Lessons Learned About Orbital Decay from the UNITE CubeSat

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Abstract

The University of Southern Indiana (USI) Undergraduate Nano Ionospheric Temperature Explorer (UNITE) CubeSat, funded by NASA's Undergraduate Student Instrument Project – 2 (USIP-2), was deployed from the International Space Station on January 31, 2019 (Figure 1). UNITE was a 3U CubeSat without deployables that was passively stabilized magnetically and aerodynamically. The UNITE CubeSat reentered the atmosphere on October 21, 2021, its 995th day in orbit. One of the mission objectives of UNITE was to track its orbital decay with the intent of updating CubeSat drag models. The original predicted mission lifetime of 428 days was based on results from a spreadsheet available with *Space Mission Engineering: The New SMAD*, using standard CubeSat parameters and simply assuming "solar mean" for the solar cycle. To more accurately understand the actual orbital behavior known from the TLEs (two-line elements), a completely new algorithm was coded for orbital drag, but taking into account varying atmospheric densities consistent with the variability of the actual solar cycle experienced between January 2019 and October 2021. Using the algorithm and the updated atmospheric density model, the mission time was computed to be 976 days, only 19 days short of the actual mission time. Next, the drag coefficient was adjusted from 2.2 to 2.08, and with that change the algorithm correctly calculated the 995 days in orbit. Also of note, in the process o f the development of the algorithm, a slight error was discovered in the Bessel function table available through *The New SMAD*, and that was corrected, as well. The new algorithm, developed by the undergraduate student, was implemented in an Excel program and is readily available for use by other teams. With the implementation of a new algorithm that accounts for solar cycle activity and allows for drag coefficient adjustment, it is hoped that future CubeSat teams will be able to predict mission life and the orbital decay more accurately.

Figure 1: UNITE CubeSat being deployed from the International Space Station

Introduction

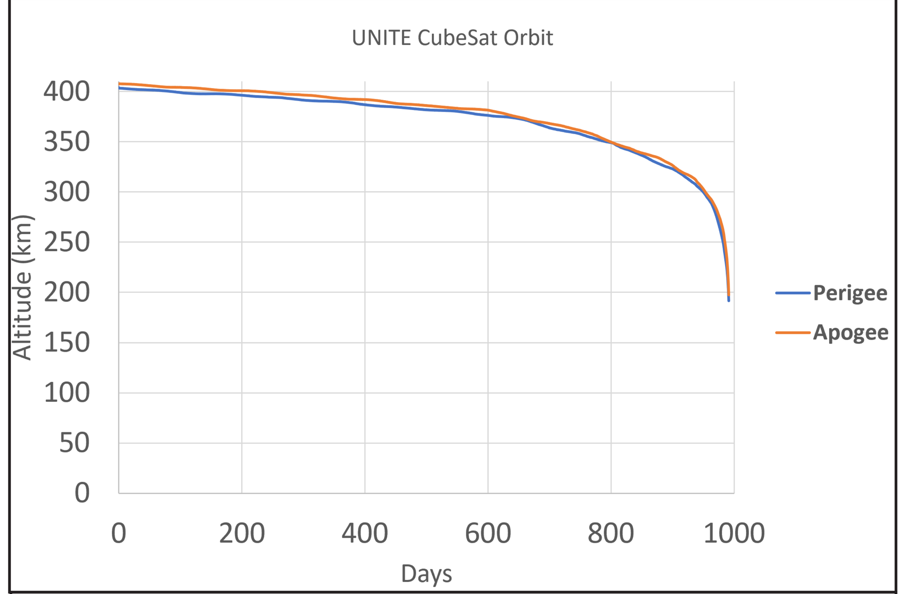

Figure 2: Actual UNITE CubeSat altitude using TLE data

The actual UNITE CubeSat orbital decay is depicted in Figure 2 using TLE (two-line element) data. Originally the UNITE CubeSat orbital decay model was developed using the *Space Mission Engineering: The New SMAD*. The book provides a list of the equations used to solve for the model. It also provides a downloadable Excel spreadsheet, created July 7, 2011, that takes the initial values of the satellite at deployment and plots the projected perigee and apogee height, with respect to the center of Earth, of the satellite over time. The equation requires initial conditions: solar cycle (min, mean, or max), plot duration (days), initial perigee height (km), initial apogee height (km), drag coefficient, satellite mass (kg), and cross-sectional area (m^2).

Predicting the Orbital Decay

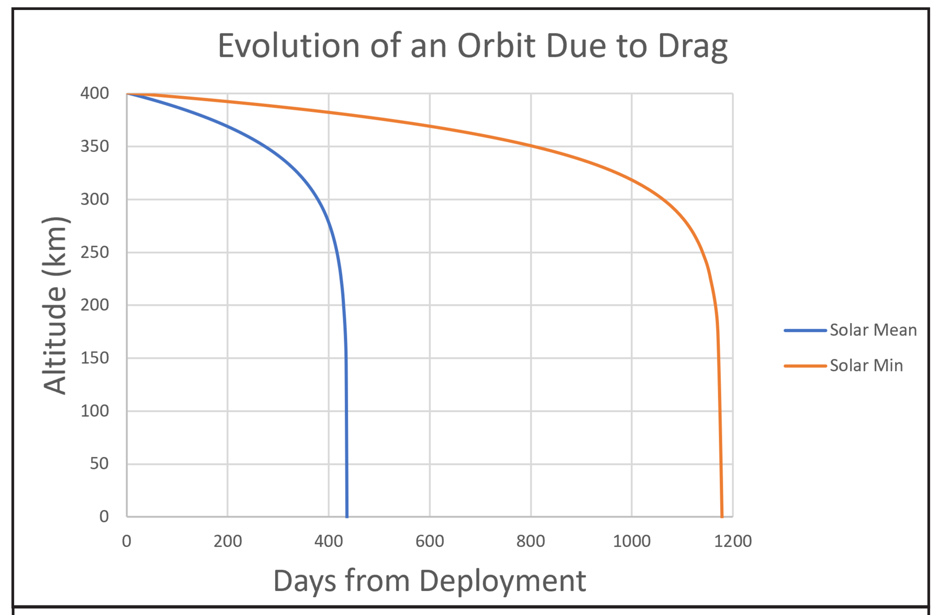

Figure 3: Predicted evolution of an orbit due to drag using the Excel program provided by *The New SMAD*, using Solar Mean and Solar Min values

The perigee and apogee will both change during the orbit. The cross-sectional area will decrease over time as the satellite stabilizes itself which can affect drag. The atmospheric density is dependent upon the height of satellite as well as the solar cycle including solar min, solar mean, and solar max. *The New SMAD* provides a table with the atmospheric density and atmospheric scale height relative to the perigee altitude of the satellite.

Using the Excel program provided by *The New SMAD*, the original satellite mission time was predicted to be 428 days at solar mean and 1170 days at solar min (Figure 3).

Accounting for the Changing Solar Cycle

The New SMAD Excel program only accounts for the atmospheric density and atmospheric scale height at a solar cycle constant: solar min, solar mean, or solar max. Both atmospheric density and scale height are greater at solar max and least at solar min. As the perigee height decreases, atmospheric density increases and scale height decreases. The solar cycle is a measure of the Sun's activity measured by the number of observed sunspots. The solar cycle directly correlates to the atmospheric density. As the atmoshepric density increases, the satellite will lose energy at an increased rate, resulting in a shorter mission time. The Space Weather Prediction Center provides a prediction of the solar cycle, actual recorded solar activity, and the average solar activity over time (Figure 4). The predicted solar cycle activity can be represented as a sinusoid prediction which is used to create Equation 3. To account for the change in the solar cycle over time, the solar cycle can be represented as a delayed cosine function, Equation 1. Where the Solar Cycle Value is [0 (solar min) < 0.5 (solar mean) < 1 (solar max)], t is the number of days in orbit, d is the number of days from the minimum point of solar min, and B is Equation 2. Where T is the period of the solar cycle in days. From Figure 4, solar min is predicted to take place on January 1, 2020, and solar max on July 1, 2025. The time between solar min and solar max is 2004 days, so the period is 4008 days. The UNITE CubeSat deployment on January 31, 2019, was 335 days before the predicted solar min on January 1, 2020. The resulting Solar Cycle Value can be represented as Equation 3. Figure 5 is the function of the solar cycle value as it relates to time. The function starts with the date of the deployment.

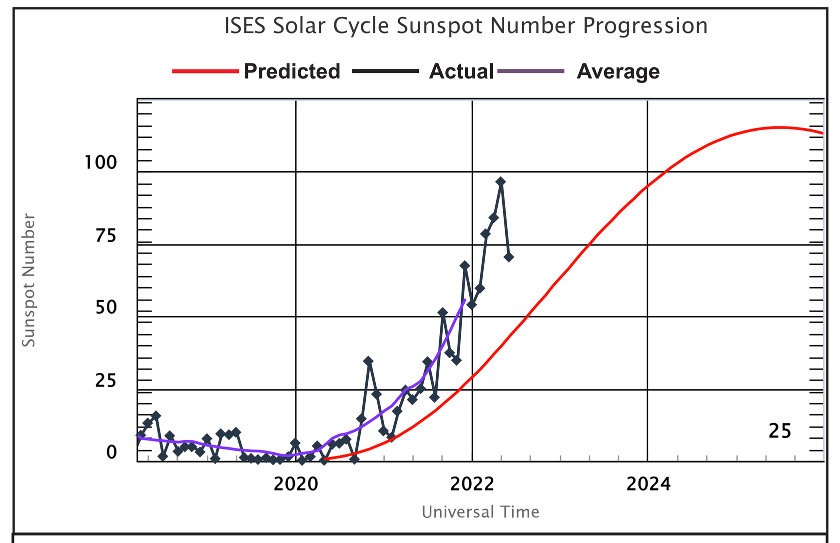

Figure 4: Solar cycle from the Space Weather Prediction Center

$$Solar\ Cycle\ Value = -\frac{1}{2}\cos[B(t-d)] + 0.5 \quad (Equation\ 1)$$

$$B = \frac{2\pi}{T} \quad (Equation\ 2)$$

$$Solar\ Cycle\ Value = -\frac{1}{2}\cos\left[\frac{2\pi}{4008}(t-335)\right] + 0.5 \quad (Equation\ 3)$$

Equations 1-3: Solar Cycle Value Equations

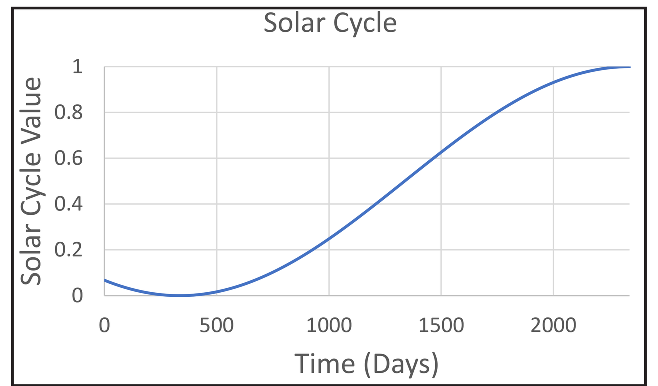

Figure 5: Solar Cycle Value (Equation 3) as a function of time

Updating the Orbital Decay Model

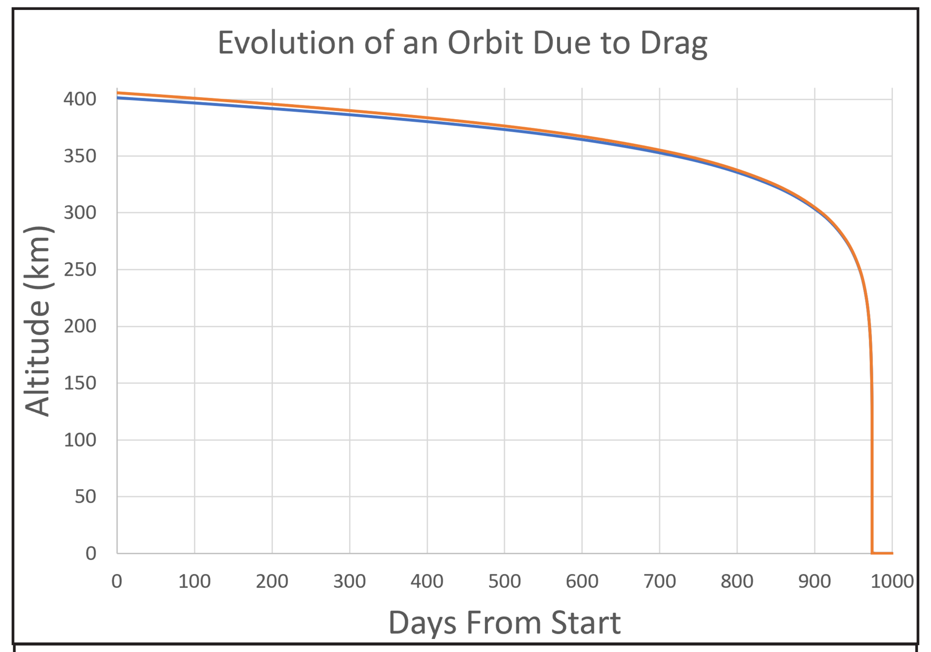

Figure 6: The updated orbital decay model using the solar cycle value from Figure 5

The perigee height must be interpolated and applied to the atmospheric density and atmospheric scale height. Then, the atmospheric density and scale height of the solar min, solar mean, and solar max, must be interpolated using the Solar Cycle Value (Figure 5) to find the actual density and scale height. The updated orbital decay model (Figure 6), brings the predicted mission time to 976 days. The actual time was 995 days, so the updated prediction falls 19 days short. 19 days is the most accurate predicted mission time out of any previous model.

Updating the Drag Coefficient

The New SMAD assumes drag coefficient for all small satellites to be 2.2; however, the drag coefficient is another variable that changes in orbit. In 2019, there was a close collision between the UNITE CubeSat and another satellite. When a near-collision occurs, the data is recorded. From the data, it can be concluded that the drag coefficient at that moment was 1.2613. Using the updated orbital decay model, the drag coefficient can be adjusted to find the actual average drag coefficient of the UNITE CubeSat throughout the mission (Figure 7). After adjusting the drag coefficient, it is found that the average drag coefficient is 2.08.

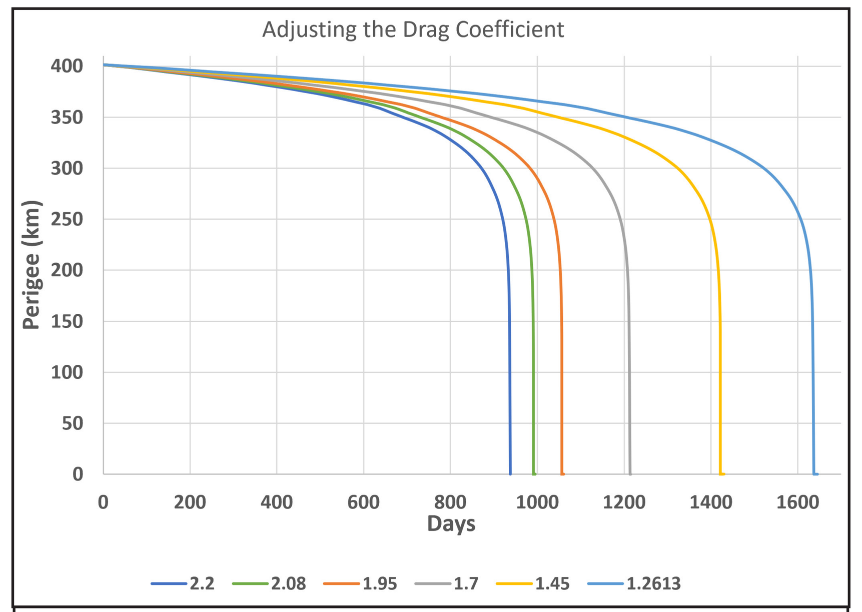

Figure 7: Adjusting the drag coefficient to solve for the UNITE CubeSat's average coefficent due to drag

Conclusion

An improvement to the orbital decay model was made to better represent the mission time of the University of Southern Indiana's Undergraduate Nano Ionospheric Temperature Explorer CubeSat. The Excel program created should be used for any future small satellite missions to better predict the mission time and orbital decay.

For the Excel program or more information, contact Charles Clayton Davis. The research paper associated with the orbital decay model can be found at:

https://claytondavis.myportfolio.com/engineering-projects

I would like to add a special thanks to Dr. Glen Kissel for guiding and advising me throughout this entire research project, and thank you to the past UNITE team members for their work on the project.

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References

Wertz, James Richard, et al. *Space Mission Engineering: The New SMAD*. Microcosm Press, 2011.

"Solar Cycle Progression." *Solar Cycle Progression | NOAA / NWS Space Weather Prediction Center*, National Oceanic and Atmospheric Administration, https://www.swpc.noaa.gov/products/solar-cycle-progression.

Reference Number

SSC22-WKP2-12