DIFFERENTIAL DRAG EFFICACY FOR CLOSE APPROACH REMEDIATION

Dr. Dolan E. Highsmith(1), Dr. James R. Clark(1), Eliot Toumey(2)

(1)The Aerospace Corporation, 14745 Lee Road, Chantilly, VA, 20151, United States, Email:dolan.highsmith@aero.org
(2)Omitron, Inc., 5450 Tech Center Dr., Suite 400, Colorado Springs, CO, 80904, United States, Email:eliot.toumey@omitron.us

ABSTRACT

Differential drag has become a viable alternative to propulsion for satellites to avoid collisions, but there is little guidance in the literature to aid mission designers in developing a differential drag capability that verifiably meets collision avoidance efficacy standards or requirements, if such requirements were to exist. This paper proposes a differential drag efficacy determination approach based on empirical conjunctions from the NASA Conjunction Assessment Risk Analysis historical database, focusing on energy dissipation rate and change in ballistic coefficient as the key satellite parameters correlated to efficacy. The data analysis informs the discussion toward adoption of recommended differential drag requirements. A case study is presented to walk through the process to determine efficacy of a proposed mission assuming several potential requirements.

1. MOTIVATION

The NASA Conjunction Assessment Risk Analysis (CARA) Program provides specialized collision risk assessment services to the fleet of NASA uncrewed satellites in Earth orbit. Services provided by CARA are defined in the NASA Procedural Requirement (NPR) 8079.1 [1], one requirement of which mandates NASA missions to develop an Orbital Collision Avoidance Plan (OCAP) very early in the development phase to ensure a sufficient collision avoidance (CA) concept of operations (CONOP). For NASA missions planning to use differential drag to avoid collisions, CARA needed to develop a technique to determine for the OCAP if the mission design could produce differential drag that would effectively remediate close approaches.

Differential drag is a non-propulsive maneuver technique in which a spacecraft alters its attitude or bus configuration to change its cross-sectional area presented to the oncoming atmosphere. Some missions use differential drag to maintain constellation spacing [2, 3], a process usually accomplished over longer time frames than collision avoidance, which typically has response times of only 12 – 24 hours for propulsive missions. The sensitivity of differential drag to response time and the variability of the specific geometry and other factors affecting conjunctions led to the development of an efficacy analysis based on statistical results from the CARA historical database of conjunctions.

Our initial analysis approach and results are described in [4, 5]. The approach recomputes the probability of collision (Pc) after applying a change to the CARA mission ballistic coefficient (Δ-BC, described in Section 3) at a specified start time prior to the time of closest approach (TCA) for a specified duration and repropagating the trajectory to TCA. If the new Pc is below a certain threshold, the conjunction is considered remediated, and the combination of Δ-BC, start time, and duration is considered effective in that case. The results from [5] showed that the satellite parameter most directly correlated to differential drag efficacy is the initial energy dissipation rate (EDR), providing a classifier for statistical binning of missions for efficacy analysis. However, key questions remained as to how to apply this analysis in practice for a mission in development, as well as implications of where to set threshold requirements to define sufficient efficacy. This paper presents three proposals for thresholds of percent efficacy required to reach a target remediated Pc and shows examples of how the results would apply to different missions. The outcome is an approach to determining the efficacy of differential drag for conjunction remediation for a mission in development based on how corollary missions from the CARA historical database would have performed under similar conditions.

2. ENERGY DISSIPATION RATE

EDR represents the instantaneous orbital energy lost due to atmospheric drag, expressed by Eq. 1:

$$EDR(t) = -\overrightarrow{A_D}(t) \cdot \vec{V}(t) \,, \quad (1)$$

where $\overrightarrow{A_D}(t)$ is the inertial drag acceleration vector at time t, $\vec{V}(t)$ is the inertial velocity vector at time t, and the resulting units are Watt/kg [6]. Clearly, EDR is directly correlated to drag acceleration. Since differential drag uses a change in area of the spacecraft to effect a change in drag, it follows that the efficacy of that technique would be strongly correlated to *initial* EDR (noting that after changing the spacecraft area, the EDR experiences a corresponding change). In other words, satellites with similar initial EDR experience similar differential drag effects given the same Δ-BC.

In [6], Hejduk discusses EDR binning used in a study of the U.S. Space Surveillance Network (SSN) catalog. Though the catalog population has greatly expanded since 2007, the same 11 bins are still in use today. For this work, we collapsed the number of bins to a total of six that span approximately a factor of two for the bins with appreciable EDR. This helped even out the population statistics among the bins. However, there is potential for the nominal EDR of a mission to change bins due to variability in the solar cycle, space weather, altitude decay, and drag area adjustments (e.g., due to Sun-tracking solar panels). One such NASA mission is CYGNSS [3], a constellation of satellites launched in 2016 that have spanned solar minimum and maximum and have decayed significantly from their initial altitude. Thus, the relevant EDR value for evaluating differential drag efficacy could change throughout the mission lifetime.

In [4], we used the perigee altitude of the primary object to bin conjunctions, but this was a weaker correlation to differential drag than EDR because altitude captures only the density correlation and not the extremely variable ballistic coefficients of objects at the same altitude. Altitude binning occasionally resulted in bins at lower altitudes with lesser efficacy than higher because of the mixing between BC and other confounding parameters. By using EDR, we can take all such factors into account and can demonstrate that the resulting efficacy landscape is much clearer, as shown in Figure 1.

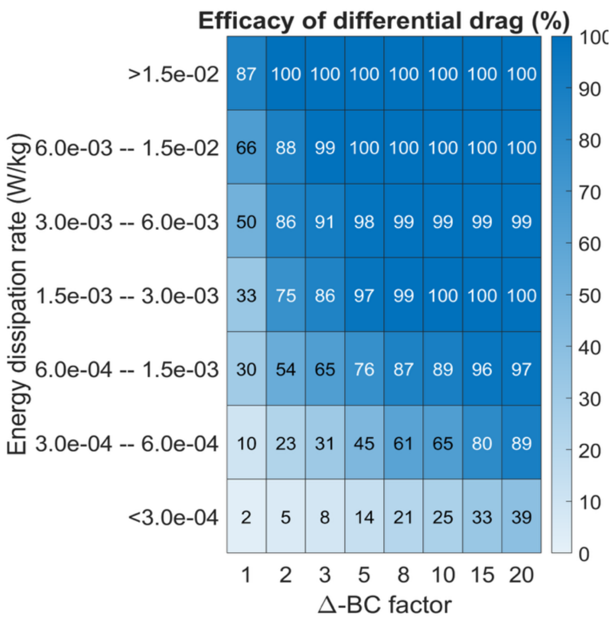

Figure 1: Percent efficacy of differential drag (color scale and values) in bins of EDR for a range of changes in ballistic coefficient. This assumes a start time of TCA – 24 hr and a duration of 24 hr and needs to reduce Pc < 7E-5 for success.

Figure 1 gives an example of the percent efficacy of differential drag for remediating conjunctions within the indicated initial EDR bins given a range of Δ-BC values applied to the empirical conjunctions within those EDR bins. In this case, a conjunction is considered remediated if the Pc resulting from the Δ-BC reduced to less than 7E-5 (from above 1E-4) assuming a start time of TCA – 24 hr and a duration of 24 hr. Under these conditions, for example, a mission with an initial EDR of 1.0E-3 W/kg (third row from the bottom) and a Δ-BC capability of 3 would expect to be able to successfully remediate 65% of high-risk conjunctions. Not surprisingly, Fig. 1 shows that missions with a higher initial EDR and a capability for a large change in area are the most effective at using differential drag for collision avoidance.

3. DATA SENSITIVITY

The input data from this study comes from the extensive CARA database of historical conjunctions. Profiling the EDR values over time provides insight into their temporal sensitivity, but this analysis uses only a subset of the conjunctions. First, the full set of conjunctions in the database is filtered to choose those with 1) Pc >= 10^{-4} within three days to TCA, 2) altitude at close approach below 1000 km, and 3) positive definite covariances for both the primary (CARA) and secondary objects. This results in ~8,200 total high-risk conjunctions that could have differential drag applied with a valid post-mitigation Pc calculated.

After filtering, the data extend from late-2014 to the present day, spanning more than a full 11-year solar cycle. Fig. 2 shows the history of EDR values in the tracked data:

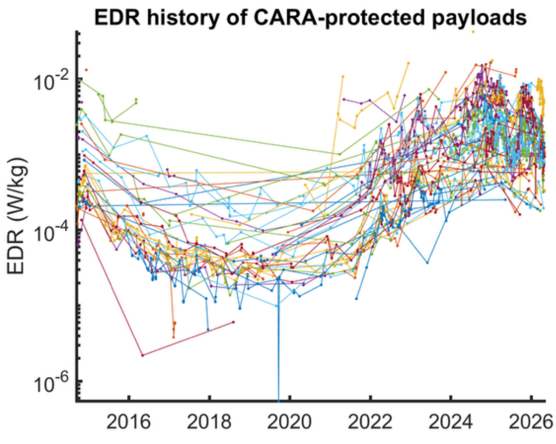

Figure 2: EDR of CARA payloads over time for filtered set of conjunctions used in this analysis.

There are two clear trends. First is the effect of the solar cycle on drag, swaying the mean EDR by a factor of 10-20 between solar maximum and minimum, also noting that the current solar maximum is more intense than the

previous by a factor of about two. Secondly, the higher density of data in recent years shows that NASA is operating more missions with more high-risk events per mission as time goes on. Among other factors, this can be attributed to increased covariances associated with higher atmospheric drag, as well as to the exponential rise in the resident space object population.
Altogether, this means that the results presented in this paper are weighted towards the recent high solar maximum, with less data coming from solar minimum and very little from the previous solar maximum. When examining conjunctions from a three-year sliding window, there is not much variation from the efficacy charts presented in Section 5 that are based on the entire time span. In other words, the Δ-BC required to remediate a certain percentage of conjunctions to below a certain post-mitigation Pc in a certain EDR band does not vary significantly with the solar cycle.

However, there is considerable variation in the underlying population of conjunctions, as shown in Fig. 3, which depicts the number of filtered conjunctions per year in each EDR bin. Clearly, there are more high-risk conjunctions in the higher EDR bins in recent years.

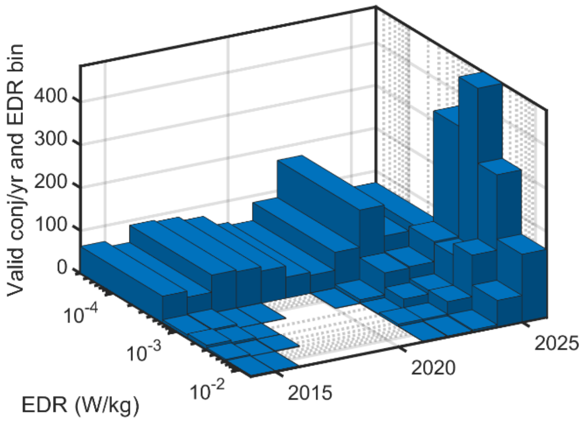

Figure 3: Valid conjunctions (i.e., after filtering for this analysis) per year in each EDR bin. Note the increase at higher EDR bins in recent years.

This sensitivity analysis indicates that the efficacy results presented in this paper binned by EDR are relatively insensitive to the solar cycle, but the conjunction density can shift among the EDR bins. From a mission design standpoint, this highlights the key consideration of the expected EDR trend over the life of the mission. If spending years on orbit, the differential drag efficacy will vary if the mission transitions between EDR bins.

4. DIFFERENTIAL-DRAG EFFICACY

To evaluate the efficacy of differential drag for collision avoidance, we begin with the filtered conjunctions described in Section 3. These are processed with the Maneuver Trade Space (MTS) tool to simulate the effect of a certain Δ-BC factor for a certain interval starting a certain amount of time prior to TCA [4]. Results are then tabulated and compared along relevant axes.

There are six key variables that interact:

1. **Δ-BC** = BC_{new}/BC_{old} - 1, a non-dimensional parameter representing the ability of the spacecraft to increase (or decrease) its drag compared to the nominal attitude profile. A spacecraft doubling its drag area has a Δ-BC of 1; most spacecraft that use differential drag in operational contexts have Δ-BC of 2 or 3. For spacecraft with drag profiles that vary in time, this value can be time-averaged for simplified analysis; this results in a conservative estimate of efficacy.
2. **Initial EDR of the spacecraft**. Δ-BC amplifies EDR, so as shown in Fig. 1, spacecraft starting in a high-drag state are more effective for the same Δ-BC.
3. **Start time of the maneuver**. Starting sooner allows the displacement at TCA to accumulate at a lower Δ-BC, but will also cause a mission to react to conjunctions that may otherwise have self-mitigated.
4. **Duration of the maneuver**. Coupled with the start time, the mission may not need to maintain the Δ-BC through TCA.
5. **Target post-mitigation Pc**. CARA advises propulsive missions to target 3E-6, ~1.5 orders of magnitude below the “red” maneuver threshold of 1E-4, but other values could be considered.
6. **Percent efficacy at achieving that target Pc threshold**. After selecting historical conjunctions within a particular EDR bin, applying a maneuver of a certain Δ-BC for a certain duration starting at a certain time in advance of TCA, what fraction of these are successfully mitigated to below the target Pc? Answers for an example scenario are shown in Fig. 1, but guidance on *required* efficacy remains lacking.

Any (set) of these variables can be chosen as dependent or independent, but for the sake of advising missions in development, we recommend that percent efficacy and target post-mitigation Pc should be set as threshold requirements. The remaining four terms (Δ-BC, EDR, start time, duration) then become design parameters for the collision avoidance CONOP, supported by a decision aid as shown in the results.

Regarding the thresholds, one could argue that missions using differential drag should be treated just like missions using propulsion, demanding, say, 95% efficacy at mitigating Pc to below 3E-6. It is difficult to imagine a mission purchasing a thruster that is not at least 95% effective at meeting mission needs. However, our results show that this exacting standard is challenging to meet for even missions designed to use differential drag. Furthermore, the analysis approach presented here is conservative in that the initial state and covariance estimates for both objects involved in the conjunction are drawn from the last available conjunction data message prior to the maneuver start epoch. In practice, both objects will receive tracking updates and benefit from reduced uncertainties as the propagation time to TCA shortens.

Alternatively, thresholds could be set such that the priority is to support missions making their best effort to mitigate conjunction risk by targeting, say, 80% efficacy at reducing Pc to less than 7E-5, landing below the “red” threshold by a small margin. The rationale from a CARA perspective would be that we do not recommend propulsive missions to begin planning for a maneuver until the Pc exceeds 7E-5, so a target post-mitigation threshold for a best-efforts basis could be to target below this “maneuver planning” threshold and just render the risk “not red.” This is more achievable but could arguably produce a moral hazard where a mission is held to a lower standard by excluding propulsion and reducing its responsiveness to risk.

Finally, a compromise standard could be to require a high confidence that the risk will be reduced below the maneuver planning threshold. This would be a 95% efficacy of reducing Pc below 7E-5. The benefit of this approach would be increased confidence (versus the 80% option) in the capability to reduce the risk to a threshold at which we would just be monitoring the conjunction for any other mission.

In summary, the following frameworks offer a spectrum of options to consider for differential drag efficacy in collision avoidance:

1. 95% efficacy to Pc < 3E-6 (propulsive mission)
2. 80% efficacy to Pc < 7E-5 (best efforts)
3. 95% efficacy to Pc < 7E-5 (high confidence to “not red”)

For context, the following section presents results based on these three frameworks.

5. RESULTS

The results center on three case studies:

1. The NASA CYGNSS mission to provide an example of a currently operational mission using differential drag;
2. A currently operational cubesat mission that CARA determined pre-flight to not be suitable for differential drag for collision avoidance; and
3. A notional mission in development that wants to use differential drag for collision avoidance at an altitude between 500 – 600 km.

In each case, the analysis procedure begins by identifying the initial EDR, and thus EDR bin, for the nominal CONOP. Next, in the case of an operational mission, the Δ-BC capability is known, but for a mission in development, that could be a design parameter. Finally, depending on the specific requirement framework, consult a grid of maneuver start times versus durations for a given EDR bin for the resulting average Δ-BC necessary to achieve the required efficacy. Reading from the grid reveals two possible conclusions: 1) the minimum Δ-BC required to be effective for an established start time/duration CONOP or 2) the start time/duration CONOPs required for a given Δ-BC to result in sufficient efficacy. The following examples clarify this construct.

5.1. Case Study 1: CYGNSS

CYGNSS uses differential drag to manage constellation spacing and to remediate conjunctions [3]. Their initial EDR is 0.01 W/kg, one of the highest in the NASA fleet, and their effective Δ-BC is 2.2. To see when they must start a slew maneuver and how long to hold it, we consult a grid like Fig. 4 based on requirements option #1.

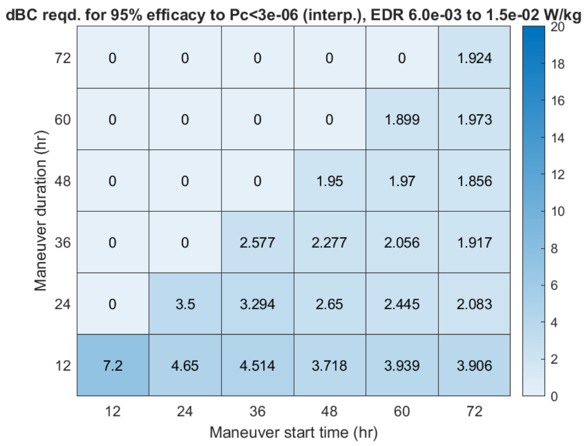

Figure 4: Average change in ballistic coefficient (color scale and values) required to achieve 95% efficacy of reducing Pc < 3E-6 for the EDR bin 6.0E-3 to 1.5E-2 W/kg.

The grid in Fig. 4 shows discrete ranges for maneuver start times and durations from 12 – 72 hr in advance of TCA, with zeros in the upper left because the duration cannot be longer than the time to TCA. The color scale indicates a range from 0 – 20 in Δ-BC with specific average values for each bin provided. For example, for a start time of TCA- 36 hr and a duration of 24 hr, CYGNSS would need a Δ-BC of 3.294 to achieve 95% efficacy of reducing a high-risk conjunction Pc to below 3E-6. Note that this analysis modeled a range of Δ-BC values from 1 to 20, so a grid value of 1 indicates a maximum for that cell, and a value of 20 indicates a minimum for that cell. This construct is repeated for the other requirements frameworks.

For Fig. 4, since we know the Δ-BC for CYGNSS, any square with a number below 2.2 is a valid choice of start time and duration to achieve, in this case, 95% efficacy to remediate below 3E-6. The latest of these is at a start time of 48 hours prior to TCA, holding for a full 48 hours. By contrast, the shortest duration is 24 hr, but the maneuver would need to start at TCA – 72 hr. By definition, 95% of all conjunctions will require less effort than this, and most of the CYGNSS risk mitigation maneuvers were closer to 24 hours in duration, with the shortest lasting 4 hours.

Relaxing the requirements to option #2 "best efforts" 80% efficacy to Pc < 7E-5, results are shown in the chart in Fig. 5.

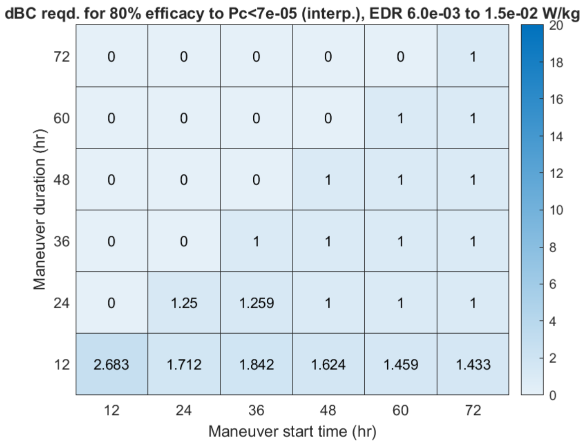

Figure 5: Average change in ballistic coefficient (color scale and values) required to achieve 80% efficacy of reducing Pc < 7E-5 for the EDR bin 6.0E-3 to 1.5E-2 W/kg.

Since all but one of the Δ-BC values is less than 2.2, any maneuver duration at least 12 hours starting at least 24 hours prior to TCA would qualify as being effective. Comparing Fig. 5 to Fig. 4 shows that this "best efforts" requirements framework is much more forgiving.

Finally, if we insisted on achieving high efficacy at 95%, but still with the more modest goal of making a conjunction "not red" at Pc < 7E-5 (requirements option #3), CYGNSS would consult the chart in Fig. 6:

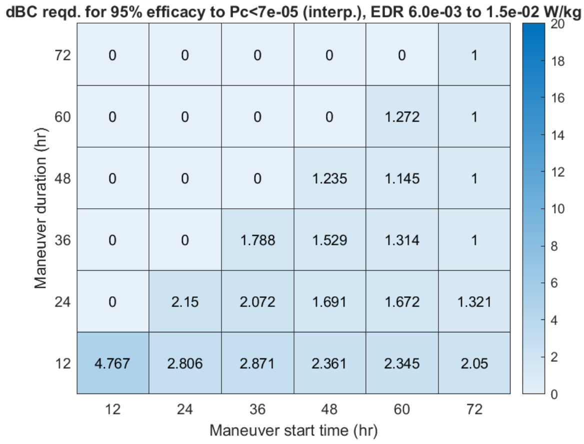

Figure 6: Average change in ballistic coefficient (color scale and values) required to achieve 95% efficacy of reducing Pc < 7E-5 for the EDR bin 6.0E-3 to 1.5E-2 W/kg.

Fig. 6 shows that any maneuver longer than 24 hours starting at least 24 hours prior to TCA would qualify as effective for CYGNSS in this case. In addition, a start time of TCA – 72 hr with a duration of 12 hr would qualify but would not be recommended as a CONOP with much later start times available. Compared to Figs. 4 and 5, this option lands in the middle, as expected, providing a compromise position from a requirements perspective.

Since CYGNSS is operational and uses differential drag for conjunction remediation, one key takeaway from this case study is that the results confirm these constructs as providing reasonable assessments of the expected differential drag efficacy and required CONOP.

5.2. Case Study 2: Revisiting Previous Mission Development

The CARA Analysis Team was previously engaged to study the use of differential drag for collision risk mitigation by a NASA cubesat prior to launch [4]. As built, the mission has a very large difference between the maximum and minimum drag areas, theoretically capable of a Δ-BC of up to 10. However, operational pointing constraints for solar charging and science collection mean that they can only change their attitude during eclipse periods and must furthermore spend much of their sunlit intervals outside of the minimum-drag state, as shown in Figure 7. Therefore, their practical, time-averaged Δ-BC is about 0.68. This is less than the minimum Δ-BC modeled in this analysis, so we round up to 1.0 for the purposes of this case study. The mission is now on orbit and experiences an EDR of 1.2E-3 W/kg, placing it in the bin spanning 6.0E-4 to 1.5E-3 W/kg.

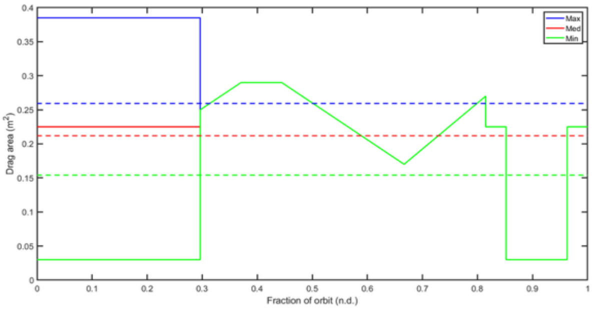

Figure 7: Drag area profile over one orbit for a NASA cubesat showing maximum, medium, and minimum drag areas during the eclipse period. Dashed lines indicate effective per-orbit drag area depending on which attitude is chosen for eclipse.

Figs. 8, 9, and 10 provide the grids of average Δ-BC required to meet the standards of the three requirements frameworks. Assuming an effective Δ-BC of 1.0, this mission does not have enough capability to clear even the most forgiving performance standard at the longest simulated maneuver duration: Fig. 9 at TCA – 72 hr with a duration of 72 hr shows a required Δ-BC of 1.4. This assessment confirms the conclusion that the CARA Analysis Team reached pre-launch using a preliminary version of this analysis that the mission would not be able to effectively remediate conjunctions with differential drag. It also reinforces the difficulty that missions face in implementing differential drag over short time scales if they cannot realize the full range of area change and can only perform attitude slews to effect the area change during a fraction of each orbit.

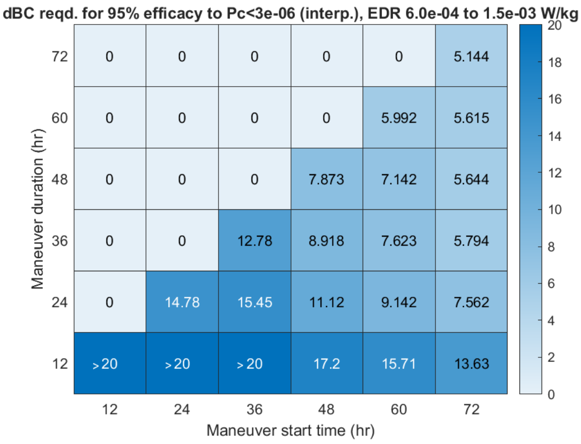

Figure 8: Average change in ballistic coefficient (color scale and values) required to achieve 95% efficacy of reducing Pc < 3E-6 for the EDR bin 6.0E-4 to 1.5E-3 W/kg.

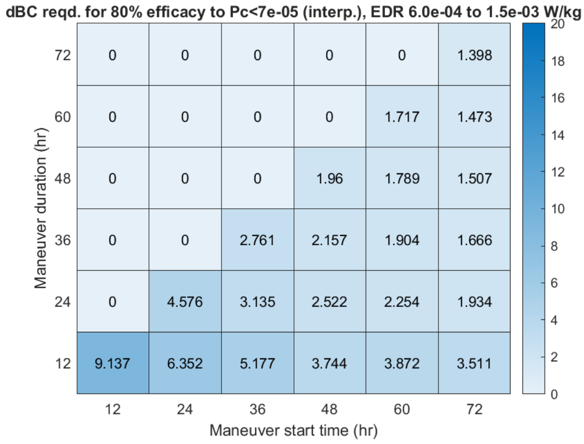

Figure 9: Average change in ballistic coefficient (color scale and values) required to achieve 80% efficacy of reducing Pc < 7E-5 for the EDR bin 6.0E-4 to 1.5E-3 W/kg.

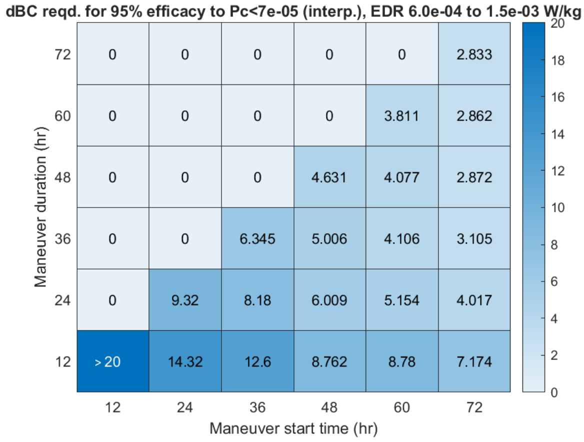

Figure 10: Average change in ballistic coefficient (color scale and values) required to achieve 95% efficacy of reducing Pc < 7E-5 for the EDR bin 6.0E-4 to 1.5E-3 W/kg.

5.3. Case Study 3: Hypothetical Mission Development

The final case is a hypothetical mission in development, intending to be launched around the solar minimum of 2031-2032, making the EDR calculated at the beginning of the mission close to a minimum value for the mission lifetime and the likely driver for differential drag efficacy. The satellite altitude is not fixed, with free choice between 500 and 600 km, and it has a ballistic coefficient of 170 kg/m^2 (which could be a 1.5U cubesat, or a half-ton smallsat with a deployable radar antenna). The mission designers want to consider differential drag for collision risk mitigation.

If the mission were deployed to 600 km altitude at solar minimum, its initial EDR would be 3.1E-4 W/kg, which would fall into the EDR bin below the one used for the charts in Figs. 8-10. The tables for this lower bin are not shown here, but even the most generous efficacy requirements (option #2: 80% efficacy to Pc < 7E-5) using a full 72 hours to maneuver would require a Δ-BC of over 8. The long durations and large Δ-BC required indicate that CARA would assess that this mission could not use differential drag effectively at 600 km altitude.

If the mission flew at 550 km altitude, it would have an EDR of 9.1E-4 W/kg, placing it within the EDR bin used for Figs. 8-10. If the mission can be designed to a Δ-BC of 3, then Fig. 9 shows that it would be able to remediate 80% of all expected conjunctions to Pc < 7E-5 by maneuvering at 36 hours prior to TCA and holding that attitude until TCA, among other options that start earlier. Fig. 10 shows that requiring 95% efficacy for the same post-maneuver Pc would necessitate starting at TCA – 72 hr for a duration of at least 48 hr. Fig. 8 at the most stringent requirements level does not include any options sufficient for a Δ-BC capability of 3. Depending on the design flexibility of the mission, if the start time and duration CONOP for this scenario is unacceptable, then the mission would need to increase the Δ-BC capability or reduce the altitude.

At 500 km altitude, its EDR would be 2.9E-3 W/kg, which falls within the EDR bin from 1.5E-3 to 3.0E-3 W/kg. The Δ-BC results for this bin are shown in Figs. 11, 12, and 13.

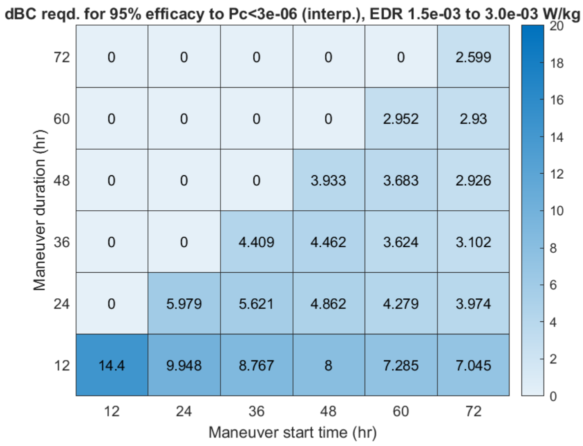

Figure 11: Average change in ballistic coefficient (color scale and values) required to achieve 95% efficacy of reducing Pc < 3E-6 for the EDR bin 1.5E-3 to 3.0E-3 W/kg.

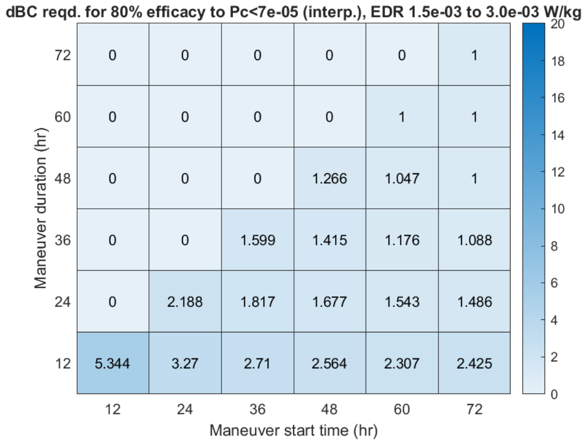

Figure 12: Average change in ballistic coefficient (color scale and values) required to achieve 80% efficacy of reducing Pc < 7E-5 for the EDR bin 1.5E-3 to 3.0E-3 W/kg.

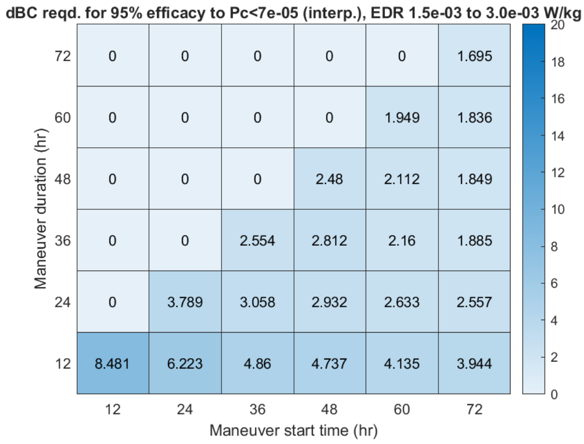

Figure 13: Average change in ballistic coefficient (color scale and values) required to achieve 95% efficacy of reducing Pc < 7E-5 for the EDR bin 1.5E-3 to 3.0E-3 W/kg.

As expected, the higher EDR bin requires overall less Δ-BC capability. The stringent threshold requirements in Fig. 11 result in a few options with early start times and long durations for a Δ-BC of 3.0. More options with Δ-BC < 3.0 appear in Fig. 13 with the reduced Pc target. Then dropping the efficacy to 80% in Fig. 12 results in all but the two shortest timings registering sufficient efficacy.

In this hypothetical case, CARA would provide these results to the mission for their consideration among their other design drivers and mission constraints. This case study illustrates the process for determining differential drag efficacy for high-risk conjunction remediation given altitude and satellite size/shape information for a mission in the development phase. These results provide a mission with insight into the trade space and informs options for enabling effective collision avoidance using differential drag given flexibility in the mission design.

Following the rubric described in this section, CARA can assess the efficacy of the collision avoidance CONOP and satisfy the OCAP requirement levied in NPR 8079.1.

6. CONCLUSION

This paper presents a framework for determining differential drag efficacy for high-risk collision avoidance with a set of lookup tables to consult given an initial EDR, a parameter shown to be highly correlated to differential drag efficacy. This framework provides CARA with an effective process for assessing the collision avoidance capability of a mission in order to offer guidance on design parameters early in the development phase. However, requirements guidance remains an open issue. The three potential options for setting percent efficacy and post-mitigation Pc thresholds presented in this paper offer contrasting conclusions about efficacy for the cases analyzed. Hopefully, this paper will engender discussion as to appropriate guidance on threshold requirements in the near future. Unti then, CARA will evaluate the spectrum of results to advise missions on their differential drag efficacy for close approach remediation.

7. ACKNOWLEDGEMENTS

The work described in this paper was carried out under contracts with the National Aeronautics and Space Administration (NASA) in support of the CARA program. NASA Goddard Space Flight Center funded research conducted by Aerospace Corporation personnel through the "NASA-wide Specialized Engineering, Evaluation and Test Services" contract (contract number 80GSFC19D0011) and by Omitron Inc. personnel through the "Flight Dynamics Support Services III" contract (contract number 80GSFC19C0072). The authors thank the civil servant and contractor team members of NASA's Goddard Space Flight Center's CARA organization for support in obtaining and processing satellite conjunction data. The authors would also like to thank the CARA Analysis Team members for helpful feedback on the analysis approach and results.

REFERENCES

1. NASA Office of the Chief Engineer (2023). NASA Spacecraft Conjunction Analysis and Collision Avoidance for Space Environment Protection. NASA Procedural Requirement 8079.1. https://nodis3.gsfc.nasa.gov/.

2. Foster, C., Mason, J., Vittaldev, V, Leung, L., Beukelaers, V., Stepan, L. and Zimmerman, R. (2017). Differential Drag Control Scheme for Large Constellation of Planet Satellites and On-Orbit Results. International Workshop on Satellite Constellations and Formation Flying, Boulder, CO, USA, 19-21 June 2017.

3. Griffith, N., Bhatia, R., Nallapu, R.T., Siegers, M., Mallik, V. & Rosner C. (2021). Small Satellite Collision Risk Mitigation Using Differential Drag. International Astronautical Congress, Dubai, UAE, 25-29 October 2021.

4. Clark, J.R. & Highsmith, D.E. (2025a). Decision Aid for Conjunction Risk Mitigation by Differential Drag. AAS/AIAA Space Flight Mechanics Meeting, AAS 25-296, Kaua'i, HI, USA, 19-23 January 2025.

5. Highsmith, D.E. & Clark, J.R. (2025b). Differential Drag Efficacy for High-Risk Conjunction Remediation. International Conjunction Assessment Workshop, Toulouse, France, 18-20 June 2025. Accessible at https://ntrs.nasa.gov/api/citations/20250004802/downloads/CARA_diff_drag_Int_CA_WS_2025.pdf

6. Hejduk, M.D. (2008). Space Catalogue Accuracy Modeling Simplifications. AAS Astrodynamics Specialist Conference, Honolulu, HI, USA, 18-21 August 2008.