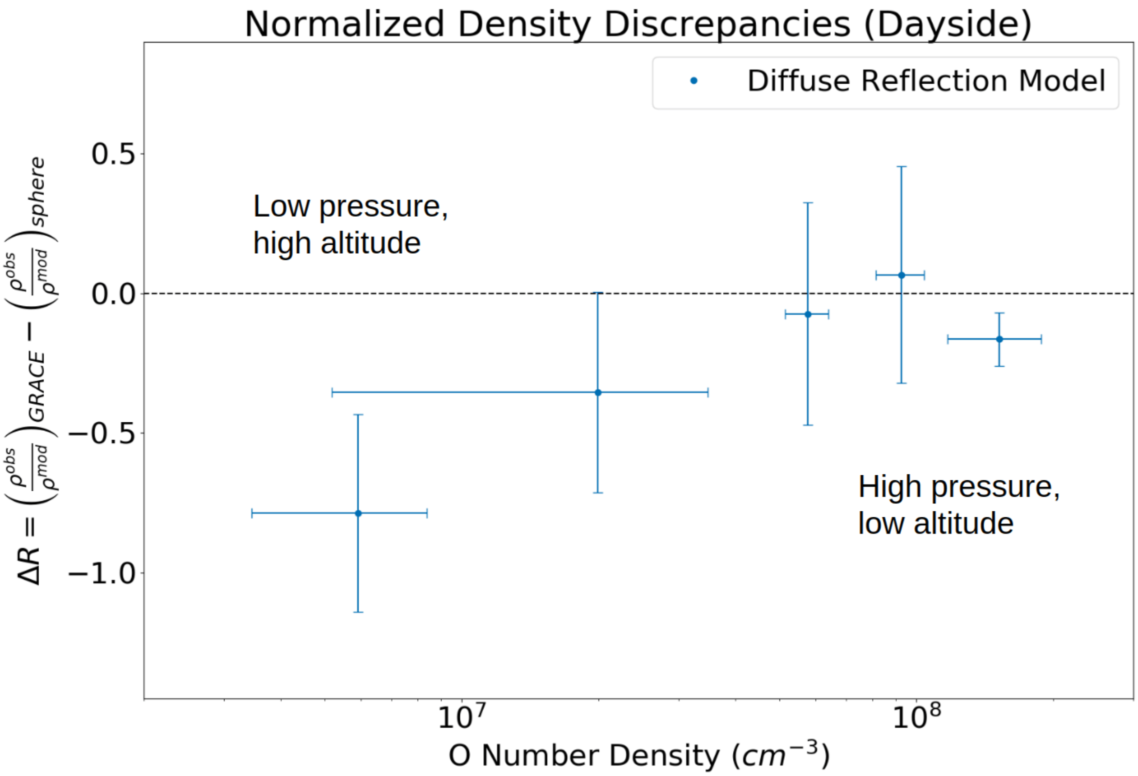
Helium Atmosphere, 1500 K
GRACE
Sphere
C_D
6
5
4
3
2
Quasi-specular
⟶
Diffuse

TESTING DRAG COEFFICIENTS

- Method to validate scattering assumptions and inform current C_D model uncertainties
- Take drag acceleration measurements → compute, modify and plug in drag coefficients → derive and compare normalized mass densities for satellites with similar orbits
- Differences in derived densities for satellites of different shapes point to C_D model inconsistencies



- Mean normalized densities for our selected satellites with similar orbits are shown above, spatially organized by their perigee altitudes
- At higher altitudes, derived densities at dayside local times are more inconsistent than nightside densities



- Largest density ratio discrepancies at the dayside low pressure, high altitude atmospheres
- Modeling C_D with diffuse reflection is inappropriate in this regime → quasi-specular would be a better choice

IMPACTS

- C_D models yield inconsistent derived densities in low pressure, high altitude atmospheric regimes.
- Drag-derived densities at low pressures are likely underestimated by up to 30% due to current C_D model scattering assumptions. Helium density estimates are likely underestimated by the same amount.
- We rely on C_D for constucting and validating atmospheric models ⇾ current C_D modeling introduces biases into atmospheric models

Sorry but time is up!