DOUBLE ASTEROID REDIRECTION TEST (DART): NAVIGATING TO OBLITERATION

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Introduction: Although there are no known threats coming from outer space, the Earth is constantly bombarded by small debris commonly referred to as shooting stars. This was recently illustrated from records of small asteroids hitting the Earth atmosphere, providing fireballs' frequency and size statistics [1]. Questions regarding the type, quantity, and orbit of small bodies in the Earth's neighborhood, forming the Near-Earth Objects (NEOs) population, have motivated numerous research and observations.

Over the past few decades, improvements in telescopic observations along with mission design techniques have fueled curiosity and development in cataloguing those NEOs, characterizing their surfaces and internal compositions, and altering their orbits. As a result, various mission concepts for planetary defense purposes have been proposed over the years. NASA's Planetary Defense Coordination Office (PDCO) now manages its planetary defense overall mission [2].

Three candidate techniques emerged as the most mature concepts for deflection and disruption: kinetic impactors, nuclear devices, and gravity tractors [3]. Deflecting a NEO implies a sufficient change in the NEO's trajectory so that it misses Earth at its close approach. This momentum exchange is directly correlated with the NEO surface and internal properties; a large amount of ejecta produced from a kinetic hit will increase the momentum imparted to the target.

This called for an experiment, and NASA's Double Asteroid Redirection Test (DART) built and managed by the Applied Physics Laboratory (APL) became the first-ever space mission to demonstrate asteroid deflection by kinetic impactor on September 26 2022. The target for this mission was the binary asteroid system Didymos composed of a larger asteroid Didymos (diameter: $\sim$780 meters), and a smaller moonlet asteroid, Dimorphos (diameter: $\sim$160 meters), which orbits the larger asteroid. Targeting this miniature Earth-moon like system allowed the deflection to be observable; the change in the moon's orbital period can be detected from Earth by examining the light curve from the main body. The DART spacecraft impacted Dimorphos nearly head-on, shortening the time it takes to orbit Didymos by up to 33 minutes [4].

The DART Navigation Team (Nav), located at the Jet Propulsion Laboratory (JPL), was responsible for determining the DART spacecraft trajectory using radiometric tracking and optical navigation (OpNav) data through orbit determination techniques. Nav supported phases of the mission from Launch to Approach, until 12 hours from impact. Nav was also responsible for updating the Didymos ephemerides using OpNav data during flight operations on approach. This was critical in the success of this mission, as the pre-launch uncertainty on the Didymos system orbit would have caused DART to miss its target.

The Navigation team had specific requirements during approach to hand-off the final steering in the last four hours. The actual target (the small moon) being visible only in the last couple hours before impact, APL's onboard autonomous system, the Small-body Maneuvering Autonomous Real Time Navigation (SMART Nav) was to handle spacecraft-target relative navigation to impact Dimorphos. The next sections describe the DART navigation from launch to impact, and detail the challenges encountered along the way: in particular, where a late spacecraft control mode update became necessary to achieve better delivery and hand-off to SMART Nav.

Mission Overview: The DART Mission Design Team (MD), located at APL, was responsible for designing the DART spacecraft trajectory. MD was also responsible for evaluating and reoptimizing the spacecraft trajectory during the flight and verifying necessary statistical Trajectory Correction Maneuvers (TCMs) throughout the mission (those maneuvers with zero deterministic components).

In the years prior to launch, the trajectory evolved from using a low-thrust propulsion system, spiraling out of Earth orbit and flying by an intermediate NEA prior to impact, to launching on a completely ballistic impact trajectory [5]. NASA's Evolutionary Xenon Thruster – Commercial (NEXT-C) solar electric propulsion system became one of DART's technology demonstration components. NEXT-C is a next-generation system based on the Dawn spacecraft propulsion system, and was developed at NASA's Glenn Research Center (dart.jhuapl.edu) refdartWeb. Once launched, DART also demonstrated newly developed solar arrays, the Roll Out Solar Arrays (ROSA), to provide the solar power needed for NEXT-C.

DART was equipped with the Didymos Reconnaissance and Asteroid Camera for OpNav (DRACO) Imager, which was the only instrument onboard. The camera was used for OpNav imaging in the last 30 days of the mission, providing ground-based optical navigation to Didymos. It also provided images and centroids for close, autonomous guidance by SMART Nav to Didymos starting four hours prior to impact.

The only survivor of the DART mission was a small cubesat, LiciaCube (LCC). This mission companion cubesat, was contributed by the Agenzia Spaziale Italiana (ASI) and built by Argotec. LCC was deployed from the DART spacecraft 15 days prior to DART's impact. As it flew by at a distance of 55 km, it captured images of the plume from DART's collision with Dimorphos [6].

Trajectory

The trajectory is shown in Fig. 1, where the blue, green and purple trajectory lines represent DART, the Earth, and the Didymos system, respectively. Dashed lines differentiate between pre and post launch. Trajectory correction maneuvers are shown using yellow triangles: seven were executed using the chemical propulsion system while one demonstration burn was executed using the low-thrust propulsion system 24 days after launch (indicated as L+24 on the figure). The launch period opened on November 24 2021 and extended through February 15 2022. A few encounter requirements dictated the trajectory constraints: intersect Didymos with a solar phase angle (Sun-Dimorphos-DART) of less than 60 degrees, and arrive with the Dimorphos-DART-Earth angle bounded between 65 and 115 degrees due to the high gain antenna (HGA) range-of-motion. The impact strategy was also designed to facilitate observations using Earth assets, including reducing the orbit period to allow variability in the measurements (due to Dimorphos' original orbit of 12-hr) [5].

The mission implementation was divided into four phases: launch and commissioning, cruise, approach, terminal:

1. Launch and commissioning
   From pre-launch to spacecraft deployment, with commissioning including the first 30 days of the mission. Luckily, DART launched on the first day of the launch period.

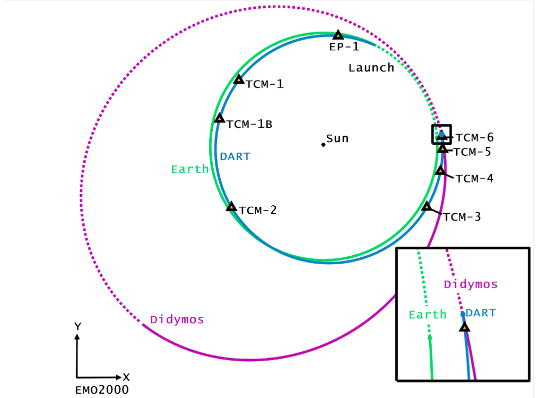

Figure 1: DART (blue), Earth (green), and Didymos (magenta) trajectories. TCMs are indicated from launch to impact, including seven executed using chemical fuel to correct for errors in flight, and one demonstration burn executed using the ion propulsion system NEXT-C at 24 days after launch (L+24) [5]

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2. Cruise
   From commissioning through initial detection of Didymos by the DART payload camera, including the launch clean up TCM. The launch clean up maneuver initially scheduled for May 18 2022 was moved up to February 7 2022. The DART mission originally had the option of using electrical or chemical propulsion for TCM-1 and TCM-3 during flight based on NEXT-C performance. The DART team also planned to demonstrate NEXT-C through neutral thrust arcs (thrusts which in combination produced no net Delta-V) in the summer 2022.
3. Approach
   Beginning at 30 days prior to impact, with the initial detection of Didymos by the DRACO camera and the start of the OpNav campaign, to SMART Nav hand-off at four hours prior to impact. The DART mission conducted three maneuvers to clean up accumulated errors in cruise and target Didymos, aided by an optical navigation imaging campaign. At 8 hours prior to impact, the mission started pre-terminal activities.
4. Terminal
   Initiation of SMART Nav autonomous terminal guidance system, four hours prior to impact, through impact. During this period,

the spacecraft downlinked DRACO images in near- real time every second.

Driving Navigation Requirement

Selecting the moon of a binary asteroid system as target has an inherent challenge in that the target moon will not be distinguishable from the primary body until very close to encounter. Even though the asteroid system was observed to great resolution, the Didymos barycenter was still only determined to a few tens of kilometers while the Dimorphos orbit phase was undetermined. Those are large uncertainties to account for when planning a 6.14 km/s collision with a 160 m object from a 10 million km distance. As detailed in the next section, ground navigation, where the main objective is to determine the states of the spacecraft and associated uncertainties to achieve a given aim, is a task that usually involve a few hours of processing time. As a result, a logical approach is to use onboard automation when the target start to be visible in the last couple hours before the planned impact.The APL's SMART Nav system was developed to perform target relative navigation, in order to execute fine maneuvering in a relatively short time [19].

To ensure an adequate transition between ground and onboard navigation systems, hand-off requirements needed to be defined. The most appropriate frame to define such conditions was to use Nav's standard coordinate plane for encounters, the B-plane. The B-plane passes through the center of the target body, and is perpendicular to the incoming asymptote of flyby trajectory, as illustrated in Fig. 2. See the reference by Kizner for details of the mathematical construction [21]. The Nav driving requirement was to deliver the DART spacecraft with less than 15 km uncertainty at a 67% confidence level (1-sigma) when projected on the Didymos B-plane, and three seconds uncertainty in the time of flight. In Fig 2, this illustrated by the red ellipse.

The mission timeline and placement of maneuvers had to be developed to satisfy this delivery requirement. In order to do so, the expected errors associated with the planned measurements, the spacecraft activities, and target uncertainty are evaluated along the reference trajectory, in an error analysis referred to as a covariance analysis [7]. In flight, this *a priori* knowledge may change, and for DART, the critical components to satisfy Nav requirements, and challenges, revolved around predicting the spacecraft performance and identifying Didymos. The next section describes how these were handled as part of the navigation process.

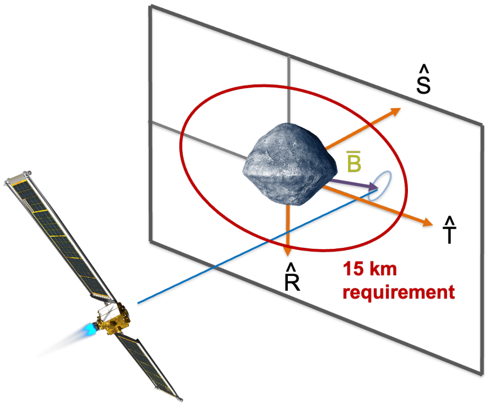

Figure 2: The B-plane passes through the center of the target body, and is perpendicular to the incoming asymptote of flyby trajectory. The navigation driving delivery requirement of 15km (1-sigma) is shown with the red ellipse.

Mission Design and Navigation in a Nutshell : Mission Design and Navigation works hand in hand during flight operations. The role of Mission Design (MD) is to generate the ideal reference trajectory the spacecraft needs to fly to achieve the mission's objectives. The role of Nav is to operationally fly this trajectory by using tracking data measurements to compute the actual trajectory and design maneuvers to correct back to the reference. Specifically, this includes:

- Process radiometric tracking data (Doppler, range, and DDOR) and optical images to estimate the spacecraft trajectory, the Didymos barycenter ephemeris during Approach, and associated uncertainties.
- Compute the desired Delta-V vector for TCMs to achieve impact and validate the TCM implementation provided by the spacecraft team.
- Reconstruct the TCM Delta-V using pre- and post-TCM tracking data.

The design reference trajectory included deterministic components, beside demonstration burns using NEXT-C, which were then dropped after commissioning (refer to Justin et al, 2023 for the trajectory evolution detailts [5]). Thus, Nav designed statistical TCM parameters to return to the reference trajectory provided by MD during approach to Didymos for implementation by the Guidance Navigation and Control team (GNC). Figure 3 schematizes the process, while the GNC interface is through the maneuver design process.

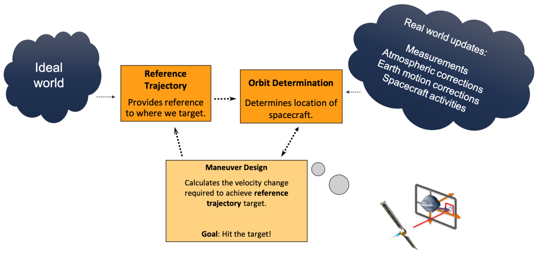

Figure 3: Navigation in a nutshell: with real-world updates, orbit termination and flight path control tasks are to return to the reference trajectory, using the B-plane as a measure of success.

Important challenges encountered by Nav were associated with data and spacecraft inputs. We describe them below as we summarize the measurements, models, and navigation filter inputs and configuration part of the OD process.

Radiometric Measurements

The following are the radiometric data types used to determine the spacecraft's orbit (depicted graphically on Figure 4. The data was provided by both NASA's Deep Space Network (DSN) and the ESA's European Space Tracking (ESTRACK) Network, although Range and Doppler primarily from the DSN.

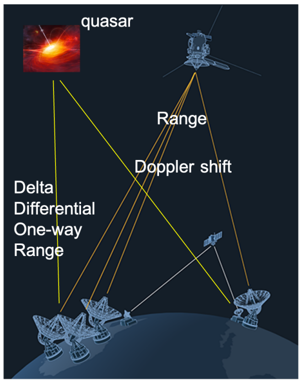

Figure 4: Common radiometric measurements used for DART.

- Range:
  Range data provides the line-of-sight (LOS) distance from a tracking station to the spacecraft, obtained by measuring the round-trip light time for the transmitted code to be received back at the station. The DSN allows use of two types of range, using sequential square wave tones or repeating pseudonoise (PN) tones [8, 9]. The ranging system correlates tones received from the spacecraft with those it transmitted. In sequential ranging, the phase shift with a maximum correlation value is related to the round trip light time distance. For a few weeks, the Nav and telecommunication teams worked hand in hand to test DSN's PN range. Here the uplink carrier signal is modulated with a combination of a range clock and several codes. The downlink signal is demodulated and correlated with local models of the range clock and PN codes. Several tests were done using various configurations with both the low gain (LGA) and high gain antennas (HGA), resulting in usable and tighter range measurements with the HGA.
- Doppler:
  Doppler data measures the LOS velocity between the tracking station and the spacecraft by utilizing the well-known Doppler effect. The relative motion of the spacecraft and receiving antenna causes the received frequency to differ or shift from that of the transmitting antenna [10], which is proportional to the LOS velocity. The Doppler measurement is perhaps the most widely used radiometric measurement, as it is highly precise and, in addition to the LOS velocity, it indirectly provides information on the angular position of the spacecraft as well (cite Hamilton Melbourne paper).
- Delta Differential One-Way Range (DDOR):
  Very Long Baseline Interferometry (VLBI) allows determination of angular position for distant radio sources by measuring the geometric time delay between received radio signals at two separated stations. An application of VLBI, known as DDOR, is where two widely separated antennas simultaneously compare spacecraft tones to the radio noise of a quasar (which are catalogued extra-galactic objects), and measure the time difference between the signals arriving at the stations. DDORs consist of an angular measurement providing information in a plane perpendicular to the Earth's line of sight [11]. With the trajectory dwelling in the southern hemisphere two months before impact, DART used both the DSN and ESTRACK network, the Goldstone-Canberra-Malargue station baseline, with great accuracy.

Media corrections will be applied to the radiometric tracking data, along with Earth motion parameter updates. Table 1 represents the schedule of radiometric measurements over the whole mission. In flight, more DSN time were added in Approach, resulting in continuous tracking for the last 30 days.

An important lesson learned for DART included the use of DDOR measurements to determine off line of sight delta-V imparted to the spacecraft caused by the various pointing activities and control modes used by the GNC controller, explained in the next paragraphs. Note that optical measurements also provide angular information similar to DDORs, where both scale with distance. For DART, DDORs had a more effective information weight since the impact was close to Earth. Solutions comparisons are discussed in the last section.

Optical Measurements

As mentioned, OpNavs were required to identify and aim at the target appropriately and to reduce the target uncertainty before handing off to SMART Nav. Hence, significant effort was spent pre- and post-launch to prepare for the analysis of a large number of images in the last month of the mission, when Didymos would become visible. This OpNav imaging was done with DART's DRACO camera, based on New Horizons' LORRI instrument. While using a similar visible narrow angle camera with a large aperture, it used of a CMOS 2k x 2k detector instead of a CCD.

Accounting for the DRACO capability and the Dimorphos orbital period of about 12 hours, an OpNav data set was acquired every 5 hours through most of approach to avoid possible brightness biases due to the binary motion. These data sets consisted of 4 minutes of imaging at 1 Hz every 5 hours from 30 days until 18 hours before impact, and then every 2 hours until 12 hours before impact. A break in this schedule was made for two science lightcurve campaigns that were planned at 15 days prior to impact for 6 hours, and at 3 days prior to impact for 12 hours. The Opnav team used images from the first of these lightcurves, while the second was canceled to achieve a more accurate and stable OD solution during the final days. As will be explained later, those science observations made a significant impact to the trajectory.

The OpNav process was based on measuring accurate centers of stars (for attitude information) and Didymos. For most of approach Didymos was too dim to get sufficient signal and SNR in individual images, while the number and brightness of stars was acceptable but far from optimal. The OpNav process therefore included coadding images, subsampling multiple images onto finer grid to recover additional spatial sampling due to subinteger pixel offsets between images. This technique is possible due to spacecraft's attitude drift between images, and was previously tested on NHPC. It provided increased SNR; more, fainter stars in each image; and improved accuracy of Opnav centers. A number of calibrations were done in flight to verify the camera predicted performance and to smooth out the optical measurements processing pipeline [24].

A Shutter Story

One of the most significant challenges to OpNav resulted from using DRACO's rolling shutter readout mode, which causes a line-dependent distortion of all images. While DRACO also has a global shutter mode, that had a much lower gain and built in background subtraction such that it could not provide sufficient SNR for Didymos or stars. Optical navigation therefore obtained images in rolling shutter mode for the higher gain and lower noise, using a 90 ms integration time as a balance between increased signal and lower smear. The downside to this was that the rolling shutter distortion, combined with high drift rates due to thruster control during imaging, resulted in stars at the end of the readout being captured at an attitude up to 2 pixels off the attitude of stars at the beginning of the readout. When uncorrected, this had a significant negative impact on the attitude determination and centroid solutions in each image, but multiple techniques were developed to minimize and correct for this distortion. [22]

Models and Apriori Information

The gravitational force model of the Sun and all planets of our solar system were included, defined by the de430 planetary ephemeris [12]. The *a priori* uncertainties for Earth were taken into consideration when estimating uncertainties in the navigation filter. The Earth gravity field is a 20x20 truncation of the GGM05c model while the Moon gravity field is a 20x20 truncation of the LP150Q lunar potential.

Non-gravitational forces included solar pressure, propulsive chemical maneuvers and those originally planned demonstration burns using the NEXT-C propulsion system, and small thrusting activities. Propulsive maneuvers were modeled as fixed time duration burns (non-impulse). Other atti-

Table 1: Radiometric measurements schedule

Mission Activities	Timeline	Tracking and support
Launch period 11/24/21-02/15/22	7 d	Continuous coverage; Dual station over deployment
Commissioning	23 d	One 8-hour pass per day Dual station over deployment
Coast	78 d	Three 8-hour passes per week DDOR monthly
EP cals	2 d	Over tracking pass DDOR before – middle - after
Coast	61 d	Three 8-hour passes per week DDOR monthly
Neutral burns	7 d, 21 d	Three 8-hour passes per week DDOR monthly
Coast	40 d	Three 8-hour passes per week DDOR monthly
Approach	30 d	Continuous coverage through impact DDOR every 3 days through I-3 days dual antenna over the last 12 hours

tude maintenance burns or slews, such as pointing for optical image acquisition, were modeled as impulsive burns.

For TCM, the flight system was carrying a specific requirement to perform correction maneuvers such that the 1-σ errors can be stated in terms of four independent errors, referred to as the Gates model[13]:

- Proportional magnitude error: 0.012
- Proportional pointing error, per axis: 0.03 rad
- Fixed magnitude error: 0.001 m/s
- Fixed pointing error, per axis: 0.00004 m/s

No Reaction Wheels...

Reaction wheels allow change in attitude without thrusting. For that reason, they are usually very much sought after by navigation teams. When firing thrusters that are not exactly balanced, a change in the spacecraft velocity is produced.

DART used 8 out of 12 thrusters; decisions were made early in the mission development to not use reaction wheels. Their nominal thrust vectors imparted no translational delta-V in the spacecraft Z axis. The GNC software included control modes dictating the required pointing accuracy. In cruise, housekeeping telemetry downlink allowed for a few degrees offset in the spacecraft pointing. However, imaging implied tighter pointing to keep Didymos in the field of view, which in turn, output more thrusting activities.

Before launch, the DART GNC team quantified the amount of delta-V associated with particular spacecraft activities and associated pointing mode. This was performed through Monte Carlo analyses, varying spacecraft inputs and simulating Opnav, HGA, EP thrusting, and attitude maintenance during cruise. The results of those Monte Carlo were delivered to Nav in terms of Delta-V cumulative distruction function (CDF) and used as *a priori* uncertainty [7].

Misalignments and possible performance degradation in flight were a cause of residual translational delta-V in and outside our line of sight. In addition, the telemetry reported delta-V did not have the accuracy needed for navigation. Much effort was put into ingesting large amount of delta-V telemetry every day [14]. Although the small thrusting telemetry was not adopted in baseline navigation solutions due to delays in receiving the information and longer processing time in including those, they were used as alternate solutions to help identifying and quantifying possible biases. Specifics on filter assumptions, and solution comparisons are described next.

Navigation Software and Filter Assumptions

Processing of radiometric tracking data and optical images to generate spacecraft and the Didymos barycenter ephemeris solutions are accomplished by the MONTE software set [20].

This software numerically integrates the equations of motion to produce a spacecraft ephemeris (i.e. position and velocity time history) given a mathematical model of the forces acting on the spacecraft. Along with the spacecraft ephemeris, MONTE can also produce a trajectory partials file, which gives the sensitivities of the spacecraft ephemeris to changes in various parameters in the mathematical model used to generate the trajectory.

This is then used in the OD process, which takes as input data and apriori errors mentioned above, as well as updated dynamical forces acting on the spacecraft such as small thrusting activities. Table 2 lists the filter configuration. Note that the “s/c” abbreviation is used for spacecraft.

After updating a priori models, computed measurements are compared to the ones observed. A linearized least squares estimation process then provides estimates for DART’s orbit, and for the Didymos barycenter ephemeris during the last month of the mission using optical measurements described in the previous subsection. In addition, non-gravitational forces which affect the spacecraft are also estimated, including solar radiation pressure, the delta-V from small burns and zero-mean stochastics accelerations for any remaining small unmodeled forces.

The OD solutions developed from this process are used for the generation of high-precision numerically integrated trajectories and related trajectory data products, while verifying the impact conditions on the Didymos B-plane. After a few iterations to manage non-linearities, the converged solution is delivered to the Maneuver team for the upcoming orbit trim maneuver design, correcting the trajectory by the desired amount in the Didymos impact B-plane.

Navigation Performance: For months, the Nav team prepared to handle the last month of the mission; the target would then be visible, resulting in more data processing and fine tuning of the OD for the last few maneuver designs. Figure 5 shows the main events planned in the last 6 weeks. In the baseline timeline, TCM3 was planned 40 days before impact, possibly modifying the impact time by up to 2 hours due to the Dimorphos error (cite Justin). In flight, the late observations before launch confirmed the binary orbit uncertainty with no time adjustment needed. TCM3 was used only to clean up for errors accumulated in cruise since the last TCM (TCM2) executed four months prior. Note that even though two early observations of Didymos had been conclusive (as in, we could see the target system!) TCM3 did not include a correction from opnavs. TCM4 would be the first to account for opnavs and estimate the Didymos barycenter ephemeris, while TCM5 would clean up after the LCC release and insure The Nav handoff requirement would be satisfied.

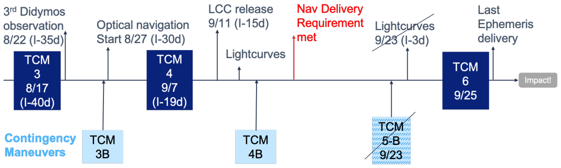

Figure 5: Approach timeline of events.

TCM4: Impact minus 19 days

After one last early observation of Didymos after TCM3, regular opnavs started 30 days prior to impact. For this period of time, DDOR frequency were also going to increase, going to one every 3-4 days instead of 1 per month. The solution illustrated in Figure 6 represents the latest OD solution at 17 days before impact, mapped to the Didymos B-plane. The Didymos target is located at the origin on this plot. This solution incorporated Opnav data for the first time. TCM4 would correct near 110 km, 19 days out.

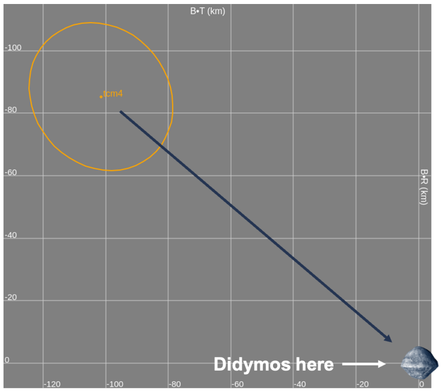

Figure 6: Latest OD solution at 17 days before impact, mapped to the Didymos B-plane

With optical data, it was now possible to estimate a correction to the *a priori* Didymos barycenter ephemeris along with the DART trajectory, as optical processing could now pinpoint the location of the target and provide improvement of its associated error. Of special interest was the improvement of the error on the time of impact for the SMART Nav handoff. Although Nav estimated the Didymos barycenter ephemeris in flight during Approach, the science investigation team used those images along with Earth-based telescopic observations to produce ephemeris updates pre- and

Table 2: Radiometric measurements schedule

Error Sources	Type	*a priori* 1 σ
Spacecraft states	Estimated	100km, 2 m/s
Solar pressure	Estimated	10 % magnitude
Range bias (per pass)	Estimated	3m
Didymos ephemeris (Estimated when visible) (scaling x2 per JPL SSD)	Cons/Est	3km, 22.1km, 2.5km RTN coordinate frame
Quasar location	Consider	1e-9 rad
Pole motion	Consider	5 nrad
UT1	Consider	0.1 msec
Media cals	Consider	0.01m Tropo, 0.4m Iono
Station locations	Consider	From latest updates
Small burns (Used for comparison case)	Estimated	10% of magnitude
TCM	Estimated	Gates listed in
In-arc non-grav (White noise, 30 min batches)	Stochastics	5e-11 km/s2 (s/c XYZ)
Future non-grav (White noise, daily batches) (For Opnavs)	Stochastics	2.5e-11 km/s2 (s/c XY) 5e-12 km/s2 (s/c Z) 5.0e-11 km/s2 (s/c XYZ)

post-impact [15]. The post-impact deliveries were used as is in the high fidelity reconstruction of the spacecraft trajectory (last hour reconstruction detailed in . Figure 7 shows a comparison of different Didymos barycenter ephemeris estimation using Opnavs and from the Investigation team, against the latest delivered ephemeris referred to as s202 [15]. Position and velocity differences are shown on the top and bottom subplots, respectively. Using Opnavs, the correction from the *a priori*, called s181, was a little more than 1-σ, roughly 30 km in position and a few mm/s in velocity. Solutions shown are the latest from Nav deliveries at the time of TCM4, TCM5 and TCM6, along with science investigation deliveries (s181 being the pre-launch *a priori* solution [16].

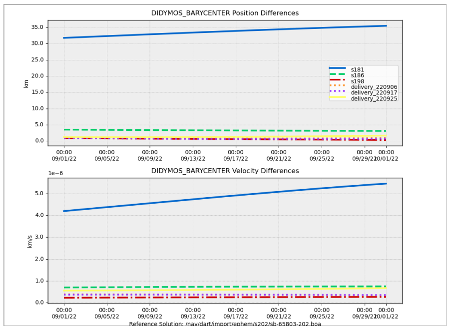

Figure 7: Figure needs to be updated... Didymos barycenter ephemeris estimations position and velocity differences against the very latest Didymos ephemeris delivery from the DART science investigation team, referred to as s202. Solutions include estimations from Nav at the time of TCM4 and TCM6. Top and bottom plots show position and velocity differences, respectively.

One Step Forward, Two Steps Backward?

In the days after executing TCM4, an uncomfortable drift in the OD solutions could be seen. Figure 8 includes a few different OD solutions between the TCM4 and the TCM5 data cutoff times. Referring to events depicted on Fig. 5, OD solutions post LCC release and lightcurves observations show a two-σ shift, after each event. Although the errors associated with those events had been accounted for, those errors had been assumed to be zero mean. Those intermediate solutions also include the latest DDOR measurements that day. As mentioned, the off line of sight component of the spacecraft drift could be identified using DDORs and optical measurements, DDORs being more efficient early on due to Earth's proximity.

(Include words on optical versus DDOR solution comparison? like Fig 17 in Opnav paper?)

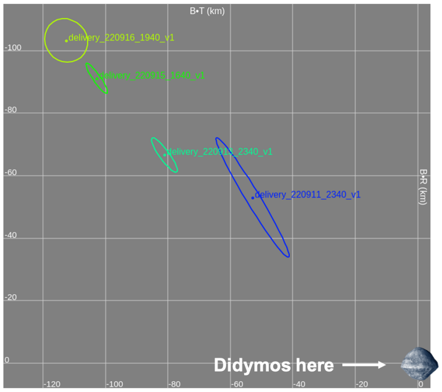

Figure 8: Intermediate OD solutions between TCM4 and TCM5

Hence, DART was slowly getting away, likely because of a mix of thrusters misalignments and possible performance degradation. The software that controls the spacecraft thrusters also had a big impact on how the various pointing control modes behaved; this visible bias in the OD was accentuated by the amount of thrusting [14]. In the final month, the spacecraft was either imaging or downlinking images, where both those control modes involved tighter pointing requirements.

Many discussions and investigations occurred to reduce the amount of thrusting, and after a few days, the GNC team was confident in an appropriate software control update that would introduce a lag in the thrusting behavior [23]. Essential when implementing a software change two weeks before a critical event, a few necessary reviews confirmed the update was ready to be implemented. Long story short, it still took a few tries to circumvent some flags inherent to the onboard spacecraft software, but the software were finally implemented 12 hours prior to the data cutoff time planned for TCM5. This is visible in Fig. 9 showing Doppler residuals during this implementation. Doppler residuals provide useful hints of possible mismodelings and how well the spacecraft behaves. A flat line indicates no difference between the OD prediction and what is actually measured. A sharp slope indicates something is clearly mismodeled. Although Fig. 9 never shows a completely flat line, testing and unmodified software periods stand out from post control update implementation. By September 17 21:20 UTC, one can clearly see the reduction in a visible drift by one order of magnitude.

Beside reducing the spacecraft drift, and although the target was becoming brighter over time, making the image processing easier, the GNC software update also improved the quality of the OpNavs. OpNav residuals steadily improved over time, representing an improvement in the accuracy of opnav measurements. The residuals improved greatly after the GNC feedback loop change. Final residuals were 0.05 pixels, which mapped to 300 meters at the distance of Didymos by the time of TCM5. TCM5 was correcting 135 km on the Didymos B-plane, shown in Fig. 10.

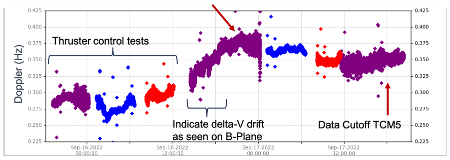

Figure 9: Doppler residuals in the few days prior to the TCM5 DCO, before the onboard software control update.

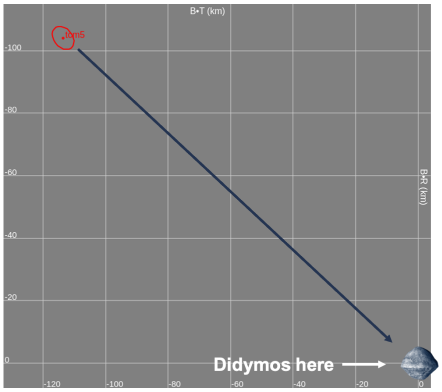

Figure 10: Latest OD solution at 9 days before impact, mapped to the Didymos B-plane

TCM6: Impact minus 1 day

The last GNC software provided some good relief for the Nav team; suddenly, no much drift was visible, about 1 order of magnitude less than experienced a few days prior to executing TCM5. Knowing one last TCM was going to be executed to satisfy a “desirement” B-plane delivery of now 2 km, defined as a desired requirement but not officially required, a few strategic decisions were made to allow for the most stable OD by the time of the TCM6 design: lightcurves were canceled due to constant thrusting necessary for tight imagery over twelve hours, no backup TCM was implemented until 1 day prior to impact (TCM6), and no opnav was obtained after the TCM6 data cutoff (at two days prior to impact). Figure 11 shows the OD movement in the last 5 days prior to the data cutoff for TCM6, going from the green ellipse to blue to pink to orange and finally the black ellipse at 1 day prior to executing TCM6. Note the last DDOR used was 3 days prior to impact, for the solution indicated as “220923del”. With a much more quiet spacecraft, and out of plane velocity biases being determined from the angular measurement, the Nav team had everything in hand for a good hand-off to SMARTNav.

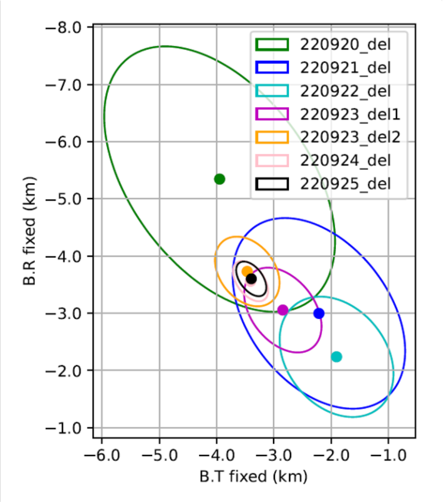

Figure 11: This figure will show solutions stabilizing between TCM5 and TCM6.

By the time of the final design for TCM6, the OD was situated just 4 km away from Didymos on the B-plane. This is shown on the left subplot of Fig. 12, with a 1-sigma ellipse, where red circles indicate the 15 km and 2 km requirement and desirement, respectively, with Didymos indicated in blue near the (0,0) location. The post TCM6 performance is show on the right, with the 3-sigma OD error ellipse shown to be entirely within the (blue) Didymos body size.

Figure 12: Pre and post TCM6 solution on the Didymos B-plane.

Originally considered a propellant tight mission, DART was heading on a direct collision with much more propellant than expected. Table 3 gives the mission maneuver performance, where executed TCM δv magnitudes are listed against their 99% from pre-launch *a priori* error analysis [5, 7].

Last Hour Reconstruction

SMART Nav started operating four hours prior to impact, where its initial conditions were to start by aiming toward Didymos until Dimorphos could be visible. With the ground Nav delivery being right on target, there was little to no activity from the autopilot for the first three hours or so. The main maneuver happened when Dimorphos exceeded SMART Nav’s brightness threshold. At this time, a near 45 cm/s maneuver was seen on the Doppler residuals feed, shown in Figure 13.

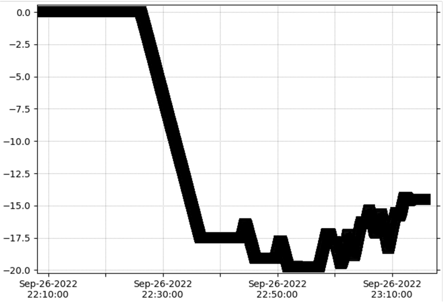

Figure 13: SMARTNav maneuver to redirect DART toward Dimorphos instead of Didymos.

The reconstruction of DART’s trajectory in the final hour prior to impact required a slightly modified OD process from the one described earlier. To recap, the standard process uses a combination of radiometric and optical data to estimate the inertial state of both the spacecraft and the Didymos system simultaneously. The filter adjusts both the spacecraft and Didymos system’s orbit relative to their *a priori* values based on the relative uncertainties assigned to each, and factoring in the relative weighting of the different data types. However, during the final hour, Didymos and Dimorphos are two distinct objects, and the errors in their relative positions must be accounted for. DART’s Science Investigation team is responsible for computing the separate orbit of Dimorphos relative to Didymos, based on both spacecraft observations and ground-based observations [17]. As of this writing, this is still an ongoing effort with periodic updates being delivered. For the Nav reconstruction of the spacecraft orbit, rather than responding to each change in Dimorphos’ orbit, we elected to effectively fix the spacecraft’s trajectory relative to Dimorphos, so whatever orbit is produced for it, the spacecraft’s path relative to Dimorphos will not change. We do this by using a combination of Doppler data and Opnavs of Dimorphos alone in the filter (both ranging and DDOR were unavailable during this time period). The computed centroids

Table 3: Maneuver Performance, where executed TCMs are compared to their pre-launch 99% estimate from error analysis. Note the backup maneuver TCM1B carried the same δv 99 as TCM1.

Maneuver	Date	δv Magnitude	δv 99
TCM1	Feb 7 2022	0.407 m/s	22.3 m/s
TCM1B	Mar 4 2022	5.583 m/s	22.3 m/s
TCM2	Apr 14 2022	0.087 m/s	2.2 m/s
TCM3	Aug 17 2022	0.580 m/s	3.7 m/s
TCM4	Sep 7 2022	0.075 m/s	0.3 m/s
TCM5	Feb 7 2022	0.251 m/s	0.1 m/s
TCM6	Feb 7 2022	0.057 m/s	0.1 m/s

of Dimorphos provide the target relative information, while the Doppler helps resolve the velocity changes from the thrusters. The spacecraft's trajectory in inertial space will move with changes to Dimorphos, but the Doppler data is largely insensitive to this effect, allowing this method to get an accurate target-relative orbit.

In addition to the initial state 1 hour prior to impact, two other parameters were also included in the filter. Since the images of Dimorphos did not have visible stars, the bearing measurements of Dimorphos will include any attitude knowledge errors from the telemetered attitude. This was estimated as a single bias parameter across the span of time in the two boresight angles, and the twist around the boresight, with an *a priori* sigma of 3 pixels (15 microrad). For the burns produced by SMARTNav, the telemetered small forces were binned into 5 sec accumulated delta-Vs and each of these was estimated separately in the filter, with an *a priori* uncertainty of 10 % of the nominal burn. Note the detailed processing of those small forces is described in [14].

The resultant impact location in the B-plane is shown in Figure 14. One point to note is that this reconstruction method produces a highly accurate result in terms of the B-plane (and impact location), but the impact time has much higher uncertainty. This is because there is no direct data informing the spacecraft's downtrack location, and thus the filter cannot adequately resolve this. In principle, if the exact separation of Didymos and Dimorphos were known, then the parallax provided by the measure of the separation would produce a reasonably good impact time. However, any errors in the knowledge of the separation distance would map into a downtrack error, so Nav did not rely on this. Instead the impact time, September 26, 2002 at 23:14:24 UTC, is based on spacecraft clock time stamps inserted into each downlink frame by the spacecraft radio[1].

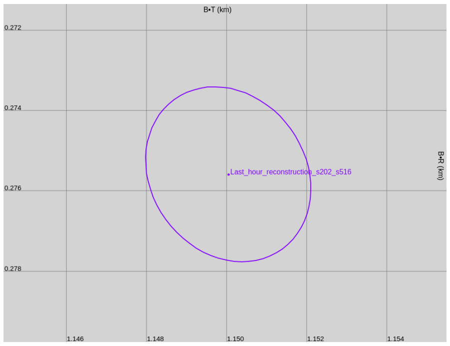

Figure 14: B-plane solution for the last hour of the DART trajectory reconstructed using the s202 Didymos barycenter and the s516 Dimorphos ephemerides.

Conclusion: DART was NASA's demonstration of an asteroid deflection using a kinetic impactor. The spacecraft launched aboard a SpaceX's Falcon 9 on November 24th 2021, on a direct collision with the binary asteroid system Didymos planned for September 26th 2022. By impacting the small moon, Dimorphos, DART altered the moon's orbit about the larger asteroid by 33 min [18].

The navigation of a ballistic mission is usually relatively simple. Other than heading to a violent demise, this mission had a number of unconventional aspects which gave the navigation team interesting challenges: a tight propellant budget for part of the mission, no reaction wheels which resulted in a noisy spacecraft with the Nav team having to rely heavily on Delta Differential One-way Ranging measurements to identify off line-of-sight delta-V, and critical operations in the last 30 days of the mission under a new thrusting control mode regime. Optical navigation was a critical element in the success of this mission, contributing

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[1] See: https://dart.jhuapl.edu/Mission

to the determination of the spacecraft and target ephemerides for refined targeting maneuvers. After strategic decisions in the final weeks of the missions, DART could have comfortably hit the larger asteroid, Didymos, which increased the probably of impact with its moon Dimorphos.

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