

## DECISION AID FOR CONJUNCTION RISK MITIGATION BY DIFFERENTIAL DRAG

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The NASA Conjunction Assessment Risk Analysis (CARA) team has conducted a review of the historical record of high-risk conjunctions involving CARA-protected missions and evaluated whether (and how much) differential drag can provide effective mitigation. From this analysis, CARA has identified a rule of thumb: missions with perigees below 560 km capable of tripling their drag area for 72 hours (or a larger scale factor for a lesser amount of time) can reliably use differential drag to remediate high-risk events.

### INTRODUCTION

In the previous five years, the number of conjunctions that the NASA Conjunction Assessment Risk Analysis (CARA) team processed and analyzed has more than tripled.<sup>1</sup> New missions in the early development phases are now required to plan for mitigating conjunctions under the present space environment, and also projecting forward into a future likely having even further increased utilization of the space environment, thereby causing a higher number of events. Some missions are investigating the possibility of using differential drag to remediate conjunctions because propulsive capabilities are not required. The NASA CARA team studied the historical record of conjunctions to evaluate the circumstances under which differential drag could have been successfully applied to mitigate those conjunctions and has developed a series of tables to use as a decision aid for missions considering whether differential drag would be an acceptable option for their operations concept.

Currently, if a CARA-protected mission with maneuvering capabilities is predicted to have a conjunction with a probability of collision ( $P_c$ )  $\geq 7 \times 10^{-5}$  (the maneuver *planning* threshold) within three days of the time of closest approach (TCA), CARA will analyze and recommend options for the timing and magnitude of a risk mitigation maneuver (RMM) based on the mission capabilities. If the  $P_c$  is greater than  $1 \times 10^{-4}$  (the maneuver threshold) at the maneuver commit point, then CARA recommends performing an RMM per the threshold specified in NASA Procedural Requirements (NPR) 8079.1.<sup>2</sup>

The magnitude of the maneuver is typically a few centimeters per second (cm/s), and CARA estimates how many will be required over the mission's nominal lifetime – typically a few per year – during the pre-launch planning process, to inform the mission's  $\Delta V$  requirement. For traditional satellites, this  $\Delta V$  requirement is usually smaller than other requirements for orbit insertion, maintenance, and disposal, but for CubeSats or other small satellite missions, a propulsion system may not provide much more than a few cm/s of  $\Delta V$ , or may not fit at all within the available budget

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of funding, time, size, weight, and/or power. Conversely, CubeSats often have deployable solar panels. Such a mission can instead use “differential drag” to remediate a conjunction – in other words, change the spacecraft drag area (usually increasing) by adjusting the spacecraft attitude to put the larger solar array area in the velocity direction, thereby increasing drag and changing the decay rate of the spacecraft. This in turn changes the timing of the close approach. With enough advance notice, this method can apply small amounts of differential drag (larger than the nominal) to deviate from the predicted collision course. Differential drag is used by Planet’s Dove spacecraft to maintain their formations and remediate conjunction risks since they do not have on-board propulsion.<sup>3,4</sup> CARA has a Maneuver Trade Space (MTS) tool that considers how variations in mitigation maneuver timing and magnitude affect the resulting Pc, and differential drag is one of the options that can be used within the tool.

## METHODS

CARA has archived records of all conjunctions experienced by their protected payloads since inception in January 2005. From this archive, approximately 7,300 events had a Pc greater than 1 in 10,000, the nominal threshold for executing an RMM, at three days prior to TCA. Of these, approximately 4,300 had fully-defined covariance matrices for both the primary (i.e., CARA) and secondary objects; this set of conjunctions is the basis of the analysis in this work to determine the efficacy of differential drag applied at three days prior to TCA.

In differential drag mode, MTS models a change in the ballistic coefficient (Bc) of the primary satellite beginning at some time prior to TCA to evaluate the change in the conjunction at TCA due to the integrated effect of the change in atmospheric drag resulting from the change in attitude/effective drag area. In this study, MTS was used to propagate the primary satellite forward beginning at TCA – 3 days using various increases in Bc. Because these conjunctions came from multiple missions, the increase in Bc was governed by a non-dimensional parameter  $\Delta\text{-Bc}$  defined in Equation 1:

$$\Delta\text{-Bc} = \frac{Bc_{new}}{Bc_{old}} - 1 \quad (1)$$

Expressed this way, a  $\Delta\text{-Bc}$  of 0 represents no change, a negative value represents a reduction in drag (but cannot be less than  $-1$ ), and a positive value represents an increase in drag. For example, a  $\Delta\text{-Bc}$  of 3 is an increase in Bc by a factor of four.

After propagation with the new Bc value, the Pc was recalculated to evaluate whether it was reduced below the “mitigation” threshold of  $3 \times 10^{-6}$  set forth in NPR 8079.1 for events having a maneuver threshold of  $Pc \geq 1 \times 10^{-4}$ . These results were then binned and sorted along several axes, including altitude, amount of  $\Delta\text{-Bc}$ , and (pre-maneuver) energy dissipation rate (EDR) – the specific rate of energy loss (W/kg) as estimated from measured orbital decay – to identify underlying patterns in what percentage of conjunctions were remediated for a given  $\Delta\text{-Bc}$ .

## RESULTS

Unsurprisingly, the efficacy of differential drag is strongly dependent on the altitude of perigee. The heat map shown in Figure 1 displays the percent of conjunctions remediated for a given increase in  $\Delta\text{-Bc}$  in 100 km altitude bins. The bar chart shows the number of conjunctions within each altitude bin, indicating sufficient samples at operational altitudes. Clearly, the lower the altitude and

the larger the change in Bc (bottom right corner of heat map), the more effective the conjunction risk mitigation, with a distinct boundary at 600 km.

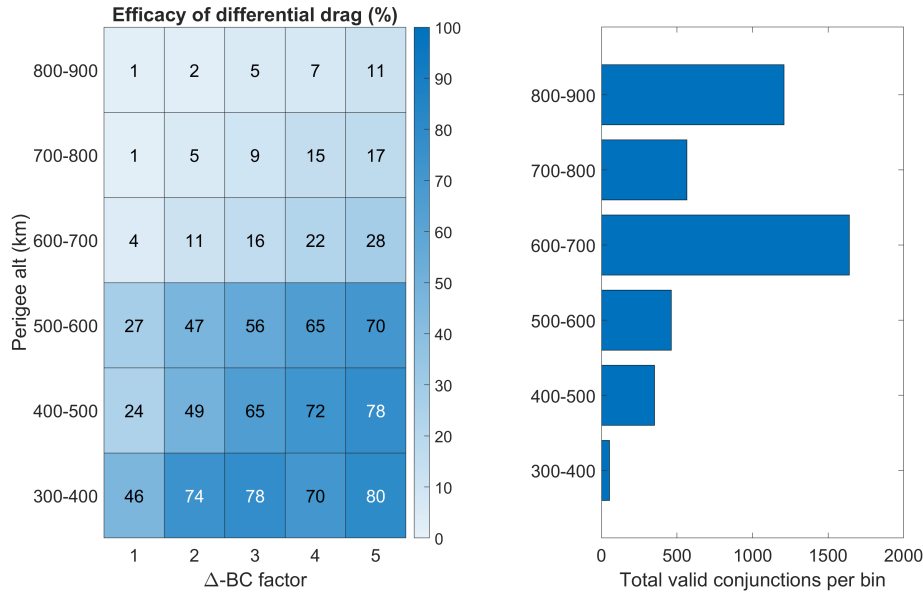


**Figure 1. Left: heat-map of the efficacy of differential drag for remediating conjunctions vs. altitude (%), at 100% duty cycle for 3 days. Right: number of valid conjunctions for each altitude bin.**

A strong correlation is also observed with EDR, shown in Figure 2 with the heat map showing percent efficacy relative to EDR bins and the histogram showing number of conjunctions in each EDR bin. Note the small number of objects in the lowest EDR bins, including negative values which indicate some primary objects with poorly modeled drag. The most relevant bins are the ones with  $EDR > 0$ , which clearly show the highest remediation efficacy with high initial EDR values and large Bc changes (upper right corner of heat map), with a distinct boundary at  $1E-4$  W/kg.

Unlike binning by altitude and EDR, binning conjunctions by the initial ballistic coefficient of the primary object presents a weak correlation to remediation efficacy. The Figure 3 heat map shows the increasing  $\Delta$ -Bc factors relative to initial Bc in  $0.005 \text{ m}^2/\text{kg}$  bins, with the histogram showing a relatively even distribution of samples across those bins. This is a reasonable result given that specific Bc values can be found across all altitudes, washing out the efficacy when binning by initial Bc value.

Figure 4 shows correlation to remediation efficacy relative to solar activity by using smoothed values of the F10.7 index in bins of 20 solar flux units (sfu). The histogram shows that most of the samples come from periods of low to medium solar activity, with very few samples in the highest bin of 160 – 180 sfu where one would expect the largest sensitivity to changes in drag. The heat map shows a spike in the top right corner, but that is likely due to a combination of increased sensitivity to drag and small sample size. This result does not provide conclusive evidence of more than a weak correlation to solar activity. Future work would expand this analysis to include more recent conjunctions during the current solar maximum to fill out the upper end of F10.7 range.

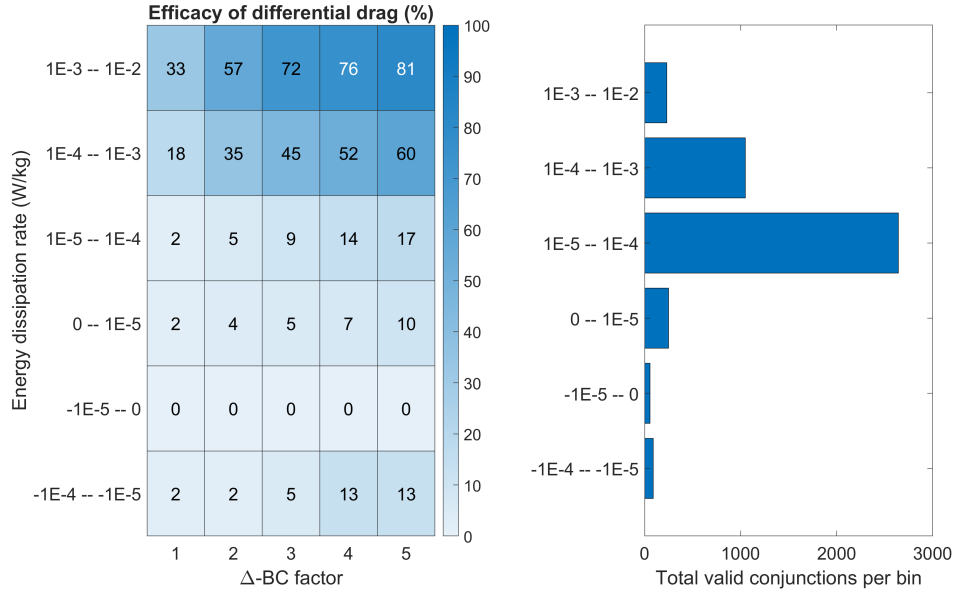


**Figure 2. Left: heat-map of the efficacy of differential drag for remediating conjunctions vs. EDR (%). Right: the number of valid conjunctions for each EDR bin.**

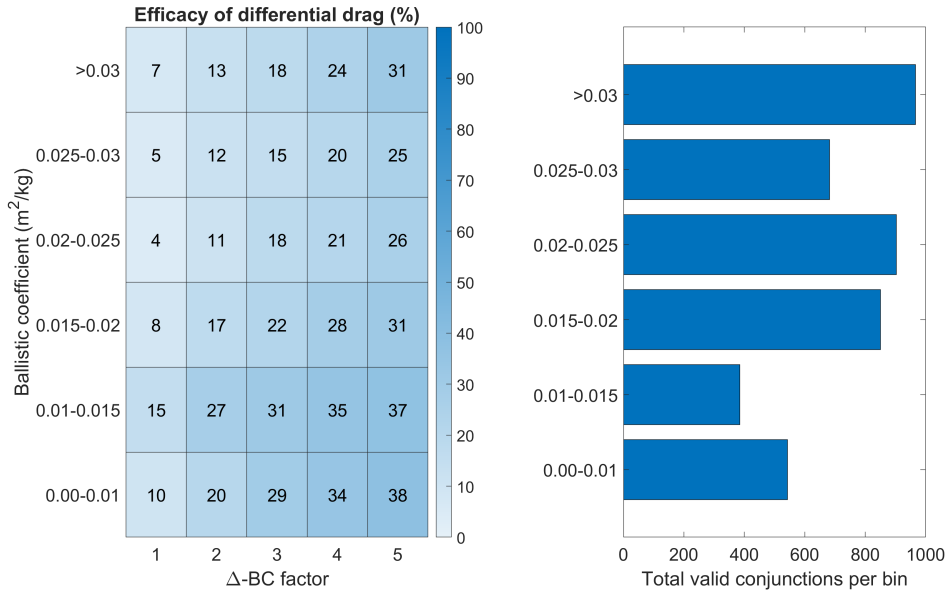


**Figure 3. Left: heat-map of the efficacy of differential drag for remediating conjunctions vs. initial Bc (%). Right: number of valid conjunctions for each Bc bin.**

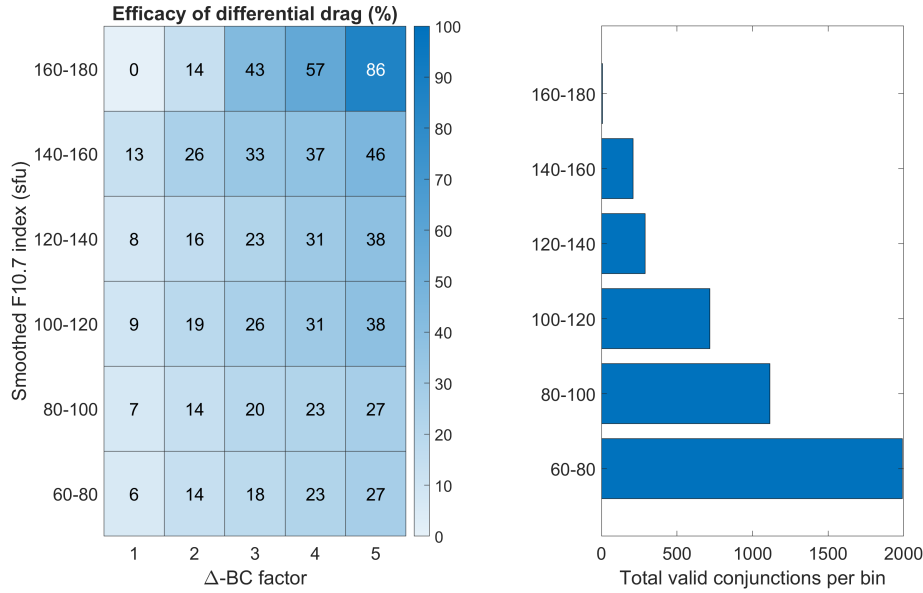


**Figure 4. Left: heat-map of the efficacy of differential drag for remediating conjunctions vs. F10.7 (%). Right: number of valid conjunctions for each F10.7 bin.**

Because differential drag efficacy is strongly correlated to altitude, and altitude is one of the earliest decisions made in the mission design, altitude will be used as the primary variable for the rest of this analysis. While EDR also shows strong correlation, it is more difficult to compute accurately for missions in development and is less intuitive than altitude. Nevertheless, if EDR could be calculated with some confidence, it could also be used to assess differential drag efficacy.

For the altitude analysis, when the efficacy results are binned in 100-km intervals, there is a clear break between 500 – 600 km and 600 – 700 km. To identify a reasonable rule of thumb, we sought the 50% break point by examining the  $\Delta$ -Bc = 2 column from Figure 1 with finer bins, shown in Figure 5. Relative to 25 km perigee altitude bins between 500 – 700 km, the left axis of Figure 5 indicates the percent of conjunctions remediated, while the right axis indicates the number of conjunctions in each bin. The break point where efficacy falls well below 50% is 560 km – that is, satellites with perigees at 560 km or below and capable of adopting an average  $\Delta$ -Bc of 2 or greater (i.e. multiplying their ballistic coefficient by a factor of three or more) for three days can use differential drag to effectively remediate high-risk conjunctions.

However, this is a difficult threshold for a mission to clear; very few spacecraft are capable of adopting a high-drag configuration for 72 hours continuously unless specifically designed to continue to accomplish their mission while in the extreme drag attitudes. Planet’s Dove spacecraft use differential drag to remediate conjunctions,<sup>4</sup> and they have a maximum  $\Delta$ -Bc factor of 9, but in practice with mission and sun-pointing constraints, they achieve a time-averaged  $\Delta$ -Bc that is closer to 2.<sup>3</sup>

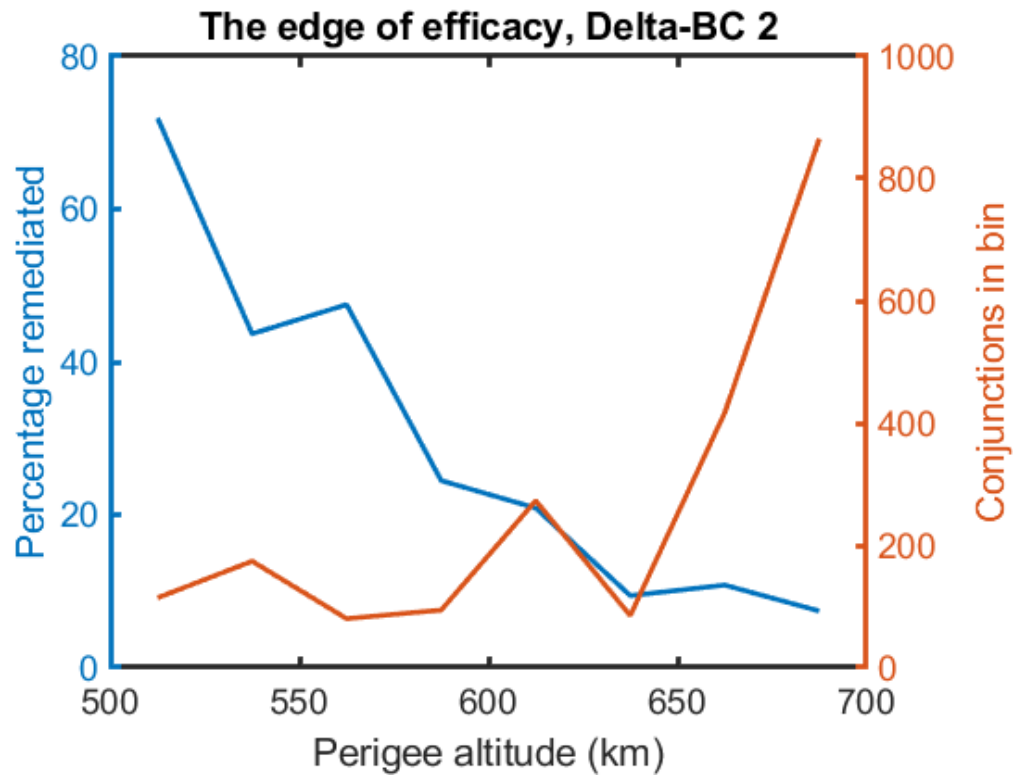


**Figure 5.** A close examination of the efficacy of differential drag between 500 and 700 km for a  $\Delta$ -Bc of 2.0 starting 72 hours prior to TCA.

To explore the efficacy of differential drag under more realistic operational scenarios, we ran similar analyses for three other scenarios: spacecraft that only adopt the high-drag attitude for a 30% duty cycle over three days (Figure 6), as for example, slewing to high drag during eclipse periods only; spacecraft that adopt the high-drag attitude for two days prior to TCA (Figure 7); and spacecraft that adopt the high-drag attitude for one day prior to TCA (Figure 8). These figures use the same altitude bins as Figure 1, as indicated by the identical histograms. It is not surprising to see that efficacy is reduced under these circumstances, but it is interesting to compare the 30% duty cycle and one day cases (Figures 6 and 8). For higher altitudes (perigee above 500 km), it is more effective to begin lower-intensity remediation earlier, while at lower altitudes, it is more effective to wait until later and then hold a high-drag attitude continuously.

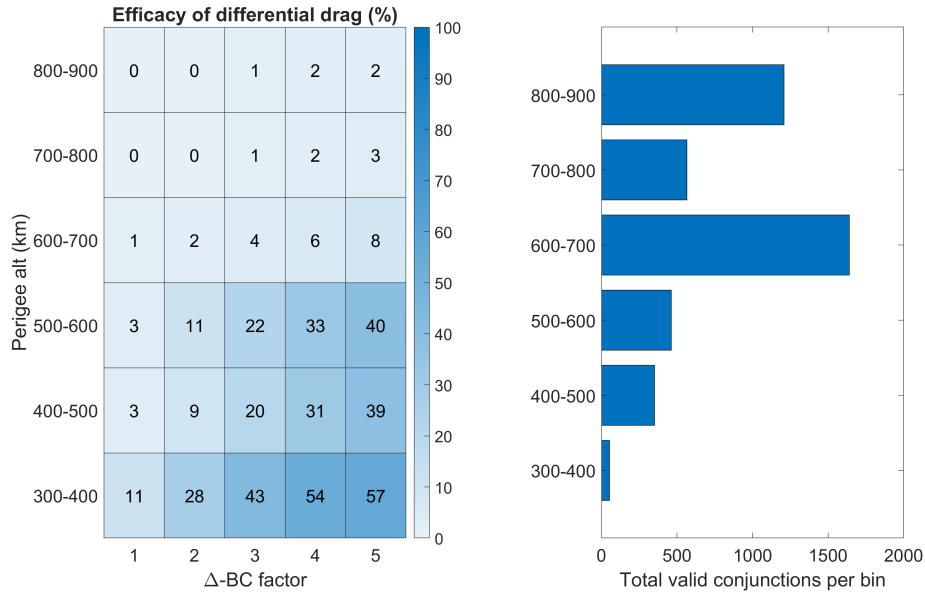


**Figure 6. Left: heat-map of the efficacy of differential drag for remediating conjunctions vs. altitude (%), at 30% duty cycle for 3 days. Right: number of valid conjunctions for each altitude bin.**

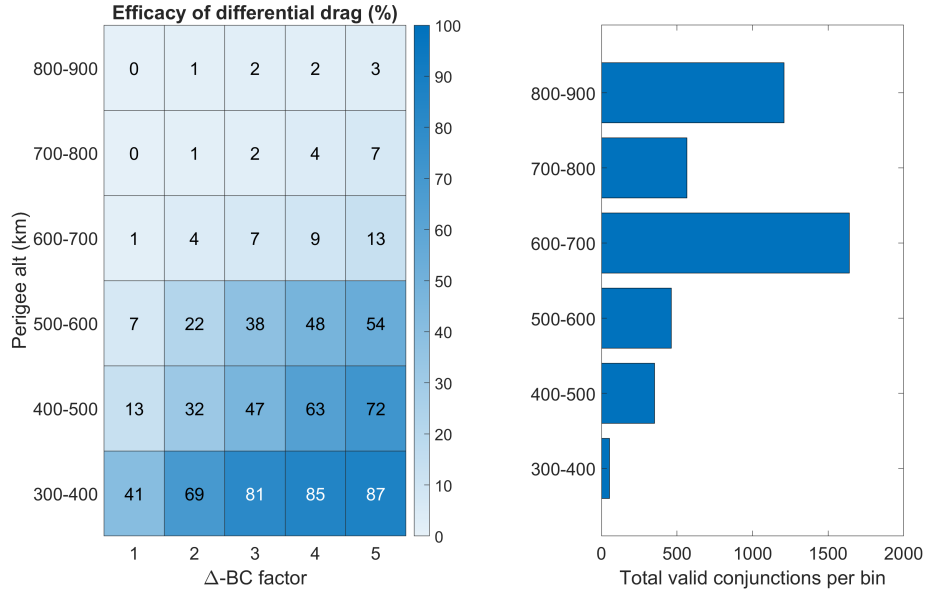


**Figure 7. Left: heat-map of the efficacy of differential drag for remediating conjunctions vs. altitude (%), at 100% duty cycle for 2 days prior to TCA. Right: number of valid conjunctions for each altitude bin.**

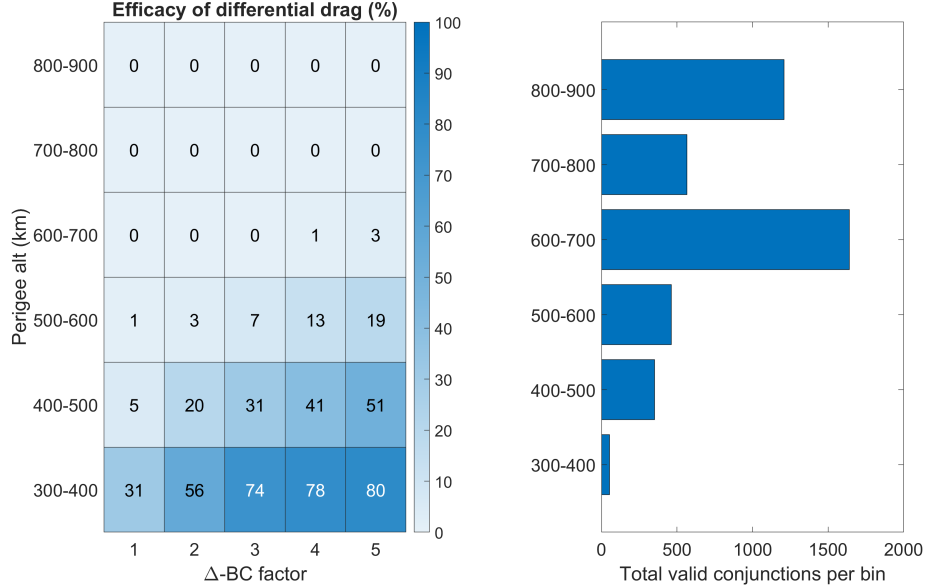


**Figure 8. Left: heat-map of the efficacy of differential drag for remediating conjunctions vs. altitude (%), at 100% duty cycle for 1 day prior to TCA. Right: number of valid conjunctions for each altitude bin.**

## Validation

To validate this analysis, we consulted the record of a NASA mission which uses differential drag to maintain its orbit (at an altitude of approximately 520 km) and to remediate conjunction risk, with RMMs typically starting around 48 hours prior to TCA. CARA's empirical record of the mission's orbit history suggests it achieves a  $\Delta$ -Bc of 2.2. This can most easily be seen at the end of the mission, plotted in Figure 9 comparing its final months of operations when it maintained tight attitude control for minimum drag to the following months when it began to tumble.

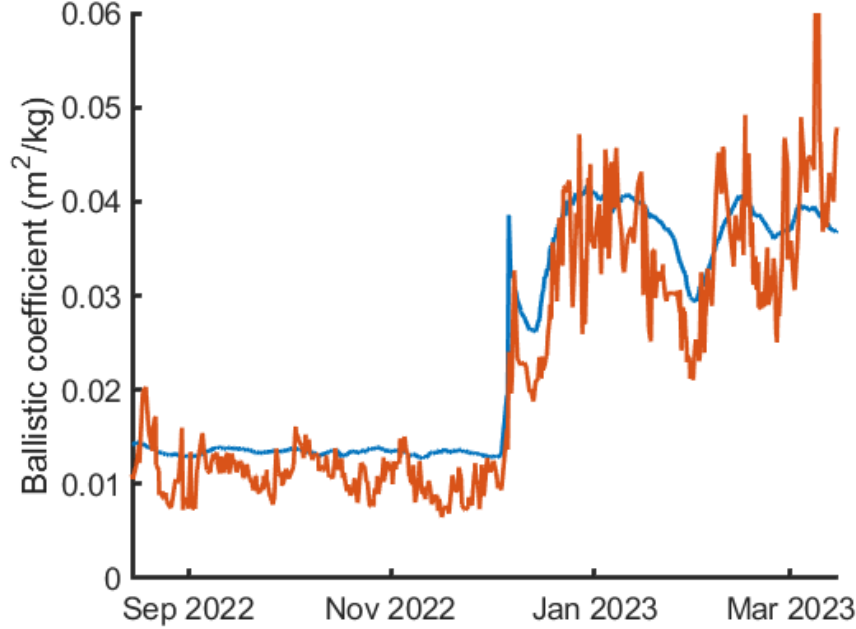


**Figure 9. Daily (red) and smoothed (blue) ballistic coefficient of a NASA mission.**

Of the 21 RMM slew plans that were submitted by this mission, 17 were matched with 16 conjunctions in the historical archive (one of the plans was revised and re-submitted). Of those 16 conjunctions, 11 were successfully remediated (final computed  $P_c < 3 \times 10^{-6}$ ), and five were not. This is a rate of 69%, which is higher than the expected efficacy shown in the MTS simulation, although not to a degree which is statistically significant. Taking into account the small number of data points, the mission's empirical results would be consistent with an efficacy between 41% and 89% at the 95% confidence level, while MTS predicted an efficacy of 44% at this mission's perigee altitude (520 km),  $\Delta$ -Bc (2.2), and maneuver duration (48 hr), as shown in Figure 10.

All the submitted maneuvers were then simulated with MTS, to compare its predictions against the reality that ensued. An example of this simulation is shown in Figure 11 with the actual  $P_c$  history starting seven days prior to TCA and the MTS-predicted post-maneuver  $P_c$  shown as a single red "x". MTS simulated the proposed maneuver, starting from the last received state prior to the maneuver plan's submission. This would have been the latest information available to the mission at the time. In this case, MTS predicted that the maneuver would successfully remediate the conjunction to a  $P_c$  of approximately  $10^{-8}$ , and following the timeline of observed  $P_c$  values forward, the actual  $P_c$  rapidly dropped below  $10^{-20}$  after the maneuver was included in the predicted

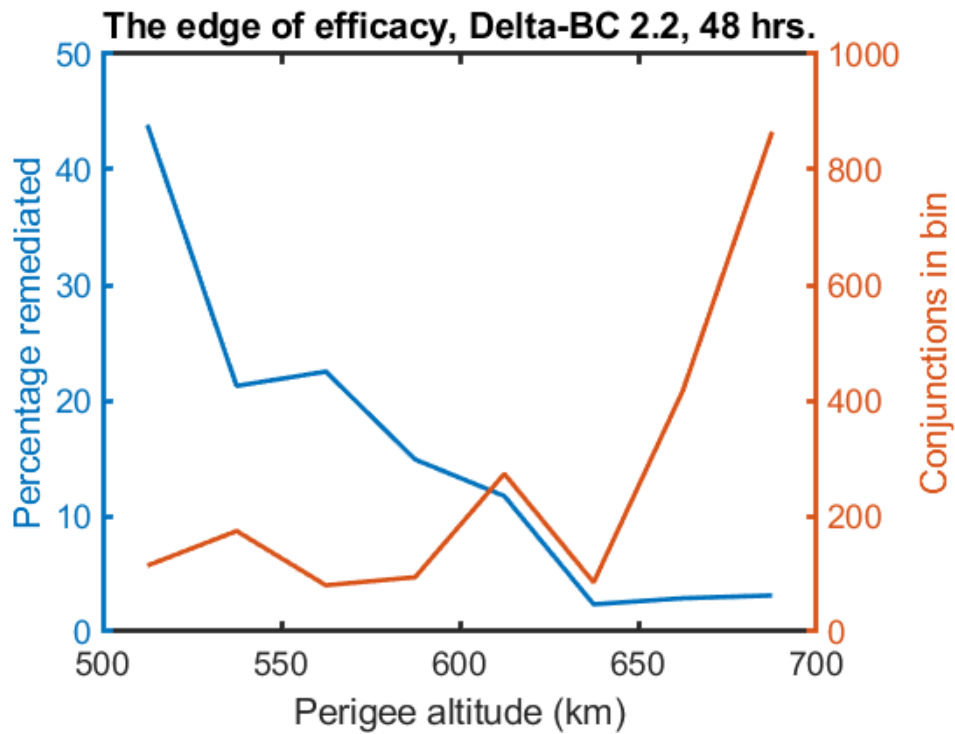


**Figure 10.** A close examination of the efficacy of differential drag between 500 and 700 km for a  $\Delta$ -Bc of 2.2 starting 48 hours prior to TCA.

ephemeris. It is difficult to attribute the drop in Pc solely to the maneuver since the conditions of the conjunction were independently changing with time, but the maneuver was undoubtedly a significant factor in the reduction of the Pc.

A comparison of the MTS predictions of the 17 RMM plans submitted versus the actual outcome is presented in the confusion matrix in Table 1. In the top row, the matrix shows the number of cases that were predicted to be remediated and actually were (true positive = 7) or were not (false positive = 1). The bottom row shows the number of cases that were predicted *not* to be remediated and actually were (false negative = 4) or were not (true negative = 5). The one false positive result was from the maneuver plan that was superseded by a much shorter (true negative) planned maneuver prior to execution.

**Table 1.** Confusion matrix of the MTS predictions compared to the actual outcome.

| Predicted \ Actual | Remediated | Not Remediated |
|--------------------|------------|----------------|
| Remediated         | 7          | 1              |
| Not Remediated     | 4          | 5              |

The four false negatives in Table 1 indicate that the MTS predictions were generally pessimistic. However, as mentioned above, the contribution of differential drag to the reduction of empirical Pc cannot be separated from other effects that may have resulted in the conjunction self-remediating (resolving without operator action). The apparent overperformance of the empirical results over

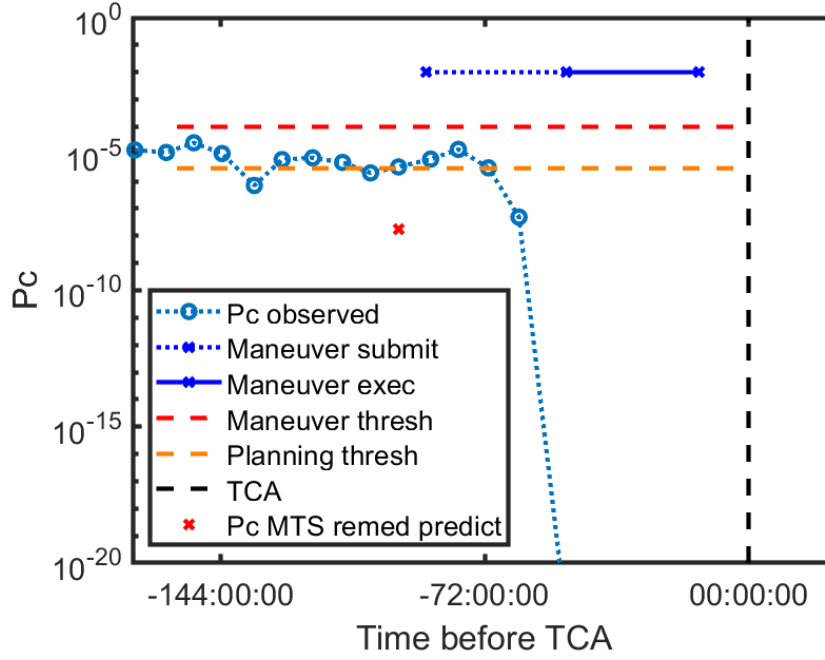


**Figure 11. Observed  $P_c$  values for a conjunction. The linked crosses indicate when a differential-drag maneuver was submitted and executed. The single red cross is the MTS result when simulating the proposed maneuver, starting from the last received state prior to the maneuver plan submission.**

the MTS analysis is likely due to a combination of differential drag efficacy and self-remediation, so we would expect the empirical success rate to be higher. Overall, this validation against flight results demonstrates that the MTS analysis produces a fair, possibly conservative, assessment of the effectiveness of differential drag.

### Positive or negative $\Delta$ -Bc

The analysis herein has evaluated the effectiveness of differential drag assuming the effect is accomplished with an increase in ballistic coefficient. For most conjunctions, “more is more” as far as  $\Delta$ -Bc goes, as illustrated in Figure 12, which shows the  $P_c$  of a historical conjunction predicted with MTS decreasing with increasing  $\Delta$ -Bc starting at a value of -1 (unlike the heat map plots above which start at +1). For reference, the actual  $P_c$  is also shown at  $\Delta$ -Bc = 0.

However, there are some conjunctions for which “less is more”, as depicted in Figure 13 ( $P_c$  decreases with decreasing  $\Delta$ -Bc), or even where a small amount of positive  $\Delta$ -Bc is worse than either a large amount or doing nothing, as in Figure 14 (local peak in  $P_c$  with mild increase in  $\Delta$ -Bc). Comparing the  $P_c$  scale in these two figures to Figure 12 shows much less sensitivity to Bc change, but the trends are still illuminating.

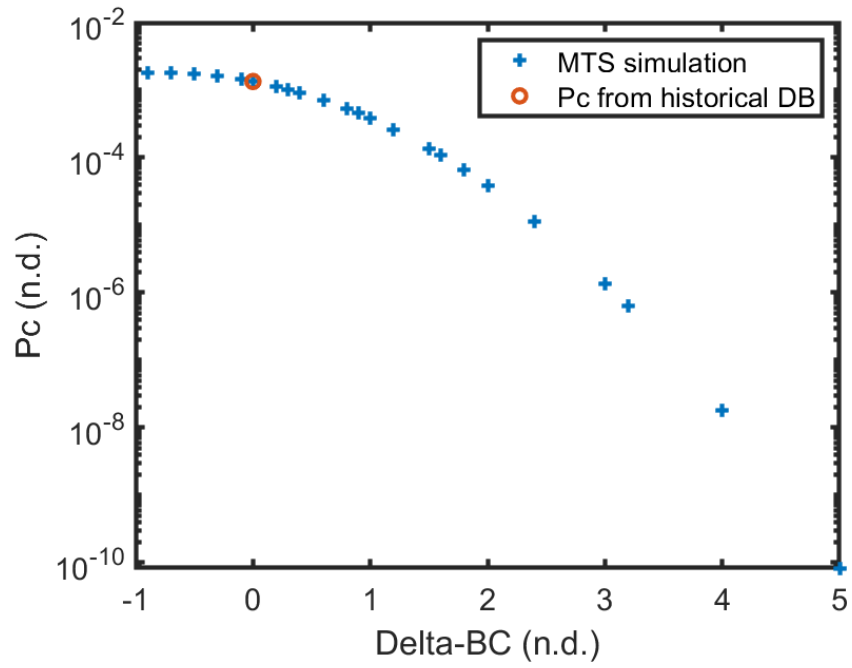


Figure 12.  $P_c$  vs.  $\Delta\text{-BC}$  for a typical conjunction, more is better.

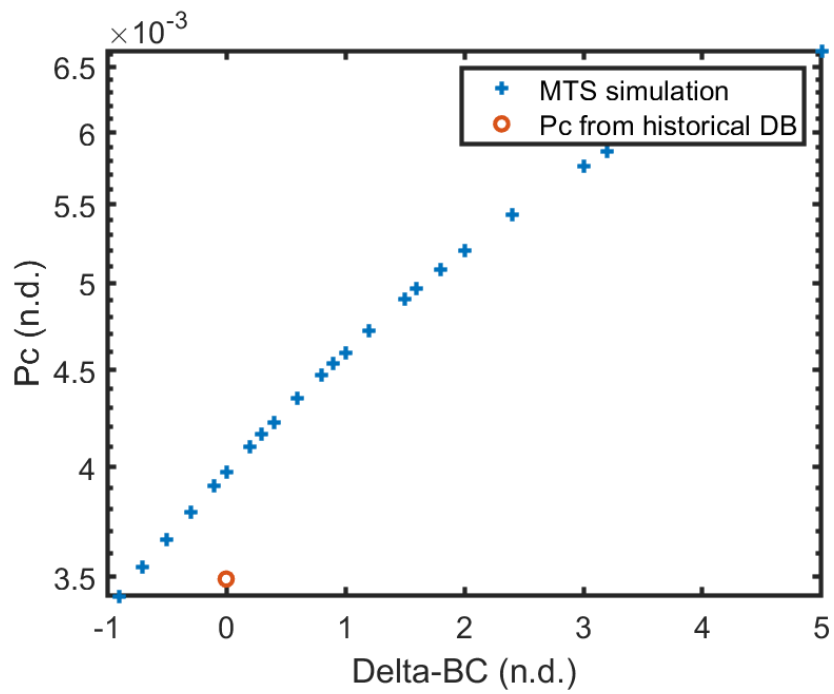


Figure 13.  $P_c$  vs.  $\Delta\text{-BC}$  for a conjunction for which more is worse.

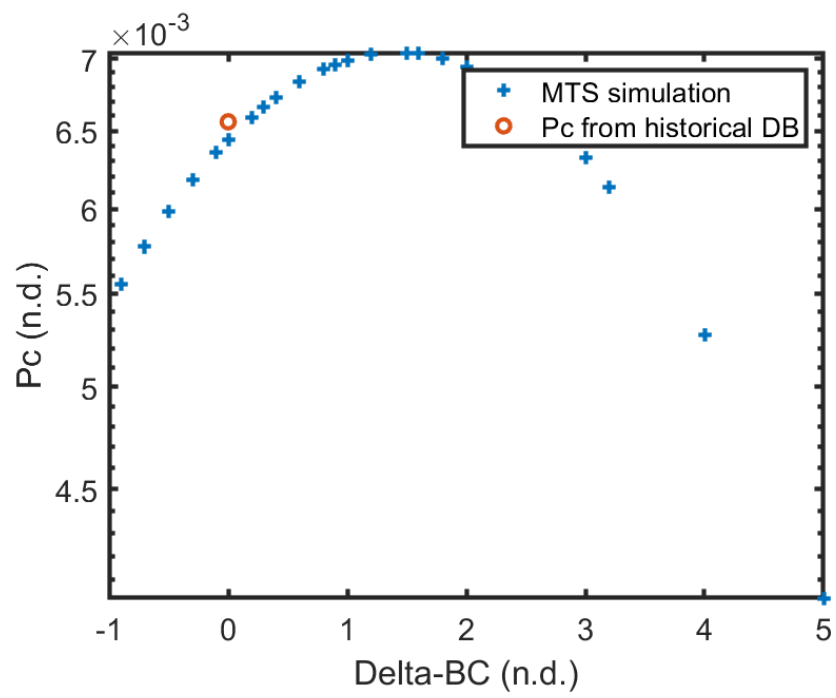


**Figure 14.**  $P_c$  vs.  $\Delta\text{-BC}$  for a conjunction with a ‘sour spot’.

These effects are most strongly influenced by the direction of the relative separation of the primary and secondary, as shown in Figure 15. The figure depicts the more effective change in  $B_c$  (increase or decrease) based on predicted relative radial, in-track, and cross-track position at TCA. Given the choice of having a  $\Delta B_c$  of positive or negative 0.9, if the secondary is passing ahead of the primary (positive in-track separation), then it is better to reduce drag, maintain a higher altitude and longer orbital period in comparison to the no-maneuver case, and allow the secondary to pull further ahead. If the secondary is passing behind (negative in-track separation), it is better for the primary to increase drag, reduce its orbital altitude and period, and increase its lead.

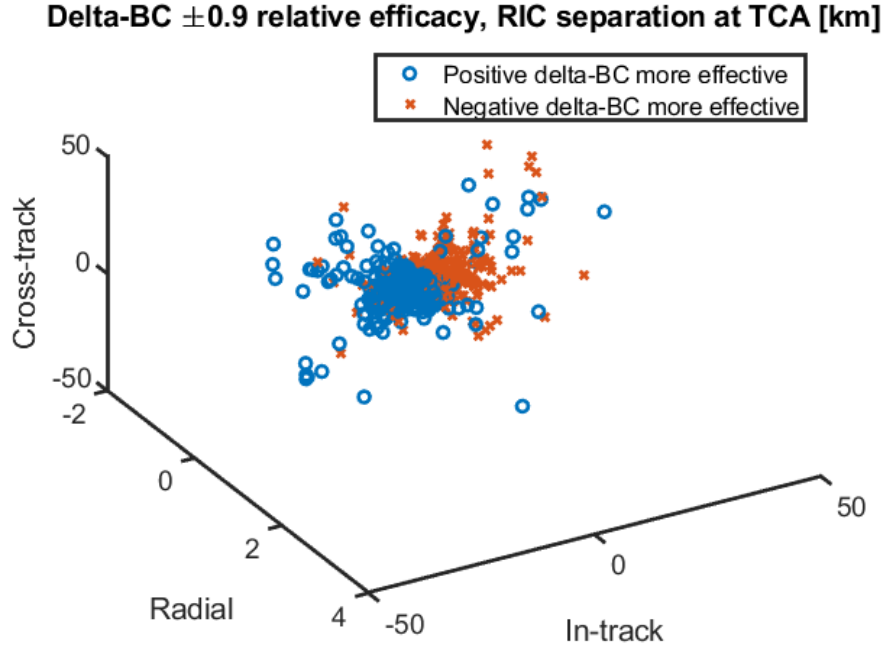


**Figure 15. 3-D scatter plot of maneuvers for which positive or negative  $\Delta B_c$  is more effective.**

Note that “more effective” is relative – neither positive nor negative 0.9 is a particularly effective  $\Delta B_c$  value. In general, it is better for a spacecraft to stay in a low-drag configuration and transition to high-drag for a maneuver. By definition,  $\Delta B_c$  could only be as low as  $-1$  if a spacecraft could present zero drag area, while positive  $\Delta B_c$  is theoretically unbounded. However, if a mission with limited  $\Delta B_c$  capability had to use differential drag anyway – perhaps one that was designed to use propulsion, but has suffered a propulsion system failure and is on course for a high-interest event – this kind of analysis might be needed to make the most of its capability.

### Example application

During the course of this work, a NASA mission in development reached out to CARA to evaluate the utility of differential drag to remediate potential conjunctions. The spacecraft orbit has yet to be finalized, but will likely be a circular orbit between 500 and 700 km, and it will not have a propulsion system. It will have large deployable solar panels and is capable of a  $\Delta B_c$  of greater than 10, but only during eclipse periods. If the spacecraft were otherwise remaining in the low-drag attitude during the rest of each orbit period, then the mission could realize the full factor of 10  $\Delta B_c$  during eclipse. Assuming eclipse periods result in a 30% duty cycle, a factor of 10  $\Delta B_c$  at that duty

cycle can be approximated to first order as a 100% duty cycle at a  $\Delta$ -Bc of 3. Referring to Figure 1 for a three-day maneuver duration, the corresponding efficacy at  $\Delta$ -Bc=3 for 500-600 km is 56%, but drops to only 16% for the 600-700 km bin. Thus, differential drag would be effective (under these operational assumptions) for remediating conjunctions in the lower half of the target altitude range for this mission assuming the slewing activity starts three days prior to TCA. Examination of Figures 7 and 8 indicate that shorter maneuver durations would not surpass 50% efficacy for that level of Bc change.

This mission, however, does not plan to maintain the low-drag attitude during the entire orbit period. In fact, due to charging and imaging activities during every orbit, the spacecraft must frequently slew to different, higher-drag attitudes. Based on that concept of operations, the actual maximum  $\Delta$ -Bc that the spacecraft can achieve over the nominal orbit-averaged Bc is just 0.68, which is not enough to meaningfully remediate conjunctions using differential drag (referring to Figure 1, the efficacy would be worse than the  $\Delta$ -Bc=1 column). Thus, CARA did not recommend implementing differential drag as a means to remediate conjunctions for this mission considering the given operational constraints.

## CONCLUSION

CARA has developed tables that can be used as decision aids to advise missions in development about the best way to utilize their differential drag capabilities. For missions below 560 km with the operational flexibility to devote multiple days to holding a high-drag configuration (or a sufficiently high drag ratio to compensate for limitations on that time), differential drag can be used successfully to remediate many high-risk conjunctions. Conversely, missions that do not meet these exacting criteria – most missions – should instead be advised to investigate other options for conjunction mitigation, such as adding an onboard propulsion system or simply slewing to a minimum area configuration during TCA.

Further analysis is required in several areas to refine the guidance on differential drag efficacy for conjunction remediation. As mentioned above, additional test cases during solar maximum would increase the resolution of the efficacy to higher levels of solar activity, providing insight into the sensitivity of this method of conjunction remediation to the solar cycle. In addition, this study considers a conjunction remediated if the Pc falls to  $3 \times 10^{-6}$  or below, but increased efficacy would clearly be achieved if the remediation threshold were not as stringent. Future analyses could investigate the sensitivity of the percentage of conjunctions remediated to higher thresholds (e.g.,  $1 \times 10^{-5}$ ) or to a target reduction from the starting Pc value (e.g., one order of magnitude reduction). Lastly, consideration must be given to the acceptable level of efficacy for differential drag remediation to be recommended for a mission. The analysis in this paper targets a relatively low 50% efficacy, assuming that anything less than that would not be worthwhile for a mission to implement. However, from both a mission protection and a space environment protection standpoint, a higher threshold for efficacy may be warranted given the ever increasing number of conjunctions in low earth orbit.

## ACKNOWLEDGMENT

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