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

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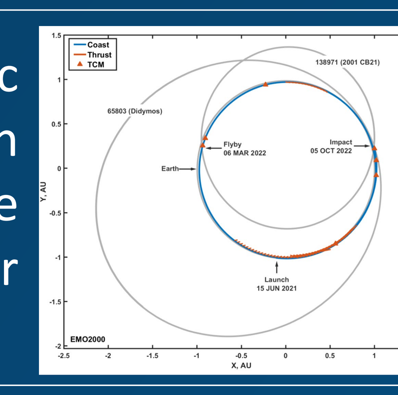
The DART MD-NAV team collected 9 lessons that future Planetary Defense (PD) or small-body missions should consider.

1.) Electric Propulsion Offers Substantial Trajectory Flexibility – Throughout DART's design life-cycle, electric propulsion (EP) provided a wide range of options that would be relevant in a real planetary defense encounter: broad launch flexibility, a second impact opportunity, tailored encounter geometry, and even multiple-asteroid flyby opportunities. EP made the DART spacecraft and GNC implementations much more complicated, so it may be tempting to discard it in favor of a simpler spacecraft design. However, EP could potentially save a PD response mission in multiple ways.



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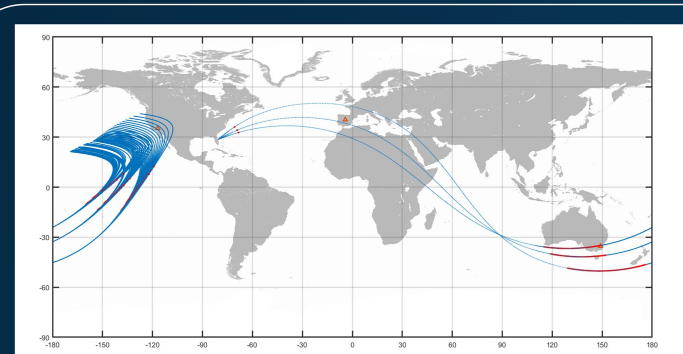
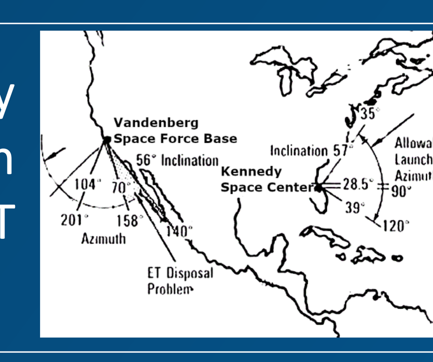


2.) Rapid Launch Targeting Analysis is Possible if the Interfaces are In Place – Less than a year prior to launch, the program asked the MDNAV and Launch teams to consider changing the launch site to Cape Canaveral Air Force Station. Thanks to having already exchanged data multiple times, the teams were able to thoroughly evaluate this possible change in fewer than 3 weeks. We advocate for standardizing these data exchanges to gain this speed in a short-warning, rapid response scenario.

3.) Vandenberg Space Force Base is Suited for Deep Space Missions – U.S. Mission Designers commonly assume that Cape Canaveral Air Force Base is the only option for deep space launches. This limits the available declination of launch asymptotes (DLAs). VSFB enables higher DLAs, which can be needed for encounters with inclined asteroids. With the success of DART and Mars InSight, it's clear that VSFB is a viable option, giving future PD missions additional flexibility.



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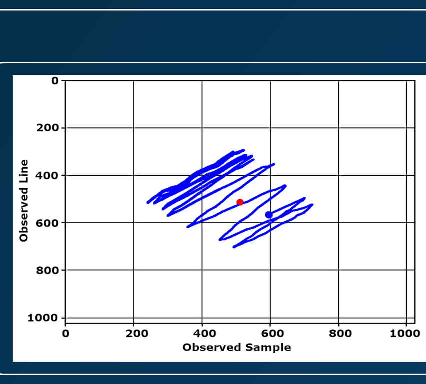
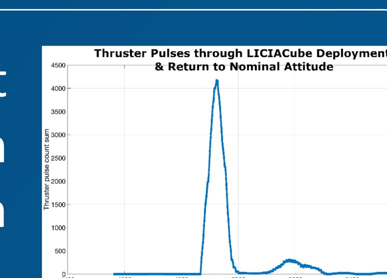


4.) Navigation Benefits from using Reaction Wheels for Attitude Control – While DART proved that thruster-only attitude control is possible in a precision targeted asteroid encounter, this choice introduced complexity and risk. Each attitude control pulse added a small, but non-zero translational Δv that perturbed the trajectory. Reaction wheels provide stable, precise attitude control without imparting residual Δv, and from a navigation perspective– is highly recommended for any PD mission.

5.) CubeSat Deployments Introduce A Non-Negligible Disturbance ΔV – LICIACube proved to be a valuable component of the DART encounter. Future small body missions will likely include CubeSats as well. However, their deployments introduce a perturbation to the host spacecraft's orbit due to uncertainty in the deployment spring and variation in the host spacecraft's attitude control system reacting to the deployment torques. The deployment timeline should include at least one maneuver prior to the encounter to correct this Δv.



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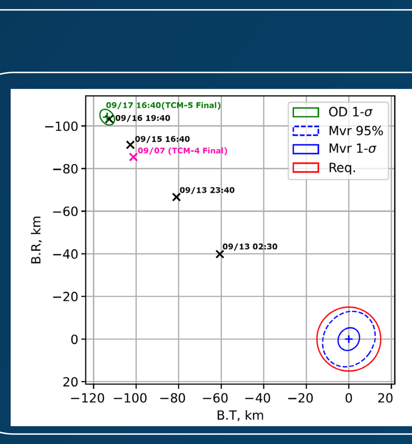
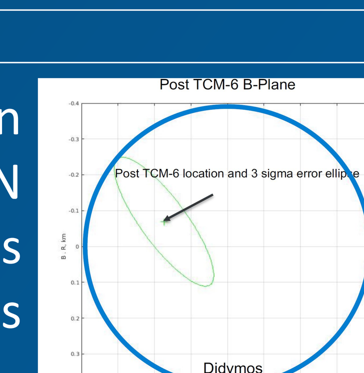


6.) DDORs Are Effective Measurements For Verifying an OD Solution – DDORs are extremely useful for determining components of the spacecraft's trajectory normal to the Earth's line-of-sight. They were critical for identifying unplanned translational Δv during the approach phase. (Likewise OpNavs measure components normal to the line-of-sight to the target. Both measurement types scale with distance so their relative merits vary depending on the situation.) Any PD encounter should incorporate a generous DDOR schedule, despite the associated cost and operations. [1]

7.) With Sufficient OpNavs, the Final Delivery Uncertainty Can Be Quite Small – The DART Navigation team achieved an unprecedented final B-Plane hand-off uncertainty of only 0.21 x 0.06 km 3σ thanks to nearly continuous DSN tracking and OpNavs for the final weeks of the approach. This was small enough to essentially ensure an impact to Didymos (the primary) had it been the target instead of Dimorphos. Future studies and encounter planning may benefit from this demonstrated performance. [1]



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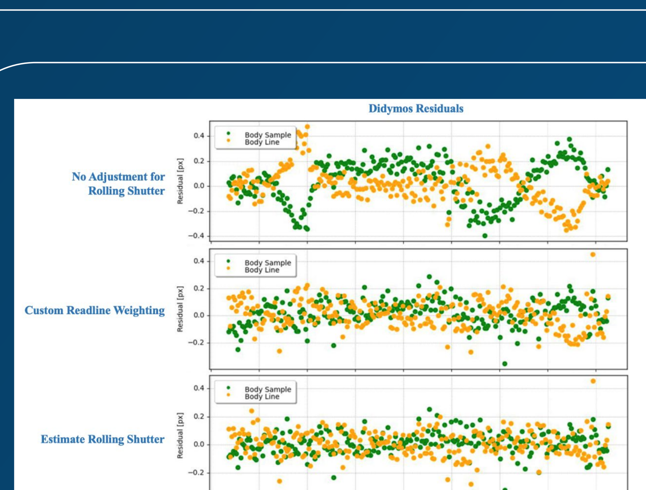
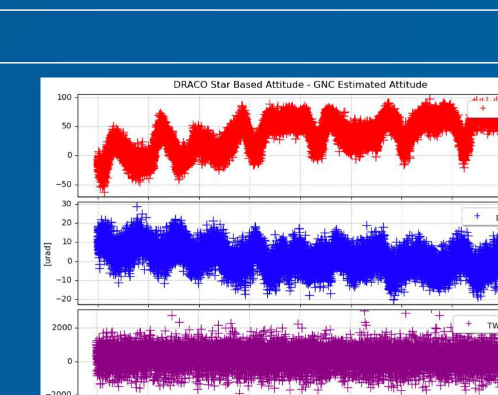


8.) Rolling Shutters Introduce Challenging Errors – Reading the image data from the detector with a rolling shutter induced a dominant error to DART OpNav measurements. If the spacecraft attitude drifts during shutter capture, the star locations in the OpNav image are distorted, which corrupts star based attitude determination. Thruster controlled attitude drift rates combine to make this error dominant. Long readout times are also of significant concern to OpNav accuracy. Whenever a project plans to use a rolling shutter for OpNav imaging, significant quantitative analysis should be done early to determine the amount of distortion and the effects it will have on OpNav analysis and the amount of additional planning and operational work that will be required to deal with it. [2]

9.) OpNavs Can Isolate Attitude Errors from Translational Errors – If the spacecraft doesn't have a sufficiently accurate attitude solution, some attitude errors can be indistinguishable from translational errors. On DART, OpNav processing was used to characterize the star-tracker noise model, including thermal distortions. While successful, this was a significant operational cost. Future PD missions should incorporate a high quality inertial measurement unit (IMU), multiple star trackers, and/or be capable of imaging stars in the frame with the target body. [2]



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[1] J. Bellerose, B. Rush, A. Vaughan, D. Mages, D. Velez, F. Laipert, Z. Tarzi, S. Bhaskaran, J. Atchison, and M. McQuaide, "The Double Asteroid Redirection Test (DART): Navigating to Obliteration," IAA Planetary Defense Conference, Vienna, Austria, 2023.
[2] B. P. Rush, D. M. Mages, A. T. Vaughan, J. Bellerose, and S. Bhaskaran, "Optical Navigation for the DART Mission," 33rd AAS/AIAA Space Flight Mechanics Meeting, Austin, TX, 23-234, 2023.

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