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Using Differential Drag to Estimate Drag Coefficients for Improved Satellite Orbit Predictions

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Abstract: The drag coefficient C_D of a satellite is an important input for predicting satellite orbits in low Earth orbit, but determining C_D is difficult due to limited knowledge of Gas-Surface Interactions (GSI), leading to orbit prediction errors and increased collision risk. We propose an experiment that leverages the concept of differential drag to gain more insight into GSI, as differential drag causes a varying frontal area and C_D while other conditions stay the same, allowing us to estimate GSI parameters using orbit determination. Both analytical and numerical methods to obtain C_D and their sensitivity to GSI parameters are discussed, and these methods are then used to determine the optimal maneuvers for the experiment. As a case study, simulations are shown of a planned experiment using the BRIK-II satellite of the Royal Netherlands Air Force. It is expected that this method can be used to obtain more knowledge on GSI modelling, as well as give satellite operators a method to estimate C_D of a satellite with less bias than conventional methods.

1. INTRODUCTION

The growing number of satellites in low Earth orbit has increased the risk of collisions, mandating precise orbit predictions. For satellites operating below an altitude of 600 kilometers, atmospheric drag is the primary source of uncertainty in orbit prediction, of which the acceleration $\ddot{\mathbf{r}}$ acts in the along-track direction and is calculated using:

$$\ddot{\mathbf{r}} = -\frac{1}{2} C_D \frac{A}{m} \rho v_r^2 \mathbf{e_v} \tag{1}$$

where C_D is the dimensionless drag coefficient, A is the spacecraft area normal to the direction of flight $\mathbf{e_v}$, m is the mass of the spacecraft, ρ is the atmospheric density and v_r is the satellite's velocity relative to the atmosphere. The major sources of error in drag calculations are C_D and ρ [1]. Errors in C_D represent inaccuracies in modelling the physical processes that drive atmospheric drag of the given satellite. Errors in ρ are the result of limitations in widely used empirical models of the Earth's atmosphere. These models are often constructed based on fitting satellite data, for which assumptions must be made again for modelling C_D. Therefore, the problem of modelling drag, parameterized in C_D, has a direct and indirect effect on Equation 1.

For the drag coefficient, a simple but still widely used approach is to choose an arbitrary constant value (e.g. $C_D = 2.2$), which is an oversimplification and leads to high errors. Alternatively, C_D can be estimated through orbit determination using satellite tracking data. This approach still leads to errors of up to 30% due to the linear relation in Equation 1, because of high correlations with other uncertain parameters, predominantly ρ. A third option is to calculate the drag coefficient by modelling the physics of gas-surface interactions (GSI), a complex process due to the irregular shape of satellites, which does not guarantee an accurate answer either due to the limited knowledge of GSI theory.

In our work, we propose to design experiments using common satellite hardware to improve knowledge on gas-surface interactions. We attempt to find improved values for the drag coefficient by estimating the main GSI parameter, the energy accommodation coefficient α, which dictates how incoming gas particles exchange energy with the satellite surface and is an important parameter in calculating C_D [1]. Different GSI theories predict different behavior for energy accommodation. However, the theories are difficult to test, and only a handful of experiments have been done to attempt to measure it.

A challenge when modelling drag coefficients with GSI is the variables needed as input: atmosphere parameters such as temperature, composition, and winds, and satellite parameters such as surface temperature and material. These variables are often not measured by the spacecraft, and assumptions have to be made or models have to be used with limited accuracy, both of which lead to errors in C_D. To isolate α and remove correlation with other uncertain variables, our suggested experiment is to track satellite motion for similar satellites and similar orbits, but with two different aerodynamic shapes. This concept is called *differential drag*, often performed in formation flight operations to maneuver satellites relative to each other, which can be achieved through attitude variations or deployed surfaces. Using this setup, we assume the parameters related to the satellite and atmosphere stay constant throughout the experiment, except for the reference area A and drag coefficient C_D. By tracking the orbit with GNSS receivers, the effect of the difference in drag can be measured, and we can estimate the energy accommodation coefficient α that results in the proper drag behavior.

This experiment has been demonstrated before for the CHAMP [2] and Swarm [3] missions using accelerometers in a limited one-off measurement. We aim to turn this demonstration into a repeatable experiment with common hardware (GNSS receivers) and explore the additional results that can be exploited for improved orbit predictions in the future.

Currently, we are preparing for an opportunity to test our hypothesis. An experiment will be performed in May 2025 using the BRIK-II satellite of the Dutch Airforce. This short paper aims to explain this experiment and data processing strategy, and communicate about the foreseen results and potential applications.

2. METHOD

2.1 BRIK-II

In this experiment, we consider the BRIK-II satellite of the Royal Netherlands Air Force, which orbits at an inclination of 60 degrees and an altitude of roughly 400 km. BRIK-II is a single CubeSat (3x2x1U) with which we expect to perform an experiment in May 2025, where it will make attitude maneuvers to change between two aerodynamic shapes with respect to the flight direction. Through tracking the satellite, the relative change in drag between the two configurations will be observed, and an estimation of the energy accommodation coefficient will be performed.

We model the geometry of the satellite as a simple six-panel cuboid, depicted in two different attitude configurations in Figure 1. In Section 3.1 a motivation will be given as to why these two attitudes were chosen. The measurements that form the basis of the experiment are satellite position measurements derived from a GNSS receiver. BRIK-II has a single-frequency GPS receiver from which on-board navigation solutions are generated with errors in the order of 5 meters.

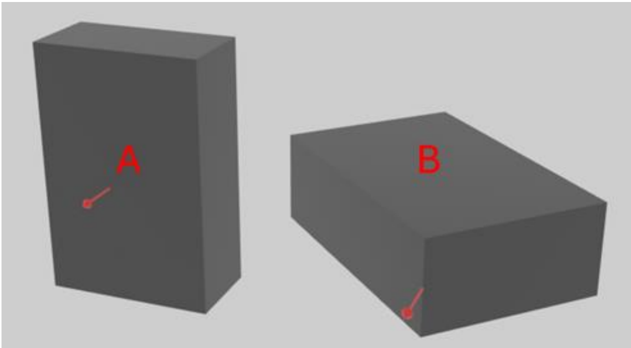

Figure 1: Simple panel models of the BRIK-II satellite in two attitude configurations. The red arrow indicates the direction of flight. Left: the BRIK-II 6U satellite in configuration A, its maximum frontal area configuration. Right: the BRIK-II satellite in configuration B, with the smallest side pointed in the direction of flight, then rotated 45 degrees around the nadir axis.

2.2 Modelling drag coefficients

For satellites in Low Earth Orbit, aerodynamic drag occurs in an environment of low density and high velocity. It can be assumed that the atmosphere comprises individual gas particles, the interaction between them can be neglected, and satellite aerodynamics can be described as individual gas particles hitting the satellite. The central physical phenomenon that needs to be described is how the particles exchange energy and momentum with the satellite, the study of Gas-Surface Interactions (GSI). A widely used parameterization for this problem is the energy accommodation coefficient α, which is 0 in case the particle is completely reflected off the surface and 1 in case of diffusion, where the energy is completely absorbed, but in reality, a value between 0 and 1, which indicates that a combination of these phenomena occurs. GSI models attempt to predict the behavior of α and calculate C_D based on α, see e.g. [4]. In the analysis in this paper, we focus on a commonly used GSI model: Diffuse Reflection with Incomplete Accommodation (DRIA). DRIA is often used in satellite drag studies and works well at altitudes up to around 400 km. We follow the implementation of DRIA from Walker et al. [5] which splits the satellite surface into two parts: a clean surface and a corresponding clean accommodation coefficient α_s, and a surface covered with atomic oxygen, a phenomenon that causes complete accommodation ($\alpha_{covered} = 1$).

Based on different GSI models, analytical expressions for C_D can be derived for simple shapes. The most interesting for most satellite shapes are the expressions for the drag coefficient of a flat panel. Following the assumption that the atmospheric particles do not interact with each other, the total drag coefficient of a satellite can be calculated by adding up the contribution of each of its panels. Calculating C_D analytically is advantageous for computational speed and the ability to estimate underlying parameters using orbit determination. However, its use is limited to satellite shapes for which a representative panel model can be created. In addition, only single connections of gas particles with the surface are assumed. Concave features on the surface will therefore cause the derivations to be invalid. [6] gives an overview of analytical expressions for panels for multiple GSI models, which we have adopted for our analytical C_D calculations.

Numerical simulation methods have been developed which can be applied to any satellite shape, by carefully modelling the interaction and possible reconnections for particles. Usually, the basis of such methods is simulating atmospheric particles hitting a satellite panel model in a Monte-Carlo analysis, calculating the momentum transfer of each particle and the satellite surface using GSI principles, and then calculating the total drag coefficient by considering the contribution of all samples. Such methods have the advantage of working on any satellite shape, but come at a high computational cost, and do not allow for any analytical analysis of the effect of GSI variables on the resulting C_D. In this work, we use the Response Surface Model (RSM) [7] for numerical C_D calculations.

For the simple panel model in the current study, we used both methods mentioned above to calculate drag coefficients for BRIK-II for different attitudes and altitudes. The numerical and analytical methods give similar solutions for drag coefficients with differences under 3%, as demonstrated in Figure 2.

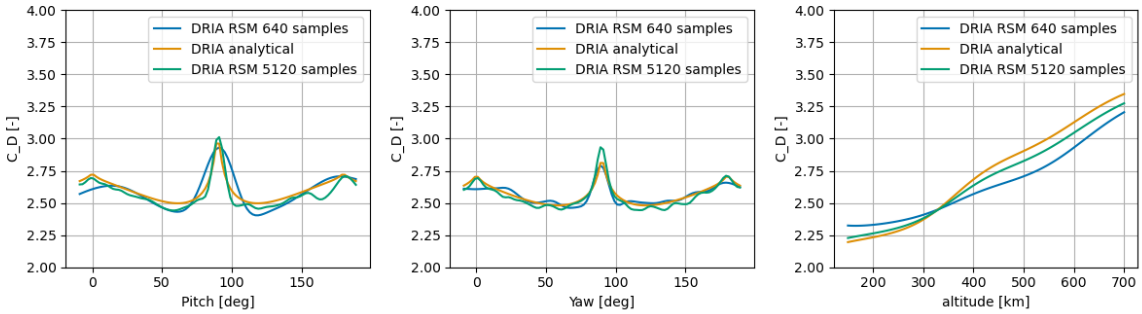

Figure 2: Drag coefficient modelling for the BRIK-II satellite using analytical methods or the RSM toolkit; the latter is tested for two different Monte Carlo sample sizes. Three different input parameters are varied to assess the corresponding change in drag coefficient: pitch angle (left) and yaw angle (middle) with respect to configuration A, and altitude (right). C_D is sensitive to the altitude due to changes in atmospheric composition and temperature.

2.3 Experiment setup

To estimate drag-related variables, we set up an orbit determination algorithm using the TU Delft Astrodynamics Toolbox (TUDAT, https://docs.tudat.space/). The orbit modelling includes gravity terms for a spherical harmonics model of the Earth and perturbations by the Sun and Moon, as well as solar radiation pressure and atmospheric drag. The following parameters are included in the estimation:

- Initial state (position and velocity) of the satellite.
- A scaling factor on the atmospheric density output of the NRLMSIS atmosphere model [8]. This model can describe the behavior of atmospheric density but is known to have a bias, which we attempt to estimate as a proxy for estimating density directly. The assumption is that this constant scale factor applies throughout the measurement arc.
- A constant clean accommodation coefficient α_s in Walker's model [5] for calculating the drag coefficient. In reality, α_s changes along the orbit due to variations in atmospheric composition, so a constant α_s is a simplification.
- Empirical parameters in radial and along-track directions are included to absorb high residuals caused by imperfect satellite and environment modelling.

In the case of analytical C_D calculations, we can estimate these parameters using orbit determination. In the case of numerical C_D calculations, a partial derivative for α_s cannot be derived. Instead, we set a value for α_s upfront and run the orbit determination separately for each attitude configuration, and analyze afterwards for which α_s the density scaling factor matches between the two satellites, similar to the aforementioned Swarm experiment [3].

Drag causes a continuous perturbation on the satellite orbit, but its effect only becomes visible after a certain tracking time, which depends on the precision of the observations. To prepare for experiments with real tracking data, we run an analysis with simulated observations to study which results can be expected given certain measurement arcs. These simulations attempt to include representative errors for GNSS measurements and orbit modelling, and the density is provided by a completely independent atmosphere model, to make the orbit determination as realistic as possible.

3. RESULTS AND DISCUSSION

3.1 Optimal maneuver strategy

In order to set up the maneuver strategy, we analyzed what changes in aerodynamic shape are the most optimal to conduct the experiment. The objective of the analysis is to find two flight configurations which produce a relative drag force that is most sensitive to α, i.e. which configuration maximizes:

$$\frac{d\left(\frac{\ddot{\mathbf{r}}_{\mathrm{conf1}}}{\ddot{\mathbf{r}}_{\mathrm{conf2}}}\right)}{d\alpha} = \frac{d\left(\frac{C_{D,\mathrm{conf1}} \cdot A_{\mathrm{conf1}}}{C_{D,\mathrm{conf2}} \cdot A_{\mathrm{conf2}}}\right)}{d\alpha} \tag{2}$$

The optimal configurations can be found by calculating the drag for a grid of conditions, the first and second configurations, and values for alpha. Subsequently, the gradient with respect to α can be calculated and the maximum gradient indicates the optimum. Figure 3 shows this a visualization of this analysis for BRIK-II.

The point that produces the highest gradient (bright yellow in the figure) is the optimal configuration when sensitivity to alpha is the only consideration. The resulting configurations of the BRIK-II satellites are shown in Figure 2. Configuration A maximizes drag by facing the largest panel in the flight direction. Configuration B has a large shear component in the drag calculations by facing the largest panels parallel to the flow (pitch rotation of 90 degrees) and inclining the two other panels by 45 degrees.

Besides this optimum, one should also consider other aspects which could act as boundary conditions. For example, an upper boundary for the drag force might be required to keep orbital decay to a reasonable amount. Alternatively, a lower boundary for drag force might be required for other reasons, e.g., very low drag configurations might prevent the drag signal from being strong enough to be measured through orbital tracking. Finally, a high ratio of drag between the satellites might cause them to drift apart quickly, which might not be desirable for certain satellite formations.

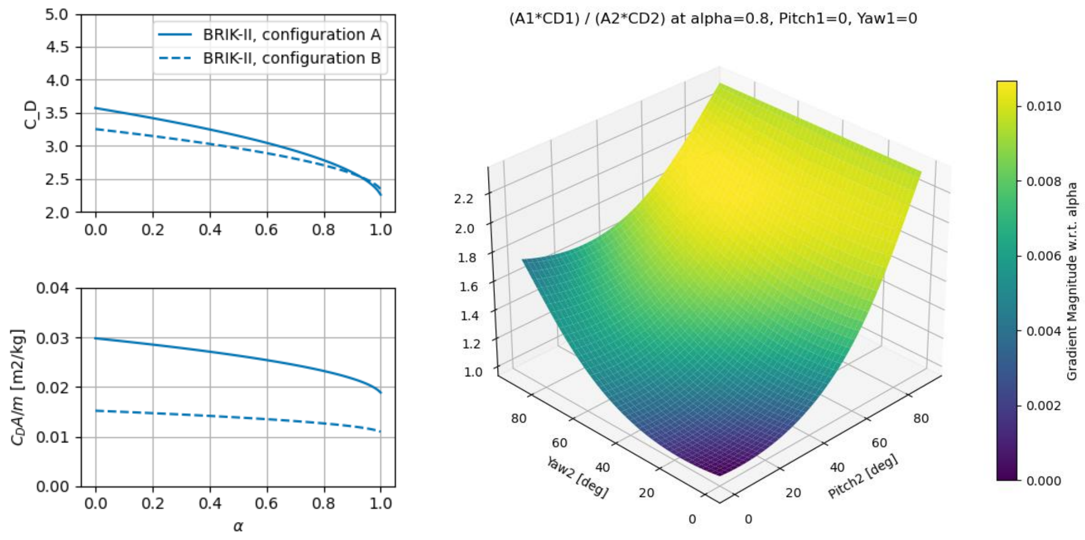

Figure 3: Analysis of the sensitivity of flight configurations with respect to α. Left: C_D and C_DA/m as a function of α. Right: Ratio of C_DA of configuration A with respect to configuration B, given that configuration A is the configuration with the largest panel facing the flight direction. The color is the gradient of this ratio with respect to α.

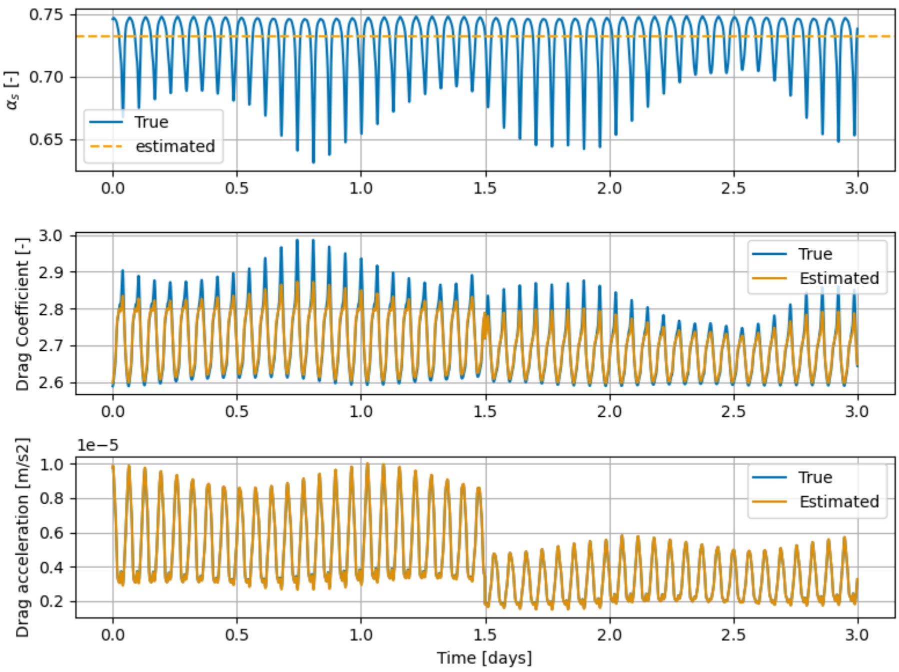

Figure 4: Results of orbit determination with simulated observations for BRIK-II. In blue: the “true” values used to simulate the observations, in orange: the solution of the estimation. Top: α_s, which in reality varies over the orbit, and the constant estimated value $\alpha_s = 0.732$. Middle: drag coefficient behavior, due to taking a constant α_s the estimation cannot reconstruct C_D perfectly. Bottom: total drag acceleration, where the change in attitude halfway can clearly be observed. The orange line overlaps the blue one as far as can be seen in this plot, indicating a match of the drag acceleration result of the estimation compared to the simulated truth.

3.2 Estimation Results

To prepare for the planned BRIK-II experiment the estimation algorithm is currently being set up. Figure 4 shows an initial result of the analysis. Here, the satellite has flown in configurations A and B for 1.5 days each, which is sufficient to estimate a constant α_s that represents the true behavior of α_s. The resulting drag acceleration can be reproduced nearly perfectly. The measurement arc length in the order of days is long considering the orbital period, but realistic for the BRIK-II measurement errors of 5 meters, as the relative difference in atmospheric drag requires time to build up.

It must be noted that results are generated in the initial testing phase, an effort to realistically simulate errors in environment models or satellite-related parameters is the next step. Therefore, the current results can be expected to be less accurate. Still, it is our experience in simulating other missions that tuning the empirical acceleration and increasing the arc duration can serve as solutions to this problem, as the signal of the drag acceleration becomes strong enough to overcome errors in the estimation.

4. CONCLUSION & OUTLOOK

Our research explores the possibility of using differential drag and accurate orbit tracking, which are increasingly performed in space missions for various reasons, to gain more information about modelling satellite drag. Even for the simple case of a single satellite with a single-frequency GPS receiver, estimating GSI parameters seems possible given the appropriate maneuvers, orbit determination setup, and measurement length.

Looking forward, we aim to process real satellite measurements soon to confirm the ability to estimate the energy accommodation coefficient. If the approach proves successful, we foresee several applications of this estimation algorithm. While in this short paper, one GSI model is considered and only one GSI parameter is estimated, the algorithm can easily be extended to accommodate more estimation strategies. Several competing GSI theories have varying success in different domains, but the lack of suitable experimental data makes it difficult to validate and compare the theories sufficiently. The capabilities of GNSS receivers in terms of inferring atmospheric drag cannot compete with accelerometer-carrying platforms such as Swarm and GRACE-FO. However, the number of experiments that could be done due to the availability of suitable missions is a benefit, as GSI models can be tested against a large quantity of data in a large variety of conditions.

Additionally, a promising byproduct is the possibility of simultaneously estimating drag coefficients and atmospheric density without the complete correlation caused by Equation 1, which normally creates ambiguous results for both parameters. The correlation between the density scaling parameter and the clean accommodation coefficient is still observed to be high in the case of the analytical approach. Still, the effects can be separated by sufficient measurements in terms of quality (GNSS accuracy) and quantity (arc length). This would, for example, allow several simple maneuvers of a satellite to estimate the drag coefficients, which could then be used in the remainder of the mission. Care should be taken, though, to use this result to precisely predict orbits, as the density still presents a large problem: many thermospheric density models are based on satellite data where drag coefficients were not properly modelled. This problem will persist as long as the datasets that form the basis of such models contain drag modelling errors.

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