ADBSat: software validation of a novel fast drag analysis program

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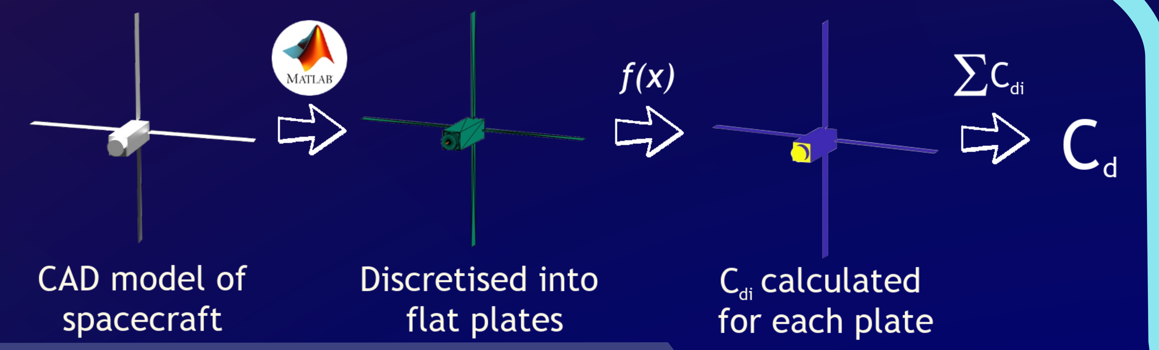
The University of Manchester

Author: Luciana Sinpetru, PhD candidate
Supervisors: Peter Roberts, Nicholas Crisp

DISCOVERER

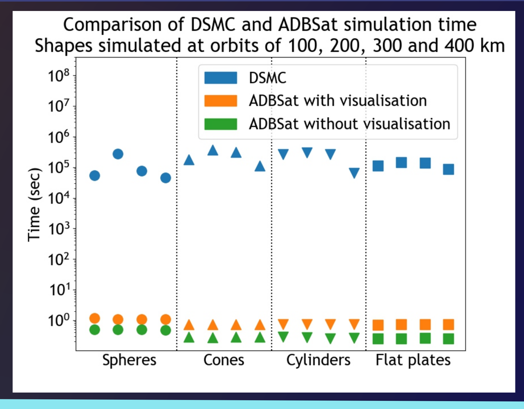
What?

- ADBSat was developed by a previous PhD student [1].
- It approximates the drag coefficient of a spacecraft in free-molecular flow by applying gas-surface interaction equations.
- Testing was necessary before it could be applied to solve real-world problems.



Why?

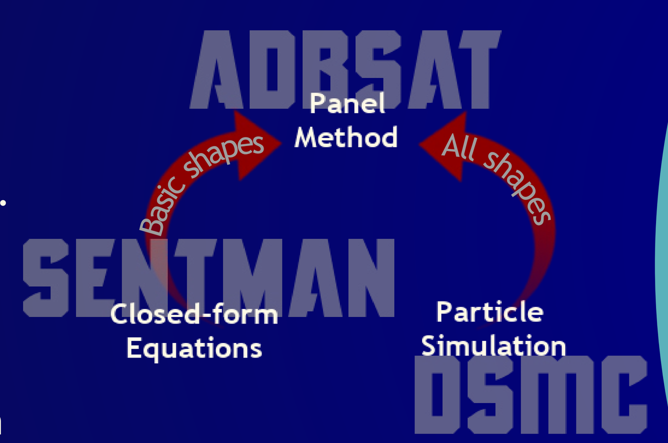
1.



- This implementation is brand new.
- Its accuracy and limits were not well understood.
- Runtime is much faster than other current methods, as shown in Fig. 1. Note the logarithmic y-axis.
- Computational load is also much smaller.
- Satellite mission design and analysis could benefit from these faster drag calculations.

Test the usage limits of ADBSat

- C_d was compared with results from Direct Simulation Monte Carlo (DSMC).
- This was implemented as a module of the OpenFOAM CFD program, named dsmcFoam [2].
- dsmcFoam results are verified, and it has been shown to accurately perform drag analysis [3].
- ADBSat results were also compared to results from closed-form equations for simple shapes.
- The goal was to determine the degree to which ADBSat is reliable for different cases.



Test cases split into three categories

Basic Shapes (100km, 200km, 300km, 400km)

Shapes which promote multiple particle reflections (200km only)

Shapes which have some panels shaded from the flow (200km only)

Case equivalency across all methods

- dsmcFoam only has one gas-surface interaction model (GSIM), the Maxwell model.
- A similar, comparable model which ADBSat implements is the Sentman model [4].
- A set latitude, longitude, date and time were chosen.
- Simulated environmental conditions such as density, flow speed, and temperature were identical.

Introduction · Aims · Method · Results

Conclusions

The accuracy of ADBSat has been demonstrated for convex satellite geometries at orbital altitudes above 200km. The aerodynamic properties of non-convex shapes are not well described. Below 200km, the flow is transitional and the free-molecular flow model is unsuitable.

Improvements to the shading algorithm are currently ongoing. It is hoped that ADBSat can be incorporated into a shape optimisation algorithm, to assist with mission planning and design.

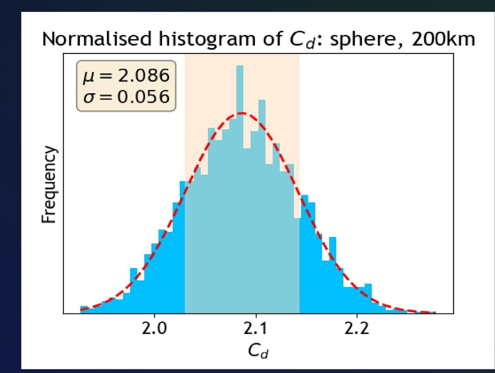
Special cases

- At an orbital altitude of 100km, the flow is transitional, not free-molecular. This was suspected to be the low-altitude operating limit for ADBSat.
- At 400km, accommodation of molecules to the surface is incomplete [5]. dsmcFoam cannot directly simulate this. Instead, this was implemented by setting the body temperature to be the temperature of the Maxwellian distribution from which the speeds of the incompletely accommodated molecules are drawn [6].
- Special shapes were devised to test the ADBSat shading algorithm, which attempts to find panels upstream of other panels and remove them from the calculation of C_d. This could be important for complex spacecraft.

dsmcFoam results

- dsmc is inherently a stochastic method.
- The instantaneous value of C_d is calculated many times throughout the simulation.
- The results for each simulation are plotted as a normalised histogram, in blue, in Fig. 2.
- The best-fit Gaussian is overplotted as the dashed red line.
- The mean of the Gaussian is the value of C_d.
- The standard deviation is the error on this value.

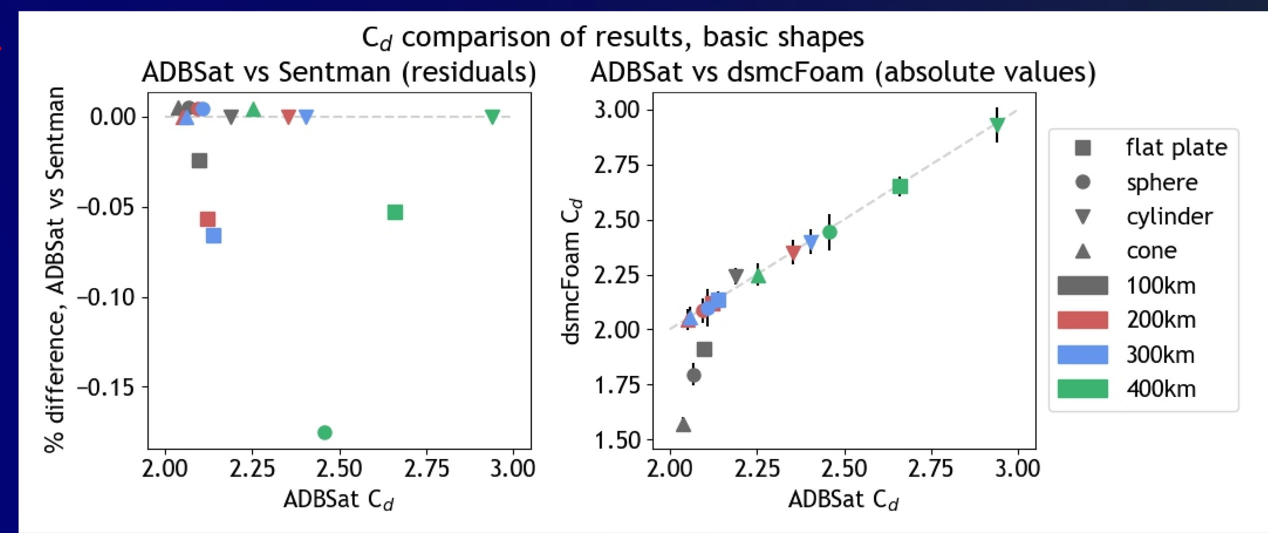
2.



Basic shapes

- Left-hand side of Fig. 3: percentage difference between ADBSat the Sentman equations.
- The results are consistent across all shapes and altitudes to within 0.2%.
- Right-hand side of Fig. 3: comparison between ADBSat and dsmcFoam.
  - Results agree at all altitudes except 100km. This is the lower altitude limit of ADBSat.
  - Here, the flow is transitional, not free-molecular. The equations applied by ADBSat are not valid.

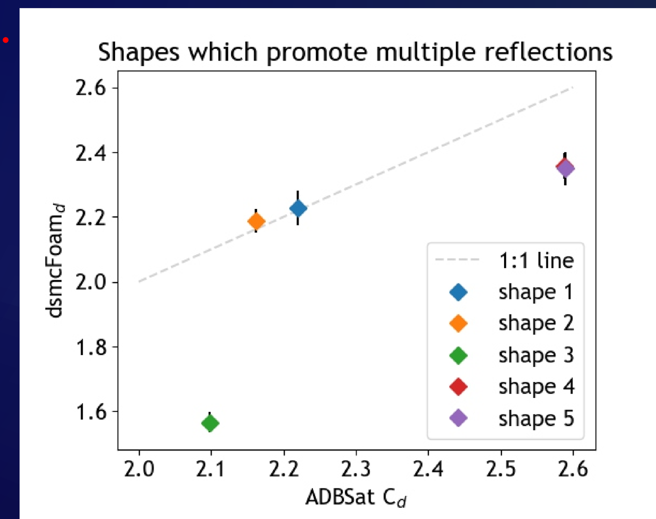
3.



Multiple particle reflections

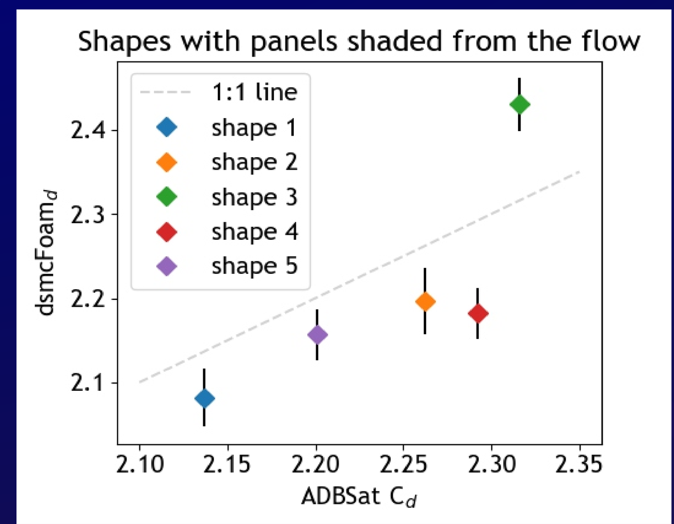
- Results are shown in Fig. 4.
- Shapes 1 and 2 are convex. The results agree within the error margin for these shapes.
- Shapes 3, 4 and 5 are non-convex. Here, ADBSat has over-estimated the drag coefficient significantly.
- For shapes 4 and 5, this is likely due to their indented sections where particles could get trapped. The significance of multiple reflections is much higher here.
- ADBSat cannot account for complicated particle motions.

4.



Shapes with shaded panels

5.



- Fig. 5 shows the results for these geometries.
- These shapes are all non-convex by definition.
- The results do not agree between ADBSat and dsmcFoam.
- This is due to the simplified nature of the shading algorithm. It projects the body onto a 2D plane, and checks whether the barycenter of a potentially shaded panel is within the area of a shading panel.
- It cannot partially shade panels, leading to inaccurate shading.
- It also cannot reliably distinguish whether panels at 90° to the flow are shaded, as their barycentres often fall on the edges of shading panels.
- Overestimation of C_d is caused by too few shaded panels, and conversely underestimation is caused by too many shaded panels.

[1] D. Mostaza-Prieto, Characterisation and Applications of Aerodynamic Torques on Satellites. *PhD thesis*, University of Manchester, 2017.
[2] C. White, M. Borg, T. Scanlon, S. Longshaw, B. John, D. Emerson, and J. Reese. dsmcFoam+: An OpenFOAM based direct simulation Monte Carlo solver. *Computer Physics Communications*, 224:22 - 43, 2018.
[3] M. D. Pilinski, B. M. Argrow, and S. E. Palo. Drag coefficients of satellites with concave geometries: comparing models and observations. *Journal of Spacecraft and Rockets*, 48(2):312-325, 2011.
[4] L. H. Sentman, Free molecule flow theory and its application to the determination of aerodynamic forces. *Lockheed Missiles & Space Company*, 1961.
[5] M. D. Pilinski, B.M. Argrow, and S.E. Palo. Semiempirical model for satellite energy-accommodation coefficients. *Journal of Spacecraft and Rockets*, 47(6):951-6, 2010.
[6] P. M. Mehta, C. A. McLaughlin, and E.K. Sutton. Drag coefficient modeling for GRACE using Direct Simulation Monte Carlo. *Advances in Space Research*, 52(12):2035-51, 2013.

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