

Estimation and Prediction of Long-duration Aerodynamic Drag Effect on Floating LEO Debris using the EDAC-adapted Model

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Abstract. The reliable estimation of atmospheric drag-induced orbital decay is quite challenging due to the limited representation of solar and non-solar forcing mechanisms in atmospheric density models and the complex operational dynamics of some spacecraft. Such uncertainties widen the gap between modelled estimates and actual orbital parameters and also hamper the ability of mission designers and/or operators to accurately estimate the remaining lifetime of spacecraft in orbit. Medium- to long-term estimation or prediction of a defunct spacecraft orbit is even more challenging when the object is no longer subject to ground commands. In this work, we present a robust atmospheric drag model adapted to the ephemeris data-assisted calibration (EDAC) simulation method, to improve the simulation and prediction of short-, medium- and long-term evolutions of the orbital decay of LEO objects, as functions of specific solar-geophysical indices. We show that the simulated long-term evolution of atmospheric drag-induced orbital decay compares well with the historical data of objects and confirms its validity using independent data. We present the EDAC-adapted model as a novel and effective approach to atmospheric drag prediction.

Introduction

The long-term estimation (or simulation) of atmospheric drag effects on spacecrafts in low Earth orbit (LEO) is particularly useful for satellite orbital prediction and maintenance, collision avoidance and debris tracking, re-entry estimations, mission plannings and constellation design, and space weather impact assessments [1-4]. The continuous long-term comparison between observed orbital decay and simulated drag can help to improve atmospheric density models and empirical drag coefficients (and vice versa), leading to improved predictive accuracy of space assets (e.g., [5, 6]). However, accurate modelling of drag over a long period is quite challenging due to a number of complex and interrelated factors such as unpredictable solar-geophysical events and the associated complex variability in atmospheric density models, complex spacecraft geometries and other perturbative forces [4,7-11]. The uncertainties introduced by these factors can widen the gap between observational data and simulated results – a scenario that can hamper the ability of mission designers and operators to estimate the lifetime of on-orbit spacecraft. Since the changing physical or orbital parameters of spacecraft (which is associated with their design evolution) requires a repetitive lifetime estimations for appropriate mission planning [1], a robust and scalable model is crucial for improved knowledge of atmospheric drag effects on their orbits.

Continuous developments in empirical, physical, and hybrid modeling methods have undoubtedly improved atmospheric drag estimations, including the integration of real-time space weather indices [12], data assimilation and machine learning techniques (e.g., [13, 14]), dynamic drag coefficient (Cd) modelling (e.g., [3,15,16]), probabilistic lifetime estimations [8] and hybrid



physical-empirical comparative analyses [17]. However, many of these investigations have been focussed on active and/or controlled spacecraft with achievable stable flight configurations [1]; making the simulations less complex. The long-term estimation of a defunct and uncontrolled spacecraft orbit is more challenging, especially when the object is no longer responding to ground commands, which is the case for most space debris. In this work, we use a robust drag model that is adapted to the ephemeris data-assisted calibration (EDAC) simulation method, to improve the simulation and prediction of the evolution of orbital decay of LEO debris, as a function of solar-geophysical indices.

Data and method

In this work, we use a numerical integration method for orbital propagation using spherical coordinate system. The decay rate of the spacecraft orbital radius (r) or semimajor axis (a) is determined as a consequence of the rate of change of the satellite's radial velocity ($\dot{v}_r$). $\dot{v}_r$ is adapted to spacecraft ephemeris data-assisted calibration (EDAC) method by introducing a unitless normalisation coefficient (γ_{mod}) that minimizes the gap between the actual orbit decay (based on spacecraft ephemerides) and the modeled or simulated decay. Thus achieving a long-duration orbital decay rate (due to atmospheric drag) using the following set of coupled equations [4, 18]:

$$\begin{aligned} (1) \quad \dot{r} &= v_r \\ (2) \quad \dot{v}_r &= -\dot{\phi} r^2 \rho \left(\frac{A_s C_d}{m_s} \right) \\ (3) \quad \dot{\phi} &= \frac{v_\phi}{r} \\ (4) \quad \ddot{\phi} &= -\frac{1}{2} r \rho \dot{\phi}^2 \left(\frac{A_s C_d}{m_s} \right) \end{aligned}$$

where v_r and v_ϕ are the radial and tangential velocity components, $\dot{v}_r$ and $\ddot{\phi}$ are the radial and azimuthal accelerations, respectively. A_s , C_d and m_s are, respectively, the projected area in the direction of motion, drag coefficient and mass of the spacecraft. ρ is the altitude-dependent atmospheric density, obtained from the Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Extended (NRLMSISE) model [19]. To achieve long-duration orbital decay trajectories (that aligns closely with historical decay records of LEO objects) we applied a drag normalization coefficient (DNC) to the radial velocity component. The DNC is expressed as

$$(5) \quad \gamma_{mod} = \frac{\Delta r_{act}}{\Delta r_{est}} = \frac{r_{at} - r_{af}}{r_{et} - r_{ef}}$$

where Δr_{act} is the difference between the actual positions at time t (r_{at}), and some future time f (r_{af}), whereas Δr_{est} is the difference between the estimated positions r_{et} (r_{ef}) at the respective times $t(f)$. The goal of EDAC is to drive towards a unitary value of γ_{mod} (i.e., $\gamma_{mod} \sim 1$).

Applying DNC is important because simplified spherical coordinate drag models tend to over- or under-estimate long-term orbital decay when using nominal aerodynamic coefficients alone. In LEO, unmodelled effects such as attitude variations, complex geometry, atmospheric composition uncertainty, and along-track averaging tend to accumulate over thousands of orbits. The DNC acts as a physically motivated calibration factor that absorbs these unresolved processes without altering the governing dynamics. This approach is suitable for long-duration decay studies where reproducing observed semi-major axis evolution is more critical than resolving short-period oscillations. It also provides a realistic, validated bridge between simplified physics and historical orbital decay records.

This form of γ_{mod} (equation 5) have been previously used to simulate the orbital decay of selected LEO objects for long- and short-term regimes (e.g., [18]). However, the resulting γ_{mod} value sometimes require some adjustments to achieve a good drag estimate. The trends in the simulated mean height and orbit decay rate (ODR) have shown that γ_{mod} significantly depends on

solar activity and the spacecraft's orbital and ballistic parameters. To achieve an improved γ_{mod} , we leveraged these observed trends to develop and implement the equation for the DNC (γ_{mod}) in the long-term orbital decay simulations. The dimensionless normalization coefficient (γ_{mod}) that scales a spacecraft's drag-driven decay rate $\dot{\alpha}$ to a known reference condition based on the influencing factors of ballistic coefficients $B = A_s C_d / m_s$, atmospheric density $\rho(h)$ at the satellite altitude h and orbital eccentricity of the spacecraft can be expressed as:

$$(6) \quad \gamma_{mod}(h_p, B, e) = \frac{\dot{\alpha}(h_p, B, e)}{\dot{\alpha}(h_{ref}, B_{ref}, 0)} \approx \left(\frac{B}{B_{ref}} \right) \cdot \left(\frac{\rho(h_p)}{\rho(h_{ref})} \right) \cdot \left(\frac{1-e}{1-e_{ref}} \right)$$

B_{ref} , h_{ref} and e_{ref} are the reference values for B , h and e , respectively. Our current implementation of the EDAC model assumes a satellite in a near-circular orbit where $e \sim 0$ such that the eccentricity factor, $[(1-e)/(1-e_{ref})]$, in equation 6 can be ignored. The mean effective atmospheric density of the spacecraft ($\bar{\rho}_{eff}$) at the spacecraft location can be used in place of the density at reference height ($\rho(h_{ref})$), which can be expressed as:

$$(7) \quad \bar{\rho}_{eff} = \frac{2(\sqrt{a_0} - \sqrt{a_1})}{B\sqrt{GM_e}(t_1 - t_0)}$$

We selected 6 catalogued debris for this investigation, based on height (typically LEO) and the ability to be measured from the ground using the satellite laser ranging (SLR) technique via retro-reflectors. The orbital and ballistic parameters are provided in Table 1. All the listed objects have near circular orbits so that $a \sim r$ as noted above. Their historical orbital (and ballistic) data were obtained from a comprehensive satellite catalogue (<https://in-the-sky.org/>) and ESA's DISCOSweb (<https://discosweb.esoc.esa.int/>). The objects' drag coefficients (C_d) were based on the shape-dependent recommendations contained in [20-22]. Solar-geophysical indices for the solar radio flux ($F10.7$) and geomagnetic Ap are from GFZ Helmholtz Centre for Geosciences database (<https://kp.gfz.de/en/data>) and were used as inputs to the NRLMSISE to obtain the spacecraft local time (SLT) density profiles. Implicit in the reminder of this text is that the F10.7 is in solar flux units (1 sfu = 10^{-22} Watts per square meter per Hertz (W/m²/Hz)) and Ap is in units of 2 nanoTesla (nT).

Table 1: The orbital and ballistic parameters of objects selected for investigation

	LEO Object	h (km)	m (kg)	A (m ²)	C_d	B (m ² /kg)	e	i (°)
1	1998-007A GFO-1	478.07	361.7	2.513	3.090	0.0214661	0.0800523	108.03
2	2005-031A OICETS	527.10	570.0	5.823	2.354	0.0240479	0.0078225	98.14
3	2011-076G ASAP-S	532.46	624.0	1.508	2.408	0.0058189	0.0048846	98.10
4	1999-064A HELIOS-1B	618.80	2544.0	9.274	2.200	0.0080196	0.0016220	98.27
5	1994-074A RESURS-O1	625.12	1900.0	11.656	3.253	0.0199562	0.0021570	97.75
6	2009-002E SOHLA-1	655.76	50.0	0.375	2.124	0.0159300	0.0058467	98.23

By incorporating Equation 6 with the appropriate space weather (density) and reference spacecraft parameters our drag model generates a suitable γ_{mod} for the long-duration propagation of a specific object's orbit. Table 2 shows the resulting γ_{mod} associated with each object. Using γ_{mod} , we simulated 6-month orbit decay evolution of the LEO objects (due to atmospheric drag effect) from January to June 2025.

Table 2: The γ_{mod} normalisation coefficient and the associated reference object parameters

	LEO Object	h_{ref} (km)	ρ_{ref} (kg/m ³)	A (m ²)	C_d	B_{ref} (m ² /kg)	e	γ_{mod}
1	1998-007A GFO-1	478.07	2.8260E-12	2.513	3.090	0.0214661	0.0800523	0.6618
2	2005-031A OICETS	527.10	1.6986E-12	5.823	2.354	0.0240479	0.0078225	0.6868
3	2011-076G ASAP-S	532.46	8.1800E-13	1.508	2.408	0.0058189	0.0048846	0.8590
4	1999-064A HELIOS-1B	618.80	2.1780E-13	9.274	2.200	0.0080196	0.0016220	0.8450
5	1994-074A RESURS-O1	625.12	3.3340E-13	11.656	3.253	0.0199562	0.0021570	0.5750
6	2009-002E SOHLA-1	655.76	1.3303E-13	0.375	2.124	0.0159300	0.0058467	0.8150

Results and discussion

Estimation of long-term aerodynamic drag effect

Figure 1 shows the actual mean height (h_{act}) obtained from the object's historical data and the simulated mean heights (h_{sim}) of satellites GFO, OICETS, ASAP-S, HELIOS, RESURS and SOHLA along with their corresponding orbit decay rates (ODR_{act}, ODR_{sim}), modeled as a function of the observed solar-geophysical indices during Jan-Jun 2025. The historical orbital data showed that the objects were orbiting Earth at the mean height of 478.1, 527.1, 532.46, 618.8, 625.12 and 655.8 km, respectively, on 1 January. Their respective actual and simulated mean heights (h_{act} and h_{sim}) after six months (on 30 June) are provided in Table 3. Their actual total orbit deviations (TOD_{act}) are 23.15, 12.7, 6.5, 2.8, 1.6, and 2.3 km, respectively, while their respective simulated total orbit deviations (TOD_{sim}) were 23.2, 13.3, 7, 2.8, 1.7, and 2.3 km, respectively. These values correspond to the standard deviation (σ) of 0.03, 0.25, 0.24, 0.02, 0.05 and 0.02 km, respectively, and a corresponding percentage error (δ) of 0.13, 1.93, 3.56, 0.89, 3.32 and 0.88%.

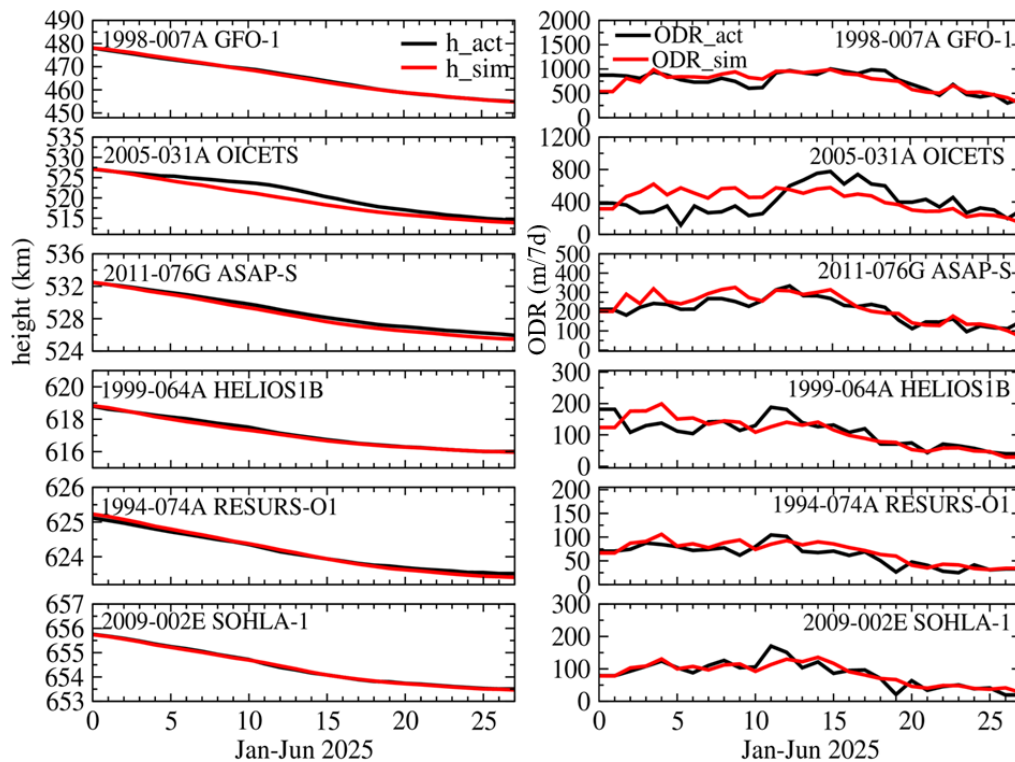


Fig. 1: Actual mean height (h_{act}) obtained from the object's historical data and the simulated mean heights (h_{sim}) of GFO, OICETS, ASAP-S, HELIOS, RESURS and SOHLA and their corresponding orbit decay rates (ODR_{act}, ODR_{sim}) during January - June 2025. The x-axes timelines are in weeks.

Table 3: The actual and simulated mean heights of the objects during Jan-Jun 2025

	Catalogued Object	Actual mean h (km)			Simulated h -OSI (km)	
	LEO Object	01.01.2025	30.06.2025	TOD	30.06.2024	TOD
1	1998-007A GFO-1	478.07	454.92	23.15	454.86	23.21
2	2005-031A OICETS	527.10	514.40	12.70	513.90	13.20
3	2011-076G ASAP-S	532.46	525.95	6.51	525.47	6.99
4	1999-064A HELIOS-1B	618.80	616.01	2.79	615.96	2.84
5	1994-074A RESURS	625.12	623.52	1.60	623.41	1.71
6	2009-002E SOHLA-1	655.76	653.51	2.25	653.47	2.29

In the present analysis, the mean σ and δ were 0.102 km and 1.79%, respectively. Four spacecraft show very small δ (0.13% (GFO), 0.89% (HELIOS), 0.88% (SOHLA), 1.93% (OICETS)), which are good fits for long-term decay modeling, whereas two spacecraft (having $\delta \approx 3.56\%$ (ASAP-S) and 3.32% (RESURS)) showed significantly larger deviations. There was also a very close agreement between the actual and simulated decay of three of the objects with low σ values of 0.02 (SOHLA), 0.03 (GFO) and 0.02 (HELIOS). The observed deviations in the h -sim and ODR_sim may be due to factors not well represented in the model such as poorly resolved normalization coefficients, unspecified differences in attitude or drag area histories, change in material or surface properties (affecting accommodation coefficients), questionable estimated mass or orientation assumptions (e.g., [1,8,23,24]). Nevertheless, the simulated mean altitudes (h -sim) and simulated orbital decay rates (ODR_sim) agree well with the historical orbital data of the objects and can be considered acceptable for mission purposes (such as lifetime planning and debris mitigation).

Prediction and validation of drag-induced orbital decay

We applied our model to predict the orbit decay of three LEO objects using NASA's estimate of solar-geophysical activity for the 25th solar cycle. (<https://www.nasa.gov/solar-cycle-progression-and-forecast/>). The predicted solar-geophysical indices ($F10.7$ and Ap) represent the smoothed values for 13 months, based on a best estimate given as the 50th percentile value, along with the statistical 95th and 5th percentiles. The orbital decay was simulated according to the estimated levels of the indices and range of predicted values for each object. Figure 2 shows the model-based prediction of orbital decay evolution associated with the observed solar-geophysical indices for Jan-Mar 2025 and the predicted activity for Apr-July 2025. Details of the predicted decay are provided in Table 4. Based on the levels of estimated indices, the range of simulated mean height of the objects were 525.8 - 529.7, 617.51 - 618.25 and 716.89 - 717.71 km, respectively.

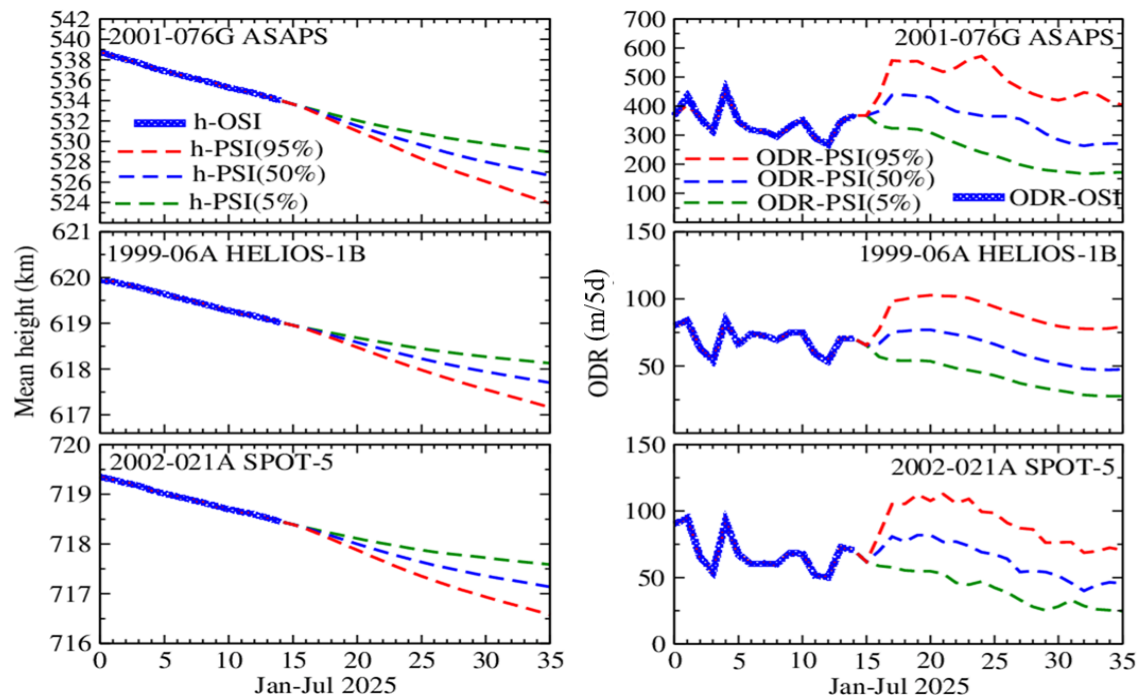


Fig. 2: The observed/predicted mean height (h) and orbit day rate (ODR) of 3 LEO objects, associated with the observed solar-geophysical indices (OSI) for Jan-Mar 2025 and the predicted solar-geophysical indices (PSI) for Apr-July 2025. The thick blue lines are the observed values, whereas the green, blue and red dashed lines are the predicted values.

Table 4: Predicted mean heights of the objects

Mean height (h) analysis							
	Catalogued LEO object	h-OSI (km)			predicted h-PSI (km)		
	LEO object	01.01.25	31.03.25 (ACT)	31.03.25 (SIML)	30.04.2025 $F_{10.7}=161.97$ $A_p=14.5$	31.05.2025 $F_{10.7}=179.47$ $A_p=14.77$	30.06.2025 $F_{10.7}=177.4$ $A_p=15.0$
1	2011-076G ASAPS	538.77	533.52	534.01	531.31±0.58	529.31±1.32	527.75±1.95
2	1999-064A HELIOS-1B	619.93	619.02	619.02	618.54±0.12	618.17±0.26	617.88±0.37
3	2002-021A SPOT-5	719.34	718.46	718.45	717.95±0.13	717.58±0.28	717.30±0.41

To validate the predicted regime, we obtained and show in Fig. 3 and Table 5 the historical orbital data of the objects during Jan-Jun 2025. The actual heights of the objects at the end of June were 525.16, 617.11 and 717.52 km, respectively, which indicates that the actual mean heights of two (ASAP-S and HELIOS) of the objects lie slightly outside their error bar. This scenario may be unrelated to the model performance but on the predicted solar-geophysical indices for the interval. The predicted mean $F_{10.7}/A_p$ for April, May and June were 162/14.5, 179.5/14.8 and 177.4/15, respectively, while the respective observed mean values were 162.3/17.6, 135.3/17.3 and 131.3/20.5. The obvious difference between the predicted versus observed regimes is that the predicted values for $F_{10.7}$ were higher during the 3-month interval in contrast to the A_p predictions, which were lower than observed. Nonetheless, the predicted estimates were within an acceptable range and can potentially provide a testbed for the model improvement. As the results presented here are still in their preliminary stage, it would be premature to draw conclusions regarding the computational limitations of the model. However, the results of the model can be improved by; (i) diagnoses of observed outliers through the inspection of parameters such as attitude or area history, possible mass changes and exposure to uncaptured solar energetic events, (ii) use of precise orbit determination (POD) and accelerometer data (where available) to estimate satellite-specific drag coefficients, (iii) replacing a single global coefficient with a parametric

normalization or applying piecewise calibrations across altitude bands, and (iv) validating the approach using cross-validation and providing operational procedures for periodic recalibration after major solar events (e.g., [1,25,26]). Also, orbit propagation and/or prediction longer than 6-month duration (as done here) may require further refinement of the normalisation coefficients used here to conclusively assess the model’s stability and predictive accuracy over the extended timescales that are typical of long-term orbit prediction.

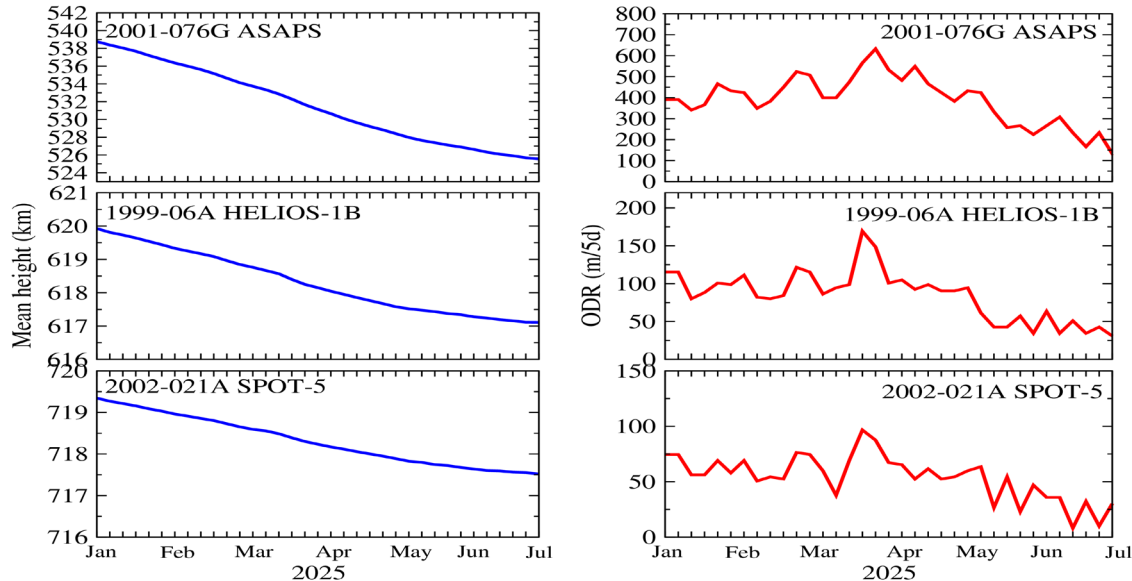


Fig. 3: Historical orbital data of the objects obtained for the period of Jan-Jun 2025 for validation of model-driven prediction of their orbital decay evolution.

Table 5: Observed mean heights of the LEO objects

Historical orbital data analysis							
	Catalogued LEO Object	h-OSI (km)			Actual h (km)		
	LEO Objects	01.01.25	31.03.25 (ACT)	31.03.25 (SIM)	30.04.2025 F10.7=162.52 Ap=17.63	31.05.2025 F10.7=135.30 Ap=17.32	30.06.2025 F10.7=131.30 Ap=20.50
1	2011-076G ASAP-S	538.77	533.52	534.01	527.97	526.32	525.16
2	1999-064A HELIOS-1B	619.93	619.02	619.02	617.67	617.34	617.11
3	2002-021A SPOT-5	719.34	718.46	718.45	717.95	717.67	717.52

Conclusion

In this work, we simulated (and predicted) the orbital decay evolution of LEO debris with varying ballistic coefficients, as a function of solar-geophysical indices, using the ephemeris data-assisted calibration (EDAC) adapted model. The comparison between the actual and simulated decays yielded standard deviations (σ) ranging from 0.02 km to 0.25 km and percentage errors (δ) between 0.13% and 3.56%. These low deviations indicate strong consistency between the observed and modeled orbital decays, demonstrating the model’s high suitability for long- and medium-term orbital prediction and decay trend estimation. The small dispersion of errors across spacecraft with different ballistic properties further suggests that the normalization coefficient effectively captures the altitude-dependent drag variability. Minor residuals were likely attributable to unmodeled spacecraft-specific parameters such as attitude, surface characteristics, or temporal density variations. The model’s validation with independent data confirmed its predictive reliability and establishes a robust framework for further refinement. Overall, the performance of the model is good and consistent, supporting its application to both predictive and analytical orbit-decay studies.

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