Improved Forecasting of LEO Satellite Orbital Decay During the 25th Solar Cycle Maximum

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ABSTRACT

Planet is a leading provider of global, daily satellite imagery and geospatial solutions. Planet's mission is to image the world every day and make change visible, accessible, and actionable. To enable this mission, Planet operates the world's largest constellation of Earth Observation satellites (about 180 Doves and 20 Skysats) in the LEO environment of 400-550 km. However, this altitude regime became a challenging environment as we approached the solar maximum of the 25th solar cycle. The solar cycle describes an 11-year rotation period of the Sun's magnetic poles, which is characterized by several activities like solar flares and coronal mass ejections. These activities elicit thermal and magnetic responses in Earth's thermosphere (85-600 km), where several LEO satellites operate. The cycle has a period of maximum activity, called the solar maxima, where LEO satellites in particular experience the highest levels of drag, ultimately leading to shorter mission lifetimes. While solar cycles are periodic, the period around the 25th solar cycle saw higher levels of activity compared to the previous cycle. Specifically, during 2023-2025, we observed LEO satellites decay at a faster rate than what was predicted using the Schatten space weather model. The Schatten space weather model has been a reliable workhorse in forecasting the solar flux in the 10.7 cm wavelength range ($f10.7$), and Earth's geomagnetic indices. These forecasts are needed to predict the atmospheric densities experienced by the satellites. However, as we approach the solar maximum, the Schatten forecasts deviated significantly from the observations. Such discrepancies, if unaccounted for, can be catastrophic to satellites that operate in low Earth orbits. The risk is even more pronounced for small satellites due to their limited maneuverability. To address some of these risks, we adopted the Solar Cycle 25 model developed by the National Center for Atmospheric Research (NCAR). The NCAR model forecasts the f10.7 flux using the observations of the past sunspot cycles, in contrast to relying on modeling solar magnetic cycles alone. In the current work, we present an application of the NCAR model to predict the altitude decay of satellites operating in the 400-550 km altitude range and compare this against the Schatten model during the solar maximum. In both cases, the NRLMSISE 00 model is used to model the atmospheric density. In addition to this, we compare the predicted decay rates to the real data noted from our fleet of satellites that operate in these altitude ranges. The results indicate that during this period, the NCAR model predicts a faster decay compared to the Schatten model and is closer to the decay rates noted from the orbiting satellites. This suggests that the NCAR model can be used as a potential tool to forecast space weather, especially around the solar maximum. Such models can help us build and operate robust spacecraft missions that are better prepared to handle the challenges of aggressive space weather, ultimately leading to improved security and space situational awareness.

INTRODUCTION

Planet's mission is to image the world every day and make change visible, accessible, and actionable. By providing global, daily satellite imagery and geospatial solutions. To enable this, Planet operates a constellation of over 200 Earth Observation satellites (about 180 Doves, and 20 Skysats) in the LEO environment of 400-550 km. This is an active region of operation for more than 4500 known satellites worldwide as of the current date [1]. This altitude band passes through a region of Earth's upper atmosphere, known as the thermosphere, and therefore experience retardation due to the drag force [2]. While drag has been studied [3, 4], and demonstrated [5, 6] as a maneuvering methodology, it is the primary end-of-life mechanism [7] for virtually all LEO satellites, as this retardation leads to an altitude decay. This makes drag an important consideration for mission design [8], as increased drag implies shorter satellite lifetimes.

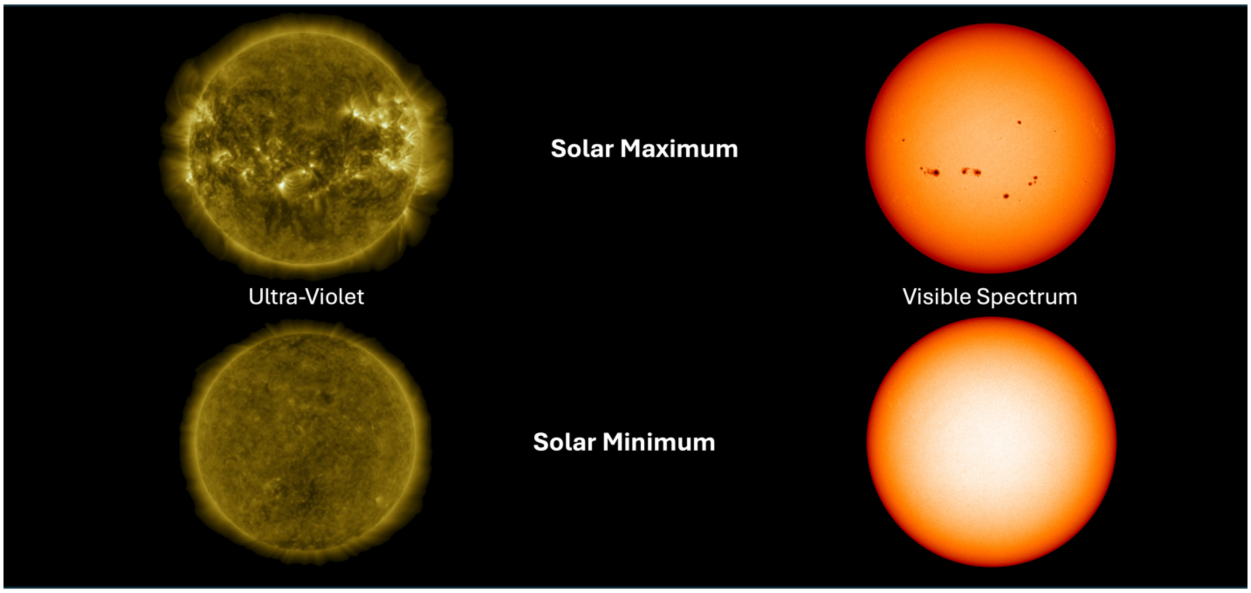

Figure 1: Differences in solar activity during the solar maximum and minimum. The UV imagery (left) solar storms, while the visible imagery (right) shows the noticeable appearance of sunspots. [Source: SDO-NASA]

The densities of thermospheric gasses responsible for drag, depend on the geothermal and magnetic processes, which in turn are driven by the solar cycle [9]. The solar cycle describes an 11-year rotation period of the Sun's magnetic poles, which is characterized by several activities like solar flares and coronal mass ejections. The solar cycle is also referred to as the Sunspot cycle due to the appearance of sunspots shown in Figure 1—areas of strong magnetic field. The period of maximum activity, known as the solar maximum, shown in Figure 1, can be particularly disruptive to satellite operations. Not only does it cause increased drag on the LEO satellites [9], but the particle fluxes emitted by the increased solar activity, can also lead to disrupt communications for all satellites, as evidenced during the major 1972 blackout [10].

We are currently in the 25th solar cycle since 1755. The Solar Cycle 25 (SC25) began in December 2019 and is expected to continue until about 2030. There are widely varying predictions about the strength of SC25. Standard models such as the Solar Cycle 25 Prediction Panel predicted activity levels similar to SC24, with a maximum of about 116 sunspots by July 2025. However, to date we have already recorded a peak activity number of about 160 [11], presenting a discrepancy between space weather forecasts and observations. This increased activity has resulted in an increase in satellite reentries as we approach the solar maximum. For instance, the number of reentry events in 2023 has increased by about 5 times when compared to those in 2022 [12]. This clearly shows that satellite mission design should account for the increased solar activity if operating around the maximum. In this paper, we will focus on modeling the loss in lifetime due to increased drag.

Standard atmospheric models such as those from NRLMSIS, use the radio emission flux from the Sun at a wavelength of 10.7 cm ($f10.7$), and the geomagnetic index, Ap, to compute the atmospheric density at the satellite altitudes, which in turn are used to compute the acceleration due to drag when propagating their orbits [13,14]. These parameters are found to be correlated and therefore can be derived from the sunspot numbers using empirical relations [15]. The Schatten space weather model has been a reliable workhorse in forecasting the $f10.7$ flux and the Ap indices predict these parameters using the Solar Dynamo theory [16]. The Schatten predicts are usually generated for one solar cycle in advance and are updated 3-4 times each year based on observations [17]. These forecasted values can be validated against the actual observations of these space weather parameters from the National Oceanic and Atmospheric Administration (NOAA) and can be accessed through Celestrak [17, 18, 19]. However, as we will note in this paper, the Schatten predicts have generally underpredicted the $f10.7$ flux as we approached the solar maximum of SC25. While the periodic updates indeed improve the accuracy, it does not help applications like lifetime forecasting where the decisions are made much in advance. Additionally, the periodic revision of the Schatten predicts each year, makes it cumbersome to bookkeep satellite ephemeris, as the space weather parameters used for early predictions can be potentially different from the ones

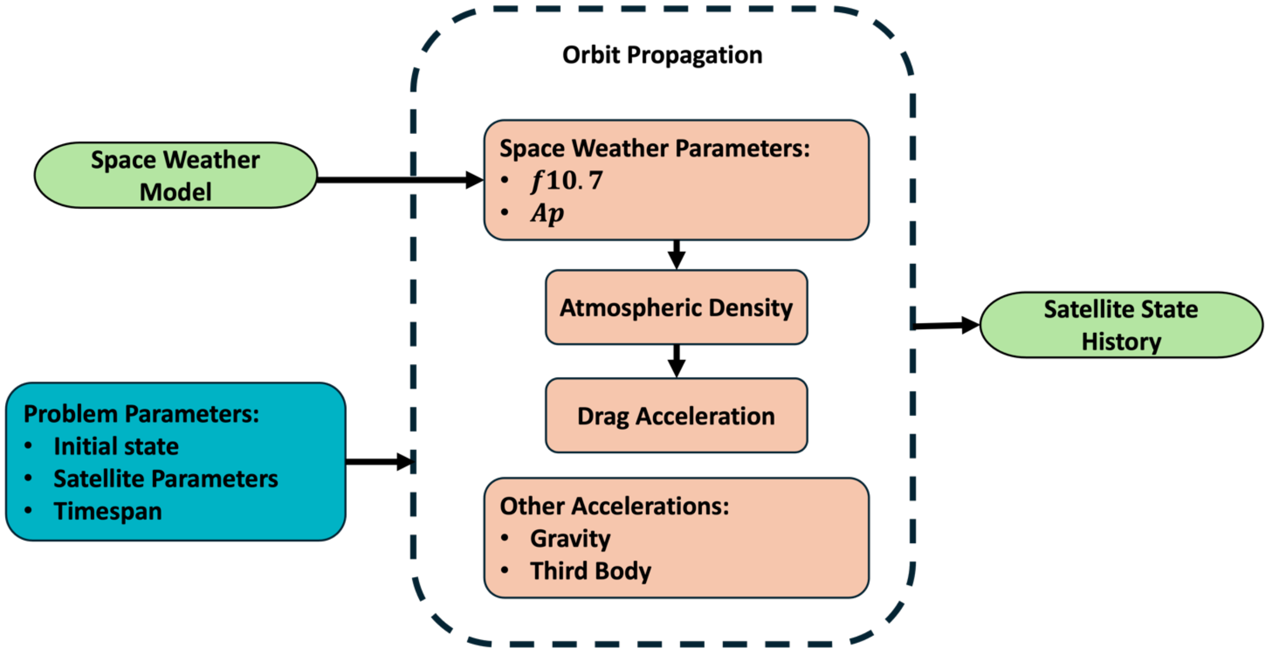

Figure 2: Architecture of the Cowell's orbit propagation scheme used in the current work to study the impact of different space weather models.

used later. The Schatten predicts can be accessed through NASA's Integrated Space Weather Analysis (iSWA) system [20].

More recently, models from the National Center for Atmospheric Research (NCAR) have predicted a more aggressive and faster SC25 compared to existing models, with a maximum of about 184 sunspots, occurring around mid-2024 [21, 22]. Therefore, owing to this conservatism over the consensus, in this paper, we investigate the impact of estimating LEO satellite lifetimes using the NCAR SC25 model. Specifically, we will examine the forecasted altitude decay of satellites in the 400-550 km altitude range using the Schatten and NCAR SC25 model as we approach the solar maximum, and then compare it to the observed altitude decay noted from real satellite ephemeris. The rest of this paper is organized as follows. We begin by going by the framework and modeling in Section 2, followed by a description of the scenarios simulated in Section 3. Section 4 will present the altitude decays simulated by different space weather models, and finally present the conclusion in Section 5.

METHODOLOGY

In this work, we examine spacecraft trajectories propagated where the drag perturbation is modeled using different space weather models. Specifically, the atmospheric density at the spacecraft's instantaneous location is calculated using the time-interpolated space weather parameters as shown in Figure 2. We assume the spacecraft parameters are similar to Planet's SuperDove fleet, for propagating these trajectories [23, 24]. In addition, we will also compare the forecasted models to observed altitude decay noted from comparable SuperDove fleets during the simulated timespan. As mentioned above, we use three different space weather models:

i. The NCAR SC25 parameters, which is the current model being evaluated.
ii. The Schatten parameters, the current industrial standard, and,
iii. The NOAA observations, which serve as the baseline reference.

Figure 3: Photograph of a SuperDove which is indicative of the test spacecraft used in the current work.

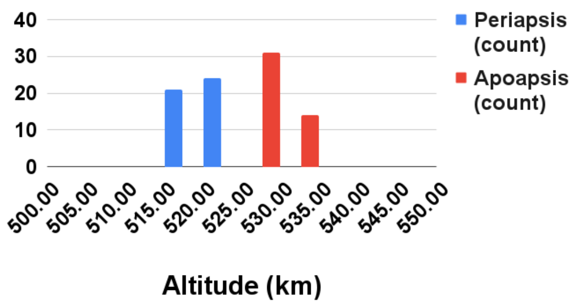

Figure 4: Histogram showing the distribution of the apses altitudes of initial spacecraft states used in the current work.

A Cowell propagation scheme is used, which uses the spherical harmonic acceleration due to gravity, cannonball drag, and the third body gravitational pull from the Sun and the Moon [25]. The atmospheric density at the satellite's instantaneous position was computed using the NRLMSISE-0.0 model [13]. We use an 12th Order, Adam-Moulton scheme to solve the spacecraft dynamics [26].

SIMULATION

To demonstrate the effect of different models, we propagated the orbits of the Flock 4x satellites of the Planet's SuperDove constellation. The SuperDoves have

Table 1: Orbit propagation parameters used in the current work.

Parameter	Value
Initial State Epoch	January 13th 2022
Timespan	February 1st 2022-2024
Time step	2 days
Ballistic Coefficient	32 $\mathrm{kg/m^2}$
MLTAN	22:30

a form factor close to a 3U CubeSat as shown in Figure 3. As shown here the spacecraft was assumed to have its solar panels deployed, and a ballistic coefficient of 32 $\mathrm{kg/m^2}$ was assumed for all satellites, which is an indicative value of when the 3U face of the spacecraft is exposed to the atmosphere. The satellites have Sun-synchronous orbits (SSO) with a mean local time at the ascending node (MLTAN) of 22:30. The orbits had initial semi-major axis (SMA) altitudes in the range of 523 to 527 km. The distribution of the periapsis and apoapsis altitudes is presented in Figure 4. The spacecraft orbits are simulated for a period of 2 years ranging from February 1st, 2022 to February 1st, 2024 using the 3 space weather models. The simulation parameters used for this study are listed in Table 1. As mentioned above, the Schatten predicts are updated periodically throughout the year. Therefore, to illustrate the impact this has on mission planning, we use the predictions issued in November 2021 [20], as it is closest

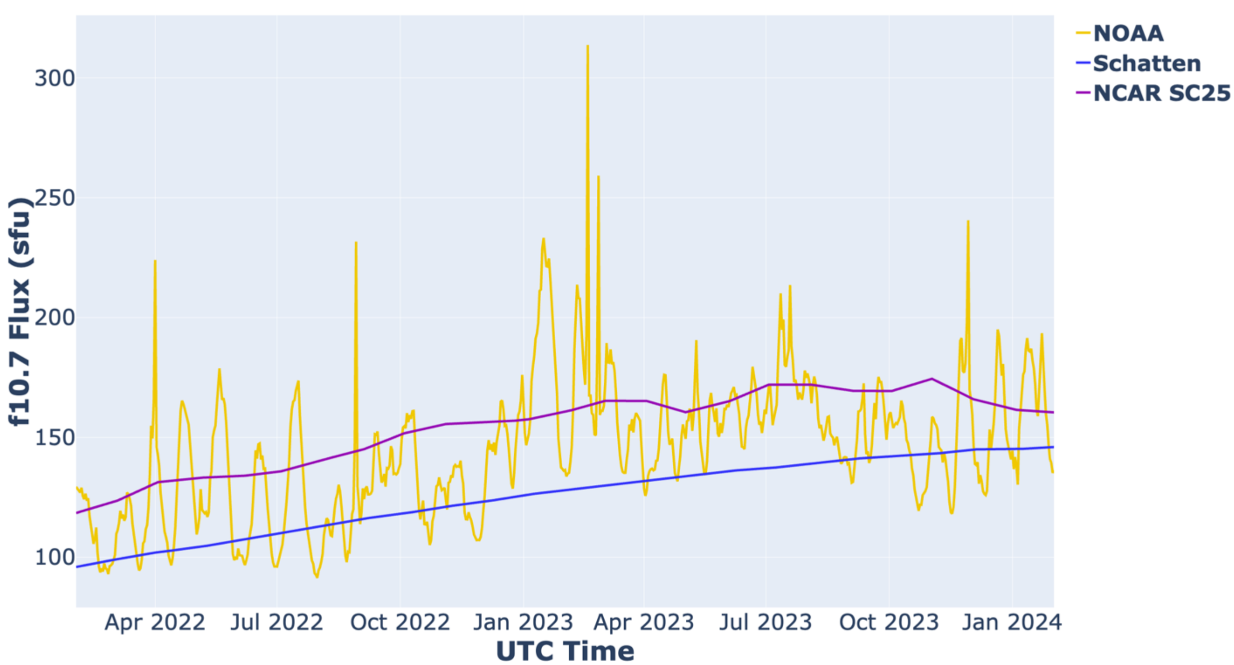

Figure 5: A comparison of the $f10.7$ flux values (predicted and observed) noted from the simulated timespan.

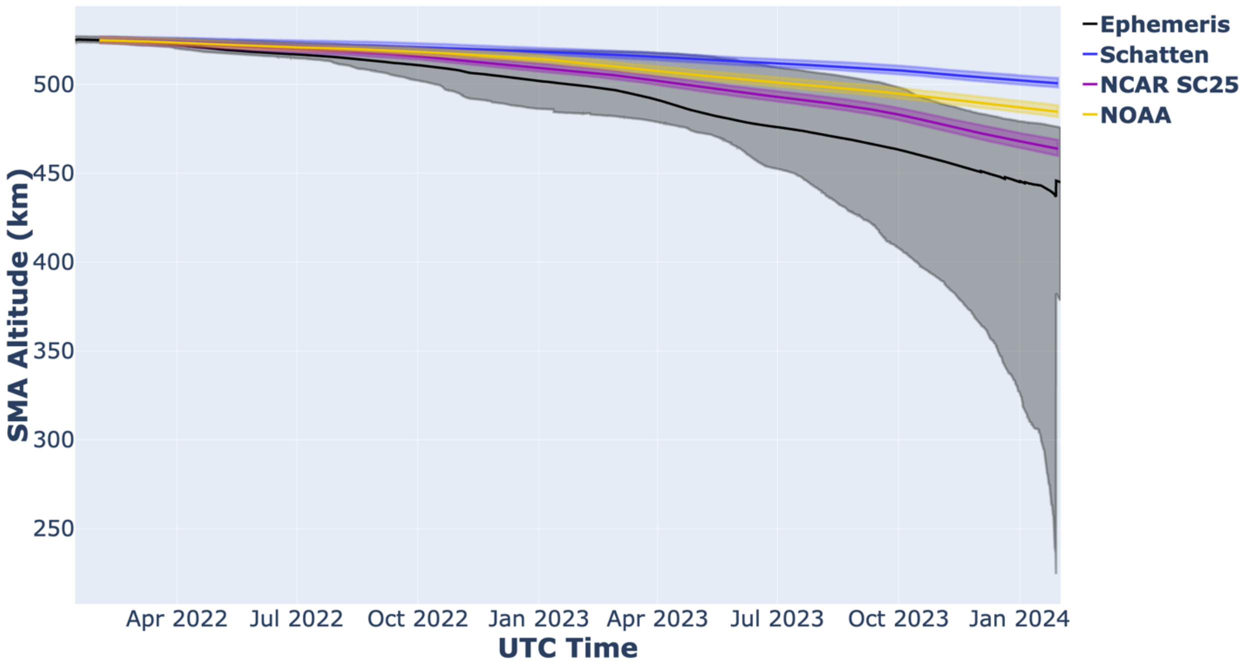

Figure 6: Comparison of Semi-major axis decay noted from propagating different models along with observed Flock 4x ephemeris. The envelopes show the instantaneous minimum and maximum SMA values of the flock, while the solid line shows the mean.

to the timespan being studied. Furthermore, in order to facilitate a fair comparison, we only use the mean flux values for the NCAR and Schatten predicts for the current work.

RESULTS

This section compares the predictions from different space weather sources described above. We begin by looking at the $f10.7$ flux predictions and observations and then examine the SMA expected SMA degradation.

F10.7 Fluxes

Figure 5 shows the solar fluxes noted from the Schatten and NCAR models and the NOAA observations. The fluxes are measured in solar flux units (sfu) where $1\ \mathrm{sfu} = 1\mathrm{e}-22\ \mathrm{W/\ Hz}-\mathrm{m}^2$. It can be seen here that the Schatten model underpredicted the $f10.7$ flux with respect to the observed data, as we approached the solar maximum. For the simulated 2-year timespan, we noted a root-mean-square error (RMSE) of about 30.8 sfu from the Schatten predicts. The NCAR predictions, on the other hand, were found to track the observations better than the Schatten model. In this case, we noted an RMSE of about 25.5 sfu. It is reminded here again that the Schatten predictions used in the current work best reflect the values issued at the beginning of the timespan being studied. The implication of these predictions on spacecraft lifetime is discussed next.

Altitude Decay

Figure 6 shows the semi-major axis decay noted from propagating the orbits with different space weather data sources. The decays here present some important challenges in forecasting orbital lifetimes. It can be seen that the observed SMA data noted from the Flock 4x ephemeris decayed slightly faster than the modeled rates from all sources. This is attributed to the consequences of modeling errors on long-term predictions. The key sources of these modeling operational effects such as changing spacecraft attitude, and more systematic effects such as this arising from, and predicting atmospheric densities, and numerical propagation. However, despite this limitation, the space weather models still play a crucial role in understanding the lifetime of assets in space. Based on Figure 6, the Schatten model predicted a slower altitude decay for the entire period in question. Furthermore, in comparison with the real Flock 4x ephemeris, the Schatten model predicted more of an optimistic scenario with longer orbit life. This challenges the use of the Schatten model for applications such as lifetime modeling, which typically involve long-term forecasting. However, the decay rates noted from the NCAR model closely tracked those noted from the

NOAA observations till July 2023, despite being conservative throughout the simulated period being studied. However, this added conservatism is used as a compensation mechanism for the modeling errors mentioned above.

Discussion

As the onset of solar maximum started for the 25th solar cycle, around early 2022, we noticed a large discrepancy between the modeled altitude decays of satellites (using the Schatten predicts), and the actual observations. As illustrated in Figure 6, the Schatten model predicted a longer orbital lifetime than what was suggested from the observations. This drove us to explore the use of different space weather models, from which the NCAR model was determined as a promising candidate. Using the NCAR model, Planet implemented several proactive strategies like planning the next launches, determining the launch altitude, and altering spacecraft design for improved ballistic stability.

CONCLUSION

Solar cycle 25 has been more aggressive than what was predicted by the current state of the art, especially as we approach the solar maximum. This not only impacted the near-term operations of several LEO satellites but also led to shorter lifetimes than what was predicted by the standard models. The Schatten model is one such industry-standard model that is used to infer the spatiotemporal atmospheric density experienced by a satellite. While the Schatten predicts are indeed updated periodically to improve accuracy, this is not suitable for predicting orbital lifetime which involves long-term forecasting. In this work, we examined the use of the NCAR space weather model for the Solar Cycle 25 as an alternative to the Schatten model. The NCAR model forecasts the f10.7 flux using the observations of the past sunspot cycles, in contrast to relying on modeling solar magnetic cycles alone.

In the current work, we modeled the altitude degradation of LEO satellites using the NCAR model, as we approached the solar maximum, and compared it to the Schatten model. Additionally, we also compared the findings to the observed altitude degradation noted from a real satellite fleet. The results indicated that the Schatten model was optimistic and predicted longer fleet lifetimes. This optimism limits the use of the Schatten models to applications such as lifetime modeling, The NCAR model on the other hand, predicted a more severe decay in altitude, which was shown to track the observed ephemeris better than the Schatten predictions. Additionally, the "surplus conservatism" from the NCAR model served as a compensation mechanism for any long-term effects of modeling errors. While no model is perfect when it comes to making long-term predictions, such conservatism can enable satellite operations to "err on the side of caution" and be robust to space weather challenges. Such paradigms will not only enable efficient profitability from space assets but also pave the path forward to improved space situational awareness.

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