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TRAJECTORY CHALLENGES AND CONSIDERATIONS FOR NASA'S DART MISSION

J. ATCHISON

The Johns Hopkins University Applied Physics Laboratory,
Laurel Maryland, United States,
E-mail: justin.atchison@jhuapl.edu

Abstract: This paper describes recent trajectory design results for the NASA Double Asteroid Redirection Test (DART) mission. DART will launch in 2021 and impact the binary target Didymos in September or October of 2022. Prior to the impact, DART will demonstrate new technologies including NASA's Evolutionary Xenon Thruster (NEXT-C).

Keywords: trajectory design, asteroid, electric propulsion.

1. INTRODUCTION

Planetary defence is comprised of the methods to detect, characterize, and mitigate asteroids that may threaten Earth. The principal mitigation options that researchers have studied are civil defence, gravity tractor, kinetic impact, and nuclear explosive devices (National Research Council 2010). The kinetic impact option involves a spacecraft or set of spacecrafts impacting the hazardous asteroid and imparting a small change in the asteroid's velocity. Given sufficient time, this change can result in the asteroid missing Earth at a future conjunction. Despite seeming to be a simple approach, this method still presents challenges and uncertainties. One example is the effect of ejected material from the asteroid's surface, which also imparts a change in velocity to the asteroid (Syal et al. 2016). This, and other challenges, cannot be easily characterized in simulation or laboratory environments. To help us understand this method, NASA is launching the Double Asteroid Redirection Test (DART) Mission as the first asteroid kinetic impact experiment (Reed et al. 2019). The DART spacecraft will impact the smaller member, Dimorphos, of the Didymos binary asteroid system. In doing so, DART will demonstrate the guidance, navigation, and control to target and impact a 163 meter diameter object at the target relative hypersonic velocity of 6.5 km/s. At approximately 600 kg, we expect DART to impart on the order of 3 mm/s to Dimorpos's velocity. If measured relative to the Sun, this 3 mm/s is only one part in ten-million relative to Dimorphos's velocity (on the order of 30 km/s). However, measured relative to Didymos, this change is one part in fifty relative to Dimorphos's velocity (on the order of 15 cm/s). This makes the small change much more detectable and measurable. In fact, the change can be measured from Earth as a change in period in light-curve observations. The scale of the system is illustrated in Figure 1 relative to familiar terrestrial objects, including sites in Serbia and the United Arab Emirates.

The DART Mission Level 1 Requirements are:

(1) DART shall intercept the secondary member of the binary asteroid (65803) Didymos as a kinetic impactor spacecraft during its September to October 2022 close approach to Earth.

(2) The DART impact on the secondary member of the Didymos system shall cause at least a 73-second change in the binary orbital period.

(3) The DART project shall characterize the binary orbit with sufficient accuracy by obtaining ground-based observations of the Didymos system before and after spacecraft impact to measure the change in the binary orbital period to within 7.3 seconds (1-σ confidence).

(4A) The DART project shall use the velocity change imparted to the target to obtain a measure of the momentum transfer enhancement parameter referred to as “Beta” (β) using the best available estimate of the mass of Didymos B.

(4B) The DART project shall obtain data, in collaboration with ground-based observations and data from another spacecraft (if available), to constrain the location and surface characteristics of the spacecraft impact site and to allow the estimation of the dynamical changes in the Didymos system resulting from the DART impact and the coupling between the body rotation and the orbit.

The spacecraft also includes new technologies that it will demonstrate prior-to or as part of the kinetic impact, including:

- Roll Out Solar Arrays – These solar arrays provide a high power-to-mass ratio. They stow compactly prior to deployment and unroll to approximately 8 m x 2 m once in space.
- Radial Line Slot Array Antenna – This flat disk-shaped antenna produces a high gain narrow pattern, similar to traditional parabolic dish antennas, but with a reduced volume.
- SMall body Autonomous Real-Time Navigation – The SMARTNav algorithms (Chen et al. 2018) are responsible for autonomously identifying and guiding to the asteroid target. This includes image processing capabilities operating at roughly 1 Hz.
- NASA Evolutionary Xenon Thruster – The NEXT-C electric propulsion thruster (Patterson et al. 2002) can operate over a wide range of power levels while providing high efficiency thrust for trajectory changes.

Approximately 10 days prior to impact, DART will deploy the Light Italian CubeSat for Imaging Asteroids (LICIACube) (Simonetti et al.2019). LICIACube will execute two manoeuvres to position itself behind DART at the time of impact. It will safely pass the Didymos system while imaging the ejecta from the impact.

As a follow-up characterization mission, the ESA Hera concept is being developed (Michel et al. 2017). The Hera spacecraft will launch in 2024 and rendezvous with the system in 2026. Hera's detailed observations of Didymos and Dimorphos will provide thorough context for the full impact experiment, including measurements of the system's bulk density and DART's crater size.

This paper describes the DART trajectory design, which has evolved over the mission's development life in response to competing objectives.

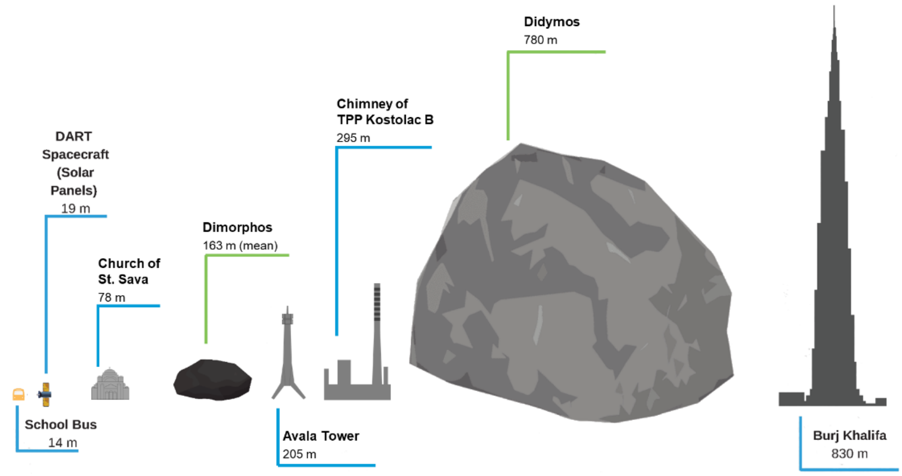

Figure 1: The scale of the Didymos and Dimorphos system relative to familiar terrestrial objects.

2. TRAJECTORY DESIGN

2.1. TRAJECTORY CONTEXT

The objective of DART's trajectory design process is to find a trajectory that departs Earth and intersects Dimorphos, while minimizing total ΔV, and subject to the following constraints:

- The launch declination must be compatible with United States launch sites
- The approach for the impact must have favourable lighting, quantified as a solar phase angle less than 60 degrees.
- The impact must occur within 30 degrees of the binary system's orbit plane (the orbit of Dimorphos relative to Didymos).
- The impact must occur at a time in Dimorphos's orbit when the imparted change in velocity will primarily change Dimorphos's orbit period (orbit energy, as opposed to orbit plane or eccentricity).

The arrival geometry constraints are illustrated to scale in Figure 2.

Finally, the trajectory must also incorporate a demonstration of NEXT-C, which cannot interfere with the impact experiment. Since the trajectory cannot exploit the on-board capabilities of NEXT-C and must minimize ΔV, we vary the arrival date to adjust the trajectory arrival conditions. This removes the need for post-launch manoeuvres. This simplifies the trajectory design process to essentially solving Lambert's problem for a series of launch and arrival dates. There are some subtleties with reconverging the two-body trajectories in the full-fidelity model (N-Body and solar radiation pressure) (Atchison et al. 2016). The primary perturbation is Earth's gravity, because DART remains in an Earth-like orbit from launch to impact.

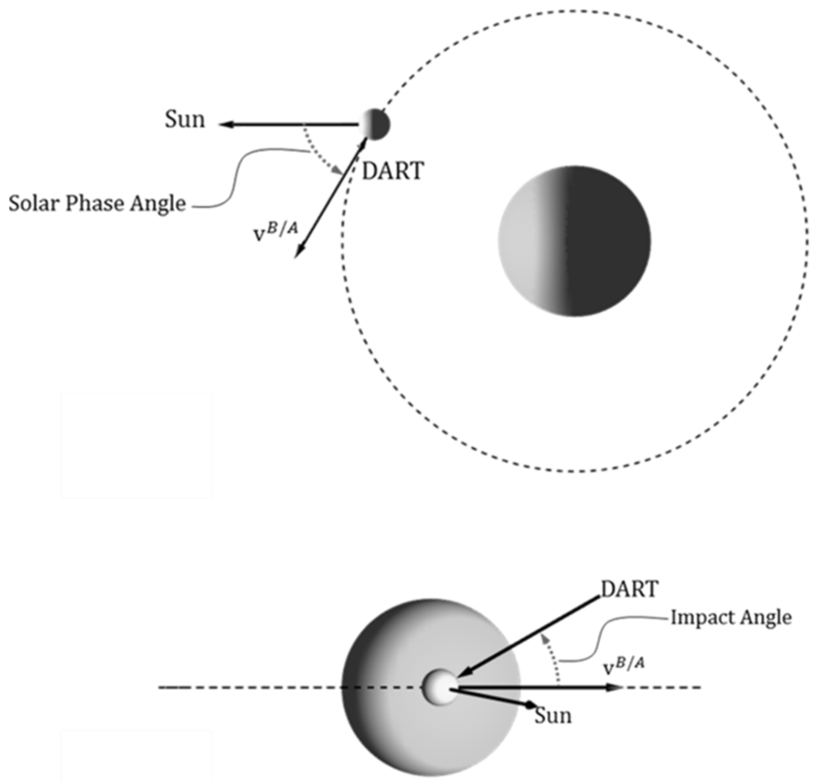

Figure 2: Dimorphos arrival geometry constraints.

2.2. PREVIOUS TRAJECTORY ITERATIONS

At one point, DART had the requirement to launch as a ride-share from a geostationary-transfer orbit, from which it would use NEXT-C to escape Earth (Atchison et al. 2018). This represented a means of saving cost by sharing the cost of a launch vehicle. DART was previously also required to execute a small body flyby prior to the impact (Atchison et al. 2016, Atchison & Ozimek 2019). This flyby would have provided the mission with a rehearsal of the terminal activities prior to Dimorphos.

2.3. CURRENT TRAJECTORY

DART launches on a SpaceX Falcon 9 from Vandenberg Air Force Base. The primary launch period originally spanned 22 July 2021 to 24 August 2021. However, in February of 2021, the DART project decided to shift to the secondary launch period, owing to delays related to hardware development and COVID. It is now scheduled for the secondary launch period, which opens on 18 Nov 2021 with 90 opportunities, ending on 15 February 2022. The transfer inclination is roughly 3.5 degrees relative to Earth's orbit. The required launch energy (C3) ranges from 3.6 km^2/s^2 to 7.6 km^2/s^2 over these periods. The impact at Dimorphos occurs on 26 September 2022 to 02 October 2022 depending on the launch date.

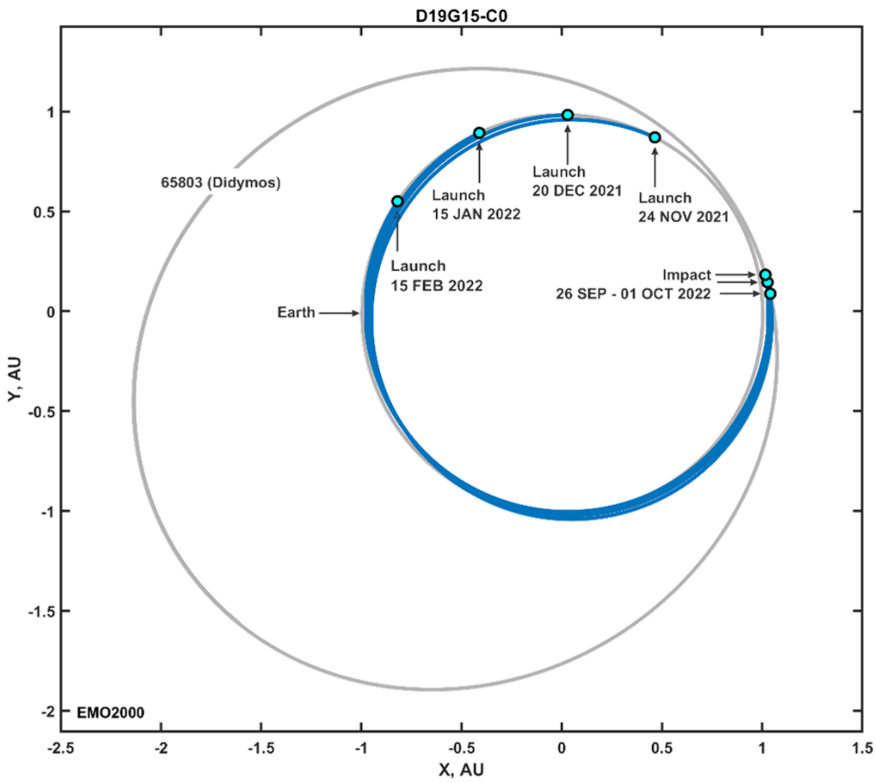

Figure 3: DART's launch period transfer trajectories.

Samples of trajectories are shown in Figure 3 in an inertial frame. Figures 4 and 5 depict the trajectory in a rotating frame. The rotating frame is centred at the Earth and rotates with Earth's annual orbit. The X direction is oriented with +X pointing from the Sun (at left) to the Earth. The Z direction is oriented with Earth's orbit normal direction, and the Y direction completes the right-handed system. In Figure 4, one can observe that DART drifts and impacts "ahead" of Earth. In Figure 5, DART's inclination is observable as motion in the Z direction. The impact occurs "below" Earth's orbit.

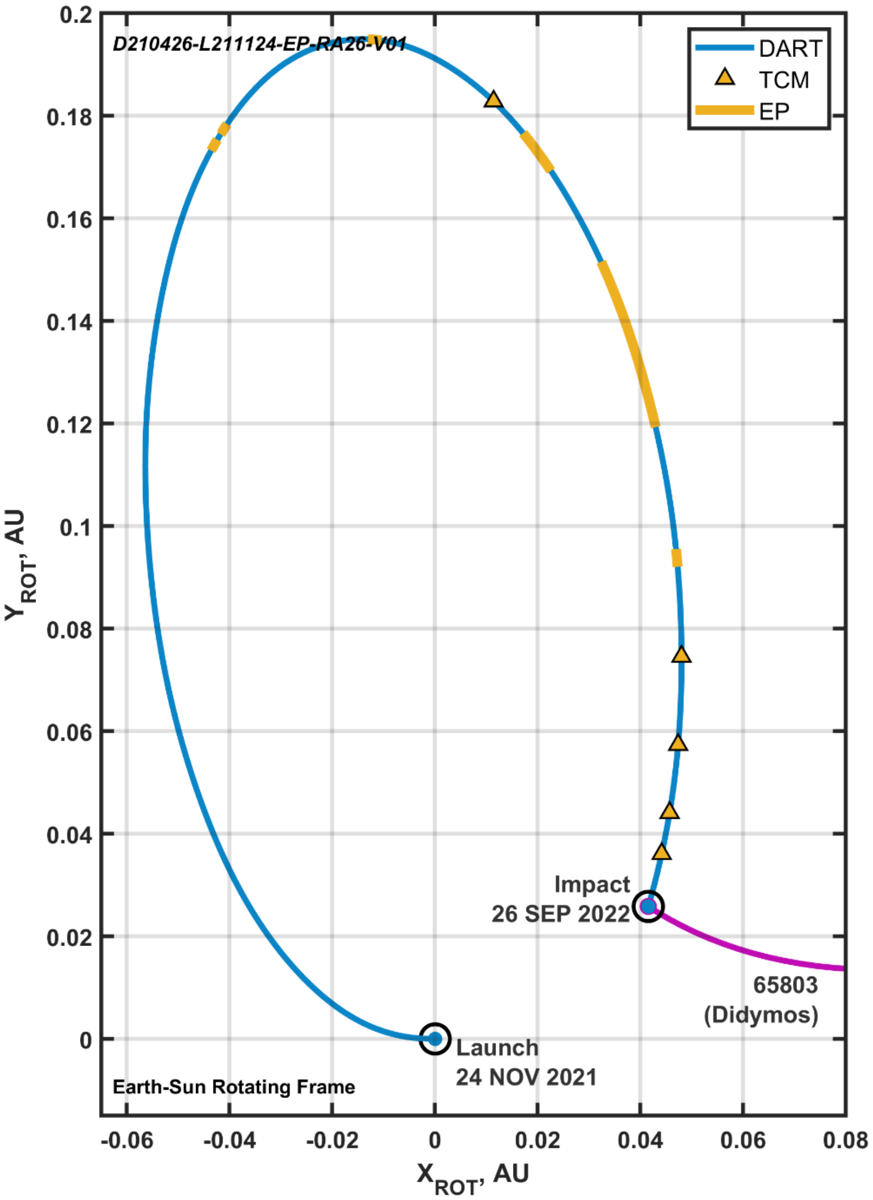

Figure 4: DART's launch period open trajectory, shown in X-Y axes of an Earth-Sun rotating frame.

The figures show trajectory correction manoeuvres as short electric propulsion segments or as red triangles. These manoeuvres keep the spacecraft on its reference trajectory, correcting for errors caused by launch vehicle delivery, model uncertainties (e.g., solar radiation pressure), Didymos and Dimorphos orbit uncertainties, attitude-control thruster misalignments, and manoeuvre execution errors.

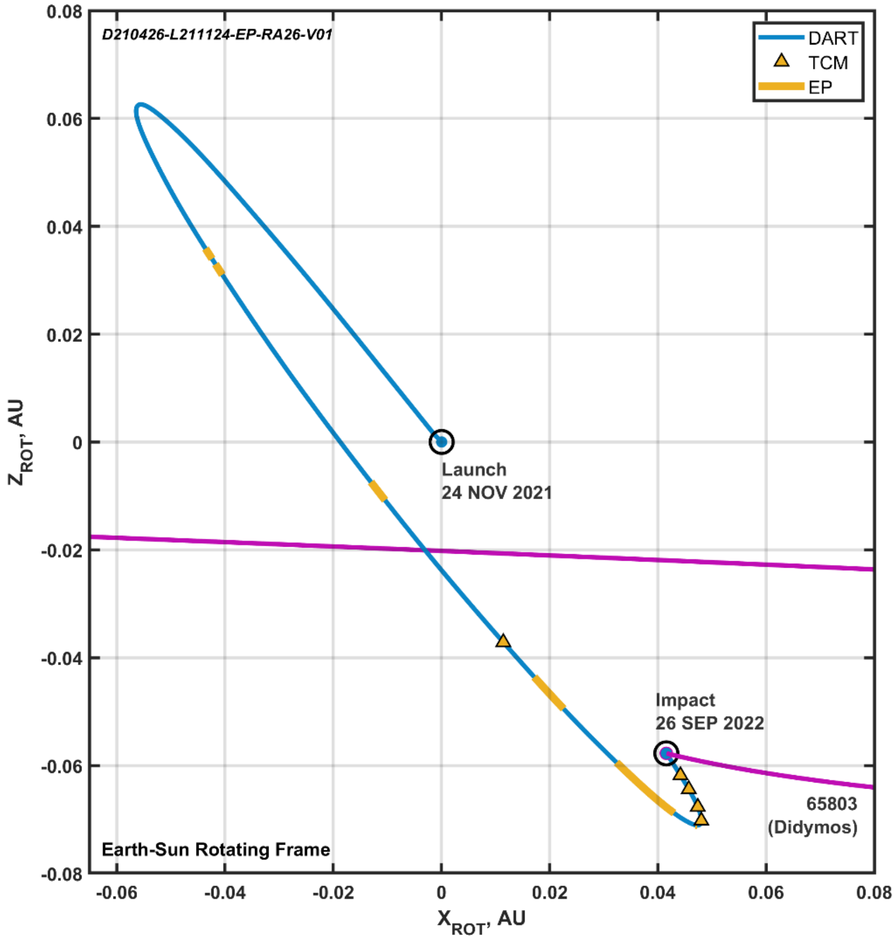

Figure 5: DART's launch period open trajectory, shown in X-Z axes of an Earth-Sun rotating frame.

2.4. ELECTRIC PROPULSION DEMONSTRATION

The NEXT-C thruster must be demonstrated without interfering with DART's impact encounter. This essentially requires us to operate the thruster without changing the trajectory, which is opposite traditional trajectory design. After reviewing many options, the DART team selected a rotating "neutral burn" approach. Here, the spacecraft is oriented relative to the Sun, with NEXT-C orthogonal to the Sun-line. The thruster is activated, and the spacecraft begins to spin with a period of 12 hours. As the spacecraft completes a revolution, the imparted ΔV cancels itself out. This behaviour is observable in Figure 6, which shows the amount of ΔV required to recover from a failure at any point during the neutral burn. That is, if the spacecraft stops the neutral burn in an unplanned manner, we compute the required ΔV from the hydrazine system to recover the impact if a correction manoeuvre were executed 10 days later. In this case, the neutral burn lasts 7 days. The 14 sinusoids correspond to full rotations of the spacecraft about the Sun-line. The maximum correction ΔV required is less than 5 m/s. At the end of the neutral burn period, the electric thruster has imparted approximately 0.3 m/s, despite operating a total of ~140 m/s. If essential, this small final error can likely be corrected by tuning the final revolution. The neutral burns are scheduled for up to seven weeks of the trajectory. These periods can be seen as yellow shaded regions in the trajectory figures above. A one-week neutral burn period is used to calibrate the process, followed by a two-week gap, and then the remaining six weeks of neutral burn. Following this, a hydrazine trajectory correction manoeuvre is used to clean up any residual errors.

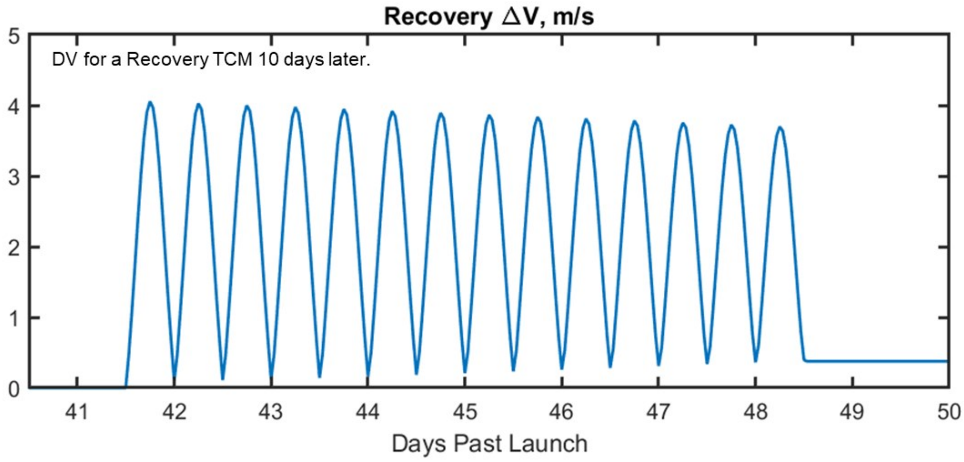

Figure 6: Recovery ΔV cost for a maneuver conducted 10 days following a neutral burn failure.

3. CONCLUSIONS

The DART spacecraft is on schedule to launch in 2021 onto a low ΔV trajectory that satisfies mission requirements and demonstrates a new thruster technology. Its impact into Dimorphos in 2022 will demonstrate our ability to autonomously deflect a small body and will expand our understanding of this important kinetic impact mitigation technique. Prior to impact, the spacecraft will execute a series of neutral manoeuvres that exercise the NEXT-C thruster without risking the terminal encounter.

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