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# From Estimation to Certainty: Enhancing SmallSat Constellation Replenishment Planning with Physics-Based Solar Forecasting

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## ABSTRACT

The rapid expansion of Very Low Earth Orbit (VLEO) and LEO satellite constellations has made the space industry, and more specifically smallsats, increasingly sensitive to the dynamic impacts of space weather. Historically, satellite operators have managed orbital assets using empirical regression models with negative skill scores for periods longer than four days, essentially reducing long-term planning to guesswork. We demonstrate that a shift from reactive management to proactive capital efficiency through the deployment of physics-based, first-principles solar forecasting models enables CAPEX optimization, resilient mission planning, and improved payload and design strategy. Precise modeling of atmospheric density and satellite drag allows operators to more accurately estimate asset lifespans, enabling the alignment of manufacturing and launch schedules with actual orbital decay rather than worst-case climatological averages. Long-range insights (up to 20 years) provide a strategic planning horizon that shapes mission-critical hardware design, radiation shielding requirements, and CAPEX management choices. High-fidelity space weather forecasting integrated into the mission planning allows the reduction of contingency loading and increases the resiliency of assets in space. Through the application of physics-based space weather forecasting models, we demonstrate how moving from estimation to certainty transforms space weather from an unmanaged threat into a solvable business risk, providing a strategic financial edge in a rapidly scaling global space economy.

## INTRODUCTION

The scientific baseline for a new approach to understanding solar activity and associated space weather was shared in 2014.[1] This physics-first approach has been integrated into a modeling framework (the Terminator Model), that generates a 22-year forecast of atmospheric density and radiation in the near-Earth environment (the Hale Forecast). This forecast can inform understanding of the consequences of drag conditions and total radiation dose and has been shown to be more accurate than conventional forecasting methodologies.[2]

Satellite operator Planet previously integrated the Hale Forecast into their in-house tools to enhance awareness of satellite altitude decay and improve operations, and Capella has used the Hale Forecast to revise satellite lifetime estimates and adjust design and operational approaches in the face of unexpectedly high drag conditions.[3,4] Additional uses of the Hale Forecast are assessed in this paper.

HawkEye 360 (HE360), a signals intelligence company operating in LEO, has adopted the Hale Forecast as a tool for constellation planning. The HE360 constellation is distinct due to its use of flying formation within clusters of three satellites, requiring precise orbital maintenance and anticipation of changing drag conditions. This paper provides an overview of a HE360 use case for the Hale Forecast and the resulting impact to company operations, capital expenditure, and financial reporting. As the small satellite industry matures and companies find themselves under growing pressure to transform initial R&D efforts into sustainable financial results, tools that can facilitate enhanced asset utilization to improve bottom line financials are attracting new attention.

## ROLE OF SPACE WEATHER

### *Maturing Industry Expectations*

For many years smallsats were primarily used for science, technology development, and early career training. Over time the platform has come to support a range of commercial, scientific, and national security efforts, and the market is in a process of maturation. We are growing from a "prove it works" stage in which companies demonstrated technical feasibility and market interest to a "prove it pays" stage. Companies are now assessed on ability to build a scalable business and provide return on investment. This makes financial metrics like cost per satellite, gross margin, and CAPEX intensity critical, flowing back to how constellations are built, operated, and replenished. Those operators with the sophistication to transition from a "good enough" operations approach to one that leverages all available data and tools for nuanced resource management are rewarded.

This dynamic is particularly consequential for companies like HE360. Accurate forecasting of how long satellites will remain on-orbit and generating revenue allows executive leadership to make precise, defensible decisions about CAPEX on replacement satellites and OPEX on current satellites. When a satellite exceeds design life, a company with reliable end-of-life data can optimize remaining capacity, delay building and launching replacements, and redeploy capital to where it generates the greatest return. This strengthens return on assets and return on invested capital in ways the market rewards.

***Mission Planning Approaches***

Standard satellite mission planning activities can be segmented into two time periods: design (pre-launch) and operations (post-launch). Space weather forecasts are typically integrated into both periods due to their impact on mission outcomes; the fidelity and use of the forecast both determine the scale of this impact (Figure 1). This paper focuses on using long-term space weather forecasting during the design phase of mission planning.

During this phase, satellite operators face a series of trade-offs within altitude selection that drive financial outcomes. While higher altitudes experience less drag (hence longer lifetimes) and broader field-of-view, total radiation doses, post-mission disposal compliance, and resolution/latency are generally favored at lower altitudes. Engineers use space weather forecasts and uncertainty assumptions to generate potential scenarios of atmospheric density and radiation likely to be experienced by the satellite if launched to a specific orbit in a specific time window. This process allows the operator to make altitude and launch choices that optimize performance, desired lifetime, satellite design requirements (radiation shielding, COTS components, etc), and mission CAPEX. The scope of control an operator holds over deployment altitude depends on launch contract structure, such as a rideshare versus dedicated launch. Launch timing requires a more specific analysis after the mission has been broadly defined, to avoid costly situations like the 2022 SpaceX loss of 38 of 49 Starlink satellites after launching into a geomagnetic storm that was not predicted by the weather models SpaceX used.[5]

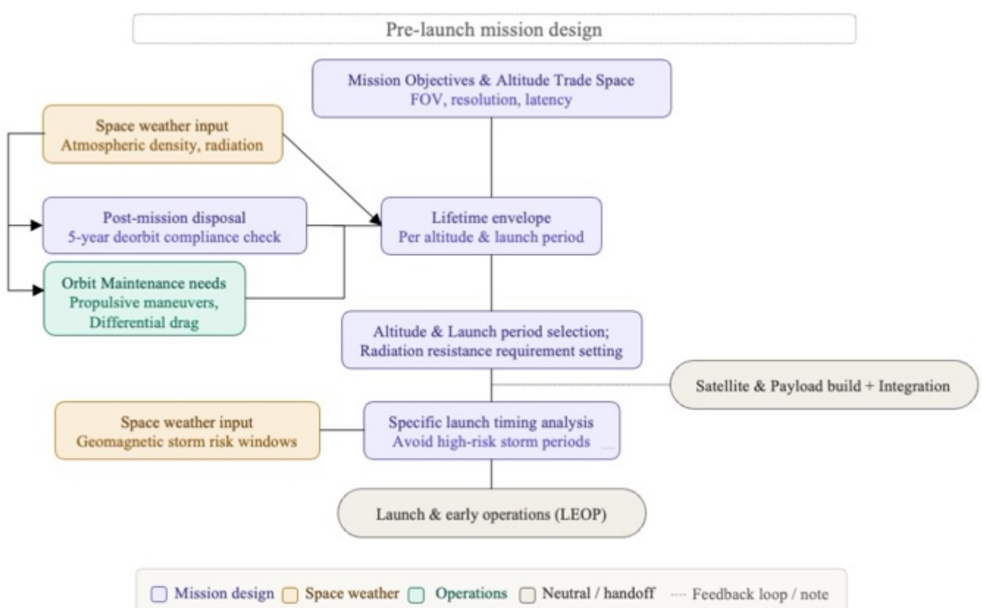


**Figure 1: Space Weather Inputs to Mission Design**

## TERMINATOR MODEL & HALE FORECAST

Hale is a systems-level weather intelligence company. Hale's Terminator Model, formerly known as the McIntosh model, was built by astrophysicist Dr. Scott McIntosh. It hypothesizes that the solar activity cycle is derivative of the 22-year magnetic activity cycle, and therefore that by understanding the evolution of the magnetic cycle one can forecast the typically observed signals of solar activity – measured in f10.7 radio flux, Kp-index, and Ap-index. This physics-based, first-principles forecasting model is distinct from traditional statistical regression models that propagate potential future solar activity based on historic numbers.

The Terminator model generates outputs including the f10.7 radio flux, Kp and Ap indices, galactic cosmic ray flux, and proton flux of the Van Allen radiation belts – enabling construction of high accuracy drag and radiation forecasts. The output Hale Forecast is formatting agnostic and can be provided in the industry-standard CSSI (same as CelesTrak) format which can be fed into most propagator systems directly. It can be used in both phases of mission planning, with its utility for the design phase seen in Figure 1 assessed in this paper.

### *Forecast Accuracy*

Commonly used models that forecast space weather are produced by NOAA Space Weather Prediction Center (SWPC) and NASA Marshall Space Flight Center (MSFC). The MSFC space environment forecasts provide bounding conditions in an attempt to define the possible ranges – providing a 5th percentile, a 50th percentile, 75th percentile, and a 95th percentile for f10.7. Historically, operators have used these various percentiles to establish bounds on the possible scenarios, though the challenge becomes anticipating which percentile will actually reflect the operating environment.

Each forecast includes f10.7 as a measure of solar flux and Kp and Ap indices that measure geomagnetic activity. The f10.7 measurement is the largest input for drag impacts, contributing 75-80% of overall drag in non-storm conditions. The Kp index measures the magnitude of geomagnetic storms in a three-hour window, while the Ap index is derived from a set of Kp index measurements and provides a daily average of geomagnetic activity.

Skill scores to compare these forecasts to observed values were calculated using solar sunspot number (SSN), f10.7, and Ap index. Validation of the long-range Hale forecast ongoing since January 2022 has found a skill score of ~0.3, compared to lesser values ranging from -7.3 to -0.4 for commonly used publicly available solar activity forecasts (Table 1). The Hale forecast accurately predicted the stronger-than-average Solar Cycle 25 that drove the premature loss of hundreds of satellites and their associated revenue across the industry.[6]

**Table 1: Forecast Skill Score Comparison, 2022-2026**

| Forecast | f10.7 Skill Score |
|---|---|
| Hale | 0.315 |
| SWPC | -1.259 |
| MSFC 95th percentile | -7.248 |
| MSFC 50th percentile | -0.576 |
| MSFC 5th percentile | -0.388 |

Figure 2 demonstrates the performance of the Hale forecast alongside current industry standard forecasts.

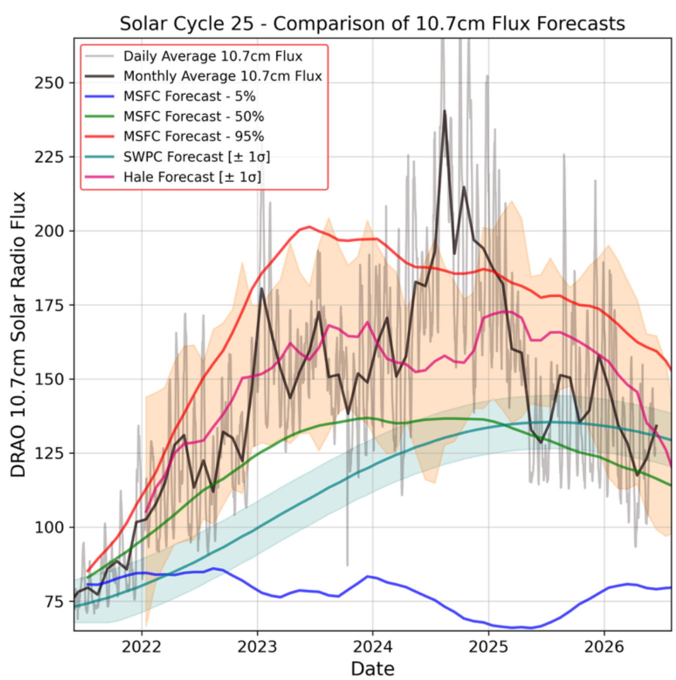


**Figure 2: Comparison of 10.7 cm Flux Forecasts, 2022-2026**

## HAWKEYE 360 CONSTELLATION

HE360 designs and operates a signals intelligence constellation that collects RF data via formations of three satellites operating between 400 and 600 km. HE360 company performance is assessed across many factors; those relevant for this paper include data consistency and reliability, CAPEX efficiency, and OPEX efficiency.

Each satellite has an operational life ranging from three to five years.[7] HE360 has launched 14 clusters of three satellites each, with plans to launch additional clusters in 2026. HE360 manages constellation size in alignment with market needs rather than as a baseline number of clusters. All current operational satellites are of the Block 2 variant. The future hybrid constellation will consist of Block 3 and Block 4 variants.

Block 2 satellites have an approximate 30 kg mass with propulsive capacity that is centered around cluster formation initialization, collision-avoidance maneuvers, and additional mission margin. Block 3's are designed around a smaller 8U cubesat class, with streamlined CAPEX and requiring less fuel mass to maintain enough delta-V for the mission, given the small form factor.

## HAWKEYE 360 FORECAST COMPARISONS

HE360 has traditionally used AGI tool suites for mission planning and operations. Prior to 2025 AGI was using the MSFC Mean ($50^{th}$ percentile) for long-range forecasting. As of 2025, AGI now uses the NOAA SWPC forecast for that same long-range forecasting. A comparative analysis across these forecasts and Hale has led HE360 to consider baselining the use of Hale's long-range forecast moving forward. To validate the accuracy of the Hale data, two basic approaches were used: theoretical and practical. In both approaches, the following data were used:

**Table 2: Input Data Sources**

| Name | Type | Origination date | F10.7 source | Kp/Ap source |
|---|---|---|---|---|
| Hale | Forecast | 1/2022 | Hale | Hale |
| SWPC f10.7 | Forecast | 1/2022 | SWPC | Hale* |
| AGI | Forecast | 1/2022 | MSFC mean | MSFC mean |
| Known truth | Observed values | As measured | Measured in Penticton, Canada | Measured at GFZ in Potsdam, Germany |

**As of January 2022, SWPC did not archive complete forecasts. A forecast file for the f10.7 values originating in January 2022 was available but did not include Kp/Ap values. Because the f10.7 is the primary driver of changes to atmospheric density and therefore drag, a hybrid forecast of SWPC f10.7 and Hale Kp/Ap was assessed to be a reasonable comparison to the complete SWPC forecast. To rigorously compare performance of the Hale and AGI models to the SWPC model, a predictive case using the complete SWPC forecast file would need to be used.*

The fitted ballistic coefficients used in the following analysis for each type of HE360 satellite are shown in Table 3.

**Table 3: Fitted Ballistic Coef. Used**

| | |
|---|---|
| Block 2 | 69.28 kg / $m^2$ |
| Block 3 | 40.17 kg / $m^2$ |

### *HE360 Theoretical Analysis*

In the theoretical approach, the Hale, SWPC f10.7, and AGI (MSFC Mean) forecasts from January 2022 were used to generate a series of long term drag predictions for theoretical Block 2 satellites with initial orbit altitudes between 400 to 500 km and a range of initial epoch dates. The example case spans a period of 4 years (2022-2026). *(note: cases were also run with initial altitudes of 550 km and 600 km, but these theoretical satellites did not deorbit during the examined period. Only cases where the full orbital life occurred during the period for which there was predictive data were included).* Known truth data (observed f10.7, Kp, and Ap-indices) was used to run the same analysis. Deorbit was defined as reaching an altitude of 250 km. The absolute error in days between the deorbit dates generated via the forecast data to those generated using the known truth data is plotted in Figures 3 and 4.

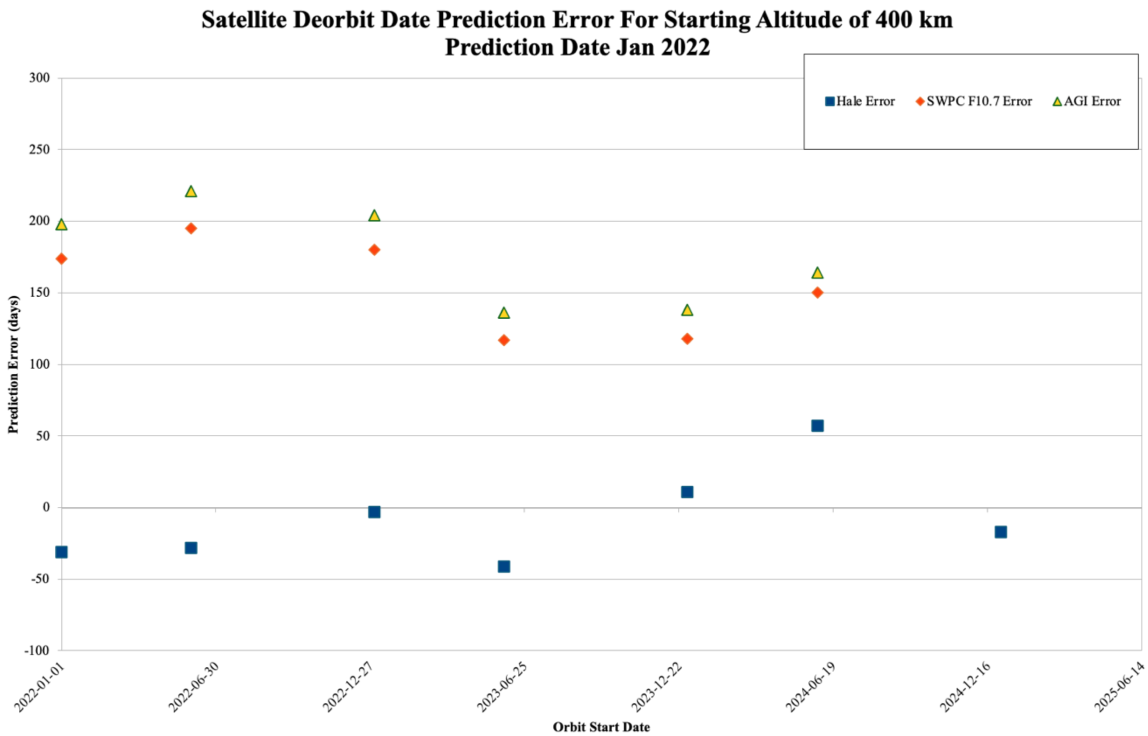


**Figure 3: Error in days for the predicted date of orbit deterioration from 400 km using forecasts when compared to observed values.**

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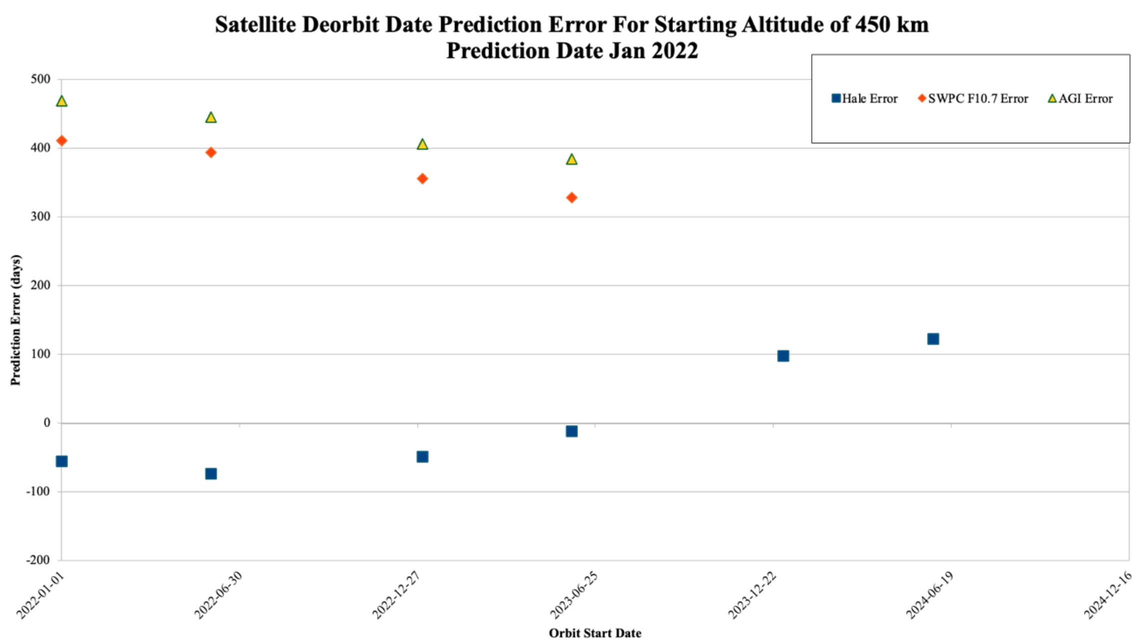


**Figure 4: Error in days for the predicted date of orbit deterioration from 450 km using forecasts when compared to observed values.**

The mean percent error for cases generated by each forecast and altitude is shown in Table 4.

**Table 4: Forecast Mean Percent Error**

| Start Altitude (km) | Hale | SWPC f10.7 | AGI / MSFC Mean |
|---|---|---|---|
| 400 | 12% | 71% | 80% |
| 450 | 16% | 67% | 77% |
| 500 | 3% | n/a* | n/a* |
| Cumulative, 400-450 | 15% | 69% | 79% |

**The predicted deorbit date at 500 km was beyond the time period analyzed, therefore an absolute error and percent error could not be calculated.*

### *HE360 Practical Analysis*

In the practical approach, HE360 historical orbit data and the known SWPC solar truth values (entered into the NRLMSISE00 drag model) were used to calibrate the satellite's ballistic coefficient. This ballistic coefficient and initial orbit conditions for Hawk-4A (Block 2) from 2022 were then used to determine the predicted deorbit date according to the Hale forecast, MSFC strong and weak, and HE360 observations of TLE (Figure 5). The same ballistic coefficient was then used to generate orbital predictions for Hawk-3A (also Block 2 variant) over the 2022-2026 time frame to determine how close the Hale-based prediction would have come to its actual orbit conditions in January 2026 (Figure 6).

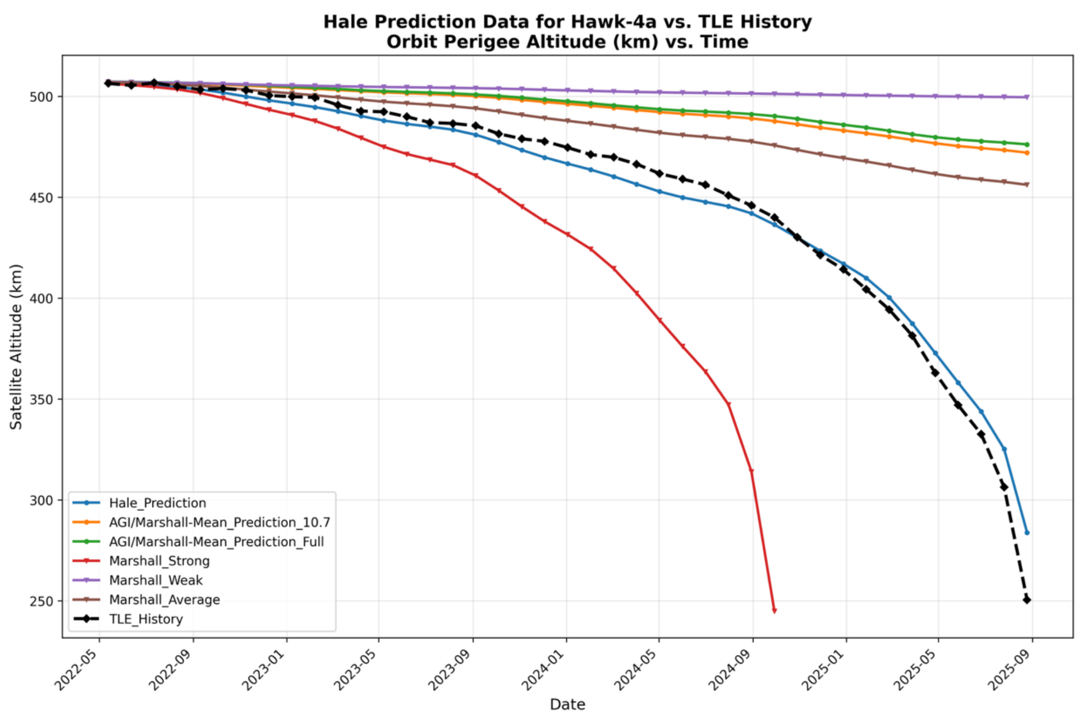


**Figure 5: Charts the TLE altitude history of Hawk-4A over the course of the satellite lifetime, compared to forecast predictions. Satellite orbit deteriorated in August 2025.**

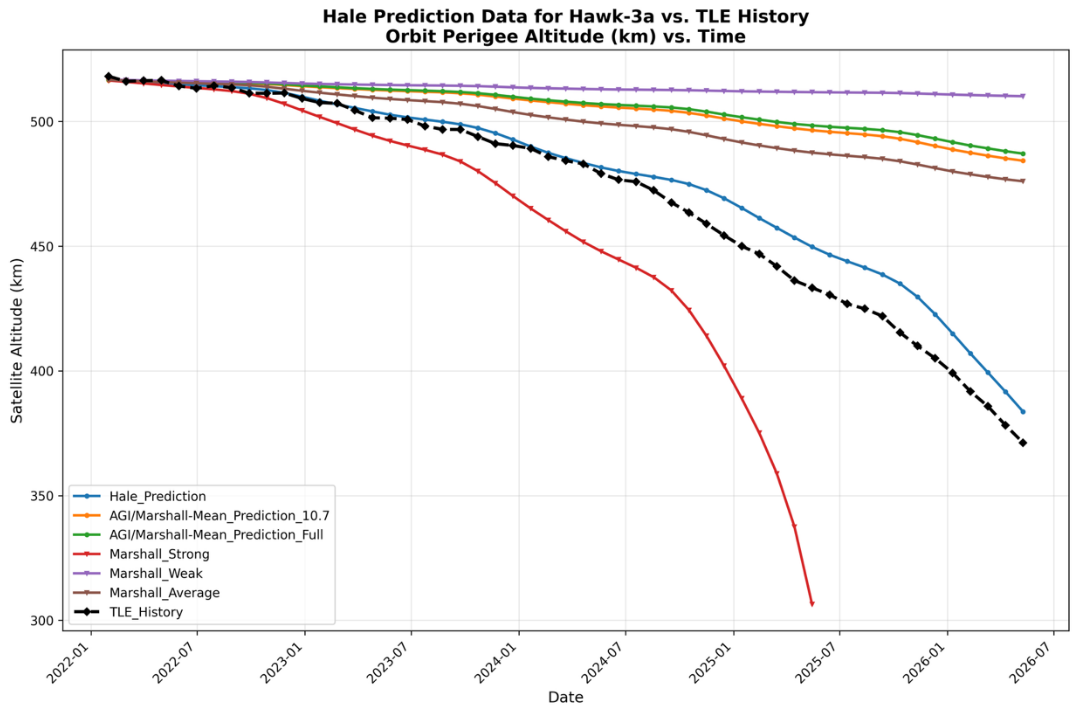


**Figure 6: Charts the TLE altitude history of satellite Hawk-3A over the course of the satellite lifetime, compared to forecast predictions. Satellite is still active and expected to deorbit at the end of 2026.**

Of the forecasts compared, Hale was closer to the observed TLE altitude values of both Hawk-4A and Hawk-3A.

## USE CASE: BLOCK 3 LAUNCH & REPLENISHMENT DECISION MAKING

HE360's Block 3 satellites have an expected lifetime of 5 years with analysis for 3 years, with upside on revenue generation realized for any operational life beyond this period. Because the Block 3 is a new form factor and only one demonstration satellite has been launched, additional ground analysis is helpful to understand on-orbit behavior and to optimize launch timing and deployment altitude.

Because Block 3 has a lower mass while having a proportionally larger drag area, it will be more strongly affected by drag than the Block 2 satellites (see representative ballistic coefficients in Table 3). Additionally, with less fuel available for orbit-raising, strategic burns are primarily used for formation initialization and collision avoidance, with limited potential use for station keeping. Therefore, the use of accurate drag predictions becomes more important in determining the likely date of orbital decay for any given Block 3 cluster.

Traditionally the MSFC Strong and Weak data have been used to provide upper and lower bounds on deorbit dates, with the SWPC prediction values or the MSFC mean used as the best-guess prediction. However, based on the findings of the forecast accuracy analysis above that the Hale data can provide a more accurate prediction – particularly in cases where the forecasts differ significantly – Hale can serve as a more effective tool for on-orbit asset management.

HE360 complies with FCC regulatory requirements to deorbit within 5 years after mission completion. However, spacecraft can remain operational during this 5-year deorbit period, enabling Block 3 to be utilized well beyond its nominal mission lifetime under favorable conditions.

HE360 operates multiple space platforms tasked and commanded to optimize mission observations, each with varying recurring hardware costs and lifetime expenses. Capital efficiency, collections per dollar invested into the satellite hardware and launch, drives platform selection (Block 2 vs Block 3) and constellation composition, balancing cost, capability, and mission lifetime. Each additional HE360 cluster operated within the constellation adds daily collection opportunities. Better prediction of mission lifetimes through high-fidelity space weather forecasting now allows HE360 to strategically select ideal launch windows aligned with available launch manifests. This capability enables mission lifetime extension when desirable for revenue generation, or intentional mission lifetime reduction to meet FCC regulatory constraints such as orbital slot limits specified in license applications or passive deorbit compliance within the 5-year post-mission window.

### *450 km Launch Analysis*

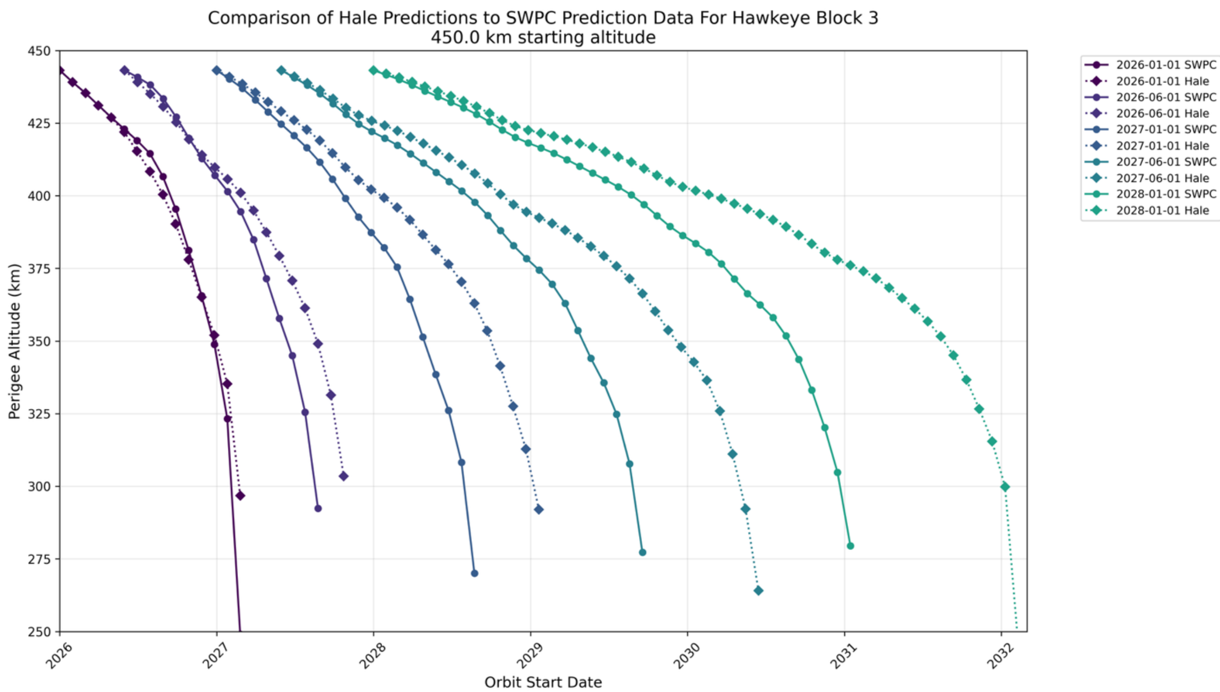


**Figure 7: Probable orbit decay dates for satellites launched to an initial altitude of 450 km at various dates in the next 3 years. Notice the satellite launched in 2028 stays up a full year longer according to the Hale data than to the SWPC data.**

**Table 5: Probable Orbit Decay for Block 3 satellites launched with initial altitude of 450km**

| Start Date of Orbit | SWPC Predicted Lifetime (days) | Hale Predicted Lifetime (days) | Difference between Decay Date Values |
|---|---|---|---|
| 2026-01-01 | 419 | 448 | 29 |
| 2026-06-01 | 475 | 542 | 67 |
| 2027-01-01 | 612 | 775 | 163 |
| 2027-06-01 | 856 | 1118 | 262 |
| 2028-01-01 | 1127 | 1497 | 370 |

*Note that in Table 5 a negative difference means that the Hale prediction deorbited first; a positive value means that the SWPC prediction deorbited first.*

Figure 7 / Table 5 provide example cases comparing the SWPC to Hale data in a timeframe from 2026-2031. While not indicative of an actual planned Block 3 launch, these analyses use an altitude of 450 km to demonstrate the differences between SWPC and Hale proprietary data, which are more prominent at lower altitudes given Block 3's ballistic coefficient.

According to the Hale predictions, a Block 3 cluster launched in January 2027 would deorbit in February 2029, whereas if the launch date were delayed 6 months to June 2027, the satellite orbit would not decay until June 2030. Thus, delaying the launch by 6 months would allow for a net 10 additional months of operating life, representing a 45% improvement in capital efficiency. The comparison between January 2027 and January 2028 launches is even more compelling, representing approximately 93% capital efficiency improvement. This demonstrates value in intentionally launching later, while simultaneously achieving significantly better on-orbit performance per dollar invested. This may help to quantify, for example, spending more time testing satellite hardware on the ground, or even justifying why an accelerated launch schedule is less favorable because the drag conditions could result in reduced mission lifetimes depending on the solar cycle.

The SWPC predictions of orbital lifetime are shorter in all examined cases than those from Hale. A Block 3 cluster launched in January 2027 would deorbit in September 2028 according to the SWPC predictions, but according to the Hale predictions would not deorbit until February 2029. As the solar cycle continues to weaken, the delta between the two predictions grows – exceeding a year for a cluster launched in January 2028. Assuming the Hale predictions are accurate (as indicated by the prior forecast accuracy analysis), this insight into a longer operational life would allow HE360 to delay launching replacement satellites, confidently delaying CAPEX while maintaining global coverage. Note that the analysis above does not include station keeping and routine orbit maintenance, which could partially offset increased decay rates with minor orbit adjustments.

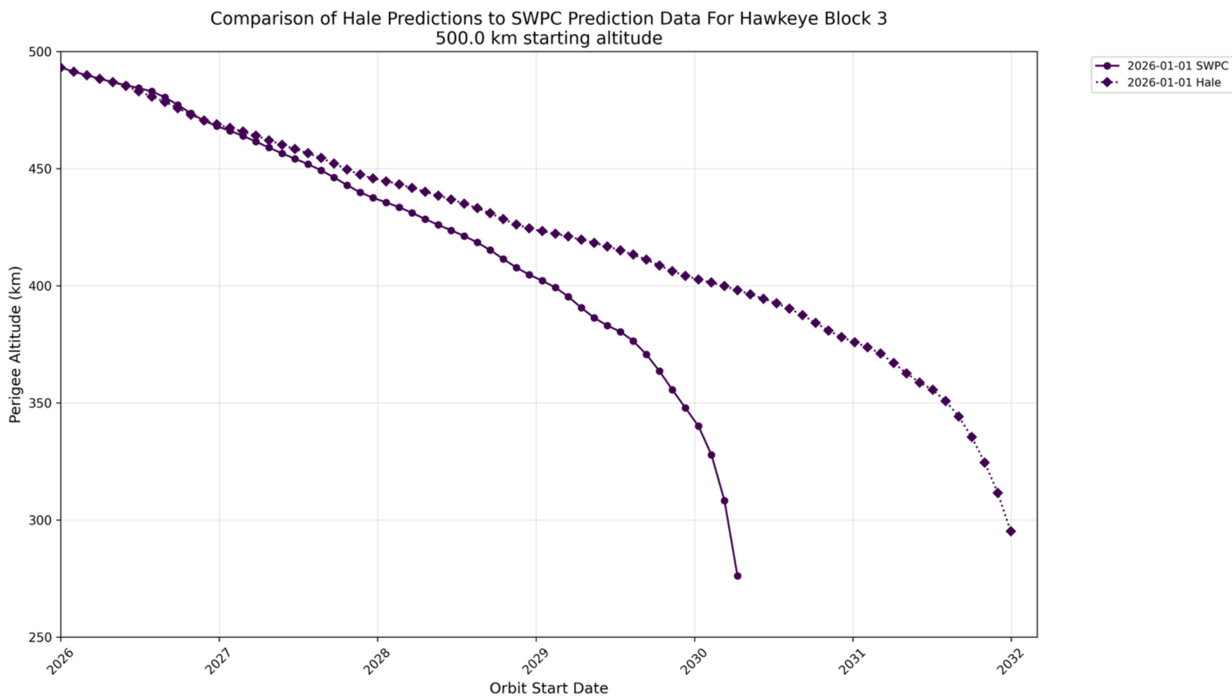


**Figure 8: Projection of Block 3 orbit decay for a satellite launched in January 2026 with a starting altitude of 500 km. The SWPC predictions show a decay date of early 2030, whereas the Hale predictions show a decay date at the start of 2032.**

### *500 km Launch Analysis*

A realistic operational use case is presented in Figure 8, which shows a Block 3 satellite launched to 500 km altitude in January 2026. Current SWPC forecast data predicts this satellite will deorbit in Q1 2030, whereas Hale data forecasts deorbit in Q1 2032. A January 2026 launch increases the example lifetime from 4 to 6-year, providing a 100% improvement over the baseline mission lifetime and a 67% improvement over what would be expected using SWPC data alone. This provides opportunity to maximize capital efficiency in HE360 designed spacecraft platforms, such as optimizing for mission lifetime as shown in Figure 6, resulting in more collection opportunities per HE360 cluster.

## CONCLUSION

Following the high drag environments of 2022-2025, maturing commercial LEO and VLEO operators are beginning to recognize inaccurate and imprecise space weather knowledge as a material business risk. This paper demonstrates that the physics-based, first-principles solar forecasting provided by the Hale Terminator Model offers a meaningful improvement over traditional approaches for satellite constellation planning and operations.

Validation analysis using HawkEye 360 historical orbit data shows that Hale-based drag predictions closely track observed TLE histories for both Hawk-4A and Hawk-3A, outperforming the SWPCf10.7, AGI, and MSFC Strong and Weak bounding cases across the 2022-2026 period. The accompanying theoretical analysis across initial orbit altitudes of 400-500 km further quantifies the accuracy of Hale predictions relative to observed truth data, with mean error at just 12% compared to 69% error using the SWPC f10.7 forecast and 79% using AGI / MSFC Mean.

The practical implications of this forecasting capability are significant. Launch window optimization based on Hale data reveals capital efficiency improvements of up to 127% by selecting favorable solar cycle timing, and analysis suggests Block 3 satellites launched in early 2026 may operate productively for up to twice their baseline mission lifetime. These findings enable HE360 to align manufacturing schedules and launch manifests with confident forecasts, directly improving CAPEX management and return on invested capital. While the Block 3 lifetime use case presented in this paper indicated longer orbital lifetimes than predicted by traditional data sources, it is possible that during other periods of the solar cycle the Hale data could predict shorter lifetimes than traditional data sources due to higher solar activity (such as was observed during Solar Cycle 25). This would remain valuable information for an operator like HE360, enabling the adjustment of launch schedule and capacity planning to avoid a loss of service or rushed replacement decision-making.

Taken together, these results support the broader thesis that high-fidelity space weather forecasting transforms a historically poorly understood variable into a manageable planning input. As the smallsat industry continues its shift from technical demonstration toward financial sustainability, tools that reduce uncertainty in asset lifespan and mission performance will become increasingly central to competitive operations. The work presented here represents an early but concrete step in that direction, with further validation and expanded use cases planned as the HE360 and Hale partnership matures and additional operators begin to leverage the Hale model.

The analysis compiled in this paper focused on Hale's long-range drag forecast capabilities compared to other models. Future investigations should explore accuracy and use of short-range drag forecasts as well as short- and long-range radiation forecasts, including for applications in proactive risk management. Being able to anticipate and plan around the radiation environment would represent a meaningful improvement in mission resilience and long-term asset value protection, and is an exciting area of future research.

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