THE NEED FOR A STANDARD FOR SATELLITE DRAG COMPUTATION TO IMPROVE CONSISTENCY BETWEEN THERMOSPHERE DENSITY MODELS AND DATA SETS

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ABSTRACT

During the past decade, an unprecedented wealth of data on neutral density in the thermosphere has become available, through new processing techniques on existing data, and via the accelerometer-carrying satellites CHAMP, GRACE and GOCE. These data sets will continue to expand, for instance with ESA's new Swarm mission. In addition, significant advances have been made in recent years in thermosphere neutral density modelling, with new empirical models (Jacchia-Bowman 2008, DTM2012), and work on model calibration and data assimilation (HASDM, ATMOP). These advances have brought to the foreground a long-standing problem in this research field and its applications: the inconsistent computation of drag coefficients and ballistic coefficients.

Many analysts have used fixed values for the drag coefficient in the past. These values were sometimes based on simplified theory, such as Jacchia's choice for CD=2.2. In other cases, drag coefficients were estimated on a per-object basis from tracking observations, making use of a thermosphere model. This leads to drag results that are more or less consistent with the scale determined by that density model, but that can not readily be compared with other models and data sets. In reality, there are dependencies on the orientation and atmospheric temperature and composition, which vary with satellite shape.

This issue of inconsistent drag-derived neutral density data sets and models has become all the more relevant now that a long-term downward trend in thermospheric density has been identified, which has a large impact on the long-term evolution of the space debris population and on future mission planning. In order to remedy this situation, a new standard for satellite drag computation will be proposed. The standard will be based on physical theory, validated by measurements. If adopted by the thermosphere density modelling, data processing and user communities, such a standard should lead to a heightened accuracy of drag-related computations, such as orbital lifetime estimates and conjunction analysis.

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1. INTRODUCTION

Aerodynamic drag is often the most significant non-gravitational force acting on objects in low Earth orbit. The modeling of this force is crucial to orbit specification and prediction. The drag force on a satellite results directly in energy dissipation, leading to a reduction in orbital period and height. At lower heights, ever higher densities are encountered, speeding up the orbital decay. Eventually, all LEO objects will therefore be removed from orbit after reentering in the thicker lower layers of the atmosphere. This natural cleanup mechanism for LEO space debris objects is of prime importance for the sustainability of LEO space operations.

Variations of the thermospheric temperature, density and composition are strongly driven by energy inputs from the Sun. Either directly, through absorption of extreme ultraviolet (EUV) radiation and precipitation of solar wind particles, or indirectly through Joule heating by ionospheric currents. Coupling with the lower layers of the thermosphere can be considered a secondary source of variations in the thermosphere, which are currently not included in empirical models. Variations in Sun-Earth geometry and solar and geomagnetic activity are represented in such models [5, 26, 3] using a series of parametric equations, depending on time, location and a selection of solar and geomagnetic activity proxies and indices, such as $F_{10.7}$ and k_p. During model generation, the coefficients of these equations are estimated by making use of various datasets. These datasets originate at ground-based incoherent scatter radars, satellite accelerometers and from the orbit tracking of LEO objects.

These datasets and models have served very well in the investigation and representation of thermosphere dynamics and variations in density. The high quality total neutral density data derived from accelerometer-carrying satellites starting with CHAMP [4] and GRACE [6, 32], has opened new lines of investigation into the various forms of solar and lower atmospheric forcing of the thermosphere. The past decade also saw a renewed interest in densities, at much lower temporal resolution, derived from Two-Line Element orbits of space debris objects [27], leading to analyses of long-term density change and [8] and the recent anomalously low densities at solar minimum [9].

However, the accuracy of the absolute scale of the densities has often not received enough attention in the past. Inconsistencies in scale between empirical density models and data sets have been reported [7, Chp. 5], [25], but so far this problem has not been sufficiently addressed. The afore-mentioned long-term drifts in the true density [8], which are not included in any current models, play a role in these inconsistencies as well, as are possible historical errors in the representation of satellite geometry. But an equally important contributing factor is the way that satellite drag has traditionally been computed, making use of a constant drag coefficient.

We are therefore proposing to standardize the computation of the aerodynamic force on satellites, in a way that will make future datasets, models and the use of such models in orbit computations consistent with each other. The purpose of this paper is to describe the origins and background to the problem in somewhat more detail. The details of the proposed standard will be the subject of a separate paper.

2. ESTIMATED DRAG COEFFICIENTS AND BALLISTIC COEFFICIENTS

Before we can go further, some introduction of nomenclature is required.

The drag coefficient C_{D} is a normalised representation of the drag force F_{D} or drag acceleration $a_{\mathrm{D}} = F_{\mathrm{D}}/m$, defined according to:

$$C_{\mathrm{D}} = \frac{m\, a_{\mathrm{D}}}{A_{\mathrm{ref}} \frac{1}{2} \rho v_{\mathrm{r}}^2} \qquad (1)$$

in which m is the object's mass, A_{ref} is a reference area, ρ is the density and v_{r} is the relative velocity of the atmospheric particles with respect to the satellite. The reason why aerodynamicists use dimensionless coefficients like C_{D} is that they can often be considered constants for a wide range of conditions. A value for C_{D} can be determined in flight using the above equation, when v_{r} and ρ are assumed to be known. The drag acceleration itself can be derived from accelerometers [4], satellite tracking observations or Two-Line Elements [21, 27], making use of models of other significant accelerations acting on the satellite.

This approach leads to an *estimated drag coefficient*. More specifically, when the density ρ is the result of a density model, this is a *model-based estimated drag coefficient*. If a different model were used, a different value of the drag coefficient estimate would be obtained. Since there are no sensors which can independently measure the local density in orbital conditions, drag coefficients estimated in this way are nearly always linked to a certain density model.

These estimated drag coefficients can subsequently be used to compute the drag force or acceleration under different conditions, for example, in an orbit prediction, using the following equation:

$$a_{\mathrm{D}} = \frac{F_{\mathrm{D}}}{m} = C_{\mathrm{D}} \frac{A_{\mathrm{ref}}}{m} \frac{1}{2} \rho v_{\mathrm{r}}^2 \qquad (2)$$

For space debris, when a characteristic reference area and mass are often unknown, it makes more sense to estimate the (inverse) ballistic coefficient, instead of the drag coefficient. The inverse ballistic coefficient is defined as follows:

$$B = \frac{1}{b} = \frac{C_{\mathrm{D}} A_{\mathrm{ref}}}{m} \qquad (3)$$

The fact that the estimated drag or ballistic coefficient is linked to a density model, and therefore has absorbed density model errors, has both positive and negative consequences. The most important positive consequence is that on the short-term, the density model error due to long-term change and solar activity dependence likely does not change significantly, so a good estimate of the true drag will be returned when using equation (2) in orbit prediction. On the longer term, if the factors that drive atmospheric conditions have changed significantly, the density model error has also likely changed, and the estimated coefficient might well not be appropriate anymore. It is therefore not advisable to use a drag coefficient estimated over a short arc of tracking data, for long-term predictions, such as in orbital lifetime calculations.

The use of model-based estimated drag coefficients has also been applied in the past when using orbit estimation techniques to retrieve information on the density from tracking data. For instance, Bowman [2] used the average of very long timeseries (up to 30 years) of Jacchia 71-based ballistic coefficient estimates from long-lived low perigee space debris objects, as the 'true' ballistic coefficient basis for the datasets on which the HASDM calibrated density model was build. The use of such long time series ensured that shorter period fluctuations in the density model error have averaged out. However, the initial bias in Jacchia 71, as well as the mean effect of the long-term drift in true densities since the creation of the model, were hereby incorporated in the ballistic coefficients, the resulting density data, and the resulting HASDM model output.

It is important to note here that the Jacchia 71 model [16, 17], was based on orbit analyses made by Jacchia and Slowey in the 1960s [18, 19, 20], making use of a fixed drag coefficient of 2.2 for all satellites, regardless of shape. The scale of density models in these early years and later decades was set by Jacchia's choice for $C_\mathrm{D} = 2.2$, based on a representative value for a spherical object. Hedin's work on spectrometer data in the early 1970s, which eventually led to the MSIS series of models [14, 15, 26], made extensive use of Jacchia's models [13].

3. PHYSICAL DRAG COEFFICIENTS

To get data on the true absolute scale of thermospheric density, it is required to use basic physical principles to compute the drag force in the analysis of accelerometer and orbit tracking data. In contrast to the estimated drag coefficients discussed earlier, this leads to a *physical drag coefficient*. The theory behind what is commonly named rarefied aerodynamics, or, alternatively, free-molecular flow, is available in many publications from the early days of the space age [31, 30]. The practical usefulness of such theory recently came to light in the processing of CHAMP accelerometer observations into density data [22, 33, 7]. Modern summaries of this theory, in various level of detail, are available as well [24, 11, 29, 7], therefore the theory and associated equations will not be described in detail here. The theory has also been implemented in software making use of Monte Carlo test particle methods, for computations on arbitrarily complex shapes [1, 10, 29].

In principle, the theory in the above references is exact, but certain inputs are not precisely known. For example, the theory takes into account important phenomena such as the effect of the random thermal motion of the atmospheric particles. This effect is expressed in terms of the *speed ratio* of thermal velocity over the bulk velocity of the atmosphere with respect to the gas. The thermal velocity depends on the molecular mass of the particles, as well as on their temperature. The physical drag coefficient therefore becomes dependent on the atmospheric temperature and composition. Satellites with elongated shapes, such as the recent, current and future accelerometer missions (CHAMP, GRACE, GOCE, Swarm) are especially sensitive to the speed ratio, because of the additional shear force exerted by the moving particles on the panels of the satellite that are oriented close to parallel to the flow.It is clear that future missions with accelerometers should therefore be equipped with independent sensors for these parameters. In the meantime, only modelled values can be used, and the proposed standard will give recommendations on this.

An additional very important component of the theory to compute physical drag coefficients is the gas-surface interaction, which describes the spatial distribution of the particles after they have interacted with the spacecraft wall, and the change of their temperature after this interaction, expressed in terms of the so-called *energy accommodation coefficient*. Experiments to characterise the gas-surface interaction have been done both in labaratories on the ground [11] as well as in space [12, 23, 28], but the results have in general not been compatible. The proposed standard for computing physical drag coefficients will make recommendations based on the space-based experiments. Information on accommodation coefficients can in principle be obtained by studying the effects of different aerodynamic interactions on the same spacecraft (i.e. drag, lift and torques), because the sensitivity to the energy accommodation for these interactions is different. The optimal accommodation coefficient would be the value that brings consistency to measured aerodynamic accelerations and torques.

4. APPLICATIONS TO SPACE-DEBRIS RELATED PROBLEMS

The proposed standard for computing satellite drag coefficients will have an effect on research in the field of space debris in several ways. First of all, the increased consistency between several thermosphere density data sets will lead to more consistent empirical density models. This means that there should be less variation in the future between life time analyses based on various empirical atmospheric models. The increased consistency will also make it easier to characterize long-term density trends in the available data, and to characterize the solar-activity dependency of total density and the density trends to a higher accuracy. If there is sufficient reason to believe that density trends will continue in the future, these trends should be included in thermosphere density models. This could significantly affect predictions for the evolution of the low Earth orbit space debris environment, which will in turn affect mitigation procedures.

Finally, some mission planners and spacecraft operators will in the future be able to implement the computation of physical drag coefficients according to the new standard. This will only be feasible if sufficient information on the geometry and orientation of the satellite is available. The benefit will be a computation of the drag acceleration which is consistent with the observations that were used for the model. For all other objects, which include the majority of space debris objects, it will probably remain a better option to continue to use an estimated drag coefficient. Whether the constant drag coefficient estimate can perhaps be improved by modulating it with variations isolated from computations on a physics based drag coefficient, based on true atmospheric temperature and composition, will have to be investigated.

5. CONCLUSIONS

There is a strong need for improved consistency between thermospheric density models, and between these models and data sets, especially when it concerns the absolute scale of thermospheric density. Besides improvements in the characterisation in terms of geometry and attitude of space objects, such consistency can for a large part be achieved by using a standardised method for the computation of the aerodynamic force on a satellite. Through the more consistent aerodynamic analysis of accelerometer-carrying satellites, and space objects used in the analysis of orbital decay, this will lead to more consistent thermosphere models. These models can in turn lead to more accuracy and consistency when used in predictions of orbital lifetime, and in predictions of the future evolution of the low Earth orbit space debris environment.

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