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Double Asteroid Redirection Test (DART) Phase D Mission Design & Navigation Analysis

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NASA's Double Asteroid Redirection Test (DART) mission is the first demonstration of kinetic deflection of an asteroid. DART uses terminal guidance to impact Dimorphos, which orbits Didymos, during its 2022 close-approach to Earth. The close range to Earth allows Earth-based observations to reconstruct the impact's effect. Light-curve data will be used to measure the resulting change in orbit period of Dimorphos due to the momentum change associated with the impact experiment. This paper describes the current DART trajectory and recent Mission Design and Navigation analysis preparing for launch.

I. Introduction

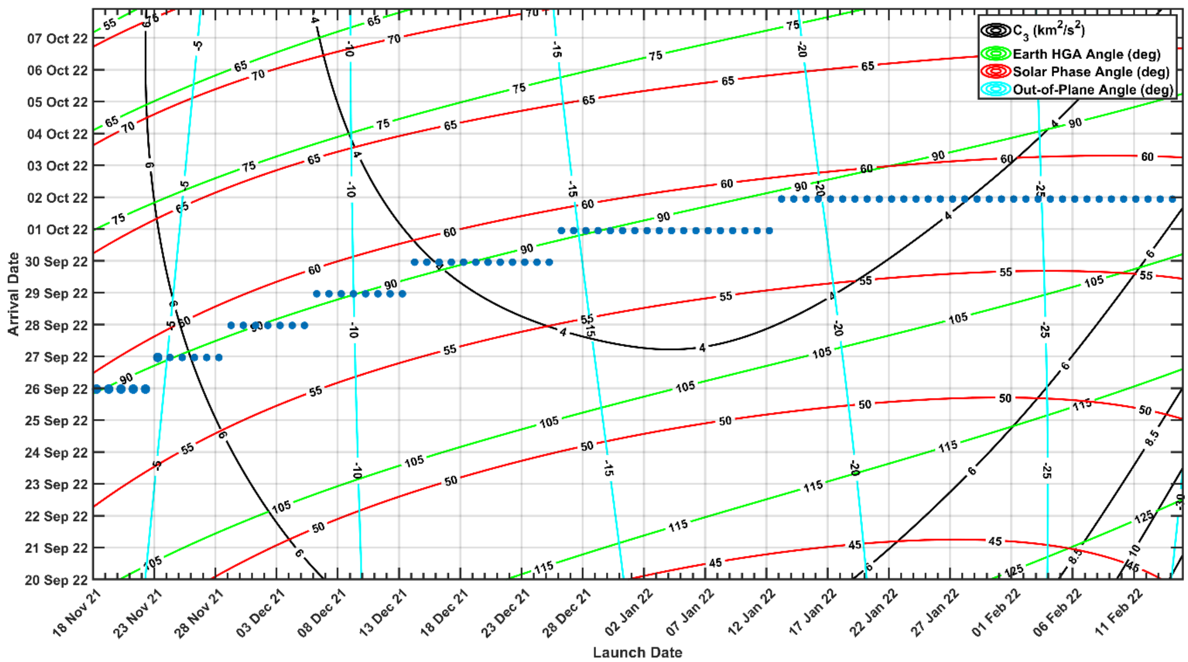
NASA's Double Asteroid Redirection Test (DART) mission is currently in Phase D of development with a Launch Readiness Date of 18 Nov 2021. This phase is associated with final pre-launch integration, testing, rehearsals, and analyses leading to launch. DART uses a dedicated launch vehicle to transfer directly to the Didymos/Dimorphos Near-Earth asteroid binary system. It will use autonomous terminal guidance to impact the smaller member, Dimorphos, with a relative velocity ranging from 6.1 to 6.8 km/s. During the deep space transfer, it will also demonstrate NASA's Evolutionary Xenon Thruster (NEXT-C) Electric Propulsion (EP) system for trajectory correction maneuvers (TCMs) and so-called neutral burns. The TCMs are all statistical in nature, correcting the as-flown trajectory to the reference trajectory. The EP neutral burns are designed to maximize the thruster use without appreciably changing the trajectory. In this paper, we describe the final pre-launch analyses and decisions associated with mission design and navigation.

II. Trajectory Overview

DART will launch from Vandenberg Air Force Base with a short-coast ascent and escape profile on a Falcon 9 launch vehicle. The launch vehicle first stage will be recovered using an autonomous droneship. The only eclipse during the mission occurs during the ascent and completes prior to spacecraft separation.

Formerly, DART was scheduled for its primary launch period, from 22 July 2021 to 24 Aug 2021 [1]. 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. This long launch period results from the few requirements on the transfer trajectory - it is more typical for spacecraft trajectories to require specific gravity assists or rendezvous opportunities that reduce the feasible launch period to roughly 21 days. DART has the requirement that it intersect Didymos with a solar phase angle (Sun-Dimorphos-DART) of less than 60 degrees. It also must arrive with the Dimorphos-DART-Earth angle bounded between 65 and 115 degrees. This constraint results from the available range-of-motion of DART's high gain antenna (HGA) while DART's telescope is pointed at Didymos. There is also a goal to arrive as late as possible to maximize pre-impact radar opportunities. These requirements are plotted as contours on the so-called porkchop plot given in Figure 1.The blue points indicate the selected DART impact times for each launch date. The impact dates shift later throughout the launch period, following the 60 degree solar phase angle contour.

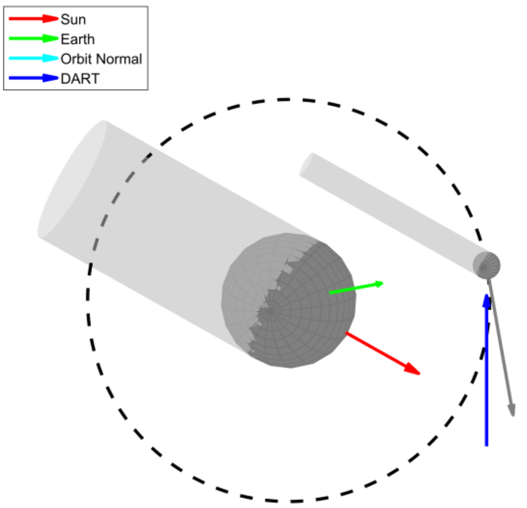
The porkchop plot also contains contours for characteristic Earth escape energy (C3) and the impact out-of-plane angle. The C3 relates to the required launch vehicle capability. The out-of-plane angle is defined as the angle between the incoming DART relative velocity and the plane containing Dimorphos's orbit about Didymos. The angle



is signed according to whether the velocity is nearer to the orbit-plane normal (negative) or anti-normal (positive). The magnitude of this angle limits the fraction of DART's momentum that is transferred to Dimorphos's orbit period.

The impact geometry for the first launch opportunity is depicted in Figure 2 and Figure 3, with the asteroid bodies shown as spheres. The impact is retrograde, in that DART and Dimorphos's velocities are oriented opposite one another (i.e. "a head-on collision"). The first 11 launch opportunities bias the impact time early by 20 minutes (~10 degrees of Dimorphos's true anomaly) to improve DSN coverage of the event. The first unbiased impact case, which launches on 29 Nov 2021 is shown in Figure 4 and Figure 5. This 10 degree angle can be seen most clearly when comparing Figure 2 and Figure 4, where the projected DART and Dimorphos velocities are not collinear.

Figure 1*. Earth-Didymos "Porkchop" plot depicting contours of DART's relevant transfer requirements. The blue points correspond to the planned DART impact date choices. Black is C3, red is solar phase angle, green is Earth-HGA angle, and cyan is out of plane angle.*



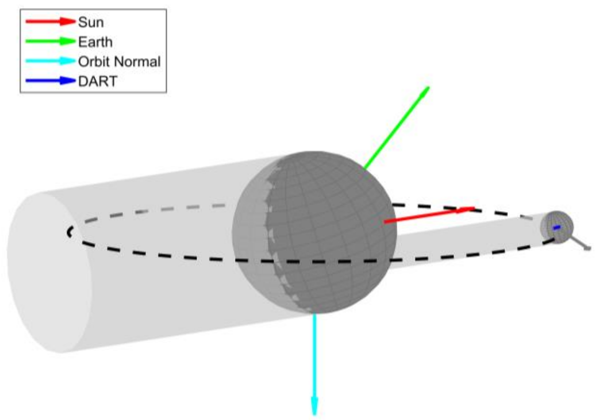
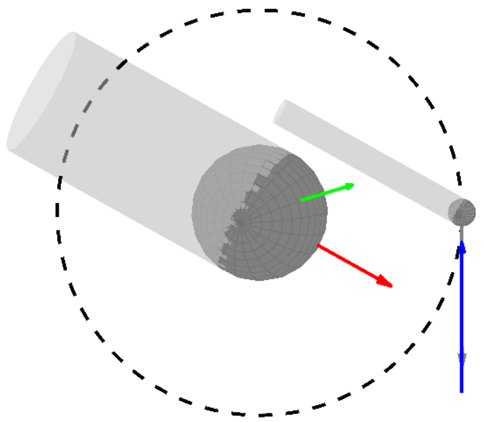


Figure 2. *Impact geometry viewed from the Didymos/Dimorphos orbit normal (pointed into the page), for the first (18 Nov 2021) launch opportunity*.

Figure 3. *Impact geometry viewed along DART's incoming relative velocity, for the first (18 Nov 2021) launch opportunity.*



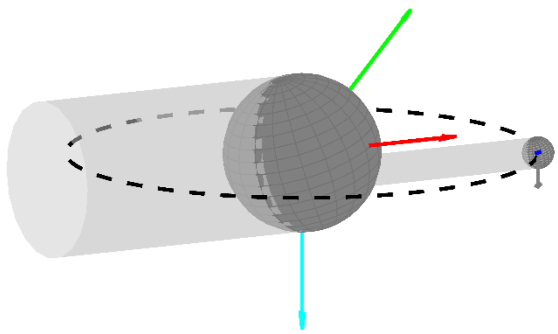


Figure 4. *Impact geometry viewed from the Didymos/Dimorphos orbit normal (pointed into the page), for the 29 Nov 2021 launch opportunity.*

Figure 5. *Impact geometry viewed along DART's incoming relative velocity, for the 29 Nov 2021 launch opportunity.*

Dimorphos orbits Didymos with a period of 11.92 hours. The planned retrograde impact will reduce this orbit period. The retrograde impact was chosen over a prograde impact partly because the resulting increase in the orbit period for a prograde impact would cause Dimorphos's orbit around Didymos to be nearly exactly 12 hours, synchronized with Earth's diurnal period. Earth-based observations would see Dimorphos in the same configuration each observing opportunity. A retrograde impact and resultant orbit period reduction allows for more unique observations from night-to-night. Finally, the retrograde impact also provides for better lighting conditions, as it occurs on the sunlit side of Didymos. Secondary reflection from Didymos may allow imaging of the night side of Dimorphos.

Table 1 summarizes the values in the porkchop plot and impact parameters and Figure 6 shows a plot of the transfer trajectory for the first launch opportunity in the ecliptic frame. The Dimorphos impact occurs below the ecliptic requiring an inclination change, relative to Earth, of roughly 3.5 degrees. The 7 TCMs and planned NEXT-C activities are annotated.

Table 1. DART Trajectory Summary

Parameter	Min Value	Max Value
Launch Dates (UTC)	18 Nov 2021	15 Feb 2022
Launch Time-of-Day (UTC)	03:36	07:16
Characteristic Energy, C3	3.44 km^2/s^2	7.66 km^2/s^2
Declination of Launch Asymptote, DLA (J2000)	29.1 deg	49.9 deg
Right Ascension of Launch Asymptote, RLA (J2000)	247.2 deg	296.0 deg
Earth Range	-	0.22 AU
Sun Range	0.93 AU	1.07 AU
Impact Dates (UTC)	25 Sep 2021	01 Oct 2022
Impact Time-of-Day (UTC)	22:32	23:26
Impact Velocity	6.12 km/s	6.76 km/s
Impact Out-of-Plane Angle	-33.5 deg	-6.9 deg
Impact Solar Phase Angle	58.3 deg	59.9 deg
Impact HGA Angle	87.7 deg	99.1 deg

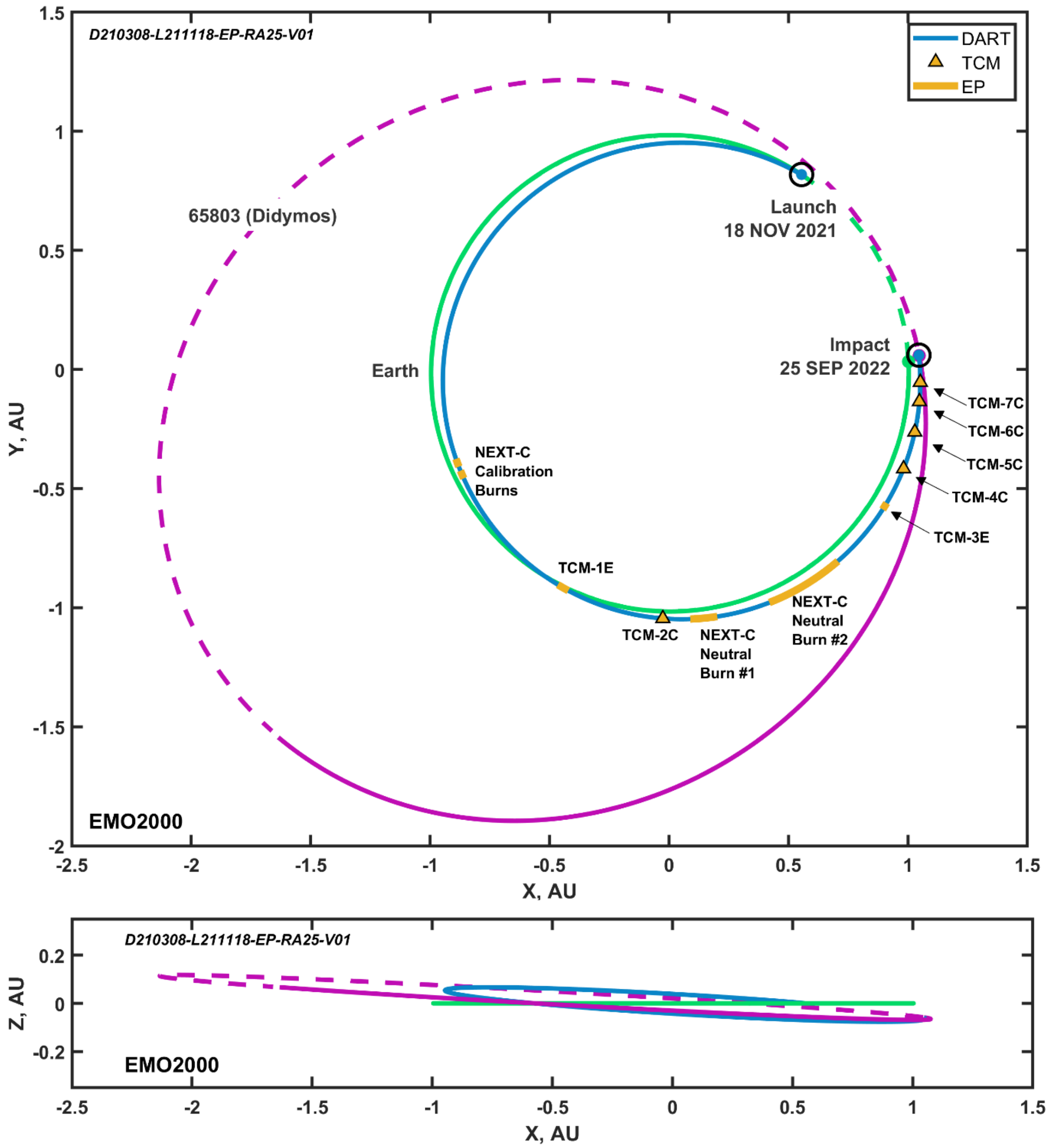
III. NEXT-C Demonstration

Previous iterations of DART's mission design utilized NEXT-C as the primary propulsion system. This enabled a rideshare launch opportunity [2] and opportunistic asteroid flyby [3] prior to the impact. However, following the Mission Critical Design Review (CDR), the decision was made for the NEXT-C thruster demonstration to be completely independent from the kinetic deflection experiment. The thruster will be demonstrated using TCM-1 and TCM-3, as well as a series of "neutral burns". In the event of a thruster failure, the spacecraft's hydrazine propulsion system can be used to execute all of the maneuvers.

The NEXT-C demonstration thrust arcs are termed *neutral* because they are designed such that the thruster can operate for a significant duration without meaningfully changing the trajectory. In this way, NEXT-C can be demonstrated without jeopardizing the asteroid impact. To execute the neutral burns, DART is oriented to put NEXT-C orthogonal to the Sun-line. The spacecraft then spins about the Sun-line with a rotation period of 12 hours. By the end of each rotation period, the net ΔV imparted to DART integrates to nearly zero, despite having operated over a duration that could produce 10 m/s if the thrust directions were constant in an inertial frame.

Figure 6. *Transfer trajectory for the first launch opportunity, shown in the ecliptic frame. The top figure shows the projection in the ecliptic plane. The lower figure shows the out-of-ecliptic component of the trajectory.*

A sample time-history of the thrust directions are shown in Figure 7. The total integrated ΔV after a 7 day burn is less than half a meter per second, despite having demonstrated NEXT-C for roughly 140 m/s. The mission is planning to execute up to 28 days of Neutral Burn for an effective 560 m/s.



The as-flown duration will depend on the observed hydrazine usage required for attitude control during NEXT-C execution. The hydrazine usage is expected to be high compared to typical EP missions because DART no longer carries a gimbal to align the NEXT-C thrust vector with DART's center-of-mass. As a result, NEXT-C imparts a torque when operating, which must be counteracted with the chemical hydrazine propulsion system.

The burns are designed in increments of 12 hours so that the ΔV integrates to nearly zero at the end of the full thrust arc. The worst-case failure scenario would be for NEXT-C to fail midway through a rotation. However, the ΔV needed to recover at any time is less than 4 m/s if the TCM is conducted 10 days later. Figure 8 gives the recovery ΔV required for this situation, if the EP system failed at any moment during a 7 day neutral burn.

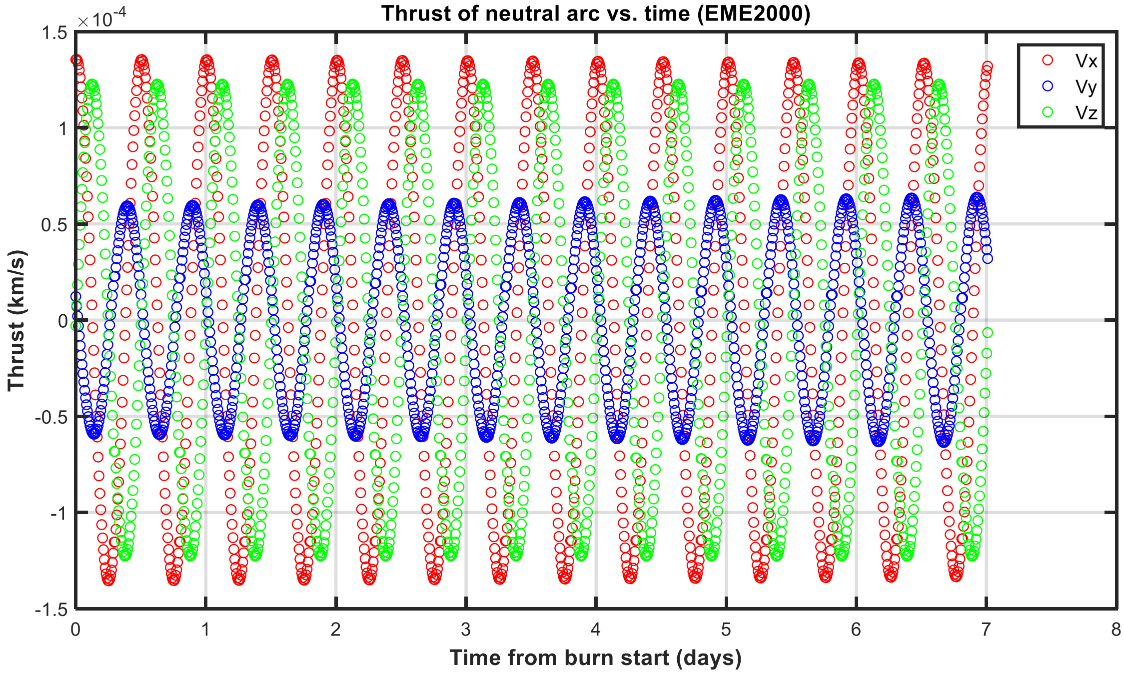


Figure 7. *Neutral burn thrust components (EME2000) over a 7 day demonstration period*

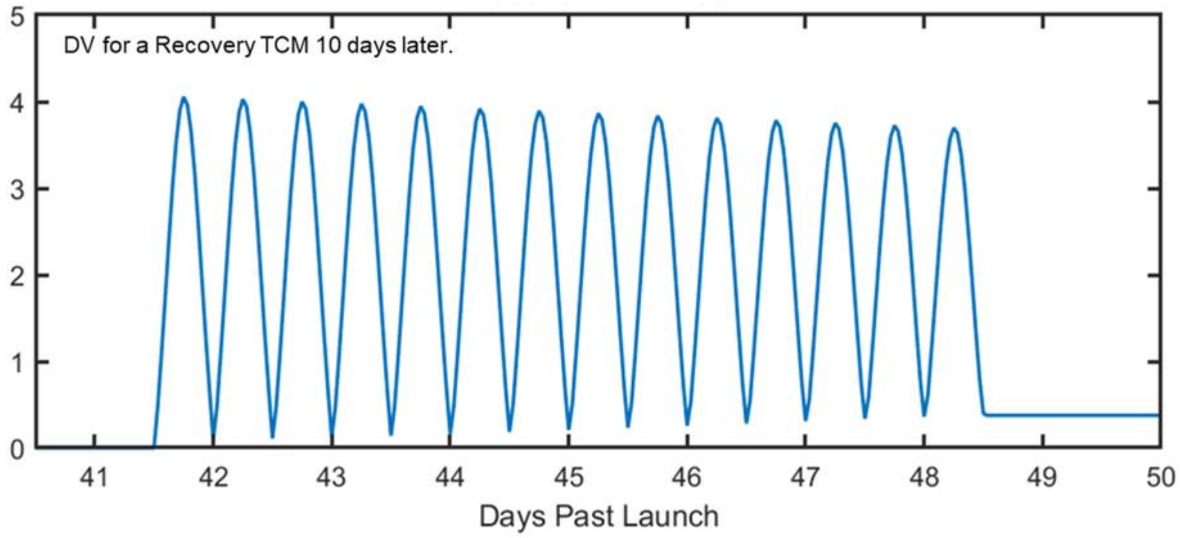


Figure 8. *ΔV required to recover from a thruster failure during a neutral burn. In this case, the recovery maneuver is performed 10 days after the failure.*

IV. Launch Cleanup Maneuver Placement

DART's largest TCM is allocated for the cleanup of post-launch injection errors. In order to minimize this ΔV and save propellant, most missions perform the maneuver as soon as possible after launch. Launch errors typically grow with time until a correction maneuver is performed. However, due to the geometry of DART's trajectory, an uncommon low ΔV maneuver opportunity exists several months after launch.

This maneuver timing is not wholly dependent on the launch date. The dispersions grow in the time after launch, reaching a peak in mid-March or early April 2022, and then drop dramatically when Earth and DART's orbit planes intersect. As DART is on an inclined trajectory relative to the ecliptic, this happens twice, the first time being at launch. The low ΔV opportunity in mid-May allows for a fixed TCM date across the entire launch period, and provides ample time for post-launch checkout activities. Referring to Figure 6, one can see that TCM-1E is located near to where DART's orbital plane intersects Didymos's.

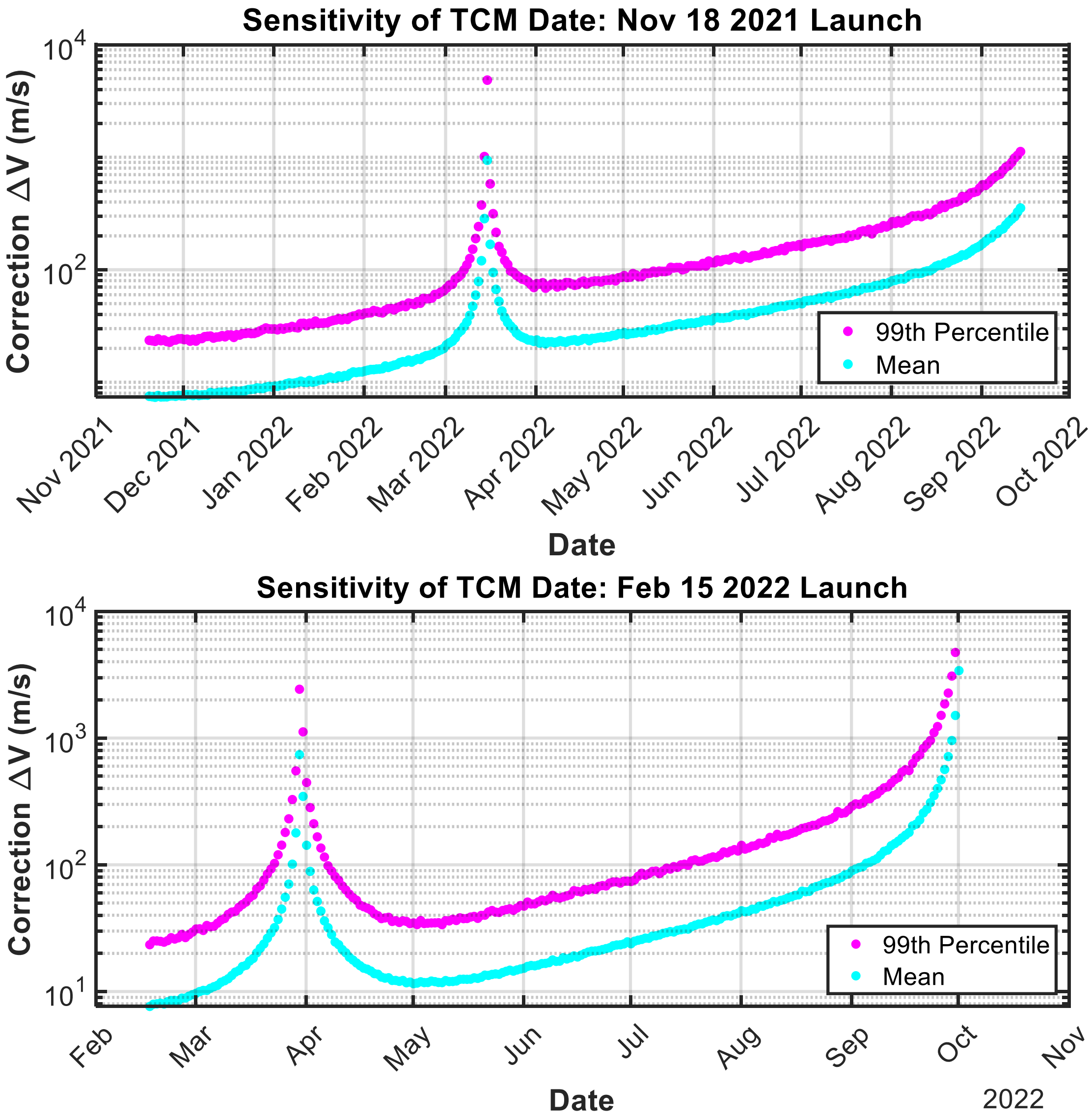


Figure 9. *TCM-1 ΔV statistics required to clean-up launch vehicle dispersions.*

Figure 9 depicts the ΔV required to return to the nominal trajectory as a function of the date at which the TCM is performed. An injection covariance matrix (ICM) provided by the launch vehicle provider was used to seed a Monte Carlo analysis. The perturbed injection state was propagated to a range of days past launch. For this figure, a Lambert solver was used to solve for the TCM magnitude. Both the beginning of the launch period, November 18, 2021, and the end of the launch period, February 15, 2022, are shown. For both cases, a peak of extremely high ΔV occurs in March-April 2022, and a subsequent trough occurs in May. The peak corresponds to the point in the orbit opposite the impact when DART is farthest above the ecliptic. The ΔV then decreases near the plane crossing.

An alternative analysis can be performed by looking at the gradient of the B-plane targets over time. As shown in Figure 10, the B-plane plane is perpendicular to the asymptote of the incoming trajectory. The B-vector is defined as the vector joining the body center and the point where the asymptote meets the (perpendicular) B-plane, which is the closest point if the body had no mass. With S defined along the incoming velocity, T lies in the ecliptic plane, and R completes the triad. The target point and B-plane error are described by the R and T components of the B-vector, B•R and B•T., and the time of flight (ToF).

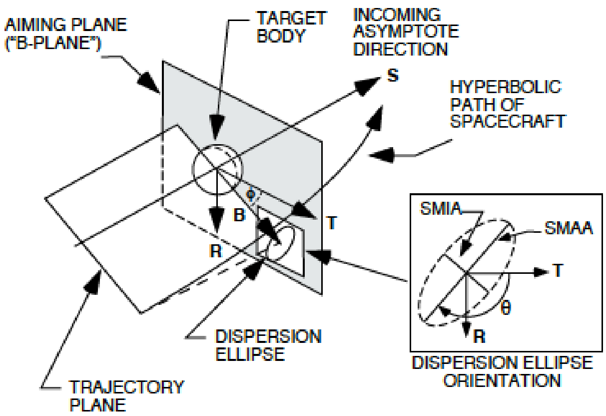


Figure 10. *B-plane geometry representation.*

For a given reference trajectory, the gradient of the B-plane targets with respect to the Cartesian velocity components can be computed along the given trajectory. This forms a 3x3 matrix which is used to design a maneuver that corrects a statistically generated B-plane offset. Looking at the angles between each row and the plane formed by the other two rows can indicate the degree of difficulty in implementing a launch clean up maneuver. When two gradients are near-collinear, a much larger DV is needed to make an impact.

Figure 11 shows the gradients to plane angles for a launch on November 24th for two B-plane projections (B•R and B•T), and the time of flight. In this case, the three colored lines on the plot show the angles between each row and the plane formed by the other two rows, as indicated in the legend. The matrix can be shown to be singular where the lines merge at 0 angles for all three cases, as is the case in mid-March 2022. This indicates that it is physically impossible to design a maneuver which controls all three B-plane targets. Before that time, the angles formed by the gradient rows and the plane of the two other components are smaller compared to post March 2022. In this case, a maneuver is possible to implement but the small angles indicate a small degree of control independence. Hence, the DV needed might be larger due to the coupling between gradient components.

Around May 15th, the gradient to plane angles have the highest values. In this case, the maneuver shows greater control independence than placing a launch clean-up maneuver 30 days after launch, leading to smaller statistical ∆V.

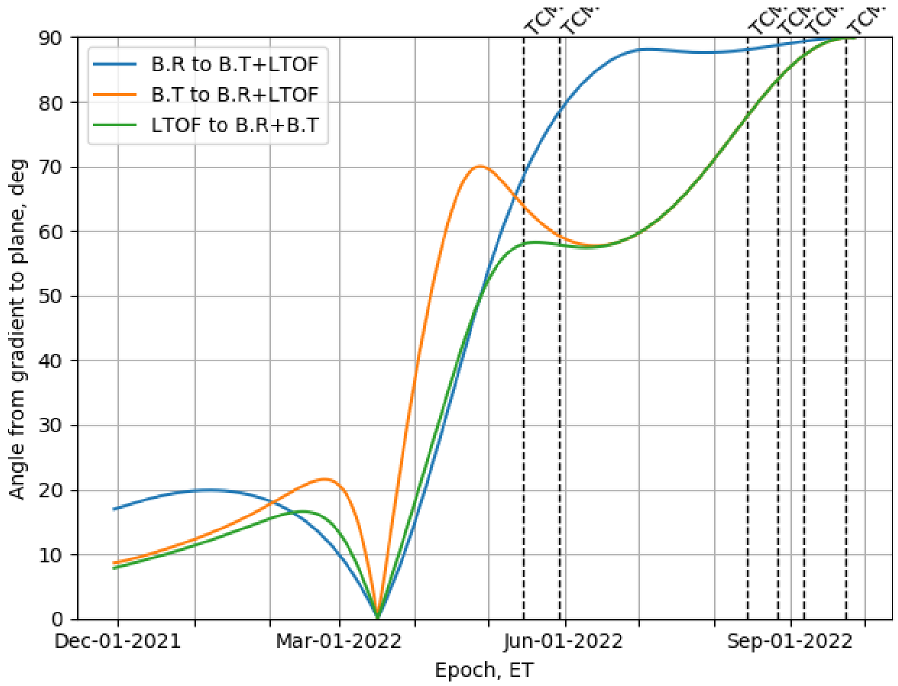


Figure 11. *B-plane gradient curves for the November 24th 2021 launch opportunity.*

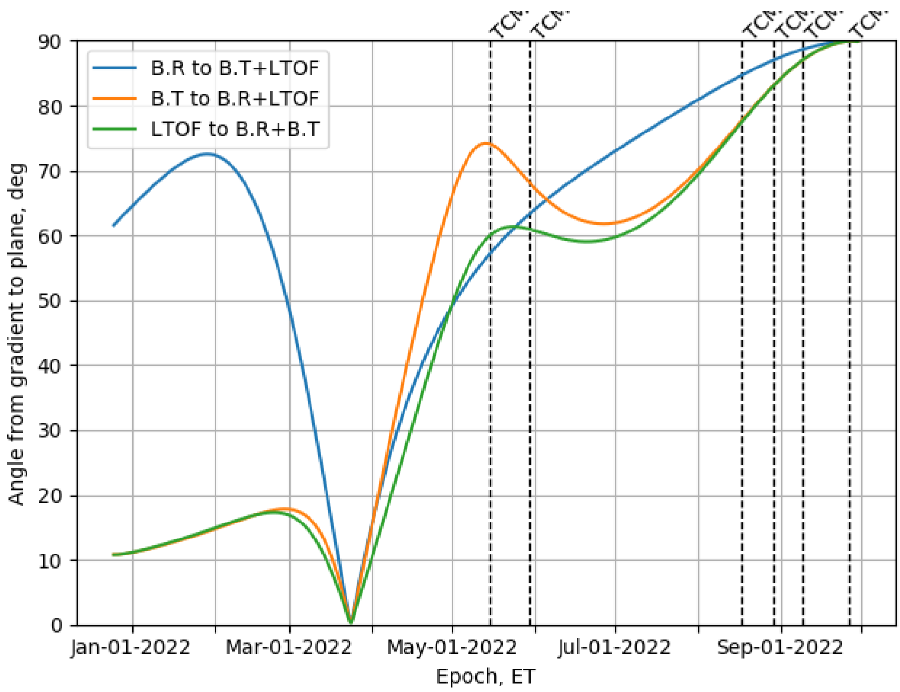


Figure 12. *B-plane gradient curves for the December 20th 2021 launch opportunity.*

The December 20th launch case, in Figure 12, shows a different control characteristic at 30 days after launch, and the advantage of placing the maneuver around mid-May is less apparent. Nonetheless, the low ΔV opportunity in May is still present, and from an operations standpoint, it is simpler to have the TCM occur on a fixed date, independent of the date of launch. The mid-May TCM provides ample time for commissioning and a low ΔV opportunity across the launch period.

V. Launch Requirement and Figure of Merit

The launch provider injection accuracy is a measure of how precisely the launch vehicle can deliver the spacecraft based on the specified set of launch targets. This is usually represented by an injection covariance matrix, composed of scattered spacecraft states from Monte Carlo simulations of the launch trajectories done by the launch provider. If the launch injection error is large, the required delta-V to retarget the Didymos system can be large. DART is particularly sensitive to propellant use, thus an appropriate injection accuracy requirement needed to be set. An often-used approach is to set requirements on the C3, RLA, and DLA of the trajectory target specifications. This method doesn't account for correlations among these components; an acceptable combination of C3, RLA, and DLA may result in a correction maneuver using more propellant than allocated. This results in points at the edges of the requirement "box" defined by C3, RLA, and DLA being statistically unlikely, but drive the propellant allocation requirements. The DART team wanted to avoid this situation.

A launch vehicle requirement in terms of what is called a Figure of Merit (FoM) was adopted in order to tie the launch vehicle performance to the propellant budget [4]. In the current context, the FoM measures how the spread in the launch injection error maps to a spread in the launch clean up TCM magnitude. The following three items are required in the computation of the FoM:

1) A reference trajectory with state partial derivatives from the state defined at an agreed interface time, referred to as the Targeting Interface Point (TIP) time, to the state at the TCM-1 target time.
2) A reference time for TCM-1.
3) An injection covariance matrix (ICM) that describes the scatter of simulated launch trajectories for the spacecraft state at TIP in EME2000 coordinates.

Items 1 and 2 are used by the Navigation team to compute a Jacobian matrix containing the partial derivatives of the velocity at TCM 1 with respect to the Cartesian TIP state. This matrix has been (arbitrarily) assigned the letter W within the DART project as a convenient shorthand. The W-matrix is computed via a mapping from the TIP state to the Didymos impact and then a reverse mapping from the impact time back to the TCM 1 time. It can be schematized as shown in Figure 13, and computed as shown in Equation 1.

$$W = \frac{\partial v_{TCM}}{\partial x_{TIP}} = \left[\frac{\partial b_{enc}}{\partial v_{TCM}}\right]^{-1} \frac{\partial b_{enc}}{\partial x_{TIP}} \qquad \textbf{[Eq.1]}$$

In Equation 1, v_{TCM} is the velocity at TCM1, b_{enc} is the B-plane target vector at the time of Didymos encounter, and x_{TIP} are the Cartesian states at TIP. W is a 3 x 6 matrix and can be conceptually divided into left and right halves. The left half is the derivative of the TCM velocity with respect to the TIP position, with units of second^{-1}. The right half is the derivative of the TCM velocity with respect to the TIP velocity and is unitless.

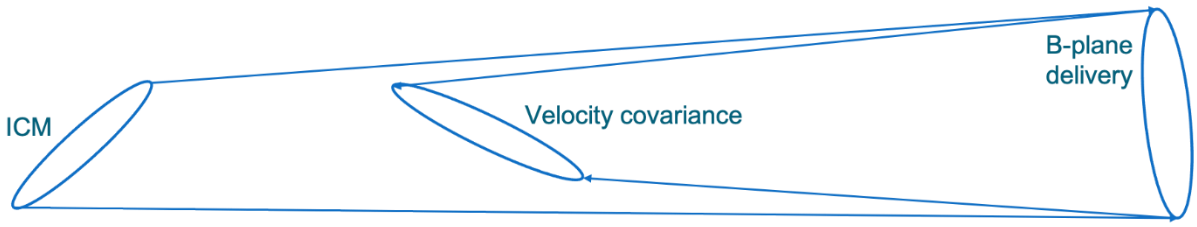


Figure 13. *Velocity covariance as a function of B-plane encounter and launch provider injection errors.*

To complete the FoM computation, an ICM, referred to as Λ_{TIP}, must be used. Λ_{TIP} is the covariance of the Cartesian state at TIP in the EME2000 frame, and should be a 6 x 6 matrix without the TIP time as a variable. The velocity covariance, $\Lambda_{\Delta v}$, can then be computed by mapping Λ_{TIP} via the W-matrix as follows:

$$\Lambda_{\Delta v} = W\,\Lambda_{TIP}\,W^T \quad \textbf{[Eq.2]}$$

The FoM will have the same distance units used in the ICM. It is expressed as:

$$FoM = \sqrt{Tr(\Lambda_{\Delta v})} \quad \textbf{[Eq.3]}$$

Putting an upper limit on the allowable FoM is equivalent to limiting the magnitude of TCM-1.

The W-matrices were computed by the Navigation team and provided to the launch vehicle team in an agreed-upon format so to verify launch requirement themselves. Requiring the ICM to have a certain FoM means the launch dispersions are considered acceptable if DART can afford the cleanup maneuver.

The FoM approach assumes that the dispersions at the TIP time given by the launch vehicle provider are centered around the nominal value, i.e. it only maps the distribution, not the mean. In order to quantify the bias in the launch provider Monte Carlo states, the Navigation team needed to retarget the encounter using the mean states and place the associated DV at the time of TCM-1C. That is, the FoM analysis only captures the precision aspect of the launch performance, leaving the accuracy for later assessment by the Navigation team, described in section VIII.

VI. Navigation Overview

The DART Navigation Team (Nav), located at NASA/JPL in Pasadena CA, is responsible for determining the DART spacecraft trajectory and associated parameters' uncertainties using radiometric tracking and optical navigation (OpNav) data through orbit determination techniques. Nav is also responsible for updating the Didymos system barycenter ephemeris using OpNav data during flight operations on approach. Pre-launch, navigation's error analysis serves to size and place TCMs for quantifying the TCM propellant budget and satisfying error requirements.

The Navigation team's main driving requirement is to deliver the DART spacecraft to a location within 15 km when projected on the Didymos B-plane, and within three seconds of the desired impact time. At 12 hours before impact, the navigation is formally handed over to APL's Small-body Maneuvering Autonomous Real Time Navigation (SMARTNAV) for final impact. This autonomous optical navigation system will direct the spacecraft toward the smaller body, Dimorphos [5]. At 12 hours prior to impact, Nav also delivers the best estimated spacecraft and Didymos ephemerides as the very last ground update to SMARTNAV.

In flight, Nav will design TCM parameters to meet error requirements and to return to the reference trajectory provided by the Mission Design team (MD), for implementation by the Guidance, Navigation and Control team (GNC).

VII. Assessing Launch Vehicle Injection Error Effects on Initial Acquisition

One of the pre-launch tasks of the Navigation team is to assess the pointing dispersions caused by the launch injection errors for initial acquisition by the Deep Space Network (DSN) and the European Space Agency's tracking station network (ESTRACK). For DART, ESTRACK's New Norcia is the first station to acquire, followed by Madrid. The size of the injection errors and their variations in the first day after launch will impact the ability of a station to acquire the spacecraft signal, and influence signal search strategy.

This initial acquisition analysis uses a technique that samples the ICM provided by the launch provider, and propagates 4000 sampled states for 30 hours past TIP. We then compute the pointing variations at rise and every 10 minutes after TIP for Madrid and 2 minutes for New Norcia. Figure 14 shows the ground track for a launch on November 24th, with station rise times indicated along the trajectory.

The products delivered to DSN and ESTRACK are trajectory files for the nominal and 3-sigma pointing dispersion at rise, and pointing dispersion time history files. Figure 15 gives a geometric visualization of the dispersion in terms of elevation and azimuth at the rise time for the New Norcia and Madrid antennas. On those figures, the nominal rise is indicated in green with the 3-sigma dispersion indicated by the green circle. The plus and minus 3-sigma pointing cases are shown in red and blue, respectively. The half power, 1st null and 2nd null beam width provide insights on antenna performance.

VIII. Mission timeline and Navigation Predictions

The mission maneuver timeline is defined as shown in Figure 16 from launch to impact. After calibration activities, TCM-1E (EP) or TCM-1C (chemical) will be designed to clean-up the launch errors. TCM-2C will be cleaning up the remaining errors from the larger TCM-1, while the remaining five TCMs are designed to clean-up errors in cruise and during the approach phase to target the Didymos barycenter. DART plans on using NEXT-C for TCM-3. The EP neutral burns are described in Section III.

Pre-launch error analyses are referred to as covariance analyses. A covariance analysis was performed to support the placement of the last five TCMs and satisfy the Navigation error requirement mentioned in section VI. For this, simulated range and range rate measurements and *a priori* errors related to the dynamic modeling of the trajectory and spacecraft related error sources are used in a least squares filter.

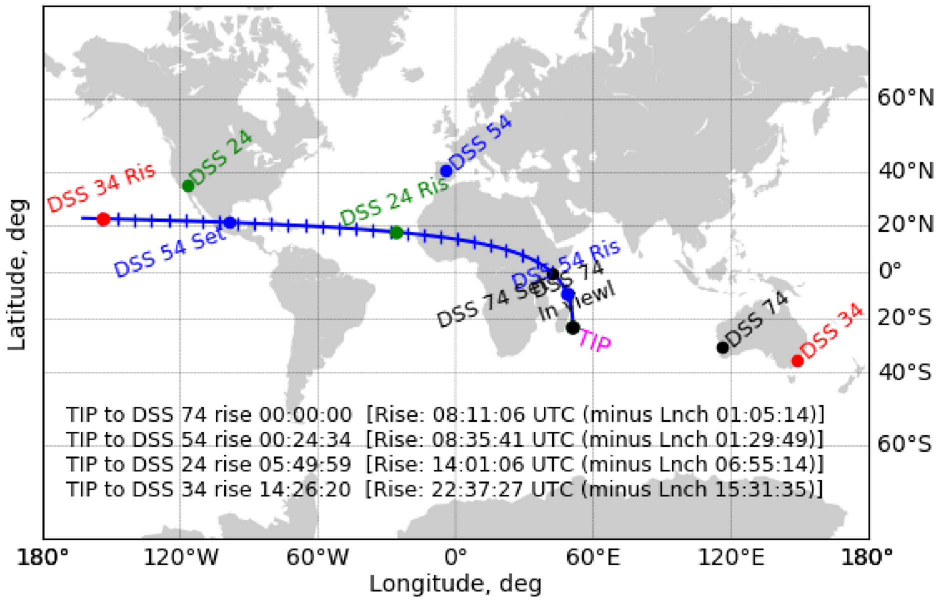


Figure 14. *DART ground track for the first 15 hours. Rise times and indicated for New Norcia, Madrid, Goldstone, and Canberra*.

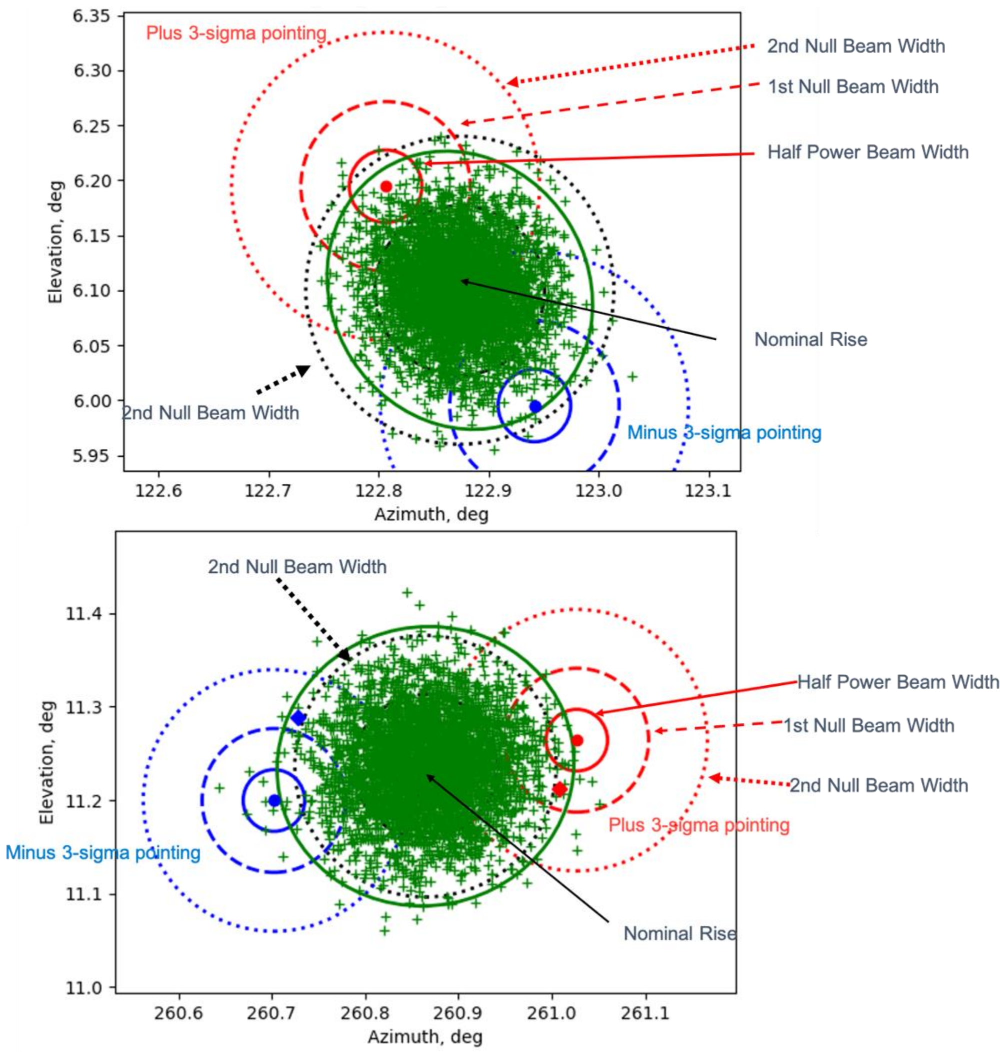


Figure 15. *Station pointing at rise time for the New Norcia and Madrid antennas.*

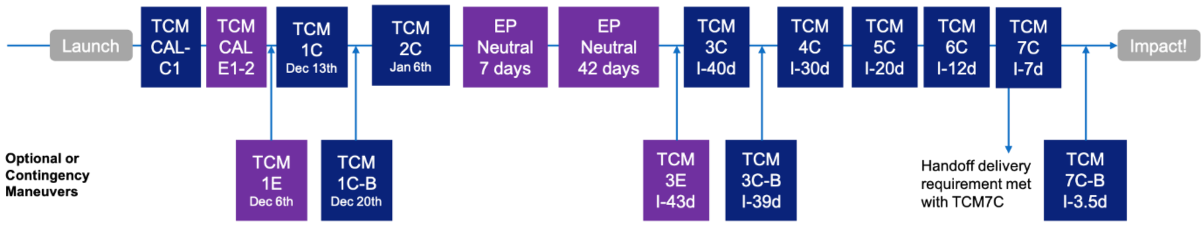


Figure 16. *Trajectory Correction Maneuvers Timeline.*

OpNav is the critical data set of this mission to bring DART to impact. Simulated images were used for the last month of the mission, at every 5 hours until impact. During this time, the tracking coverage includes Doppler and range measurements every day, and delta Differential One-way Range (DDOR) measurements every 3 days. These sets of inputs provide the errors in the spacecraft states at the times of each TCM data cutoff, which are nominally two days prior to execution.

A Monte Carlo technique is used to sample the trajectory, taking into account the injection dispersion from the launch vehicle after separation and the spacecraft trajectory errors as the orbit is being determined. For each sample, a TCM is designed using the linearized state transition matrix to compute the DV required to retarget to the Didymos barycenter impact states. The maneuver execution errors are added at the time of the TCM data cutoff from a Gates maneuver execution error model [6] *a priori* estimate by the GNC team. The technique was set to use 10000 samples, from which statistics on the mean, standard deviations and 99th percentile of the size of the TCMs planned are obtained.

Assuming data schedule and error above, Figure 17 shows the evolution of the errors mapped to the impact plane geometry while Table 2 lists the statistics on the TCMs for three launch opportunities of the launch period. TCM-3 and TCM-4 serve as clean up maneuvers for errors accumulated in cruise from EP neutral burns and other thrusting activities. The asteroid ephemeris then becomes the primary source of error until optical sighting of the asteroid system is possible, as the OpNav measurements allow a reduction in the ephemeris error resulting in more accurate deliveries by TCM-5C and TCM-6C. TCM-7C meets the delivery requirement with ~20% margin. The LICIAcube [7] release is planned 10 days prior to impact with a backup opportunity 6 days out. The timeline also includes a backup TCM at 3.5 days out if TCM-7C is missed or the LICIAcube deployment is delayed.

Table 2. TCM Statistics, 3 Launch Opportunities

Launch Date	TCM-1C Placement	TCM-1 ΔV99 (m/s)	TCM-1 Deterministic (m/s)	Total ΔV99, TCM 1-7 (m/s)	FoM
24-Nov-21	May 18th	14.4	2.20	27.4	6.2
24-Dec-21	May 18th	26.3	1.02	39.8	10.3
24-Jan-22	May 18th	28.9	3.23	42.7	11.2

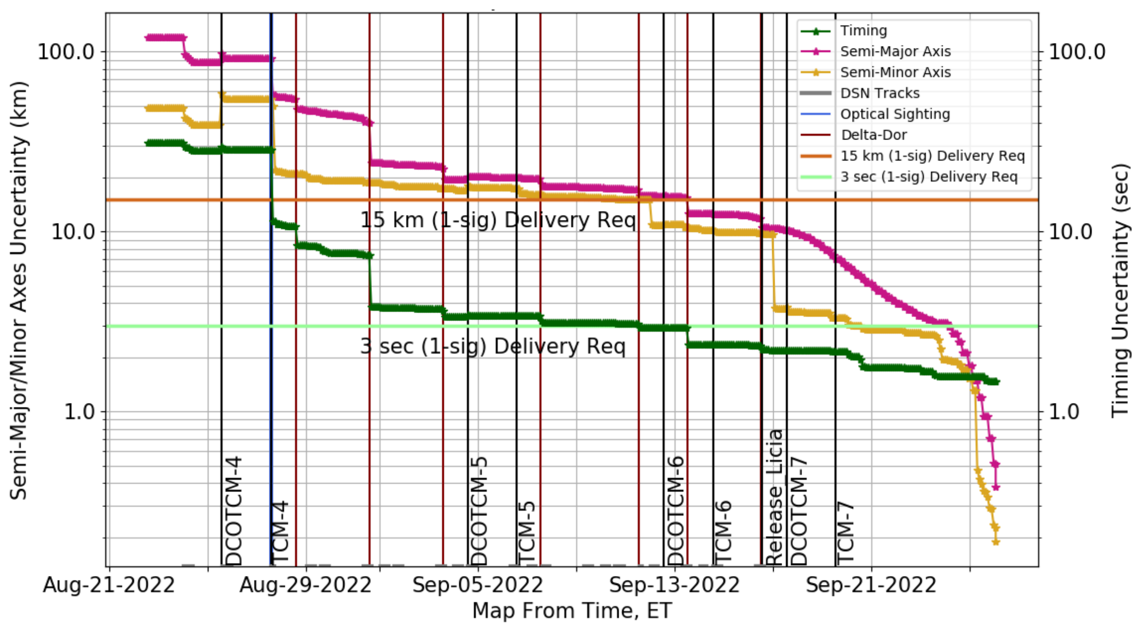


Figure 17. *DART uncertainties mapped to the Didymos impact plane.*

IX. Conclusions

The DART mission's Phase D trajectory and navigation plan is mature, with no open trades or risks. DART will launch as early as November 18 2021, with 90 opportunities. The electric propulsion subsystem is demonstrated independently of the kinetic impact experiment using neutral burns. There are no deterministic maneuvers. A set of 7 TCMs are used to correct launch vehicle dispersions and statistical errors.

The Mission Design team has developed and analyzed a reference trajectory for each launch opportunity that satisfies impact requirements. With no deterministic maneuvers, the trajectories are solved by varying the impact date and time-of-day.

As part of their pre-launch analyses, Nav evaluated the pointing dispersions caused by the launch injection errors for initial acquisition by ESA's ESTRACK and DSN over the launch period. In addition, Nav developed a mission maneuver timeline that delivers the spacecraft with the required accuracy for the onboard SMARTNAV to impact Dimorphos.

The Mission Design and Navigation teams will continue preparations for launch, including maneuver rehearsals, final mission event planning, and pre-launch documentation.

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