Precise Aerodynamic Modelling through Swarm Attitude Maneuvers

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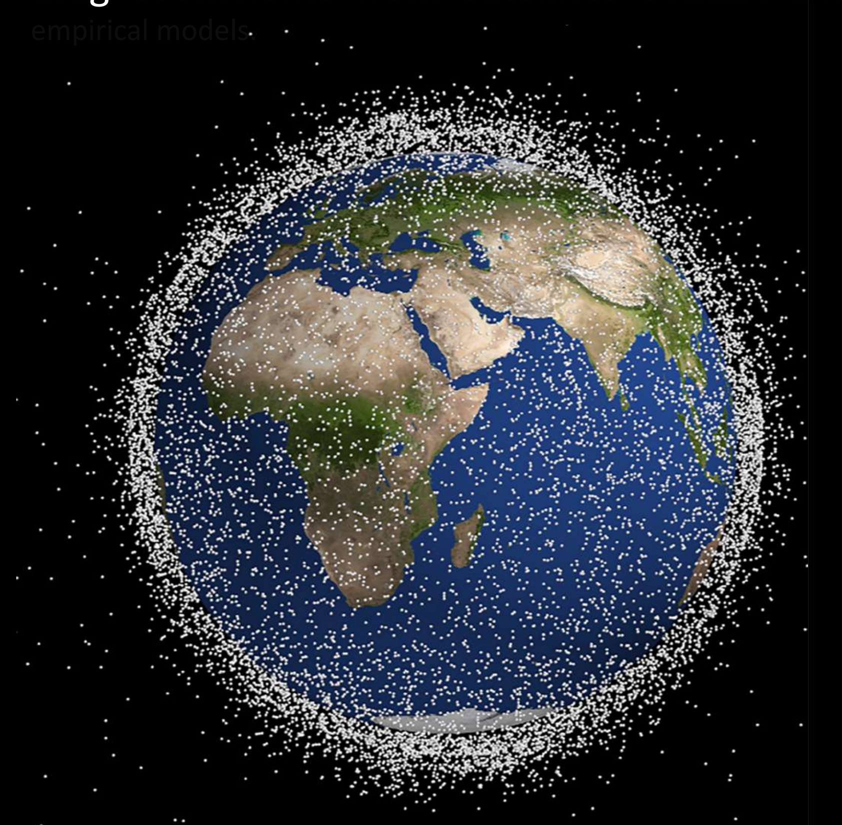
Background & Motivation

As the density of objects in Low Earth Orbit (LEO) increases, the accuracy of aerodynamic modelling becomes crucial. Existing models using simple one or two-parameter kernels for gas-surface interactions—assuming either diffuse or quasi-specular reflections—prove inadequate above 400 km altitude, where the disparity between model predictions and experimental data, such as the drag coefficients from satellites STELLA and GRIDSPHERE, becomes evident.



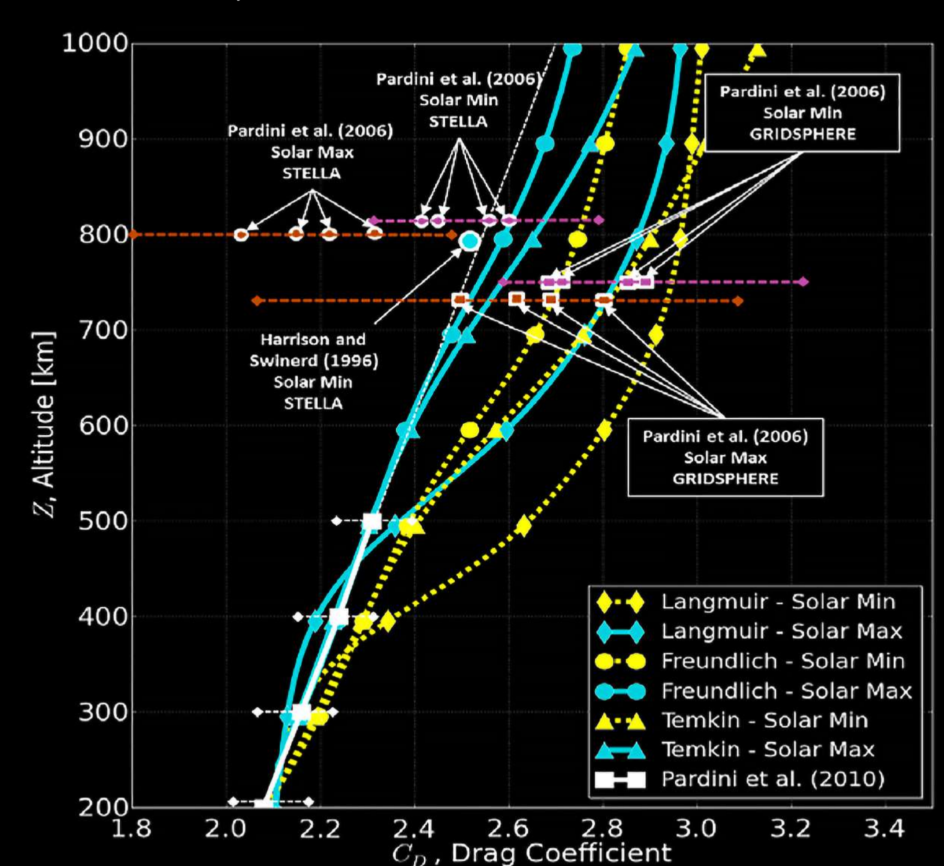


Figure 1: On the left: US Space Catalog orbital debris (2023). On the right: the modelled drag coefficient of a sphere vs. altitude, assuming diffuse reemission, for different solar conditions, plotted against drag coefficients of the STELLA and GRIDSPHERE satellites [1].

Modelling Surface Roughness Scales

The influence of geometric surface roughness on gas-surface dynamics, often overlooked, could account for observed discrepancies in data. A new kernel, $K_R(\boldsymbol{n_L}, \boldsymbol{v_i})$, rooted in electromagnetic wave scattering theory and paired with a local scattering kernel, $K_L(\boldsymbol{v_{i_L}} \rightarrow \boldsymbol{v_{r_L}})$ is proposed to address these roughness effects.

$$P(\boldsymbol{v_r}|\boldsymbol{v_i}) = \frac{1}{|\boldsymbol{v_r}\cdot\boldsymbol{n_G}|}\int_{\boldsymbol{v_i}\cdot\boldsymbol{n_L}<0} K_L(\boldsymbol{v_{i_L}} \rightarrow \boldsymbol{v_{r_L}}|\,\boldsymbol{n_L})\frac{\partial \boldsymbol{v_{r_L}}}{\partial \boldsymbol{v_r}} K_R(n_L|\,\boldsymbol{v_i})d\boldsymbol{n_L}$$

where $v_i, v_r, v_{i_L}, v_{r_L}$ are the incident and reflected velocities in the global and local reference frames; and n_L, n_G are the local and global normal vectors. When accounting for self-shadowing and multi-reflections with the escape probability $S(v_r\,|v_i)$, the total scattering probability becomes

$$P_{tot}(v_r|v_i) = \sum_{c=0}^{\infty}\left\{\int_{v_{r_1}}\dots\int_{v_{r_c}}\left[\prod_{k=1}^{c}P(v_{r_k}|v_{r_{k-1}})\prod_{k=1}^{c-1}\left(1-S(v_{r_k})\right)S(v_{r_c})\right]dv_{r_{c-1}}\dots dv_{r_1}\right\}.$$

The Swarm satellite pair serves as an excellent testbed, through its variety of rough surface materials.

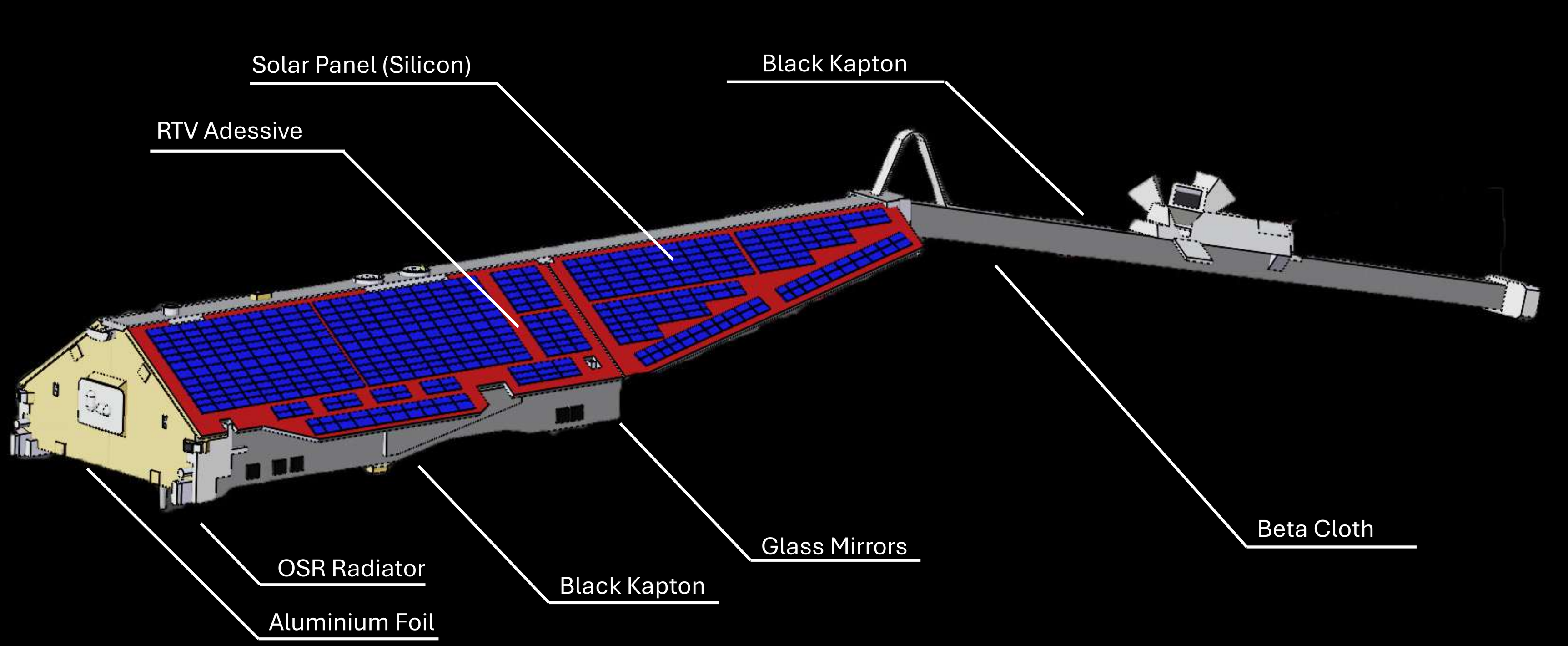


Figure 3: Swarm geometry model for aerodynamic simulations, with representative assigned materials. These materials may show large levels of roughness.

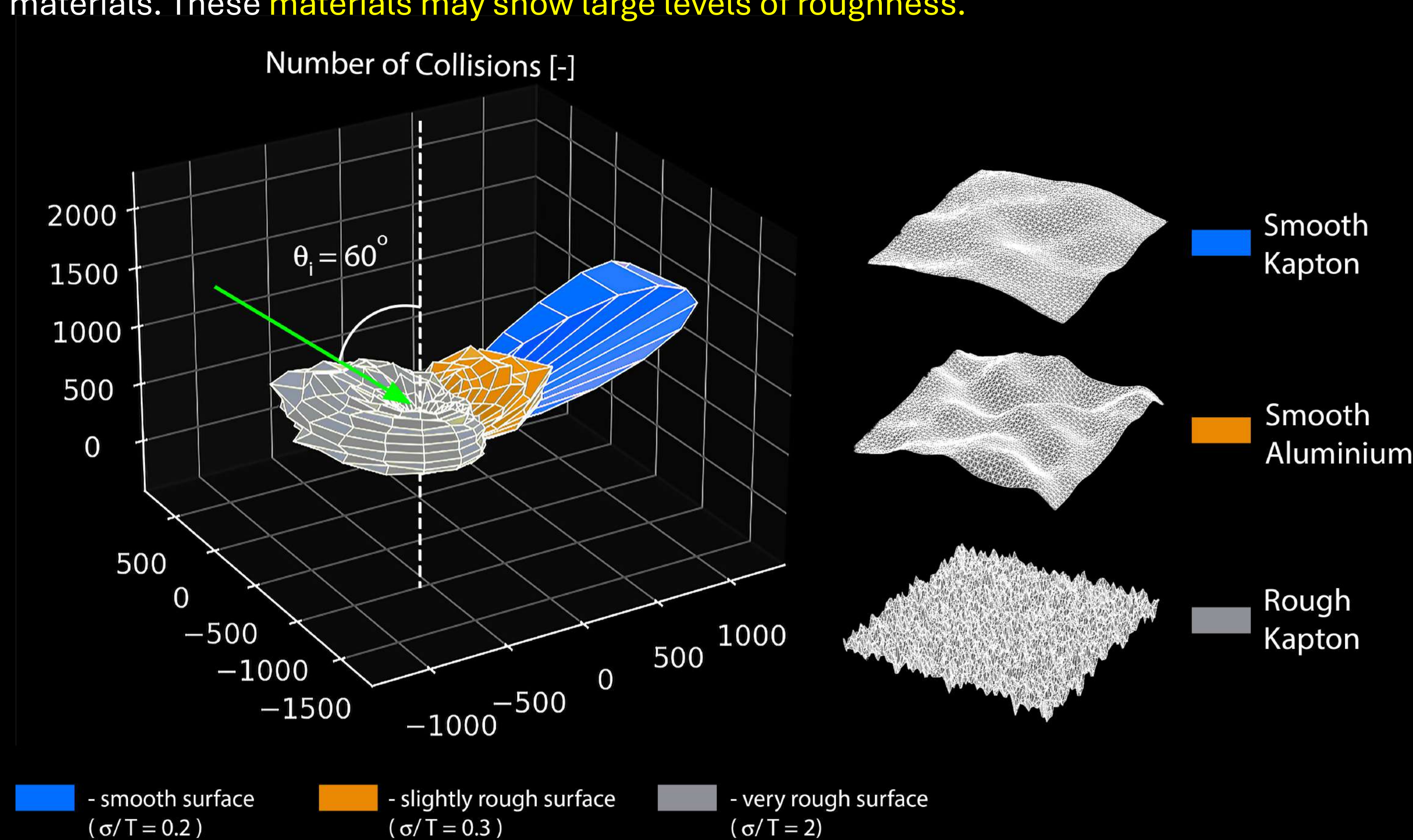


Figure 4: The influence of surface roughness on the 3D scattering indicatrix of Helium, assuming a normal energy accommodation coefficient of $\alpha_N = 0.2$.

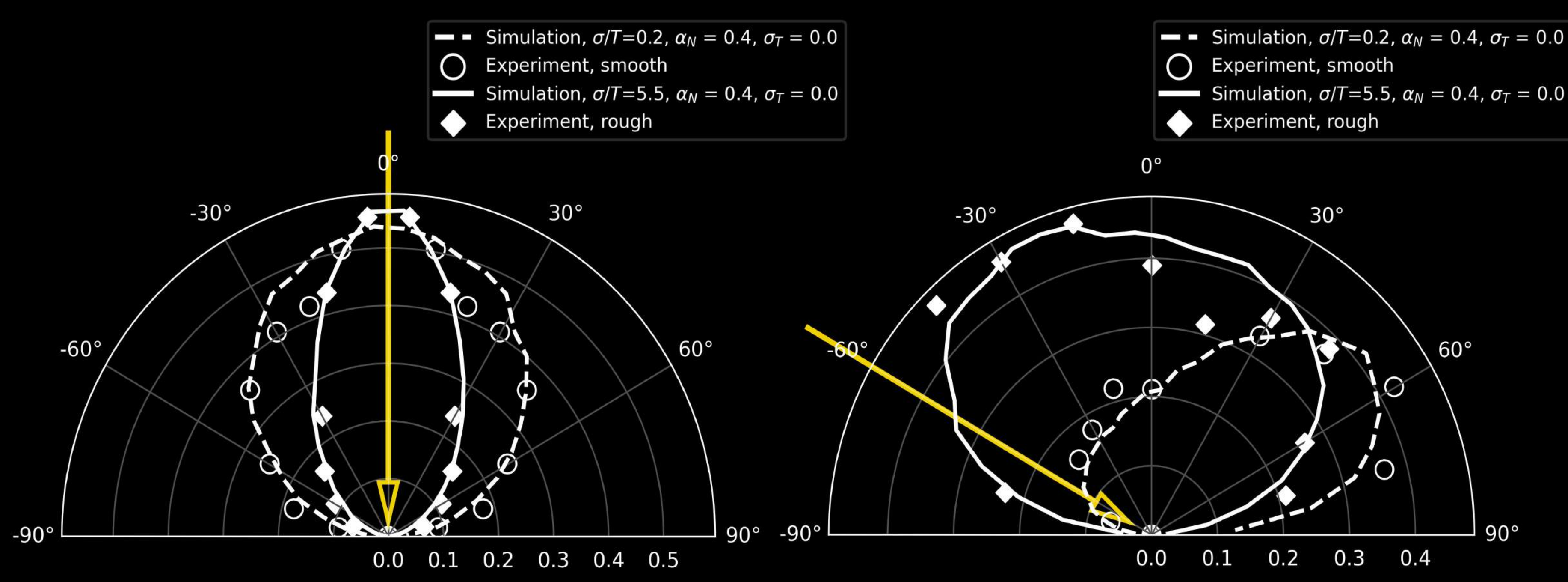


Figure 4: Angular scattering indicatrix of Argon from smooth and degraded Kapton surfaces at incidence angles of 0° and 60° – simulated vs. experimental plots by Erofeev et. al [2].

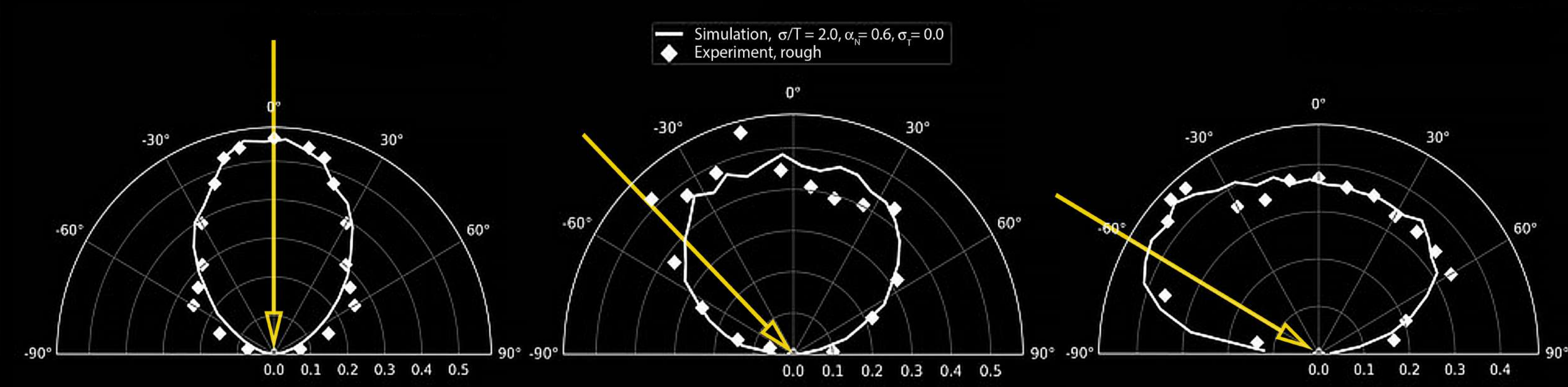


Figure 5: Angular scattering indicatrix of Helium from an Aluminium surface at incidence angles of 0° , 45° and 60° – simulated vs. experimental plots by Erofeev et. al [2]. .

Parameter Fitting with Swarm Maneuver

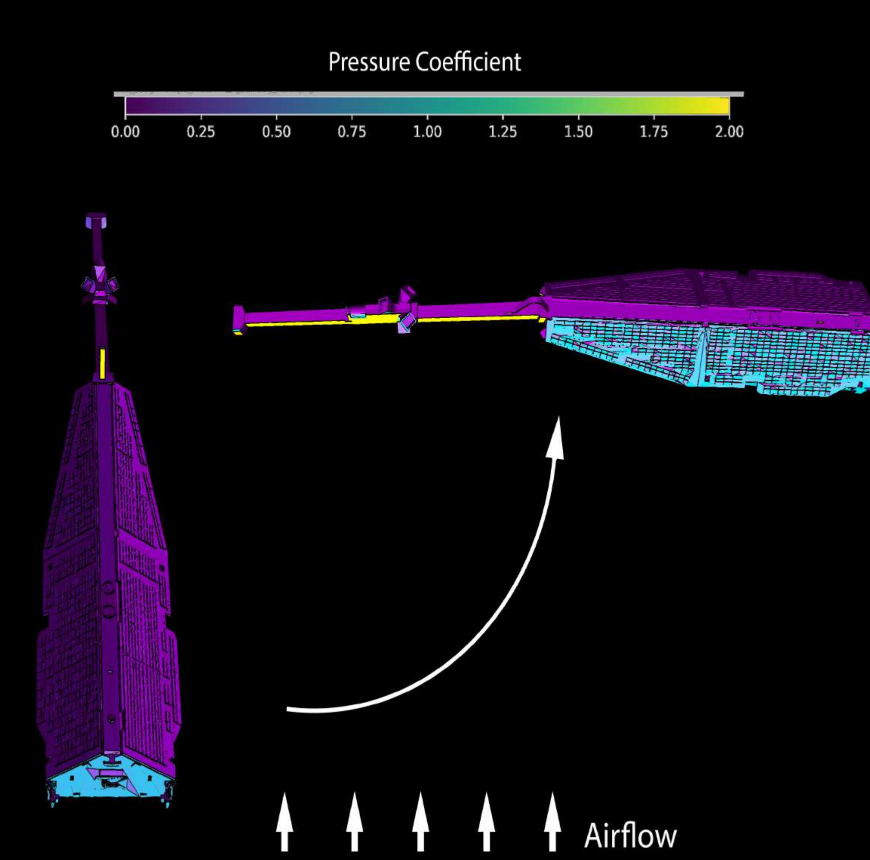


Figure 6: Simulation of Swarm's aerodynamic behavior at different attitudes using the ATHENS raytracing software.

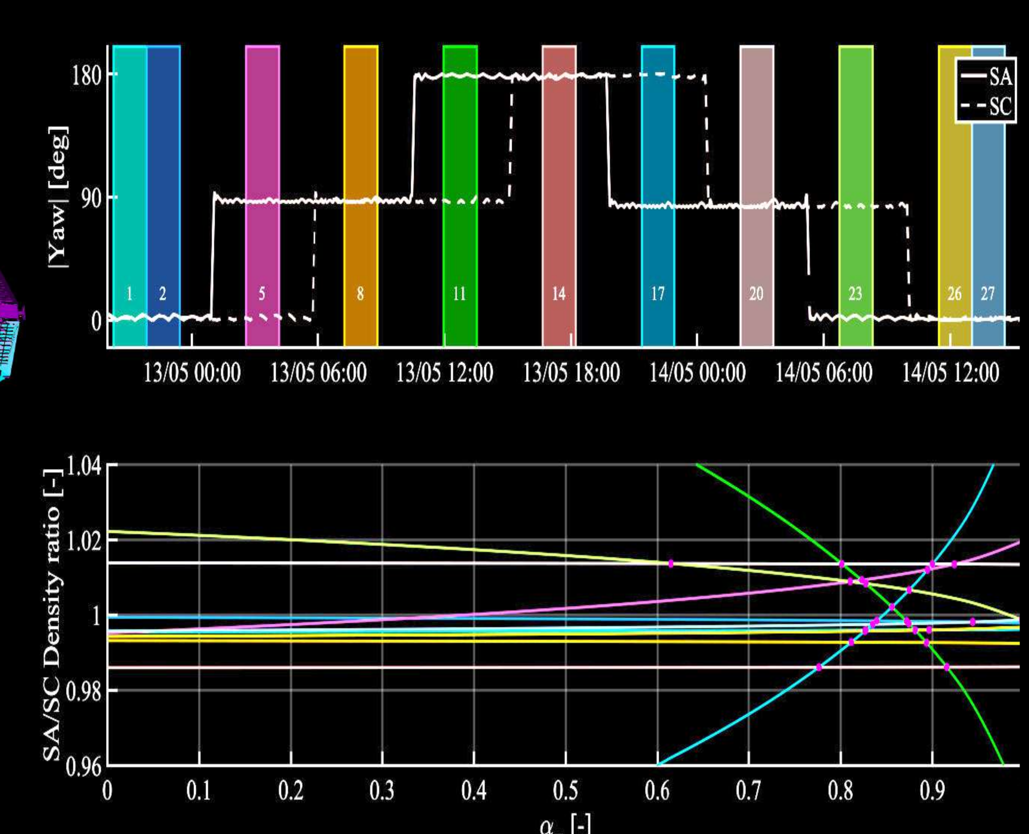


Figure 7: Aerodynamic model parameter fitting for density consistency at different instances in Swarm's attitude maneuver [3].

Key Take-Aways

- Existing gas-surface interaction models cannot capture the aerodynamic behavior of RSOs at altitudes above 400 km, where Helium becomes significant;
- The neglection of the prominent geometric roughness spectrum of real surfaces (such as Kapton and aluminium) may constitute the root cause of disagreement with observations;
- A new model based on electromagnetic wave scattering theory can accurately recreate the experimental angular scattering indicatrices of several gases on rough surfaces at the expense of one extra parameter (σ/T);
- By varying the gas incident angles, Swarm attitude maneuvers would prove very useful in fitting the parameters of this model, to enable more consistent neutral density measurements.

References

[1] Walker, A., Mehta, P., & Koller, J. (2014). The effect of different adsorption models on satellite drag coefficients. In Astrodynamics 2013 - Advances in the Astronautical Sciences (pp. 675–686).

[2] Erofeev, A. I., Friedlander, O. G., Nikiforov, A. P. et al. (2012). The influence of roughness of the surface on the interchange of momentum between gas flow 405 and solid surface. In AIP Conference Proceedings. AIP. URL: http://dx.doi.org/10.1063/1.4769673. doi:10.1063/1.4769673.

[3] March, Günther, van den IJssel, Jose, Siemes, Christian, Visser, Pieter N. A. M., Doornbos, Eelco N., & Pilinski, Marcin. (2021). Gas-surface interactions modelling influence on satellite aerodynamics and thermosphere mass density. J. Space Weather Space Clim., 11, 54. doi:10.1051/swsc/2021035