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Estimating Physical Quantities of an Unknown Object

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Environmental perturbations in orbit affect the precise orbit determination of an object. Especially in Low Earth Orbit (LEO), atmospheric drag plays a key role in determining the accurate position of the target. Determining the effect of atmospheric drag on a body is challenging due to uncertainties in choosing the appropriate atmospheric model and the lack of knowledge about the object's physical properties. The goal of my MSc. thesis is to compute the unknown physical properties (mass, area, and drag coefficient). These properties are collectively represented by a parameter called the Ballistic Coefficient (BC) and it plays a significant role in the re-entry analysis. Four methodologies can be adopted to estimate this parameter. Testing and validating are done using TLE and Orbit propagation approaches.

Key words → **Ballistic coefficient, TLE, atmosphere, re-entry, orbit propagation**

Ballistic Coefficient Estimation

The ballistic coefficient (BC) is a key parameter in the atmospheric drag acceleration equation, expressed as:

$$BC = \frac{A}{m} C_D$$

where,A is the cross-sectional area of the object in the direction of the object's motion relative to the atmosphere,m is the object's mass and C_D is the drag coefficient of the object. Since the physical properties of these objects are often unknown, estimating the BC is crucial to understanding the impact of atmospheric drag forces on the object. After extensive research, four methods for estimating BC have been identified.

Alternative Approaches

Orbit Determination Approach

Incorporates the BC into the object's orbit state vector, along with position and velocity and employs least squares orbit determination processing to obtain real-time estimates[1].

Machine Learning Approach

Improves atmospheric modeling by incorporating space weather indices and using a training dataset that enhances the estimation of atmospheric densities, which significantly impacts the estimation of the BC using Neural Networks[2].

TLEs Approach

Sang [3] approximates the BC of LEO objects from TLE data following the expression.

$$BC = -\frac{\mu \Delta_{t_1}^{t_2} a_D}{\sum_{t=t_1}^{t=t_1} a_{\mathrm{m}}^2 \rho v^3 F \Delta t}$$

Simplified General Perturbation(SGP4) is used to find the position and velocity for the corresponding Δt . After extensive experiments Δt is selected to be 20 minutes.Most uncertain parameter inside this equation is the atmospheric density (ρ). Three atmospheric density models were tested.

- NRLMSIS-2.0
- Jacchia-Roberts
- MSIS-90

TLEs have been filtered to remove non-decaying objects and TLEs with negative B*. Mean value is considered to be the reference BC of the object. Testing has been done using GRACE satellite.

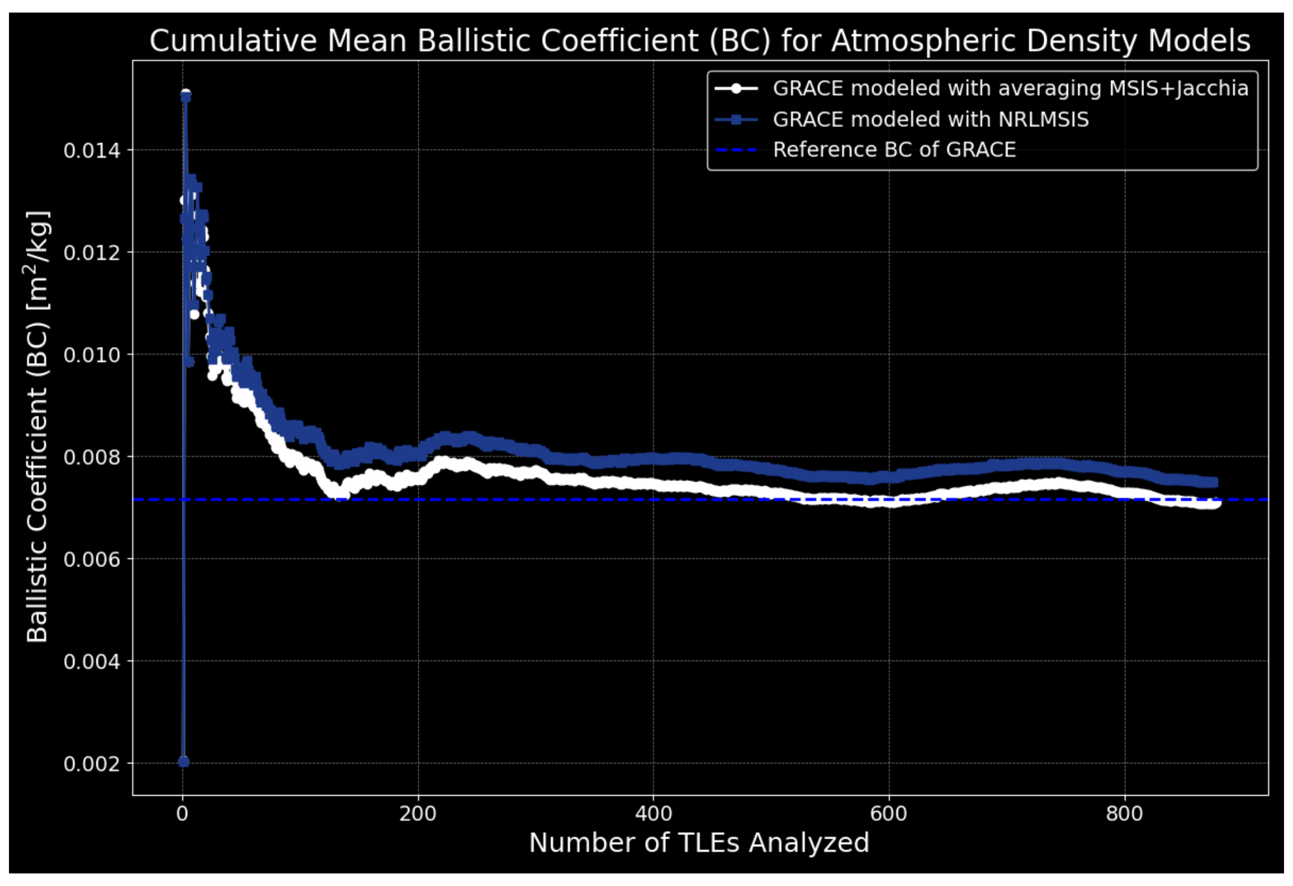

Figure 1:Testing done for GRACE

Orbit Propagation Approach

Applying a more advanced perturbation model with the decaying objects in theory should give a more accurate estimation of the BC. This is where the Orbit Propagation approach can be considered by Saunder's[4].

The selected propagator is Tudatpy[5], due to its comprehensive suite of built-in force models, including third-body perturbations, solar radiation pressure models, and the NRLMSIS model which are needed to fully cover the path of Saunder. The semi-major axis decay due to drag is computed according to J.Gondelach [6]:

$$\left.\frac{da}{dt}\right|_{\text{drag}} = 2\frac{a^2}{\sqrt{\mu p}}\left[f_{r_{\text{drag}}} e \sin\theta + f_{t_{\text{drag}}} \frac{p}{r}\right]$$

It will be numerically integrated for the time of the difference between epoch times for the TLE pairs of the object. After the computation the difference between the obtained semi-major axis decay and the semi-major axis value difference computed from mean motion of TLE pairs will be evaluated as Δa_{diff} .

Initial BC for the propagation is found using the B* available in TLEs and after it will be iterated until Δa_{diff} converges to 10^{-6} km. Secant method is applied to iterate the BC until the convergence is achieved. This approach is most applicable for spherical and tumbling objects due to assuming the area-to-mass ratio is the same as atmospheric drag acceleration for solar radiation pressure ,and the drag coefficient to de-couple the BC is given using the altitude-based drag coefficient data available with Stela propagator[7] which is only applicable for tumbling and spherical objects. Reference object selected is Starlette due to having a spherical shape and known min, max, and average BC values.

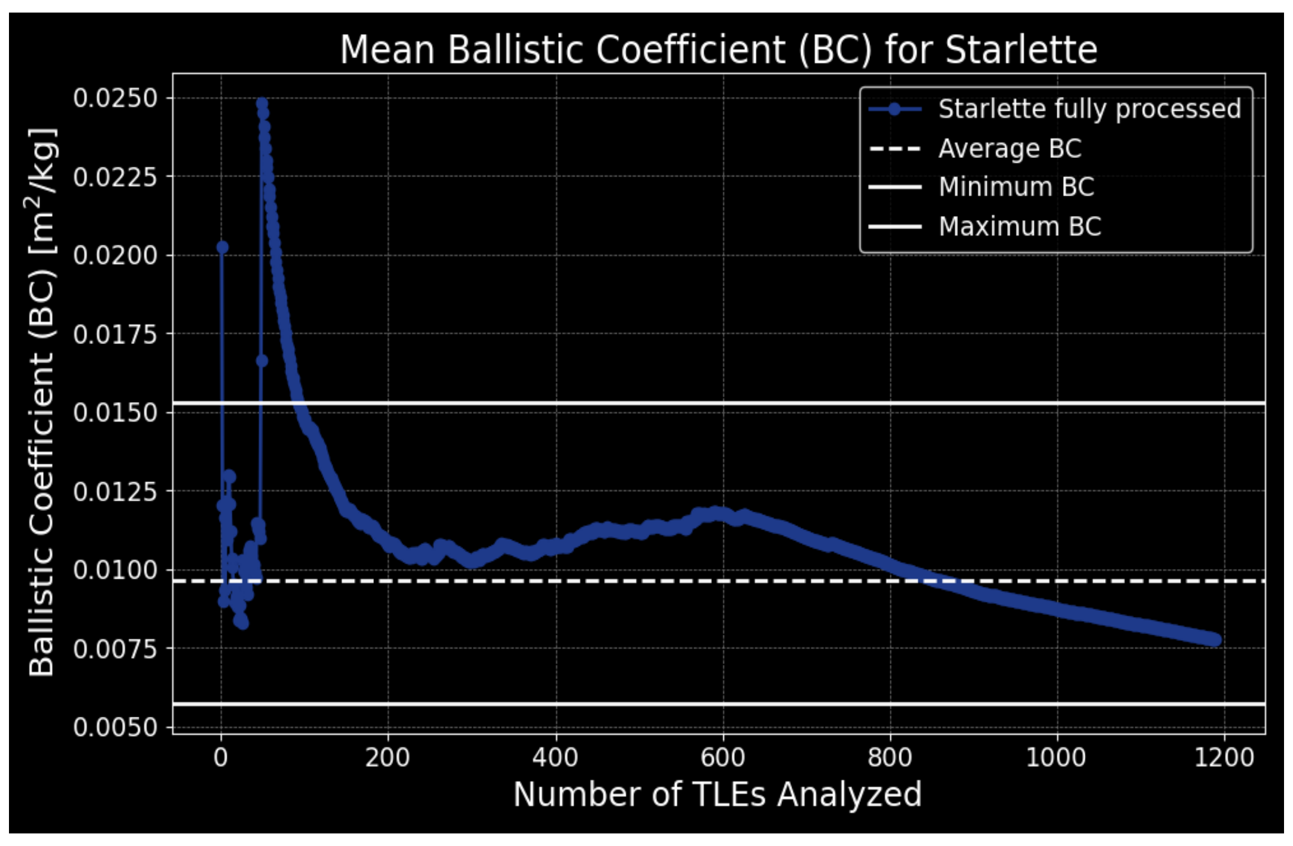

Figure 2:Testing done for Starlette

Results

After testing the approaches with the reference test objects, the comparison has been done with a common object where it is located in LEO and with spherical shape and known BC. After going through the literature Starshine satellite has been found as a suitable candidate knowing its reference BC values.

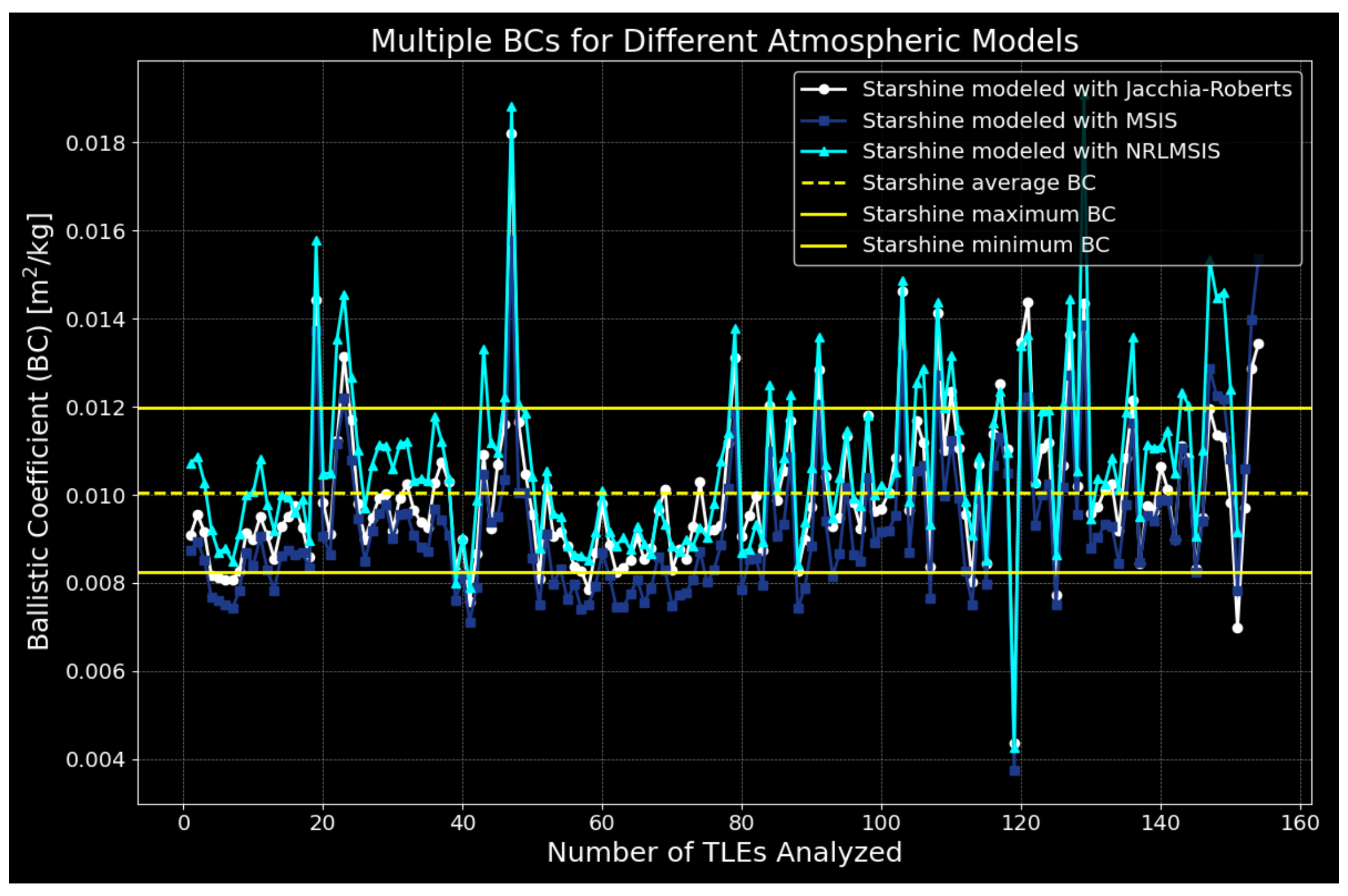

Figure 3:TLEs Approach Results

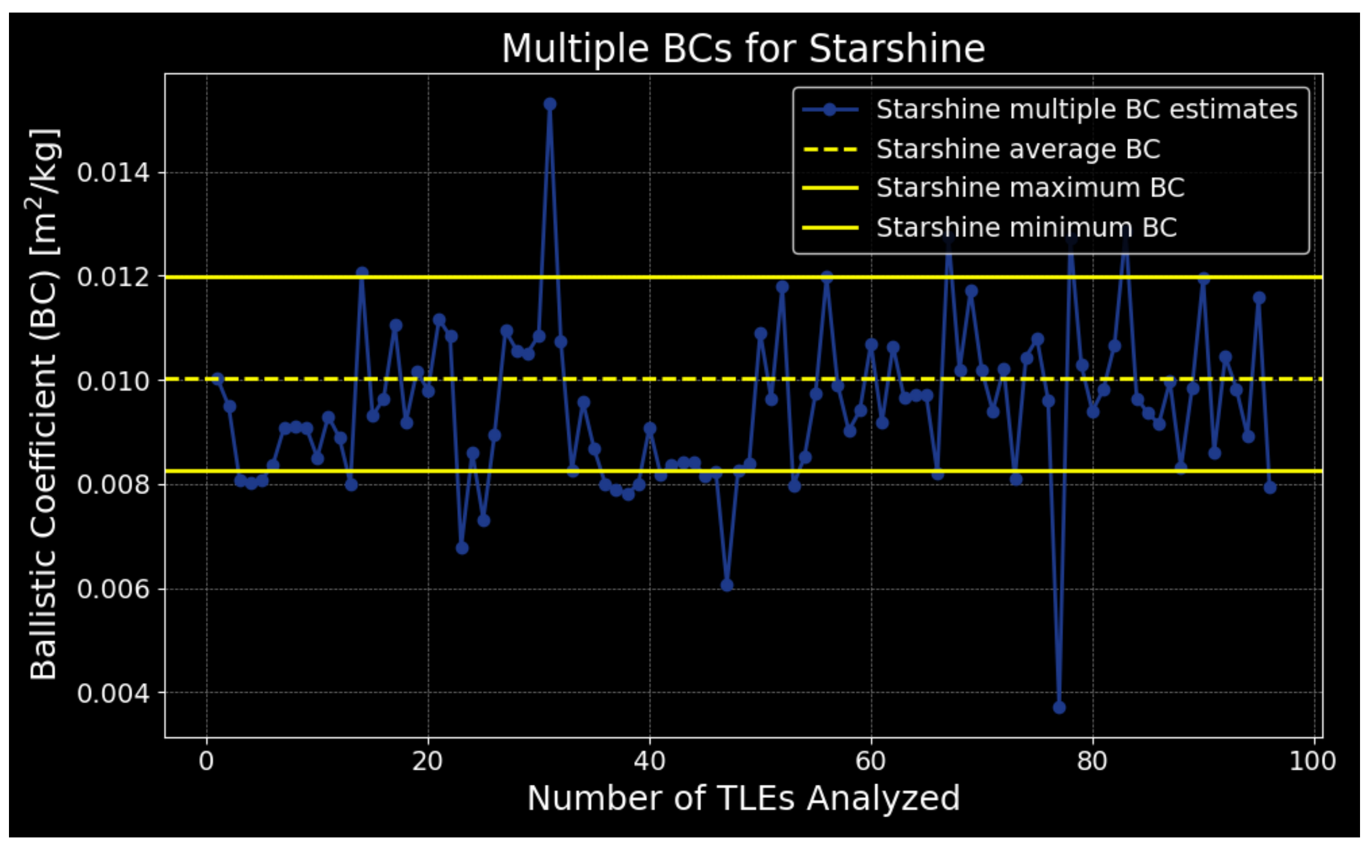

Figure 4:Orbit Propagation Approach Results

Reference BC: 0.0105 [m^2/kg]	Mean BC [m^2/kg]	Relative Error[%]
Starshine BC computed with TLEs approach	0.01002	4.571
Starshine BC computed with Orbit Propagation Approach	0.01008	4.019

Table 1:Tabulated data of final BC with estimated error

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