DART MISSION DESIGN AND NAVIGATION LESSONS LEARNED FOR FUTURE PLANETARY DEFENSE MISSIONS

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Keywords: *mission design, navigation, optical navigation*

Introduction: This paper summarizes the lessons learned by the Double Asteroid Redirection Test (DART) Mission Design and Navigation (MDNAV) team most relevant to future planetary defense missions and studies. From the perspective of its trajectory and navigation, DART is a reasonable analog for an operational planetary defense (PD) response mission: either a rapid reconnaissance flyby or a kinetic impactor mission. We have identified 9 lessons that we hope will benefit future PD response mission teams. Broadly speaking, they are ordered from mission design focused to navigation focused.

1. Electric Propulsion Offers Substantial Trajectory Flexibility: Throughout DART's design life-cycle, electric propulsion (EP) provided a wide range of options that would be relevant in a real planetary defense response mission: broad launch flexibility, a second impact opportunity, tailored encounter geometry, and even multiple-asteroid flyby opportunities. However, EP made the DART spacecraft and Guidance, Navigation, and Control (GNC) implementations much more complicated. First, we note the spacecraft challenges that EP introduced.

The EP system required very large solar arrays, spanning nearly 20 meters from tip-to-tip. This introduced low frequency structural modes. The GNC control system, including SMARTNav[1, 2], required extensive tuning to ensure that these modes were not excited when executing attitude control thruster firings or Δv thruster firings[3].

The EP system also added a non-trivial amount of additional integration and test activities and was an important schedule driver. In a PD scenario, the timeline to launch may be extremely limited.

Finally, the EP system complicated the spacecraft design itself. DART's mechanical layout, power subsystem, and thermal subsystems were dramatically different from earlier non-EP designs. Aspects of the EP-focused thermal design may have caused in-flight attitude errors that would have decreased the probability of impact were they not identified and mitigated (see Lesson 7).

Given the challenges to GNC, the additional spacecraft constraints, and the additional schedule cost, it may seem obvious to discard EP as a viable component of a PD response mission. However, EP could potentially save a PD response mission in multiple ways.

First, EP offers dramatic launch flexibility. For many years of its design life, DART was baselined as a ride-share[4], compatible with a variety of orbits, as shown in Figure 1. DART was notionally compatible with standard geostationary orbits, translunar injections (both standard and weak stability boundary types), and Lagrange point transfers. While a rideshare probably doesn't make sense for a response PD scenario, these examples highlight the possible relaxation of trajectory related requirements for a launch vehicle. In terms of launch period flexibility–there was a final date at

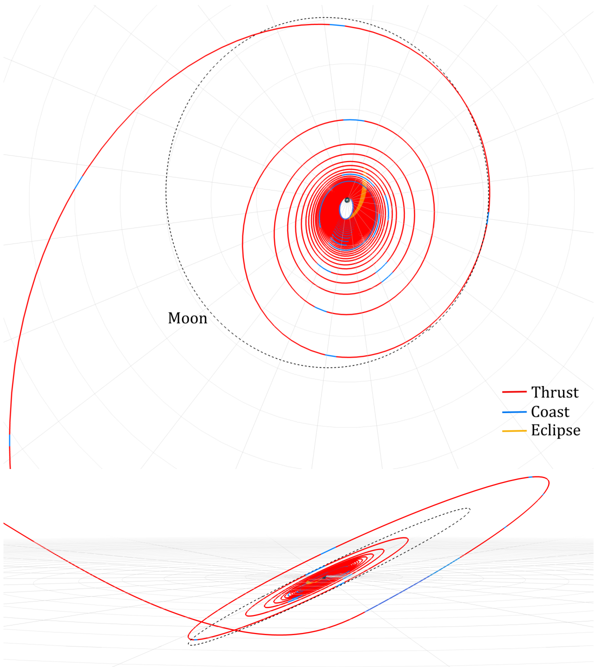

Figure 1: With EP, DART could launch as a rideshare with a GTO. It used a 9 month spiral to escape Earth and achieve the desired heliocentric inclination. Two views are shown. Figure reproduced with permission from [4].

which we needed to have launched. Prior to this final date, *any* launch date was viable.

EP also enabled multiple spacecraft to be co-manifested on a single launch. At one point, we determined that DART and the Asteroid Impact Mission (AIM)[5] spacecraft could have co-manifested and shared a single launch vehicle. In this case, AIM, which has now become Hera[6], would rendezvous with the asteroid. DART, using EP, would adjust its orbit for the impact at a later date. This could prove important for multiple kinetic impactor scenarios. The DART impact demonstrated that large volumes of debris can be generated from an impact[7]. This debris might hinder a second (or n^{th}) impactor if its encounter trajectory passes through the debris tail. With EP, the multiple kinetic impactors could be co-manifested and then adjust their approaches so that they each arrive with a safe, unobscured approach direction.

Third, EP may offer a second critical encounter opportunity. Had DART failed to impact Didymos, the team had prepared contingency uses of NEXT-C to recover the mission and attempt a second impact 2.5 years later. This recovery was infeasible with the on-board chemical (monopropellant hydrazine) propulsion system, even incorporating Earth gravity assists.

Finally, EP allows the spacecraft to adjust its encounter approach geometry *en route* to the target. In the case of DART, this option was studied multiple times but the benefits were not important for its specific experiment. The limited directionality of a kinetic impactor's imparted Δv is often noted a limitation of the mitigation approach. That is, it may be the case that the only viable impact directions move the asteroid in an unfavorable or inefficient direction. With EP, the impact direction can potentially be adjusted to reduce this limitation and increase the effectiveness of the impact.

Future PD missions should not disregard EP *a-priori* and should carefully conduct this important trade. Despite its complexity and challenges, EP may enable a more effective response mission.

2. Rapid Launch Targeting Analysis is Possible if the Interfaces are In Place: The launch campaign is an important component of a rapid response mission timeline. For a typical deep space mission, the launch campaign usually begins in earnest after the Preliminary Design Review (PDR). Once a launch vehicle is selected, the first step is to establish a set of interface control documents between the launch vehicle provider and the spacecraft teams. This process is customized for each mission since interplanetary spacecraft needs can differ significantly.

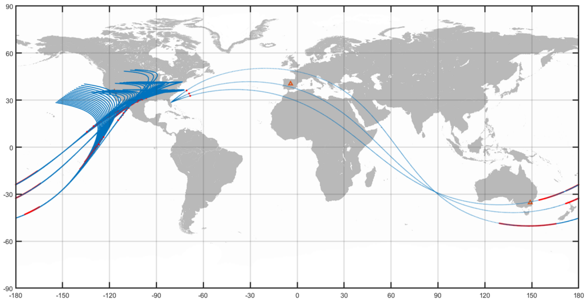

Figure 2: Ground tracks for the as-studied CCSFS DART launch period open, middle, and close.

The DART program followed this typical process, including three Performance Guidance Accuracy Analysis (PGAA) cycles, where trajectory data was exchanged between the launch vehicle and the spacecraft teams. Each PGAA cycle required many months to plan, execute, and carefully review. In this typical process, these cycles represented a substantial component of the launch campaign and timeline (though were being executed in parallel with other subsystem's analyses). However, the DART teams unintentionally had an opportunity to test a faster cycle.

Less than a year prior to launch, the program asked the MDNAV and launch teams to consider changing the launch site to Cape Canaveral Space Force Station (CCSFS) instead of Vandenberg Space Force Base (VSFB). Thanks to having already exchanged data multiple times, the teams were able to conduct a new PGAA from start-to-finish in less than a month. This included delivering two sets of escape targets (C_3, DLA, and right-ascension of launch asymptote), evaluating launch dispersions, and assessing pre- and post-separation coverage from the DSN. The final evaluated trajectories are shown in Figure 2. Ultimately, the program decided to keep the launch at VSFB, but it was not for lack of MDNAV related analyses.

Given this experience, we advocate for standardizing the launch vehicle data exchanges in advance. Our experience demonstrated that the analysis itself can be conducted rapidly if these interfaces are already in place.

3. Vandenberg Space Force Base is Suited for Deep Space Missions: U.S. Mission Designers sometimes assume that Cape Canaveral Space Force Station is the only option for deep space launches. This is likely because the National

Launch Service (NLS) contract provides Earth escape performance curves for maximum declination of launch asymptotes (DLAs) of ±28.5 degrees. (The maximum DLA for an escape burn with no out-of-plane steering is the latitude of the launch site[8]).

With the successful launches of DART and Mars InSight, it's clear that VSFB is a viable launch site option. VSFB's higher latitude of roughly 34.5 degrees enables higher DLAs without a loss of performance. For DART, high DLAs were needed to achieve the heliocentric inclination to hit Didymos without a gravitational assist. (It should be noted that out-of-plane launch vehicle steering may not represent a substantial loss of performance, but requires analysis beyond the NLS pre-computed values.)

In addition to these trajectory related reasons, as a second launch site, VSFB offers future PD missions additional flexibility. A rapid response mission may need to appropriate the first available launch vehicle, including those at VSFB. Or, the program may find that VSFB offers a less crowded launch manifest when needed.

4. Navigation Benefits from Using Reaction Wheels for Attitude Control: When designing a spacecraft, the choice of attitude actuator must account for many competing factors, including: required attitude stability, required attitude rates and accelerations, system mass, power, and even cost. One such cost is the additional analysis and operations required by the Navigation team to address residual Δv —the translational acceleration imparted by thrusters that are not oriented in perfectly balanced couples. Each thruster pulse imparts a disturbance to the trajectory, which the Navigation team must process as part of the orbit solution. Although this process is well understood, it introduces additional complexity and potentially even risk to the final delivered accuracy. This experience played out in DART's final weeks prior to impact.

On DART, the GNC algorithms employed a "round-robin" approach to attempt to cancel out the net accumulation of residual Δv from imperfectly balanced thrusters [3]. While this mitigated the issue through most of the mission, its original implementation was insufficient during the Approach phase when DART began to frequently point its DRACO imager at Didymos with "tight" deadbands. The increased number of pulses caused a steady residual Δv to accumulate in a fixed inertial direction. Figure 3 shows the on-board attitude estimate of the DRACO imager with respect to the targeted Didymos point (in red) early in the Approach phase. The attitude is seen to oscillate from the upper right to the lower left set of pixels. Each change in direction is associated with a thruster pulse. This demonstrates that the pulses are frequent and not equally distributed in all directions. There is a "ping-ponging" back and forth along a preferred direction.

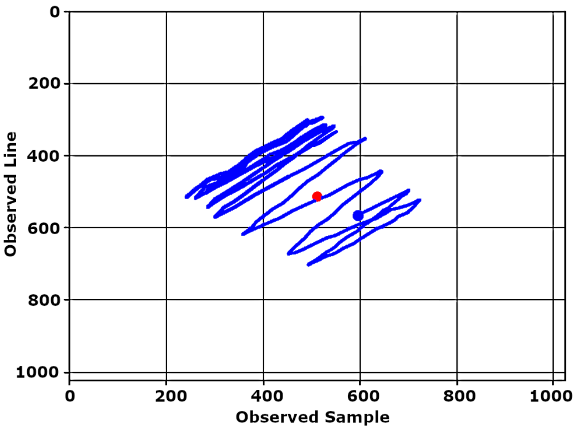

Figure 3: Attitude motion during a tight-pointing period of roughly 6 minutes. Each change in direction corresponds to one or more thruster pulses. The axes are pixel row and column.

The Navigation team was working to deliver the state of DART to the on-board autonomous terminal SMARTNav guidance [1] with a maximum uncertainty of 15 km 1σ. Figure 4 shows a series of B-plane points prior to the fifth and penultimate trajectory correction maneuver (TCM). (The B-plane is centered at Didymos and is perpendicular to DART's approach asymptote [10].) Didymos is located at (0,0) and is shown with the 15 km red circle around it. With each orbit determination (OD) update, the x's are seen to drift up and to the left (in the minus B.T and minus B.R direction). This drift was very concerning to the Navigation team whose job was to best predict the true B-plane point with each OD update.

Once this source of the drift, excessive residual Δv , was positively identified (See Lesson 5), the GNC team was able to upload a correction to the onboard control law that adjusted the tuning and reduced the frequency of attitude control pulses[3]. With subsequent OD updates, the drift was greatly reduced. This correction is observable in the plot as the final B-plane point (in green) is nearly identical to the prior (09/16) update.

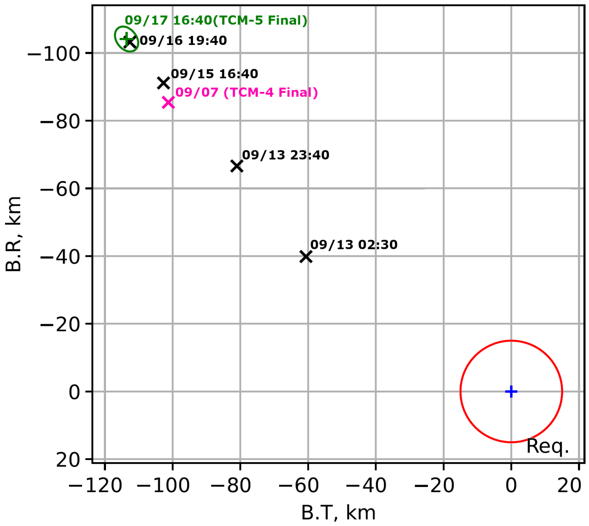

Figure 4: TCM-5 pre-maneuver orbit determination (OD) relative to Didymos. The black x's show the projected no-maneuver B-plane points with each OD update. The dates are the data cutoff for the associated OD. The green ellipse is the final pre-maneuver OD uncertainty. The red circle is the final delivery requirement. Figure reproduced from [9].

In addition to common benefits of reaction wheels, including stable imaging for OpNavs (see Lesson 7), reaction wheels eliminate residual Δv issues. The only Δv associated with attitude control occurs during wheel desaturation events, which can be planned and often observed. When selecting attitude control actuators, we emphasize that precision navigation is more challenging and more risky if residual Δv is continuously produced. We recommend the actuator trade recognizes these accuracy, risk, and cost benefits to the spacecraft's navigation.

5. DDORs Are Effective Measurements for Verifying an OD Solution: Standard DSN radiometric tracking (range and Doppler) provide direct measurements of the spacecraft's trajectory along the Earth's line-of-sight. In contrast, Delta Differential One-Way Ranging (DDOR) measures components of the spacecraft's trajectory *normal* to the Earth's line-of-sight. DDORs were critical for identifying the unplanned translational Δv described in Lesson 4. DDORs are more operationally intensive than acquiring Doppler and range, requiring two separate ground stations to alternate observations of a quasar and the spacecraft. An analyst then has to process the time-of-arrival difference in the signals to produce Differential One-Way Ranging (DOR) measurements for each of these observations. For DART, this effort proved to be extremely valuable. Given this experience, we advocate that any PD response mission should incorporate a generous DDOR tracking schedule, despite the additional overhead needed to acquire them.

It is worth noting that optical navigation measurements (OpNavs) can also measure unique components of the spacecraft's trajectory. In this case, the measurements are normal to the target's (asteroid's) line-of-sight. Both DDOR and OpNav measurement types have an accuracy that scales with distance, so their relative merits vary depending on the situation. DDOR accuracy scales with the spacecraft's distance to the Earth (higher accuracy when closer to Earth). OpNavs scale with the spacecraft's distance to the target asteroid (high accuracy when closer to the asteroid). In the case of DART, DDOR measurements allowed us to identify the B-plane drift roughly 2 weeks prior to impact. OpNav measurements allowed us to identify the drift in the final few days. This trend may not be the case for other PD missions, since DART's encounter occurred particularly close to Earth (0.07 AU). Nonetheless, even if the trend were reversed, redundant measurements are very useful for such critical operations.

6. OpNavs can Isolate Attitude Errors from Translational Errors: If the spacecraft does not have a sufficiently accurate attitude solution, some attitude errors can be indistinguishable from translational errors. DART OpNav processing was used to characterize the star-tracker noise model, including thermal distortions. This process involved DART taking many images of a dense star-field while in the same Sun relative attitude as it would be in the final terminal phase. The many stars allowed the OpNav team to accurately determine the true attitude of each image. The difference in the OpNav computed attitude and the on-board (predominantly star-tracker derived) attitude is the set of errors plotted in Figure 5. Ideally, these errors would be constant over the period of the test. (SMARTNav can tolerate a constant bias, but not a slowly changing bias.) However, the right ascension and declination plots show that there are oscillations with a period on the order of 30 minutes, in addition to a slow drift.

At least some of this error was correlated to thermal cycling by the thermostat controlled heaters. The spacecraft was able to adjust the thermal settings and mitigate those effects. Other errors were associated with the star tracker's noise model, which GNC addressed through changes to the attitude filter's gain tunings[12, 3].

While successful, this process represented a significant operational cost. The OpNav team processed hundreds of thousands of images to precisely measure these issues. Instead, future PD missions should incorporate a high quality inertial measurement unit (IMU), multiple star trackers, and/or be capable of imaging stars in the frame with the target body. These modifications to DART would have eliminated this risk and the associated operational costs. Previous studies have also shown that high accuracy attitude knowledge in the terminal phase can substantially increase the probability of impact on high speed collision of small bodies [13] [14].

7. Rolling Shutter Readouts Introduce Challenging Errors: DART's DRACO imager included focal plane electronics that read the imager data out with a "rolling shutter"[15]. That is, the pixel values in each row are recorded at a slightly different time from its neighboring row. If the spacecraft attitude drifts during rolling-shutter capture, then the star locations in the OpNav image are distorted. This distortion corrupted star based attitude determination and reduced the measurement's accuracy. In fact, it proved to be a dominant error for DART OpNav measurements. This error could have been reduced if the attitude were more stably controlled during OpNav pointing periods.

Fortunately, the OpNav team was able to remove the distortion in post-processing. Rush *et. al.* [11] describes this process. Figure 6 shows an example of the processing results. We note that long rolling-shutter readout times can also increase this distortion, though that wasn't an issue for DART.

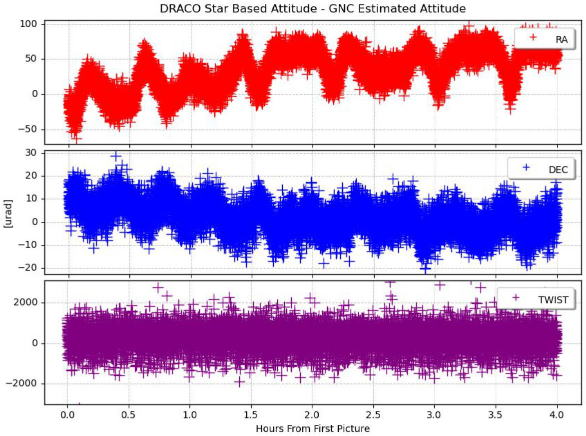

Figure 5: GNC star tracker errors computed using OpNav images of a star field. Top plot gives error in right ascension (RA), middle gives error in declination (Dec), and bottom gives error in twist. Figure reproduced with permission from [11].

Whenever a project plans to use a rolling shutter for OpNav imaging, significant quantitative analysis should be done early to determine the amount of distortion and the effects it will have on OpNav analysis and the amount of additional planning and operational work that will be required to deal with it.

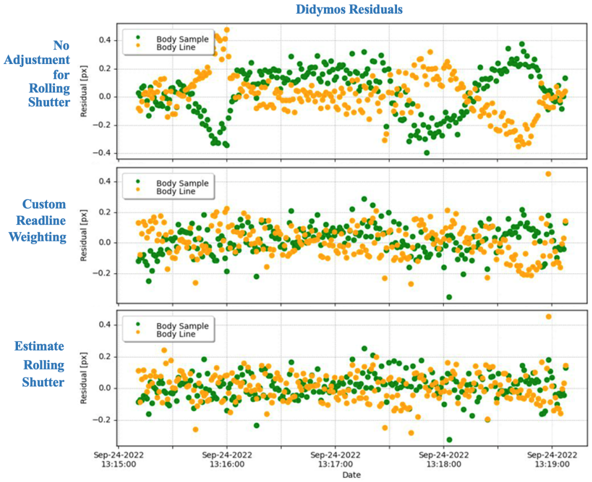

Figure 6: The Didymos OpNav residuals (top) with uncorrected effects due to rolling shutter, (middle) with custom readline weighting, and (bottom) with the rolling shutter correction estimated. The green points correspond to the pixel sample (row) residual in the body frame. The yellow points correspond to the pixel line (column) residual in the body frame. Figure reproduced with permission from [11].

8. CubeSat Deployments Introduce A Non-Negligible Translational Disturbance: The Light Italian Cubesat for Imaging an Asteroid (LICIACube)[16] proved to be a valuable component of the DART encounter, providing resolved images of the early ejecta plume after DART impacted[7]. Given this and other recent CubeSat successes, future PD missions will likely also include CubeSats as part of the encounter operations. However, it should be noted that CubeSat deployments can introduce non-trivial uncertainty to the host spacecraft's orbit. This uncertainty is not only due to normal variation in the deployment spring, but also the host spacecraft attitude control system's response to the deployment torques.

(This latter term ended up being the larger driver of the deployment uncertainty.)

Figure 7 shows telemetry from DART's GNC subsystem during the LICIACube release. It shows that DART executed thousands of thruster pulses during the period immediately after the LICIACube deployment. The message is muddied, because some component of these thruster firings are associated with DART reorienting to its nominal attitude only seconds after the deployment, a choice made to minimize the total number of thruster counts. Nonetheless, these thruster pulses represented a residual Δv that measurably increased the delivery uncertainty.

A second important source of uncertainty was the possibility of a failed or cancelled deployment. The pre-deployment B-plane propagations for DART assumed that LICIACube was successfully deployed, and imparted a $\sim$2.5 cm/s reaction Δv to DART. Had LICIACube failed to deploy, a maneuver would have been required to retarget the impact hand-off state.

This concern contributed to the decision to adjust the LICIACube deployment to be 15 days prior to impact. Doing so allowed us to accommodate two planned TCM opportunities after the deployment. (There were other benefits in addition to this, including giving the LICIACube team additional time for commissioning activities.) Based on this experience, we recommend that the deployment timeline for any CubeSats incorporate at least one maneuver prior to the encounter.

9. With Sufficient OpNavs, the Final Delivery Uncertainty can Be Quite Small: The DART Navigation team achieved an unprecedented final B-Plane hand-off (12 hours to encounter) uncertainty of only 0.21 x 0.06 km 3σ, thanks to nearly continuous DSN tracking and OpNavs for the final weeks of the approach [17]. This was small enough to essentially ensure an impact to Didymos (the primary) had it been the target instead of Dimorphos. Future studies and encounter planning may benefit from this demonstrated performance, particularly since they may not be targeting a smaller member of a binary system as DART did.

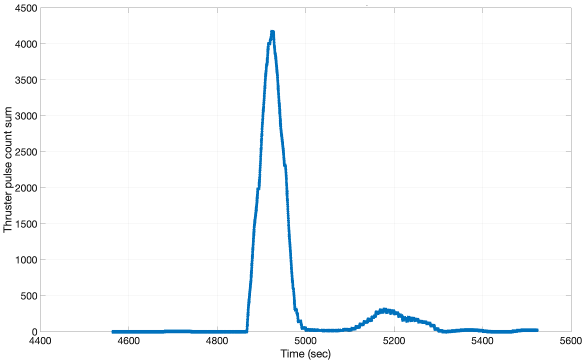

Figure 7: Number of thruster pulses during the LICIACube release and subsequent return to nominal attitude. These pulses introduced substantial Δv uncertainty for B-plane propagations.

Conclusions: The objective of this paper is to share the (sometimes) hard-learned lessons from our experience on the mission design and navigation team for DART. The nine lessons are briefly summarized as:

1. Consider electric propulsion for the flexibility it offers.
2. Establish launch vehicle interfaces in advance of a rapid response mission.
3. Consider Vandenberg Space Force Base as a launch site option.
4. Strongly consider reaction wheels for attitude control to minimize residual Δv trajectory perturbations and improve precision navigation.
5. Plan for many DDOR measurements in flight.
6. Include a high quality IMU, multiple star trackers, and/or be capable of imaging stars in the frame with the target body.
7. Plan for significant pre-launch quantitative analysis if rolling shutter focal plane electronics are used.
8. Plan at least one TCM opportunity after any CubeSat deployments.
9. If the mission plans for continuous DSN tracking and many OpNav measurements, it may be possible to achieve an OD delivery on the order of 10's or 100's of meters 3σ.

Our hope is that these lessons make future small body missions less risky and higher performing. Each mission has its own unique constraints, including those programmatic in nature. Nonetheless, we advocate that these findings be considered before designing a spacecraft for a high-speed encounter with a small body, particularly for a scenario as critical as planetary defense.

Acknowledgements: The authors wish to thank the DART Guidance, Navigation, and Control team for providing valuable inputs to this manuscript.

DART's Mission Design was carried out at the Johns Hopkins University Applied Physics Laboratory under NASA contract NNN06AA01C.

DART's Navigation was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

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