Investigating Atmospheric Drag Coefficient Composition Sensitivities

How Densities Derived from Satellite Drag are Affected by Composition and Drag Coefficient Models

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Introduction

- Atmospheric drag, the main perturbing force on LEO satellites, depends on the spacecraft drag coefficient C_D, mass density ρ, wind, and velocity assuming mass and area are known
- C_D depends on atmospheric composition and temperature and can be modeled physically with gas-surface interaction models. C_D for compact shapes (sphere, cylinder) can be modeled analytically, while complex shapes (GRACE satellite) require other methods such as Gaussian fitting with CLL scattering assumptions[3,8].
- The Cercignani-Lampis-Lord (CLL)[1] C_D model assumes:
  1. **Quasi-specular reflection**. This informs the energy and momentum accommodation coefficient model parameters.
  2. **Adsorption** of atomic oxygen is described by the Langmuir isotherm $\theta = \frac{K_L P_O}{1+K_L P_O}$ [6,7]. This provides a weighting factor for clean-surface and oxygen-covered C_D, making C_D highly sensitive to atomic oxygen concentration.

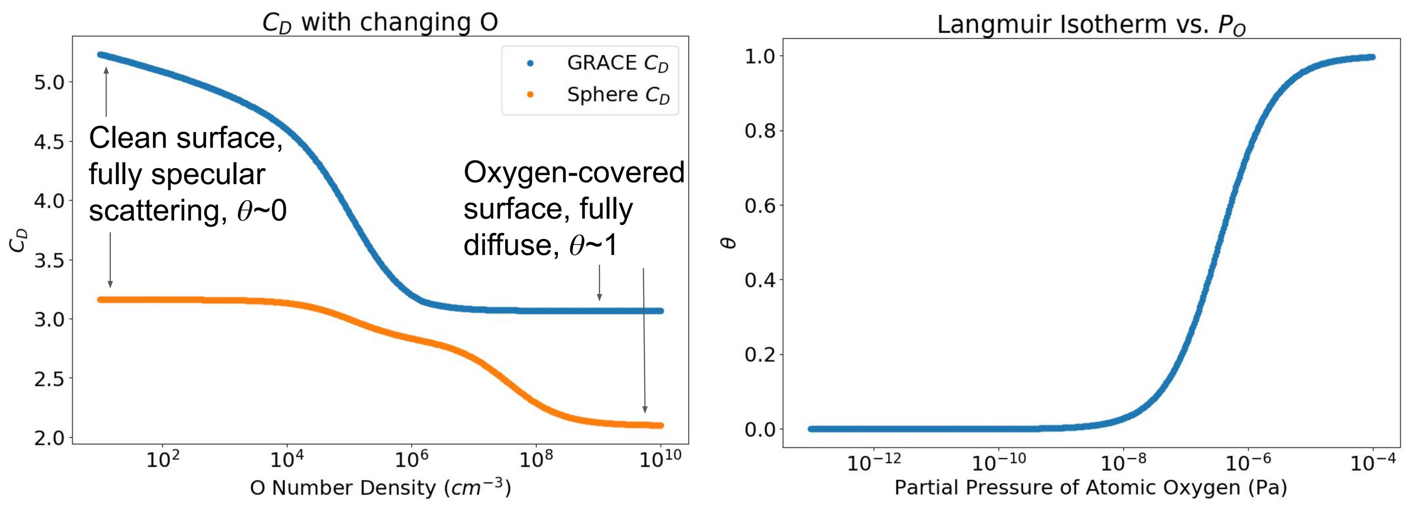

Fig. 1: C_D (left) and the Langmuir isotherm surface coverage (right) sensitivity to atomic oxygen. C_D is a function of θ.

- Due to its complex shape, GRACE should be sensitive to the CLL drag coefficient parameters in different ways than compact satellites. This will contribute to measured density offsets for satellites of different geometries.
- Previous work has analyzed measured-to-modeled density ratio offsets using C_D= 2.2/3.5 for compact/long satellites to show that the density offsets arise from C_D uncertainty[2,4]. Our study expands on this approach to include high-accuracy GRACE accelerometer-derived densities, more compact satellites to average out *A/m* errors, and both specular and diffuse-like scattering cases.

Method

In this study, 8 compact objects with periapses within a scale height of GRACE were selected for comparison and sensitivity analysis. We computed drag coefficients and effective densities for 3 one-week time periods in 2003. Effective density is the mass density weighted by drag along a satellite's orbit, and will be referred to as simply density for the remainder of this presentation.

1. Compute observational densities[5]. For compact satellites, observations come from Two-Line-Element (TLE) tracking data; for GRACE, we use accelerometer-derived densities that have been revised with CLL drag coefficients.

$$\rho_A(t_{ik}) = \frac{\frac{2}{3}\mu^{2/3}(n_M(t_{ik}))^{-1/3}(n_M(t_k) - n_M(t_i))}{\int_{t_i,t_k} C_D \frac{A}{m} v^3 F dt}$$

2. Compute atmospheric model-dependent densities[5] using the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM)

$$\rho_{TIE}(t_{ik}) = \frac{\int_{t_i,t_k} \rho_M v^3 F dt}{\int_{t_i,t_k} v^3 F dt}$$

3. Compute, compare, and tune density ratios to check for consistency between GRACE and compact satellites. Evaluate to what extent the differences are due to drag coefficients.

ID	Name	A/m	ID	Name	A/m
00011	Vanguard 2	0.01877	23606	Cerise	0.0171
00022	Explorer 7	0.01040	25520	PAN SAT	0.0034
01778	A-1 Asterix	0.0059	25735	Terriers	0.00628
04382	DFH-1	0.00454	27651	SORCE	0.003617

Results

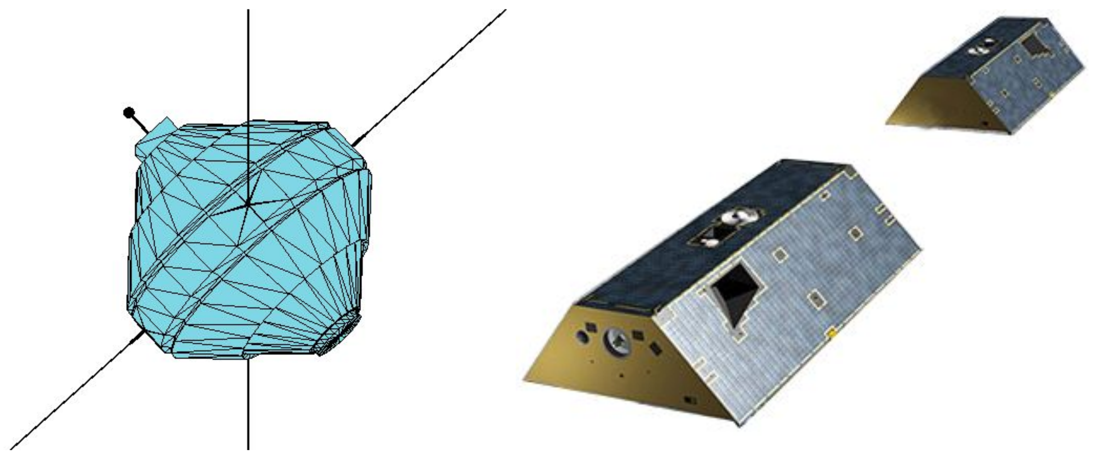

Fig. 2: Explorer 7 (left) and GRACE (right) surface models (not to scale). We treat Explorer 7 as a compact sphere in order to analytically compute its C_D, while GRACE exhibits a complex geometry represented by the Response Surface Model (RSM[3,8]).

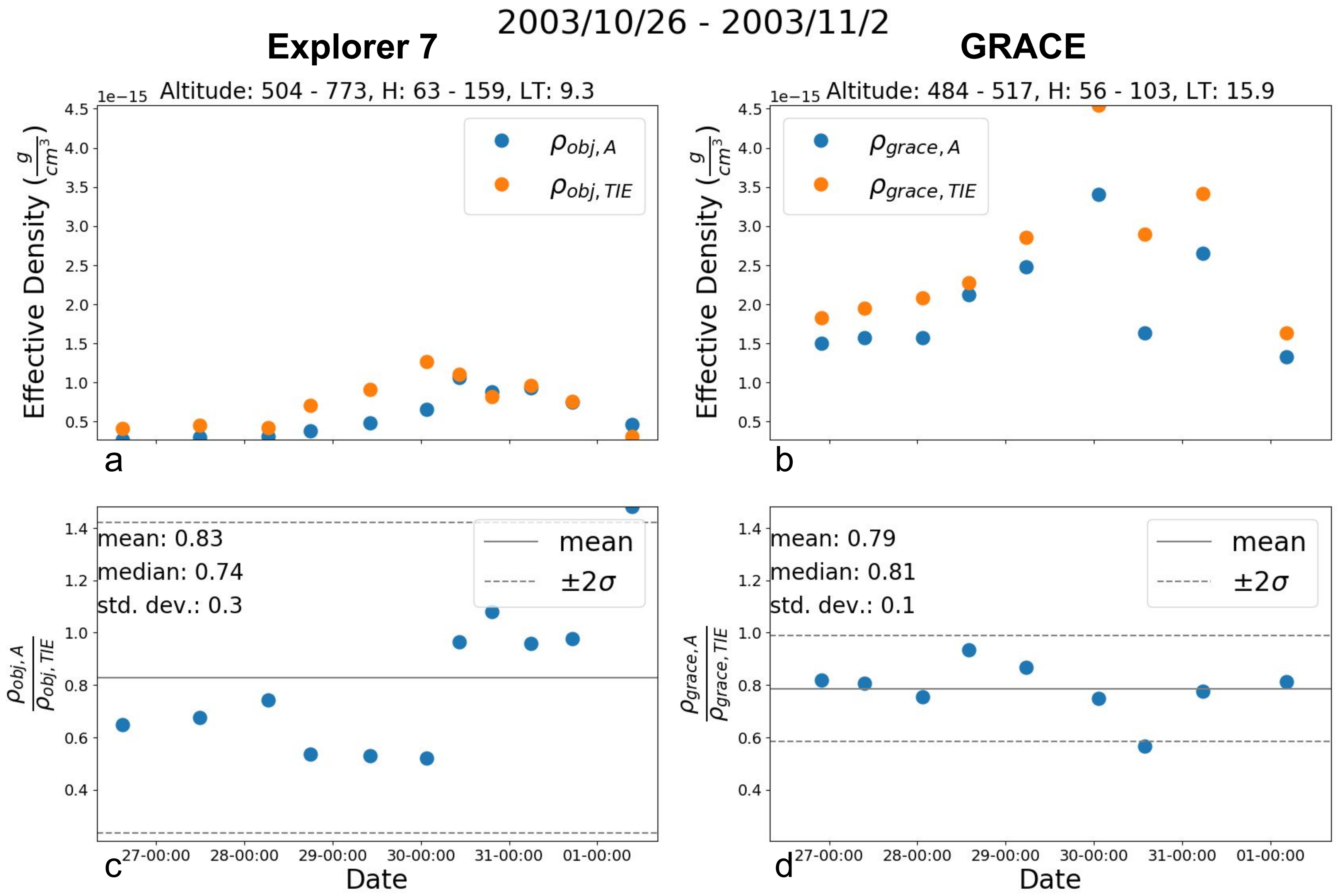

Fig. 3: Observed and modeled densities for Explorer 7 (a) and GRACE (b), and density ratios for Explorer 7 (c) and GRACE (d) for the week in October of 2003.

As an example case, we can compare Explorer 7 (periapsis = 504 km) and GRACE (periapsis = 484 km) densities and ratios. TIE-GCM modeled densities exceed observed densities for both satellites. Densities for both satellites respond to the Halloween storm, which occurs on Oct. 30. Prior to the storm, Explorer 7 density ratios are lower than those for GRACE, while after the storm, Explorer 7 density ratios are higher. We modify CLL drag coefficient model parameter θ to quantify density ratio sensitivity (as shown in Fig. 4).

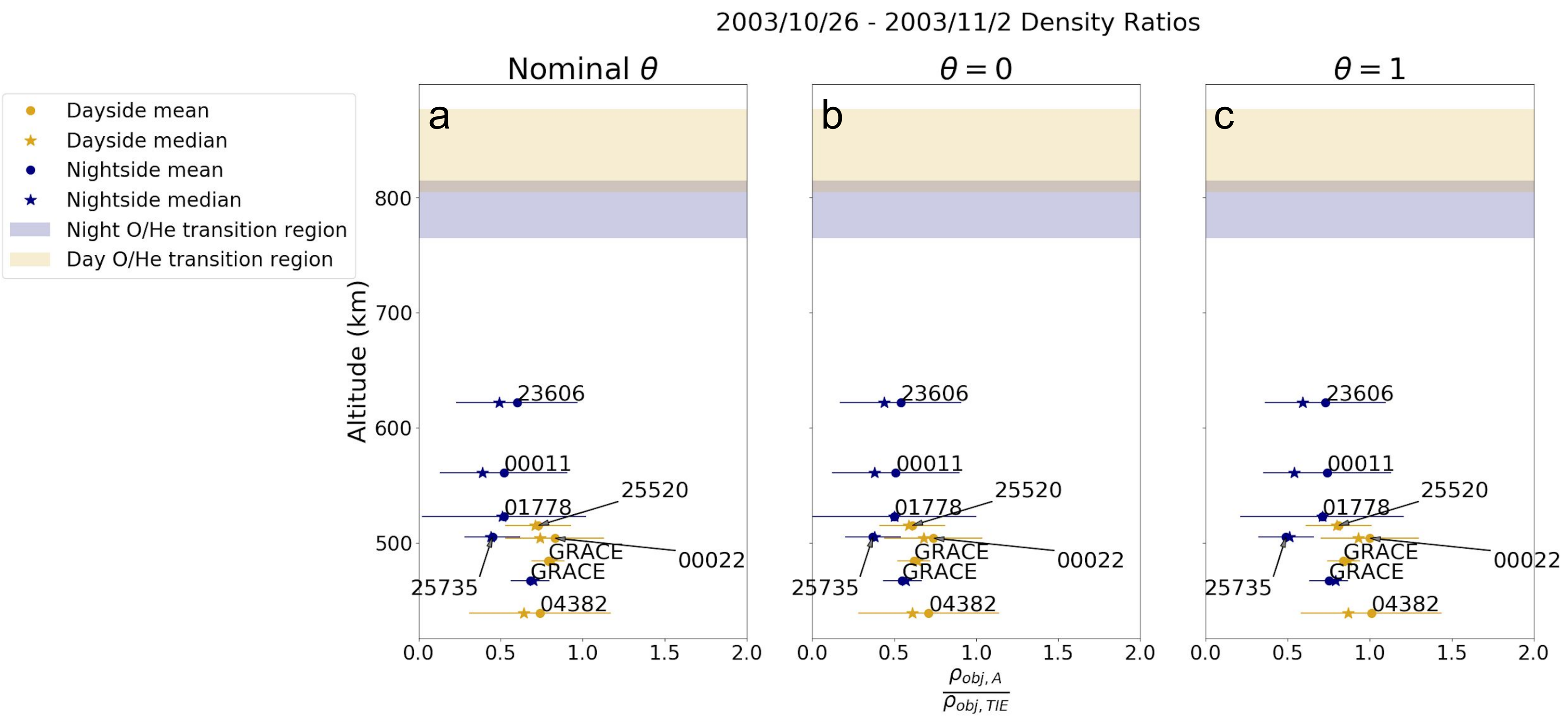

Fig. 4: Density ratio comparisons for nominal θ (a), θ = 0 (b) and θ = 1 (c). Local time differences are accounted for by plotting nightside and dayside periapsis ratios in blue and gold, respectively. GRACE is divided into dayside and nightside observations.

We compare average density ratios for each satellite to examine consistency. Dayside satellite ratios tend to be consistent with the GRACE dayside mean. Mean ratios for nightside satellites are below the GRACE nightside mean. The C_D model does well on the dayside, but may require tuning on the nightside. Changing the Langmuir isotherm surface coverage from 0 (fully clean surface) to 1 (contaminated surface) can increase the density ratios by up to 45%.

Discussion

Average Density Ratio Comparisons for Oct. 2003

		GRACE mean (med)	Compact mean (med)	Difference in mean (med)
Case 1: Nominal θ (~.4 - .8)	Day	0.79 (0.81)	0.77 (0.70)	0.02 (0.11)
	Night	0.68 (0.70)	0.52 (0.46)	0.16 (0.24)
Case 2: θ = 0	Day	0.62 (0.64)	0.69 (0.63)	-0.07 (0.01)
	Night	0.55 (0.57)	0.48 (0.43)	0.07 (0.14)
Case 3: θ = 1	Day	0.84 (0.87)	0.94 (0.87)	-0.10 (0.0)
	Night	0.75 (0.79)	0.67 (0.59)	0.08 (0.20)

- On the nightside, Case 2 produces the most consistent density ratios, so scattering closer to the specular direction may be appropriate
- On the dayside, Case 1 produces more consistent mean ratios, but further statistical analysis is needed
- TIE-GCM density factors are ~0.8 on the dayside and ~0.5 on the nightside
- RSM model can be improved, as it cannot fully resolve GRACE day-night ratio discrepancies
- The results demonstrate that C_D differences can be significant between day and night

Future Work

- Modify additional C_D model parameters (satellite surface material mass) and model densities (MSIS runs) to examine density ratio sensitivity and consistency
- Comprehensive tuning of C_D model parameters to determine optimal density ratio consistency
- Perform analysis for solar minimum time periods including weeks in 2006, 2008, and 2009. The oxygen-to-helium transition region will play more of a role in adjusting C_D and density ratios.

Acknowledgments

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Key

μ: Earth's gravitational parameter	t_{ik}: time between observations	ρ_M: model density	F: wind factor $(1 - \frac{r\omega}{v}\cos i)^2$
n_M: Satellite mean motion	A: Satellite cross-sectional area	m: satellite mass	K_L: Langmuir constant