OPTICAL NAVIGATION FOR THE DART MISSION

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Abstract. The DART mission launched in November 2021 to impact the asteroid Dimorphos in September 2022. The goal of this technology demonstration mission was to test orbital deflection as a method of defense against potential asteroid or comet hazards. The precise targeting needed to hit such a small body requires the use of optical navigation imaging during the final month of the approach. We describe the contribution Opnav made to the navigation of the DART spacecraft and the particular challenges faced when planning and analyzing the Opnav images.

Introduction. For many solar system missions, especially those to small bodies, traditional radiometric (doppler and range) tracking data provide insufficient knowledge to guide the spacecraft to its target. The DART (Double Asteroid Redirection Test) mission targeted an impact with the 180-meter asteroid Dimorphos. With an asteroid position uncertainty of at least 25 km at impact, it was had to rely heavily on optical navigation (Opnav) imaging during the last month of the mission to guide DART toward the impact.

Mission Overview. The DART spacecraft launched on a SpaceX Falcon 9 rocket from Vandenberg Space Force base on November 24, 2021. Its target was Dimorphos, the tiny ~180 meter diameter satellite of the ~800 meter diameter asteroid Didymos. The impact changed the orbit of Dimorphos around Didymos by an amount which will be measurable from Earth.

DART was the first flight project of the Planetary Defense Coordination Office[1] and was designed to test the idea of deflecting the trajectory of a potentially hazardous small body as a means of planetary defense. The mission was managed by The Johns Hopkins Applied Physics Laboratory (APL), and the navigation was done by Caltech's Jet Propulsions Laboratory (JPL).

Navigation The navigation team at JPL was charged with guiding the spacecraft from immediately after launch up to the final day before impact. They continually tracked and guided the spacecraft throughout the entire cruise and were required to deliver its position with 15-km (1-sigma) target-relative accuracy at the time of the final handover. From there the SMARTNav (Small-body Maneuvering Autonomous Real Time Navigation) process guided the spacecraft during the final hours leading up to impact.

Importance of Optical Navigation. To navigate during cruise, the navigation team used radiometric data to track the spacecraft and design maneuvers to keep it on a nominal trajectory to impact. Analyses of the spacecraft error throughout the trajectory were done before and after launch, showing that radiometric data alone could be used for this purpose during cruise, but were not sufficient to achieve the final 15-km delivery accuracy. We therefore needed to plan Opnav imaging during the last month to refine our knowledge of the spacecraft position with respect to the target and to precisely design the final few maneuvers. Each Opnav image was pointed at Didymos (Dimorphos was so close during the Opnav campaign as to be inseparable in images) and could therefore be used to estimate the relative DART-to-Didymos position more accurately than by using radiometric data alone.

Optical Navigation Plan. The Opnav images were taken using DRACO, the Didymos Reconnaissance and Asteroid Camera for Optical Navigation. The first Opnav images used to support navigation were not taken until the final 30 days, referred to as "approach." During approach, we took approximately 240 images every 5 hours, increasing the frequency to every 2 hours during the last day of the mission.

Camera Calibration. Before approach, many test images were taken to test DRACO performance, to calibrate the DRACO system, and for the navigation team to practice analysis of Opnav images. The most important test images were taken by pointing DRACO near the center of a bright star cluster and then moving it by fractions of a field of view, allowing many stars to be imaged at multiple positions on the detector. Comparison of the measured-to-predicted star positions were then used to estimate imperfections in the detector and optics of DRACO. This was done using a distortion model described by Owen 2011[2] and a least-squares estimation filter configured in JPL's Monte navigation software. We also used star-rich images to measure the offset between the designed and actual direction of the DRACO boresight with respect to the spacecraft body. These measurements were necessary to accurately process Opnav images during approach, as unknown errors in the DART-to-DRACO alignment could lead to difficulty in properly pointing the camera, and unknown errors in the camera characteristics could lead to errors in the application of Opnav data to orbit determination.

Opnav Image Processing. The usual Opnav image-processing techniques as described by Owen[2] were applied to the images. This begins with predicting star positions based on the assumed spacecraft orientation and coordinates of stars in the GAIA-2 catalog. We then detect all sources in the image data that are expected to be stars using techniques based on the Source Extractor tool.[3] Then, using an affine transformation from the astroalign library[4] to match the two patterns allowed us to estimate the inertial pointing of DRACO for each image. Precise measurements are then made of the centers of all stars and Didymos which are used to further refine the pointing. After thus accounting for pointing (i.e., DART orientation), any remaining offset between the predicted and observed center of Didymos in the image provides information about the Didymos-relative position of DART. This optical-based information is then combined with radiometric data to determine the state of the spacecraft and target.

Application of the above techniques was complicated by several factors, most notably the number and frequency of images, the need to coadd multiple images, and accounting for distortions caused by the DRACO rolling shutter.

Image Volume. During approach DRACO took about 35,000 Opnav images. This large number of images was required since Didymos was so faint until the very end that we had to coadd many individual images to get single useful images and to guard against occasional image loss or corruption. Developing tools and procedures to process the individual images, coadd them, and then to further process the coadded images, in a largely automated way, was essential for this mission. This entire process, even the standard steps noted above, had to be incorporated into JPL's Monte navigation software and used there for the first time.

*Drizzle Coadding***.** Throughout most of approach this analysis could only be partially performed on individual images. The initial star prediction and registration could be done on each image, but determining the center of a faint Didymos, as well as that of fainter stars required that we combine multiple individual images into higher-signal coadded images. We could not simply stack multiple images because the lack of reaction wheels and reliance upon thrusters for fine attitude control caused too much movement between images. This factor, as well as the required sub-pixel accuracy in our final Didymos location, also prevented us from doing plain coadding (integer-pixel shift-and-add). We therefore had to perform a version of sub-pixel shifting and adding of images known as the drizzle method.[5] This was recently done for the New Horizons extended mission[6] whose LORRI camera is very similar to DRACO. That case served as a proof-of-concept and encouraged us to add a drizzle coadding method to our image processing software. This allowed us to get sub-pixel accuracy on Didymos centers, often as good as 0.2 pixels.

*Rolling Shutter Corrections***.** To achieve those results we had to make another correction to the data. DRACO images were taken using a rolling shutter (RS) method, in which each row is exposed to the sky and then read out at a different time. This induces a distortion in the images that increases with the readout delay between rows and is exacerbated by rapid spacecraft motion. In some missions that use a RS, the spacecraft is so stable during imaging that this effect is negligible. However, due to the lack of reaction wheels noted above, the RS distortion was very noticeable in DRACO images, as a positional offset of stars that increases with their distance from the center row of the detector. The magnitude of these distortions could be several pixels which was large enough to significantly degrade our results. We therefore developed a method to measure this distortion, by assuming that the component of positional residuals of stars that increases with row number is caused by the RS and therefore subtracting this component. Details of the RS distortion and our correction method are given in Mages 2022.[7]

Summary and Conclusions

Without Opnav images our covariance analysis showed that we could not have navigated DART accurately enough to impact Dimorphos. The combination of traditional and new analysis techniques that we applied to DRACO images allowed us to determine the location of Didymos to within 0.5 pixels in most images and much better in some cases. This accuracy, combined with the enormous number of images acquired, allowed the combined radio-plus-optical orbit determination solution to achieve the required accuracy in the final hours of approach. We will therefore continue to use similar techniques for future Opnav missions, especially those with similarly difficult spacecraft and camera characteristics such as lack of reaction wheels or a rolling shutter camera readout.

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