BlueWalker 3
Updated Orbital Debris Mitigation Unified Response
August 2021

Pursuant to Section 5.64 of the Federal Communications Commission's ("FCC") rules,[1/] AST&Science LLC ("AST") has provided numerous filings and responses regarding the design and operational strategy of the BlueWalker 3 ("BW3") spacecraft to demonstrate how it will mitigate orbital debris and other end-of-life concerns.[2/] As a result of certain operational changes to the BW3,[3] AST is filing this unified update to those filings, which seeks to address all of the Commission's requests for information.

Executive Summary

The following document outlines how the AST BW3 mission has been designed to meet or surpass all of the Section 5.64 orbital debris mitigation rules. Specific assessments include a list of on-orbit objects and their associated de-orbit casualty risk, the probability of accidental explosions, the probability of collisions with large and small objects, and the satellite de-orbit plan and analysis.

Analysis using the NASA DAS 3.0.1 software demonstrates that the primary spacecraft will naturally de-orbit within 2.5 years and presents a total casualty risk of only 1:19,700, surpassing the requirement of 1:10,000 by nearly a factor of two. A secondary object, the Launch Vehicle Adaptor, will naturally de-orbit within 1.2 years and presents a total casualty risk of only 1:12,500, also surpassing the requirement.

The possibility of explosions due to over pressure of propellant tanks, unanticipated mixing of fuel/oxidizer, or overcharging/damage of batteries has been mitigated in several ways. The propellant is an inert gas and the tank has a passive overpressure relief valves. The batteries are constantly monitored by highly redundant electrical power system modules and discharged/taken out of service if their operational parameters exceed acceptable thresholds.

The probability of collision with large objects, as demonstrated here, is no greater than that for a much smaller spacecraft due to the orientation of BW3 during operation (*i.e.*, flying edge-on). Nevertheless, AST shall maintain all best practices with regard to conjunction assessment, collision avoidance maneuvers using onboard propulsion, and sharing of ephemeris data.

1/ 47 C.F.R. § 5.64.

2/ This filing is subject to a request for confidential treatment. Information highlighted in yellow is subject to that request and has been redacted in AST's publicly available filing.

3 The spacecraft will operate at a new orbit of between 375 and 425 km, at a different inclination of between 51 and 55 degrees.

Finally, despite meeting the de-orbit casualty risk for uncontrolled re-entry, AST will conduct a controlled deorbit of BW3 at end-of-life to ensure safe disposal of the spacecraft in accordance with IADC Guidelines.

I. Assessment of Debris Risk; List of Objects and Casualty Risk (§ 5.64(b)(1))

AST has chosen materials and developed a spacecraft design with the aim of minimizing all possible risks. AST has assessed and limited the amount of debris released in a planned manner during normal operations, and has assessed and limited the probability of the BW3 becoming a source of debris by collisions with small debris or meteoroids that could cause loss of control and prevent post-mission disposal.[4/] Table 1 presents the list of objects (mission-related objects or space debris) planned to be released as part of the nominal mission, including physical characteristics, orbital characteristics and predicted orbital lifetime.

These total causality risks were generated using the NASA Debris Assessment Software (version DAS 3.0.1) using characteristics of the spacecraft and launch vehicle interface. This launch vehicle interface consists of the launch vehicle adapter and separation ring, which will be released by the spacecraft, as retaining this object with the spacecraft would interfere with the operation of the spacecraft payload. Furthermore, this object may not be kept with the launch vehicle for disposal due to the requirements of the launch vehicle provider. However, it presents a low risk, because the casualty risk complies with the 1:10,000 requirement, it will be released from the spacecraft outside of the GEO protected region, and it will not remain in LEO orbit for greater than 25 years. The expected lifetime of the launch vehicle adaptor (LVA) after release is at most 1.2 years, assuming a worst case minus two sigma solar flux magnitude and a late peak activity timing. In this analysis, the maximum cross-sectional surface area of the LVA is 10.04 m^2 and the minimum cross-sectional area is 1.85 m^2. The total mass is estimated at 300 kg.

Table 1 - List of objects for BW3

Object	***Description***	***Orbital Lifetime***	***Total Causality Risk***[5/]
ControlSat and Phased Array	Main body with phased array composed of individual Micron elements	2.5 years	1:19,700
Launch Vehicle Adapter and Separation Ring	Launcher to satellite interphase ring with hold-down and release mechanism (HDRM)	1.2 years	1:12,500

4 / BW3 will occupy a circular orbit at an altitude between 375 km and 425 km. For purposes of the analysis here, AST assumes operations at 400 km.

5 / Based on the fragment survival analysis and total casualty risk to the population. *See* NASA NSS 1740.14 [RD4].

The ControlSat and Phased Array can be subdivided into its constituents, and the analysis demonstrates that any individual component that survives re-entry with an impacting kinetic energy greater than 15 J will contribute to the total debris casualty area that results in the total casualty risk of 1:19,700. A summary of all surviving objects with their corresponding debris casualty areas and kinetic energies can be seen Table 2. Of the materials surviving re-entry, only the ControlSat, in entirety, and [redacted] have sufficient impacting kinetic energy to contribute to the total debris casualty area *(as denoted by the red text in the table below).*

Table 2 - List of objects that survive re-entry

Object	***Quantity***	***Modeled Material***	***Debris Casualty Area (m2)***	***Kinetic energy***
ControlSat	1	Aluminum	2.67	147,993
[redacted]	[redacted]	PERMENORM	33.5	12.7
[redacted]	[redacted]	Aluminum	1.75	57.7
[redacted]	[redacted]	Graphite Epoxy	184.27	0.06
Total Debris Casualty Area (m2)				4.42
Total Causality Risk				1:19,700

II. Probability of Accidental Explosions (§ 5.64(b)(2))

AST has assessed and limited the probability accidental explosions that would result in the spacecraft becoming a source of debris. The two sources of on-orbit explosions are propellant tanks and batteries, both of which will be continuously monitored throughout the spacecraft lifetime for failure modes. The batteries are continuously monitored by an electrical power system (EPS) module to avoid over-charging/discharging. Should battery operation fall outside of an acceptable range it will be discharged and taken out of service, removing any stored energy it contained. All batteries on-board the control satellite will have a 1.5 mm aluminum casing and will be thermally isolated to mitigate thermal loads. Additionally, the batteries will have protective circuitry to regulate safe and nominal voltage and current levels. The propellant for the electric propulsion system is an inert and non-reactive noble gas and does not present a source of energy conversion in the event of a gas leak. The pressurized propellant tank will be continuously monitored with downlink of state-of-health telemetry. Propellant safety measures include a system of pressure control and relief valves, with complete thermal isolation and temperature control. Any stored energy remaining at the spacecraft's end-of-life will be removed via depletion of the propellant tank and permanently discharging the on-board batteries.

III. Failures Leading to Debris: Collision with Large Objects Assessments (§ 5.64(b)(3))

The probability of a collision occurring between any two objects in Earth's orbit depends primarily on the likelihood of them passing close to one another -- a situation referred to as a conjunction --

but also on the apparent cross-sections of the two objects as projected along their relative velocity vector at the time of conjunction. So, as an example, the probability of a CubeSat colliding with something the size of the International Space Station is much greater than the probability of it colliding with a second CubeSat. Of particular importance is that it is the apparent cross-section projected along the relative velocity vector that matters in this calculation.

The vast majority of objects in low Earth orbit can be found in low eccentricity orbits. As a result, when two such objects pass near one another, the relative velocity vector lies very close to the local horizontal plane -- they do not tend to come from "above" or "below". This is true regardless of the relative inclinations of the two orbits, which would merely determine if the secondary object came from the "left" or "right" relative to the primary object's own direction of motion. In fact, among the operational satellites that will cross the BW3's orbital plane, the highest relative velocity angle above the local horizontal of any satellite is less than 4 degrees. *This means that it is the projected cross-section of the BW3 satellite within 4 degrees of the local horizontal plan that determines it collision probability.*

AST has assessed and limited the probability of BW3 becoming a source of debris by collisions with large debris or other operational space stations. The probability of collision with large debris can be estimated using the NASA Debris Assessment Software (version DAS 3.0.1). *The probability given the edge-on flight configuration is 1.3(10^{-5}), well within compliance by a significant margin.* While the planform (as viewed from above) of the BW3 satellite is about 60 square meters in area, the cross-section of the satellite as viewed within the local horizontal plane is less than 1 square meter. This is because the BW3 satellite flies in the same orientation as a Frisbee -- although the satellite is not rotating as a frisbee would. In this "edge-on" flight orientation, the probability of a collision is therefore more than 60 times smaller than what it would be if the satellite were to fly perpendicular to its velocity vector. While the usual approach in calculating the probability of a collision is simply to use the largest dimension of the spacecraft as if it were the diameter of a spherical object, this would result in overestimating the probability of collision by more than a factor of 60.

Even this calculation is an overestimate, as it assumes that the spacecraft will make no effort to perform collision avoidance maneuvers during its operational lifetime. However, the spacecraft also will have the capability to be maneuvered to avoid collisions with large objects, limiting even further the probability that the spacecraft will become a source of debris. Satellite station-keeping within a given orbital plane is monitored by both a primary and secondary flight operations location, one in Midland, TX and the other in College Park, MD. GPS receivers and batched least squares orbit determination methods provide precise satellite positions, known to (much) less than 10 m, that will be used to maintain a precision ephemeris for each spacecraft. The satellite will be registered with the 18th Space Control Squadron or successor entity prior to deployment. Its initial deployment, ephemeris, and planned maneuvers will be shared with the 18th Space Control Squadron or successor entity, the Joint Space Operations Center (JSpOC), other operators with assets flying at the same orbital altitude, and may also be made publicly available. Every maneuver will be coordinated with NASA, 18th Space Control Squadron or successor entity, JSpOC, and any other appropriate agency or commercial operator throughout the entire operation and deorbit time lifetime. AST is in the process of establishing a Space Act Agreement with NASA outlining the responsibilities, schedules and milestones associated with COLA activities during the entire mission lifetime. Provided information is made available on new launches that might cross the operational altitude of Blue Walker 3, these can be monitored, however there is no possibility of action should the launch vehicle malfunction and cross paths with the AST satellite. Conjunction warnings will be provided by JSpOC and potentially private data providers. AST has contracted with [redacted] a third-party company that will assess the probability of collision as it evolves over time up to seven days preceding the conjunction. Should a collision avoidance maneuver be necessary, a maneuver decision will be made based on this assessment of the collision probability. [redacted] will also assist with communicating ephemeris and planned maneuvers to the above agencies.

The spacecraft will contain an on-board electric propulsion system that is required to provide a collision avoidance maneuver within a 24-hour window of an identified probable conjunction event. Any uncertainty in the time or distance of closest approach with a secondary object will be driven by its state uncertainty, given the position precision described above. The collision avoidance process is illustrated in Figure 1. The state vectors of crewed space stations (*e.g.*, the ISS) and visiting vehicles are known very accurately, so the collision probability will drop off very rapidly outside of a predicted close approach distance of about 50 m. Given a collision probability that exceeds the acceptable threshold, the time required to put sufficient distance between the objects at the time of closest approach will be relatively short, and certainly less than a day. Should the propulsion system fail during critical mission operations, collision avoidance maneuvers can still be performed using the [redacted] to maneuver the spacecraft into a high-drag configuration where the planform area is normal to the velocity vector. The altitude would be lowered sufficiently to avoid collision with the secondary object before returning to its operational configuration. While the spacecraft cannot be returned to its initial orbit, this ensures that collision avoidance capabilities are maintained throughout the mission, while still maintaining an orbit sufficient for continuation of the mission.

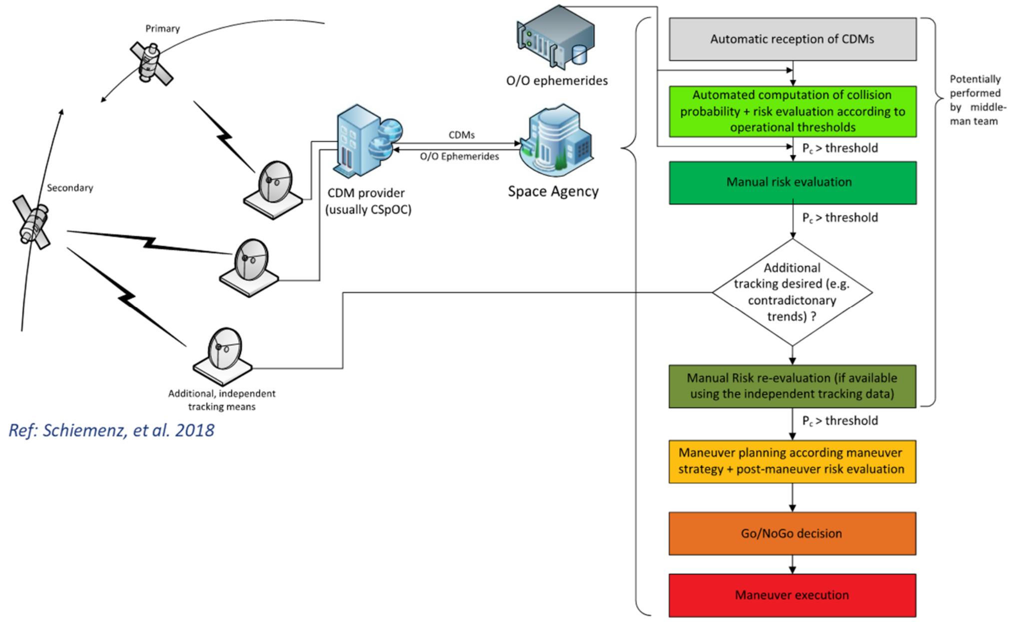

Figure 1 - Collision avoidance system

If a conjunction event exceeds the probability threshold of Pc $\geq 10^{-4}$, the satellite's electric propulsion system will be capable of providing an altitude changing maneuver in order to mitigate the conjunction event. The altitude will be increased or decreased by 100 m then returned to its operational altitude prior to the conjunction mitigation. This maneuver can be performed in a matter of hours and meets the requirement to react to a high-risk conjunction within 24 hours. CARA analysis codes indicate that screened conjunctions for BW3 among currently cataloged satellites will occur at a rate of about 16 unique-events per week, which is similar to that currently experienced by the GPM satellite (SCN 39574). BW3's rate of red-level events with a last-update Pc $\geq 10^{-4}$ will occur at a rate of $\approx$0.24 per year (i.e., about one red-level event every four years among currently cataloged satellites), which is lower than that estimated for GPM, a difference due to the different hard-body radii of the two satellites.

Collision Avoidance Timeline

Within 24 hours of receipt of an initial CDM (5-6 days out), a preliminary propulsive maneuver will be determined and scripted to begin no later than 24 hours prior to the predicted conjunction event. Within 24 hours of the predicted time of closest approach (TCA), the propulsion system can safely maneuver the spacecraft out of range of the conjunction location. The ballistic coefficient of BW3 is quite high due to the very low projected area in the velocity direction, and the position and velocity of the system will be known very precisely due to the onboard GPS units, so the predicted ephemeris uploaded to Space-Track can be quite accurate even several days out. The uncertainty in the conjunction will then be driven primarily by the secondary object.

Over the 4-5 days prior to the conjunction event, the covariance of the secondary object's ephemeris and the probability of collision will be updated with every new CDM between the initial report and the conjunction event. Any anticipated avoidance maneuver will be revised and remain in an "active" state until the probability of collision falls below 10^{-4} (0.01%) and tracks downward over several CDM updates. No later than four days prior to the expected conjunction, the electric propulsion system will undergo a state of health check and conditioning procedure. If the propulsion system is operating nominally, and the collision probability remains above the 0.01% threshold, the scripted maneuver will be executed as planned 24 hours in advance of the predicted TCA.

At no later than the TCA-4 day point, the electric propulsion system undergoes a state of health check and conditioning procedure. If it fails this check, a contingency high-drag maneuver will be planned while attempts are made to bring the thruster online. The required duration of the high-drag maneuver will depend on the level of solar activity at the time and its influence on the atmospheric density. A direct evaluation of the density will be known at the time from tracking long-term drag effects, but for now a prediction will have to suffice. Figure 2 shows the predicted level of solar activity over the next cycle from 2020-2035. Figure 3 shows the drag versus altitude using data from the most recent cycle. The targeted Pc threshold to execute a maneuver is $>10^{-4}$ within 24 hours of TCA to use the propulsion system, or within 48 hours of TCA to use the high-drag configuration. If the time required for a high-drag maneuver to reach this level is predicted to exceed 48 hours due to unexpectedly low drag conditions (something that would have been monitored for weeks), then the time will be adjusted accordingly.

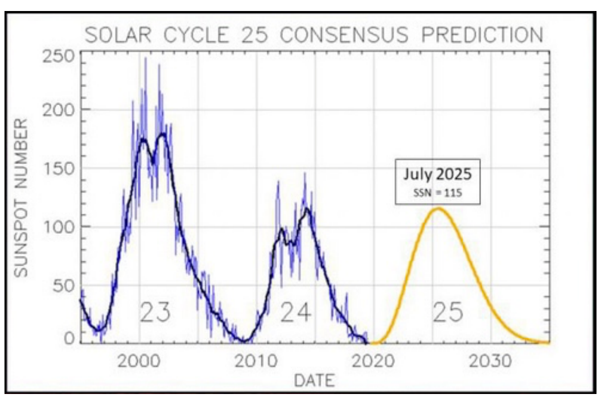

Figure 2 - NOAA / NASA solar cycle prediction for upcoming Cycle 25

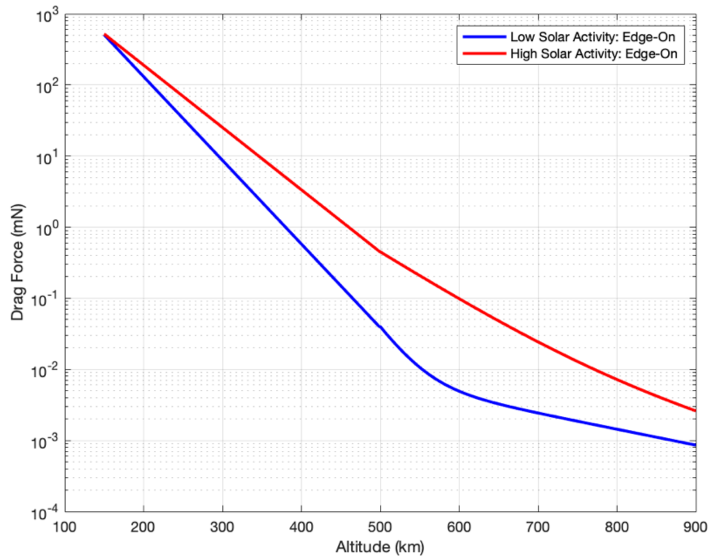

Figure 3 - Atmospheric drag on BW3 satellite as a function of orbital altitude

Initial processing of a new CDM can be done within a matter of minutes. However, the determination of whether a propulsive maneuver is required occurs over the course of multiple days and several CDMs. This is because the ephemeris information that goes into determining whether a CDM will be provided by the Air Force has a level of uncertainty, and the farther in advance the CDM is provided relative to the predicted time of closest approach (TCA) the larger this uncertainty is. By tracking how the CDM data evolves over time, the collision probability can be evaluated as either increasing or decreasing, and then a decision to implement a maneuver is made early enough in advance for the maneuver to be executed, as is standard practice.

IV. Failures Leading to Debris: Damage from Small Objects Assessments (NASA-STD-8719.14B, Requirement 4.5-2)

Requirement 4.5-2 from the NASA standard limits the probability of a spacecraft being disabled and left in orbit at the End of Mission (EOM). Specifically, it is concerned with the probability that systems critical to EOM disposal may be damaged over the operational lifetime or during EOM disposal (EOMD).

As presented in the next section, under the assumptions of 1) an orbit injection that is 25 km above nominal, 2) a minus 2 sigma confidence for the predicted level of solar activity, 3) a late peak (6 month) of solar activity, and 4) the satellite being dead on arrival (undeployed), the maximum lifetime of the BW3 spacecraft will be 48 months. Under similar assumptions, the maximum lifetime of the Launch Vehicle Adaptor will be only 14 months.

V. Post Mission Disposal Plans: Satellite Deorbit Plan and Analysis (§ 5.64(b)(4))

BW3 will be in operation for approximately two years before the end-of- life deorbit commences. The BW3 satellite decay time is derived from the drag profile of the satellite. Atmospheric densities for high and low periods of solar activity are obtained from the Jacchia-Roberts spherical drag model. The satellite geometry is that of a nadir-facing plane with a 10 m aperture targeted for a 400 km altitude, circular orbit and operating over a 2-year mission lifetime. The spacecraft consists of an array of Microns and a ControlSat, with a total allocated mass of [redacted]. The coefficient of drag is assumed to be 2.2, applied over a drag area of 7.82 m^2. For the spacecraft either flying edge-on, the atmospheric drag as a function of altitude for low and high levels of solar activity can be seen in Figure 3. The corresponding orbital decay starting at the maximum potential altitude of 425 km using the drag profile of Figure 3 can be seen in Figure 4. The blue, green, and red lines each represent the longest, nominal, and shortest dwell times for the satellite, respectively. The longest time uses a -2 sigma confidence for the total number of sunspots with a late peak of solar activity. Conversely, the shortest time uses a +2 sigma confidence for the total number of sunspots with an early peak of solar activity. In the event of any failure, the satellite can be expected to deorbit naturally in 2.5 years, well under the IADC Guidelines for Space Debris Mitigation requirement of 25 years. To ensure a controlled deorbit at end of life, the satellite will be equipped with an electric propulsion system. Should the satellite be inserted into an altitude any lower than 425 km, the worst case dwell scenario does not exceed the 2.5 years shown below. Similarly, the results for the launch vehicle adapter can be seen in Figure 5.

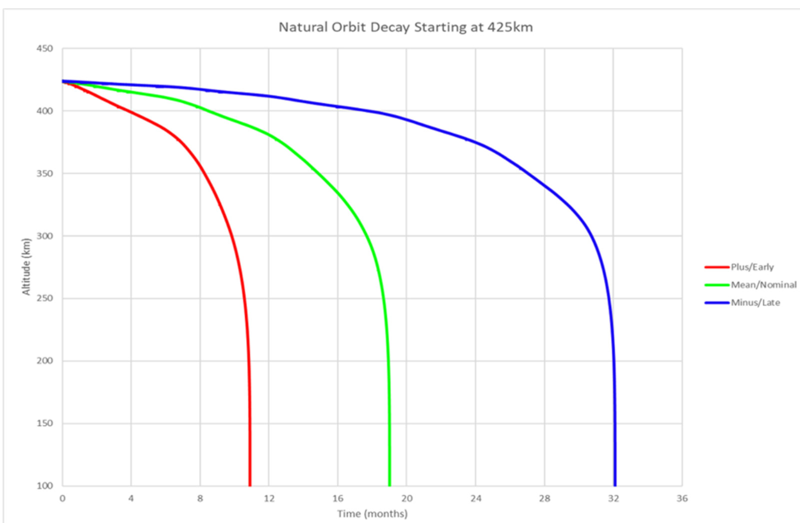

Figure 4 - Natural deorbit time (without propulsion) for the BW3 satellite

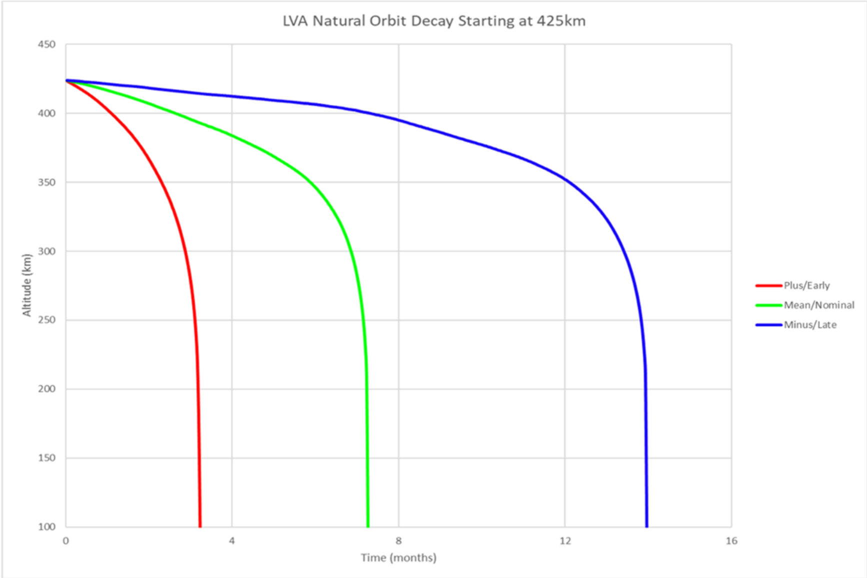

Figure 5 - Natural deorbit time of the launch vehicle adapter

In order to achieve the two-year mission lifetime, periodic orbit maintenance of the spacecraft will be performed, using the propulsion system. For nominal operations, the satellite will be inserted in a circular orbit with altitude 400 km. The satellite will then undergo an orbit raising maneuver to reach 415 km, at which point the propulsion system will be used to provide drag compensation maneuvers such that the mission lifetime can be extended to reach the two-year requirement. The satellite lifetime with the orbit raising maneuver and periodic maintenance can be seen in Figure 6. For higher than nominal drag conditions, the satellite lifetime requirement is not satisfied as a result of drag forces that cannot be compensated with the propulsion system, but the satellite dwell time is well below the 25-year requirement. Even by extending the lifetime of the satellite with the propulsion system at nominal operating conditions, the expected dwell never exceeds the maximum expected 2.5 years assuming the lowest drag conditions at the highest possible altitude of 425 km from Figure 4.

Figure 6 - Satellite lifetime after orbit raising to 415 km from 400 km with routine orbit maintenance

Given that the drag dominates the thrust provided by the propulsion system at lower altitudes, the satellite is expected to naturally deorbit within the dwell requirement. Propellant budgeted for collision avoidance maneuvers shall be maintained for the entirety of the deorbit to assist with mitigation maneuvers in the event of a highly probably conjunction. Remaining propellant will be maintained throughout the decommissioning to provide any required additional maneuvers at end-of-life, in accordance with NASA standard NASA-STD-8719.14B for all debris mitigation practices.

In the event of a critical mission failure before deployment, an orbital decay analysis was performed to investigate the deorbit time of the spacecraft [redacted]. The lifetime [redacted] can be seen in Figure 7. Again, the longest time uses a -2 sigma confidence for the total number of sunspots with a late peak of solar activity. Conversely, the shortest time uses a +2 sigma confidence for the total number of sunspots with an early peak of solar activity. In the event of a failure to deploy, the satellite can be expected to deorbit naturally in no more than 2 years, satisfying the 25-year IADC Guidelines for Space Debris Mitigation requirement.

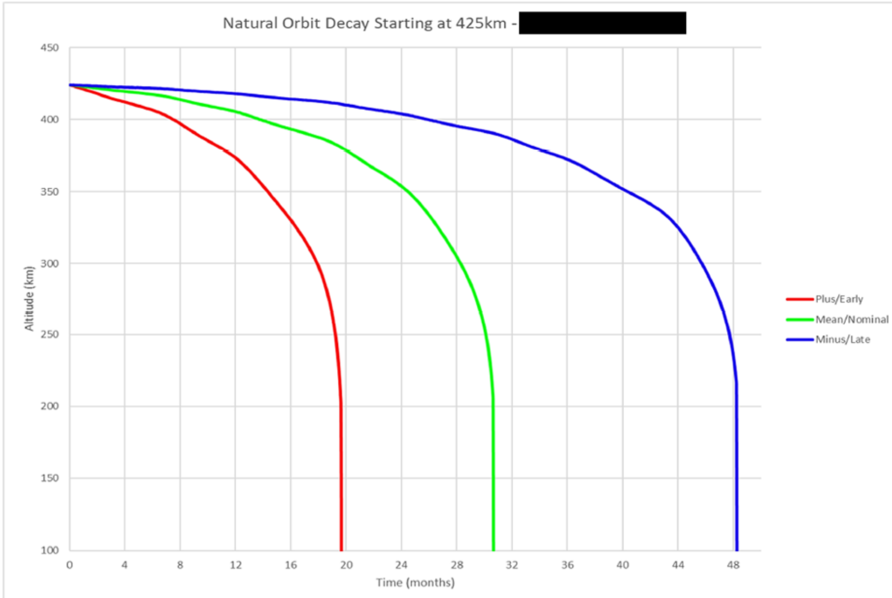

Figure 7 - Orbital decay of BW3 [redacted]

Total Impulse and Propellant Mass Allocations

Based on historical debris mitigation maneuvers assessed by NASA, the BW3 baseline is two maneuvers per year with a total propellant mass of 0.085 kg of propellant total. With an expected one red event per four years, this is a conservative allocation in the event of a necessity to facilitate a maneuver should a yellow event escalate. The impulse and propellant budget can be seen in Table 3.

Table 3 - Impulse and propellant mass budget for BW3

Function	Total Impulse	Propellant Mass	Description
Deorbit	27.8 kNs	2.365 kg	Controlled re-entry in addition to drag.
Collision Avoidance	1 kNs	0.085 kg	Raise altitude by 100 m then return to orbit. Six total maneuvers budgeted.
Orbit Maintenance	61.2 kNs	5.2 kg	Station-keeping and periodic orbit raising. Six maneuvers per day nominally.
Margin	10 kNs	0.85 kg	Unforeseen required maneuvers, such as additional collision avoidance or orbit maintenance maneuvers.
Total	**100 kNs**	**8.5 kg**	

Atmospheric Re-Entry

In the event the AOCS system fails, resulting in an uncontrolled descent of the BlueWalker 3 mission, a casualty risk assessment using the NASA Debris Assessment Software (version DAS 3.0.1) indicates a total risk assessment of 1:19,700, which is lower than the 1:10,000 requirement. Of the debris that does not demise before reaching the surface, those substantially contributing to the total casualty area are well below the 15 Joule kinetic energy requirement. Those components above the 15 Joule requirement contribute a total debris casualty area characterized by the 1:19,700 casualty risk assessment. The total casualty risk assessment for the launch vehicle adapter, which will be released during the deployment state, is 1:12,500.

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CERTIFICATION OF PERSON RESPONSIBLE FOR PREPARING ENGINEERING INFORMATION

I hereby certify that I am the technically qualified person responsible for preparation of the engineering information contained in this application, that I am familiar with Part 5 of the Commission's rules, that I either prepared or reviewed the engineering information submitted in this application, and that it is complete and accurate to the best of my knowledge and belief.

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