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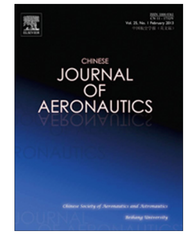

Estimation of ballistic coefficients of space debris using the ratios between different objects

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Abstract This paper proposes a new method to estimate the ballistic coefficient (BC) of low earth orbit space debris. The data sources are the historical two-line elements (TLEs). Since the secular variation of semi-major axes is mainly caused by the drag perturbation for space objects with perigee altitude below 600 km, the ballistic coefficients are estimated based on variation of the mean semi-major axes derived from the TLEs. However, the approximate parameters used in the calculation have error, especially when the upper atmosphere densities are difficult to obtain and always estimated by empirical model. The proportional errors of the approximate parameters are cancelled out in the form of ratios, greatly mitigating the effects of model error. This method has been also been validated for space objects with perigee altitude higher than 600 km. The relative errors of estimated BC values from the new method are significantly smaller than those from the direct estimation methods used in numerical experiments. The estimated BC values are used for the prediction of the semi-major axes, and good performance is obtained. This process is also a feasible method for prediction over a long period of time without an orbital propagator model.

1. Introduction

At operationally important orbits, there is a significantly increased amount of space debris created by spacecraft launch, loss, collision and explosion.[1,2] The presence of such debris causes a risk of collision, which threatens the safe operation of aircraft.[3–5] Management of the space debris population, which includes its cataloguing, prediction and mitigation, is crucial for the continued security of the space environment. For this reason, many methods have been proposed for space debris control and removal.[6–9]

Since space debris is consistently increasing, it is becoming ever more important to confirm its origin and assert clear legal responsibility. However, because of the large number and small size of space debris, cataloguing based on direct observation is difficult, and a ‘‘group catalogue‘‘ is a more appropriate and efficient method.[10] The cataloguing of debris should be started immediately following its production, and debris derived from the same object should be processed together as a group. Space debris, more or less, maintains the orbit of

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its parent satellite. Thus, debris objects from the same parent have similar orbital elements and there is stable variable relationship between the values of their parameters. The ratios between these parameters provide new information for a debris group. Based on this, the state of individual debris pieces can be deduced from other debris in the same group. This information can be used as a criterion for judging which debris group a particular piece of debris belongs to, and the "group catalogue" can be achieved.

A ballistic coefficient (BC) is an important parameter for the research of space objects and consists of object's drag coefficient (C_D), mass and the cross sectional area in the direction of motion relative to the atmosphere. The atmospheric drag is a significant perturbing force for low earth orbit (LEO) space objects. The physical properties of the upper atmosphere and the ballistic coefficients of the space objects are needed for the calculation of the atmospheric force. The BC value is usually unknown for space debris and hard to measure. Thus, many methods have been proposed to estimate this parameter.

One way is to use the additional parameter B^* given in the two-line elements sets (TLEs).[11] However, the B^* is a fitting parameter in the process of producing the TLEs, and includes the biases related to model error.[12] Moreover, the value of B^* may even be negative in TLEs.[13] Thus, the B^* is an inaccurate and unreliable estimation of the satellite's ballistic coefficient.

Combined with the atmospheric drag equation, the BC value can be obtained from the filtering process. However, since stable and accurate measurements cannot be obtained, accurate target motion estimation is difficult to extract, and this process has very low accuracy.[14]

Using satellite track data through a 30-year historical time span, a batch least-squares differential correction algorithm is used to estimate the ballistic coefficient for the use of high accuracy satellite drag model (HASDM).[15,16] Since this method is, to a large extent, based on measurement data, it cannot be widely used for space objects.

The methods used in recent years have always estimated ballistic coefficient from long-term TLE data, e.g. the methods proposed by Picone et al.,[17] Saunders et al.[18] and Sang et al.[19] Based on the simplified relationship between mean motion and atmospheric drag, the atmospheric drag can be estimated through the mean motion extracted from the TLEs. The results are obtained with use of over 30 years of TLE data. However, since orbit propagator and empirical atmospheric models are used in those methods, accuracy depends on precise modeling and is limited. Consequently, of the quality of an estimated ballistic coefficient is dependent upon model accuracy.

From the works mentioned above, it can be found that the most difficult aspect of BC estimation is the availability of the accurate values for the parameters needed. Many cannot be measured and use empirical models for approximation. This paper presents a method to estimate the ratios of the ballistic coefficients between different objects. The proportional errors of the approximate parameters are cancelled out in the form of ratios, greatly mitigating the effects of the model error. Through this approach, the relative error of estimated BC values is significantly reduced compared with direct estimation methods. Moreover, it has been validated that this approach can be used for the objects with a perigee altitude higher than 600 km. The proposed method is used for space debris from a debris group, and results show stable ratios for estimated BC values between different debris objects. These ratios can be used to confirm that the debris objects originated from the same source and also to deduce the states of debris objects from the others in the same group. This process provides new information about the debris group and gives theoretical and methodological support for a group catalogue. The estimated BC values are also used for the prediction of semi-major axes without an orbital propagator model.

The paper is organized as follows: Section 2 proposes a comparison approach to estimate the ballistic coefficient. The fitting process for the change of semi-major axes is necessary and presented in Section 3. The results and analyses of numerical experiments are shown in Section 4. Section 5 tests the proposed method for the LEO objects higher than 600 km in perigee altitude. The method is used for space debris in Section 6. Section 7 discusses the inverse use of the proposed approach for orbital prediction. Finally, conclusions are drawn in Section 8.

2. Ballistic coefficient estimation

2.1. Atmospheric drag

Atmospheric drag is a nonconservation force and continuously affects orbit semi-major axes and orbit period decrease.[20] For LEO objects, atmospheric drag is the major source of the secular term on semi-major axes. The mean semi-major axis is a mean orbital element without periodic terms.[21] The variation of mean semi-major axes does not include periodic gravitational perturbation, and remaining secular gravitational terms are small.[17] Thus, the variation in mean semi-major axes mainly reflects the effects of atmospheric drag.

The atmospheric drag on an object will continually decrease the osculating semi-major axis a, according to,[22]

$$\frac{\mathrm{d}}{\mathrm{d}t}a = \frac{2a^2 v}{\mu}\dot{\boldsymbol{v}}_{\mathrm{D}} \cdot \boldsymbol{e}_v \tag{1}$$

where μ is the product of the gravitational constant and the mass of the Earth, v is the speed of the object, $\boldsymbol{e}_v$ is the unit vector in the direction of $\boldsymbol{v}$, and $\dot{\boldsymbol{v}}_{\mathrm{D}}$ is the acceleration of the object due to drag, given by g

$$\dot{\boldsymbol{v}}_{\mathrm{D}} = -\frac{1}{2}\rho \mathrm{BC}|\boldsymbol{v} - \boldsymbol{V}|^2 \cdot \boldsymbol{e}_{\boldsymbol{v}-\boldsymbol{V}} \tag{2}$$

where ρ is the atmospheric density at that altitude, $\boldsymbol{V}$ is the atmospheric wind velocity vector, and $\boldsymbol{e}_{\boldsymbol{v}-\boldsymbol{V}}$ is the unit vector of the object's motion relative to the atmospheric wind. The ballistic coefficient BC is defined as

$$\mathrm{BC} = C_{\mathrm{D}}\frac{A}{m} \tag{3}$$

where C_D is the drag coefficient of the object, A is the cross sectional area of the object in the direction of the object's motion relative to the atmosphere, and m is the object's mass.

Based on Eq. (1), the change rate of the mean semi-major axis due to atmospheric drag is derived by Picone et al.[17] as

$$\frac{\mathrm{d}}{\mathrm{d}t}a_{\mathrm{D}} = -a_{\mathrm{m}}^2\mu^{-1}\rho \mathrm{BC}v^3 F \tag{4}$$

where a_m is the mean semi-major axis, and the dimensionless wind factor F is given by