Operational Responses to LEO Satellite Orbital Decay during the 25th Solar Cycle Maximum

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ABSTRACT

Planet is a leading provider of global daily Earth Observation imagery and geospatial analytics. Enabled in part by PlanetScope Monitoring, the largest constellation of Earth Observation satellites (around 150 Doves), we drive towards our mission to make change visible, accessible and actionable. Planet's Dove satellites operate within 380 - 550 km, which has been increasingly challenging as we approach the peak of the 25th Solar Cycle. Intense space weather around solar maxima increases atmospheric density throughout the Earth's thermosphere (85 - 600 km); This effect is the most pronounced at Low Earth Orbits (LEO) altitudes. Consequently the drag force that Doves experience within their operational altitudes increases dramatically as we approach solar maximum. In LEO constellations with limited maneuverability, mission lifetime is significantly shortened by heightened solar activity without accurate forecasting and the appropriate operational responses. Accurate forecasting of altitude decay is then of high importance in assessing and implementing operational responses. During 2023-2025, our LEO satellites orbit degraded at a faster rate than expected by predictions based on the Schatten model that is widely adopted as the industry standard by satellite operators. While the Schatten model has been a powerful tool in describing and forecasting solar flux in the 10.7 cm wavelength range (f10.7), recent Schatten predictions have not accurately reflected on-orbit flux values of the solar maximum. To ensure that we are accurately planning and assessing operational responses to the high flux, we adopted the Solar Cycle 25 model developed by the National Center for Atmospheric Research (NCAR). Instead of solely relying on solar magnetic cycles, the NCAR model also utilizes observations of previous sun-spot cycles to forecast f10.7 flux. In this work, we present both our operational responses to the solar maximum and utilization of the Lynker model to predict and evaluate the orbital lifetime utility of these responses. We also compare the forecasted improvements with actual improvements of each operational response. A critical improvement was achieved by experimenting with various differential drag configurations. The aim in our exploration was to minimize the impact of drag on our Planet's Doves while preserving separation within the fleet. This separation is key to providing our customers with timely and useful imagery. Another avenue of improvement was incorporating extra mass in our build to increase the ballistic coefficient. We conclude that not only is the NCAR model a valuable tool in forecasting space weather and subsequent satellite orbital lifetime, it is also an effective tool in evaluating operational responses to high atmospheric density.

1. INTRODUCTION

Planet's mission is to image the world daily, enabling visible, accessible and actionable change by providing global and daily Earth Observation imagery and geospatial analysis. This is enabled by PlanetScope Monitoring, a constellation of about 150 Doves that operate in the LEO environment of 380-550 km. Satellites operating within this altitude band pass through the thermosphere, a region of the Earth's upper atmosphere with low, but still significant air density. Through this region, satellites' orbits are affected by drag, causing altitude decay over time; the higher the gas density, the higher atmospheric drag a satellite operating within the thermosphere experiences [2]. While drag has been employed as an effective means of maneuvering [3, 4, 5], the induced altitude decay is a prominent cause of retirement and can cut mission lifetimes short. From a commercial perspective, enabling satellites to serve their full mission lifetime, up to regulatory limits, is crucial to provide consistent and high-quality products and services to customers. Drag within the thermosphere, and its fluctuation in response to external factors, is then an undeniable focus of analysis and prediction for mission design and operation.

The solar cycle describes the 11-year rotation of the Sun's magnetic poles and is often characterized by oscillating sunspot numbers. We are currently approaching the peak of the 25th solar cycle, estimated to last from 2024 to 2025. Due to the increased magnetic activity on the Sun's surface, the drag spacecraft experience within the thermosphere increases [2, 9]. It is widely accepted that the current solar cycle greatly deviates from the standard solar cycle model, resulting in a discrepancy between the expected altitude decay and the observed altitude decay of the PlanetScope Fleet [8, 12].

To accurately address and mitigate this risk of premature retirements due to altitude loss, Planet switched from the industry-standard Schatten model to the Lynker model, developed by McIntosh et al [6][7]. This decision was motivated by its higher fidelity to on-orbit flux levels and more accurate predictive capability [8]. Not only do we employ this model to predict satellite lifetime, but we also adopt the model to evaluate the efficiency of different operational responses under varying severities of space weather conditions. Since our Doves only employ differential drag as a means of maneuverability, we are unable to mitigate this decay through propelling ourselves to higher altitudes and need to rely on alternative methods to prolong satellite lifetime, such as changing our drag profile to reduce overall drag. Because we employ differential drag in part to maintain separation within the fleet for better Earth coverage by equally spacing out Doves launched within the same orbit, each change to our fleetwide differential drag configuration to combat solar weather is evaluated as a potential trade. The ability to accurately predict the efficiency of different strategies allows us to mitigate higher rates of altitude decay while protecting our company mission of providing daily and global Earth Observation imagery. This paper provides a summary of different operational responses evaluated by Planet using the Lynker model.

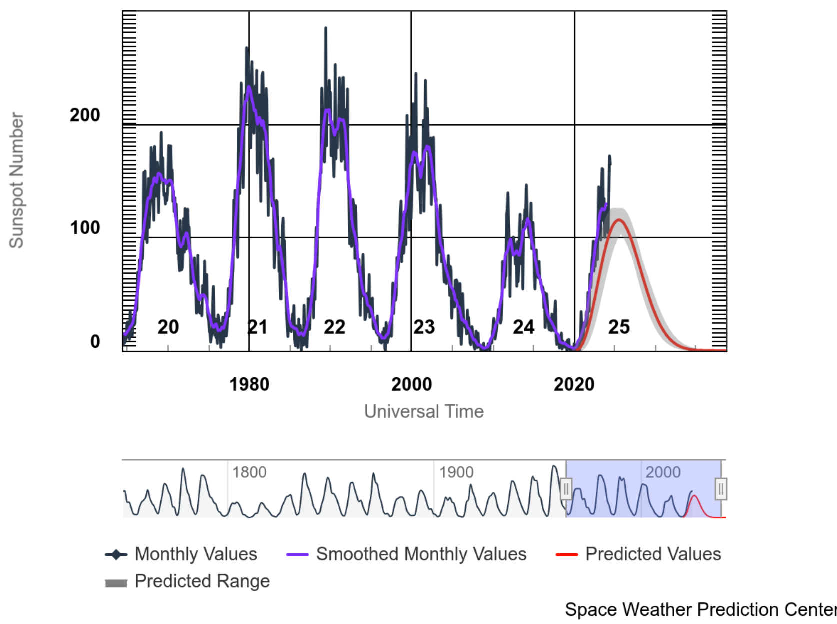

Fig. 1. ISES Solar Cycle Sunspot Number Progression [11]

2. DOVES, DIFFERENTIAL DRAG, AND MANEUVER CAPABILITY

Planet's Doves maneuver using differential drag. Due to Dove's high surface-area to mass ratio, it has been demonstrated in [3] to be sufficient for conjunction avoidance and [4] for constellation phasing. Differential drag is employed through utilization of two differential drag modes: a nominal, low drag mode and a maneuvering, high drag mode [4]. In nominal operations, we utilize differential drag for two major use cases: conjunction avoidance and achieving and maintaining fleet separation. Given the knowledge of an upcoming conjunction and the proper CDMs, we have the ability to determine and place spacecraft into various differential drag configurations that reduce the probability of collision and maximize miss distance.

By design of PlanetScope operation, Doves are constantly imaging over any landmass with enough solar illumination. To image as much land as possible and downlink efficiently, Planet's Doves need to be equally separated across the fleet. This minimizes overlapping imagery for full Earth coverage, and contact overlap over our ground stations to ensure each Dove gets enough downlink time to reduce acquisition to downlink latency. To achieve fleet separation and maintain control, there needs to be a significant distinction between the low and high drag modes, primarily characterized by their ballistic coefficient difference. To date, Planet's Doves have successfully utilized differential drag as a means of both conjunction avoidance and constellation phasing.

3. SOLAR CYCLE AND IMPACT ON DOVES

Gas density within the thermosphere can fluctuate largely due to geothermal and magnetic processes; these processes are linked with the Sun's solar cycle. The solar cycle describes the 11-year rotation of the Sun's magnetic poles. During this cycle, the magnetic activity on the Sun's surface oscillates, which can be observed through the number of sunspots, hot pockets of magnetic fields. As the cycle reaches its peak, solar activity greatly increases, characterized by solar flares and coronal mass ejections. These events can cause geomagnetic storms, and provide a large amount of incident energy to the Earth's atmosphere. As the thermosphere receives this energy, the gas density in LEO orbits increases, resulting in higher drag [2, 9]. The peak period of solar activity, known as the solar maximum, is then a considerable risk to satellite lifetime.

The current solar cycle marks the 25th solar cycle since 1755, starting from December 2019 through 2030. The peak of Solar Cycle 25 is estimated to last from 2024 to 2025 and the solar activity observed as we approach the solar maximum has already exceeded most expectations. Standard models such as the Solar Cycle 25 Prediction Panel predict similar magnitudes of solar activity to the previous solar cycle. The cycle was predicted to peak with a maximum number of sunspots of 116 by July 2025. However, as of July 2024, we have observed a peak of 160 sunspots to-date [11]. For a depiction of the current solar cycle along with previous cycles, see Fig 1.

This increased solar magnetic activity and large deviation from standard predictions not only inspired work to develop new, experimental models for solar cycle modeling and prediction, but also posed a critical challenge for satellite operators who did not expect this intense solar activity and atmospheric drag. In particular, Planet observed a higher rate of altitude decay on our Doves from 2023 to 2024 as a result of the solar maximum. As an example, we can compare two flocks launched about 2 years apart, Flock 4S (launched early 2021) and Flock 4Y (launched early 2023). Both flocks have the same differential drag configuration and build. At ~520 km in 2021, Flock 4S semi-major axis altitude dropped 1.13km in a month, whereas in 2023, Flock 4Y's semi-major axis altitude dropped 3.88 km in a month, more than double that of Flock 4S.

Beyond a long term increase in the rate of altitude decay, constellations have also experienced sudden altitude drops during solar storms [1], which increase in frequency as we approach the solar maximum. Planet's Doves are no exception. For example, during the May 2024 Gannon Geomagnetic storm, Planet's Doves dropped dramatically in altitude fleetwide (see Fig 2.) on May 11th. Since forecasting of geomagnetic storms can be unreliable and solar storms often happen too quickly to react appropriately, we focus on mitigating the long term increase of altitude decay rather than transient effects of solar storms.

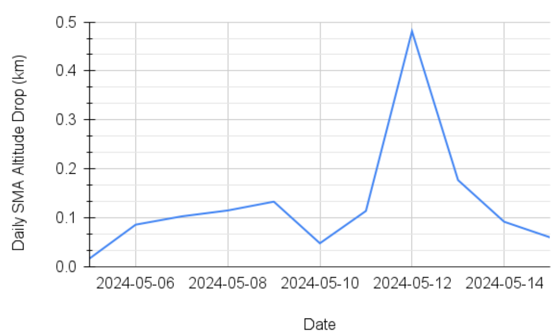

Fig. 2. Daily Semi-Major Axis (SMA) Altitude Drop of Flock 4Y Around May 2024 Gannon Storm

4. ALTITUDE DECAY MITIGATION METHODS AND EVALUATION USING LYNKER MODEL

Satellite lifetime is crucial to a constellation's success. To combat the higher rates of altitude decay brought about by intense solar weather, we primarily focus on two methods: differential drag management and ballasting Planet's Doves. The aim of both these methods is to increase the ballistic coefficients of Planet's Doves, reducing the effect of drag on their orbits. Prior to employing these methods on-orbit, we utilized the Lynker model of the 25th Solar Cycle to evaluate their effectiveness under multiple space weather conditions. We previously established the Lynker model as an accurate forecasting tool [8]. Using our in-house algorithm, we modeled the altitude decay of sample flocks using each mitigation method, and adapted the base Lynker model by adding varying multiples of the standard deviation to the base f10.7a flux values. We generally consider three cases: the nominal case (base Lynker values), the pessimistic case (base Lynker values + 1 standard deviation) and the optimistic case (base Lynker values - 1 standard deviation) to provide a range of altitude decay to expect. A more detailed description of our modeling process can be found in Improved Forecasting of LEO Satellite Orbital Decay During the 25th Solar Cycle Maximum [8].

4.1 Differential Drag Management

We can modify our low drag and high drag modes to experience less drag overall. This was our immediate first response to strong solar weather as it is quick to implement on-orbit. We characterize the susceptibility of each configuration to drag by the expected ballistic coefficient. To reduce the effects of increased drag on altitude decay, we experimented with various differential drag configurations assuming different ballistic coefficients, assuming the same spacecraft specifications as a PlanetScope Dove [10]. The goal was to extend orbital lifetime from launch (assuming a semi-major axis altitude of ~520 km) down to 380 km without sacrificing fleet separation, outlined above as a crucial configuration to serve our mission efficiently. We both modeled orbital lifetime and coverage to ensure that our daily Earth Observation imagery would not be affected by drag-reducing configurations.

4.1.1 Differential Drag Modes

We considered multiple differential drag modes with varying ballistic coefficients, achieved by rotation of the spacecraft relative to the Z-axis. We needed to select a new high drag mode and a new low drag mode, but aimed to preserve a decent differential (> 10 kg/m^2) between the two to maintain attitude control. We considered the following differential drag modes for each slot:

Table. 1. Considered PlanetScope Drag Modes

Drag Mode	**Ballistic Coefficient**	**Usage**
Drag Mode 1	~20 kg/m^2	High drag
Drag Mode 2a	~40 kg/m^2	Low drag/high drag
Drag Mode 2b	~40 kg/m^2	Low drag/high drag
Drag Mode 3	~70 kg/m^2	Low drag

Drag Mode 2a and Drag Mode 2b have no ballistic coefficient difference, but have different implications on spacecraft power generation at specific LTANs. This implies an additional concern of drag configuration selection we were conscious of.

Fixing the frequency of high drag (discussed below) to very frequent, assuming a launch altitude of 525 km and a launch date of 2024-01-01 (such that most of the lifetime of the modeled flock would center around the solar maximum), we modeled the following configurations:

Table. 2. Modeled Differential Drag Configurations and Lifetime Gain Compared to Control

Drag Configuration	**High Drag Ballistic Coefficient**	**Low Drag Ballistic Coefficient**

Drag Mode 1/Drag Mode 3	~20 kg/m^2	~70 kg/m^2
Drag Mode 2a/Drag Mode 3	~40 kg/m^2	~ 70 kg/m^2
Drag Mode 1/Drag Mode 2 (Control)	~20 kg/m^2	~ 40 kg/m^2

We found that by far, increasing the ballistic coefficient as much as possible on both drag modes was the most ideal (see Fig. 3.). Raising the low drag ballistic coefficient but fixing the high drag coefficient return similar results to the control case. This is largely due to the high high drag frequency; the more time a spacecraft spends in high drag mode, the more impact the ballistic coefficient of the high drag mode has on altitude decay. Because the separation is at least 20 kg/m^2, we were confident in retaining enough control authority for both conjunction avoidance and constellation phasing. Based on the results of this study, we rolled out a new configuration of Drag Mode 2a/Drag Mode 3 to the fleet.

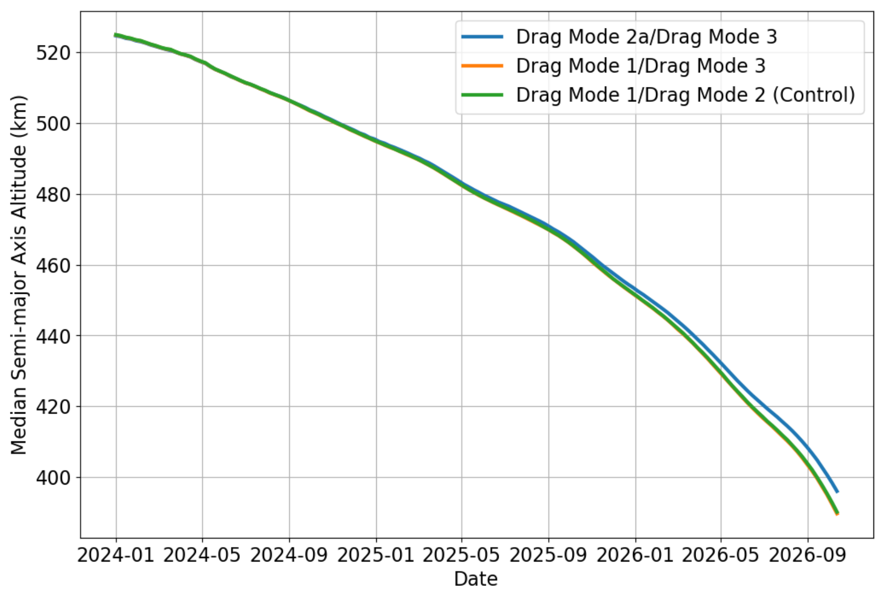

Fig. 3. Modeled Altitude Decay of Different Differential Drag Configurations from 2024 - 2026

4.1.2 High Drag Duty Cycle

In addition to deciding on suitable differential drag configurations, we needed to decide on a suitable high drag duty cycle, or a limit on how often and how long a satellite is placed into a high drag configuration. To minimize orbital decay due to drag, we want to spend as little time in high drag as possible. We experimented with a high drag duty cycle of 1 (Very Frequent), 3, 4 and 7 (Very Rare), where increasing numbers denoted less time spent in high drag overall.

The high drag duty cycle, along with differential drag modes, are crucial in bringing a newly launched flock online. It is ideal to have good separation between spacecraft as soon as a new flock launches to allow for less contact competition, which then in turn accelerates the commissioning and Payload readiness process. The time to commission and validate imagery onboard new spacecraft is a key consideration in replenishing the constellation on-orbit. Any resultant delay from modifications to both the high drag duty cycle and differential drag modes must be considered with overall fleet production.

Selecting the differential drag mode in 4.1.1., and assuming a launch altitude of 525 km and a launch date of 2024-01-01 (such that most of the lifetime of the modeled flock would center around the solar maximum), we modeled a high drag duty cycle of 3, 4 and 7:

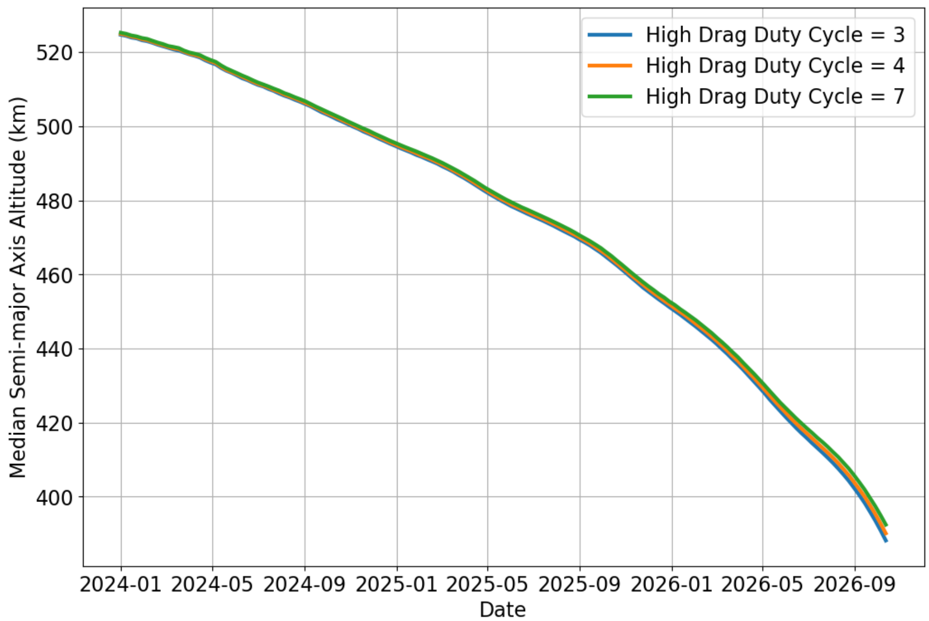

Fig. 4. Modeled Altitude Decay of Different High Drag Duty Cycles

We found that while having a high drag duty cycle of 7 was preferable in extending orbital lifetime, it was not good for phasing; the increase in orbital lifetime from a duty cycle of 3 to 4 is fairly insignificant, so we rolled out a high drag duty cycle of 3 to the fleet. However, a few months later we realized that this was not enough control authority, so we changed the high drag duty cycle back to 1, confident that the differential drag configuration was enough to extend lifetime.

4.1.3 Implementation and Evaluation

Following the work described above, we decided on the following differential configuration to roll out across the fleet on-orbit:

- A high drag mode with an estimated ballistic coefficient of 70 kg/m^2
- A low drag mode with an estimated ballistic coefficient of 40 kg/m^2
- An infrequent high drag duty cycle of 1

This configuration provides us with instrumental control authority to maintain fleet separation and extend orbital lifetime, measured as the time from launch (at ~520-525 km) to when the semi-major axis altitude crosses 380 km. To illustrate the effect of this change, we compare on-orbit altitude decay of a sample flock to our simulation results under different solar weather conditions.

Our sample flock launched in early 2024 at 520 km, so we model a flock with similar configuration and the applied differential drag mitigations (Fig. 5.):

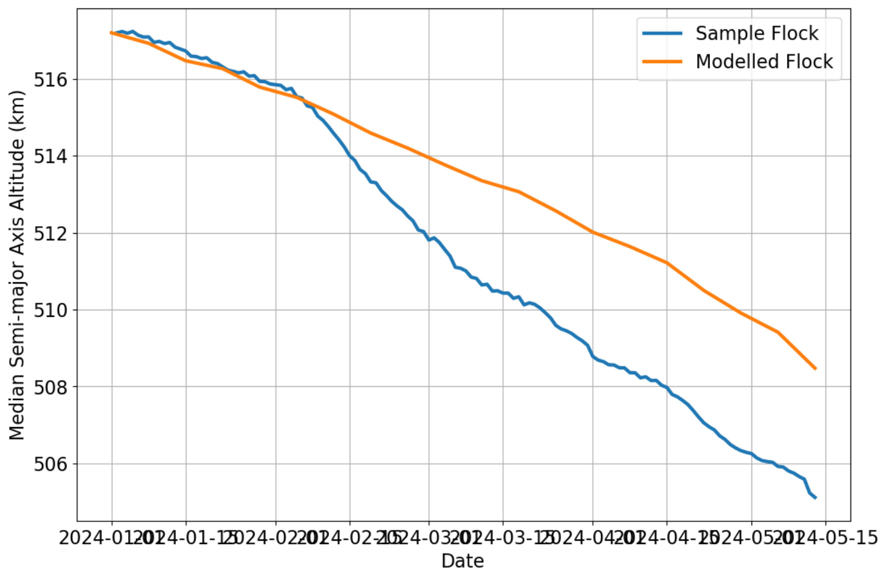

Fig. 5. Altitude Decay of Sample Flock vs. Modeled Flock with Drag Mitigation

The divergence beginning around February 2024 to March 2024 is due to a temporary period with a more aggressive differential drag configuration (higher drag overall) to accelerate phasing. After March 2024, despite the offset in altitude, the slopes of the modeled and sample flock are similar. The sudden drop in altitude of the sample flock mid-May is due to the 2024 May Gannon Geomagnetic storm. We can conclude that our modeling is capable of predicting altitude decay under various experimental conditions, guiding us towards effective mitigation strategies for increased drag at LEOs.

4.2 Ballasting Planet's Doves

To improve the ballistic coefficient of Planet's Doves moving forwards, we integrated ballasts into our build. The motivation for this is simple; the equation for the ballistic coefficient is:

$$BC = \frac{M}{C_d \cdot A}$$

where M is mass, C_d is the drag coefficient and A is the cross-sectional area. To increase spacecraft mass then proportionally increases the ballistic coefficient. However, due to the limited form-factor and deployer qualification for PlanetScope Doves, there is an upper limit to the mass of the ballast that we can safely add. Additionally, the placement and installation of the ballast must be careful as to not interfere with other spacecraft components. While adding a ballast is an easy way to mitigate increased drag on-orbit without a phasing trade-off, there are physical limitations to how much mass can be safely added. On our flocks launched since 2024, we added ballasts that would summount to a ~7% increase in ballistic coefficient.

We can compare our modeled flock with ballasts to a sample flock which launched with the ballasts in 2024 (see Fig. 5.):

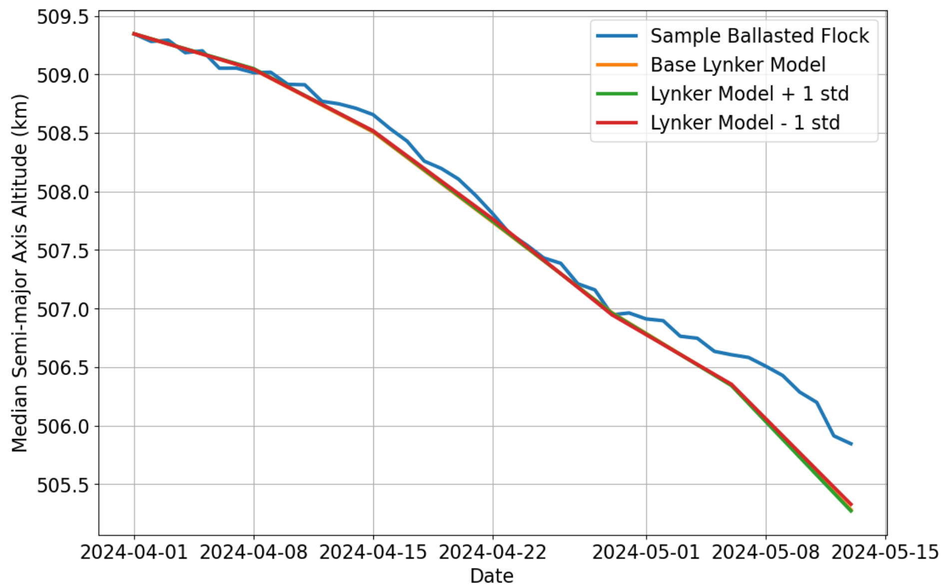

Fig. 6. Comparison of Sample Flock with Ballast Altitude Decay vs. Modeled Flock with Ballasts

In Fig. 6., the on-orbit performance of our sample flock with ballast very closely follows the modeled performance with the same differential drag configuration up until May 2024, during which we modified the differential drag configuration again for further lifetime savings. This gave us confidence that we can accurately predict altitude decay, and therefore subsequent lifetime savings, for ballasted Doves.

5. CHALLENGES AND LESSONS LEARNED

We provide a short summary of challenges faced and lessons learned as part of our experience mitigating altitude decay:

- On-orbit flux values were significantly lower (-1 standard deviation) than the Lynker model up until early 2024. From early 2024 onwards, on-orbit flux values were significantly higher than the Lynker model (+1 standard deviation). The variability of f10.7 flux on-orbit over time introduced uncertainty to our predictions, which assume a constant deviation from the standard Lynker model.
  - As on-orbit flux increased dramatically in 2024, we needed to take more drastic measures to preserve orbital lifetime across the fleet, such as temporarily suspending high drag mode and operating solely in low drag mode.
- On-orbit calibration of ballistic coefficient values varied with the space weather itself; this was also noted as a concern for conjunction events during solar storms.
- Additional features to our in-house modeling tools needed to be developed to support more complicated modeling (e.g. having a variable differential drag configuration, incorporating different solar weather models with variable standard deviation multipliers).
- Ballasted spacecraft must be phased separately from unballasted spacecraft.
- The PlanetScope fleet received a huge blow during the May 2024 Gannon Geomagnetic storm. While subsequent storms have not caused any significant altitude drops, we need to better understand and predict huge solar storms in order to further maximize spacecraft orbital lifetime.

6. SUMMARY

In 2023, Planet recognized that the altitude decay of its Doves was higher than expected and observed in previous iterations due to the increased solar flux that exceeded standard expectations as we approached the solar maximum. Planet adopted the Lynker Solar Cycle 25 model and demonstrated its accuracy in modeling spacecraft altitude decay [8]. Planet then utilized the Lynker model to evaluate various differential drag configurations and design changes to mitigate increased altitude decay caused by high drag. By integrating the Lynker Solar Cycle 25 model into Planet's in-house orbits modeling tooling, Planet was able to accurately forecast changes to altitude decay from our operational responses. More work is required to model more complex situations on-orbit, for example, changing differential drag configurations over time to match on-orbit configurations and allow for further experimentation, and evaluate the long-term predictive capability over an entire flock's lifetime.

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