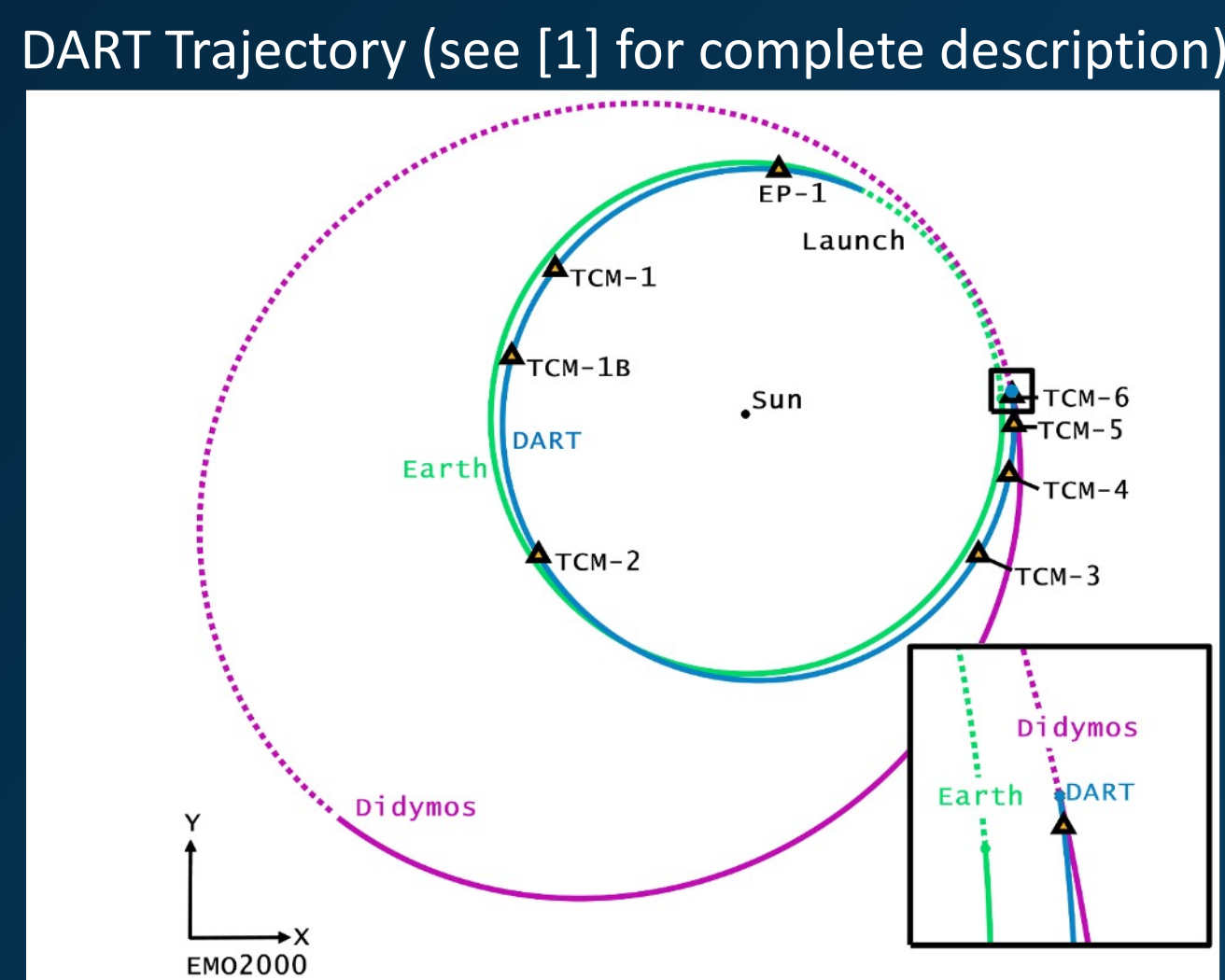


# DOUBLE ASTEROID REDIRECTION TEST (DART): NAVIGATING TO OBLITERATION

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DART is NASA's demonstration of an asteroid deflection using a kinetic impactor. By impacting the small moon, Dimorphos, DART's objective was to alter the moon's orbit about the larger asteroid by several minutes, and provide greater insights into the momentum exchange dynamics. 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 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 probability of impact with its moon Dimorphos.

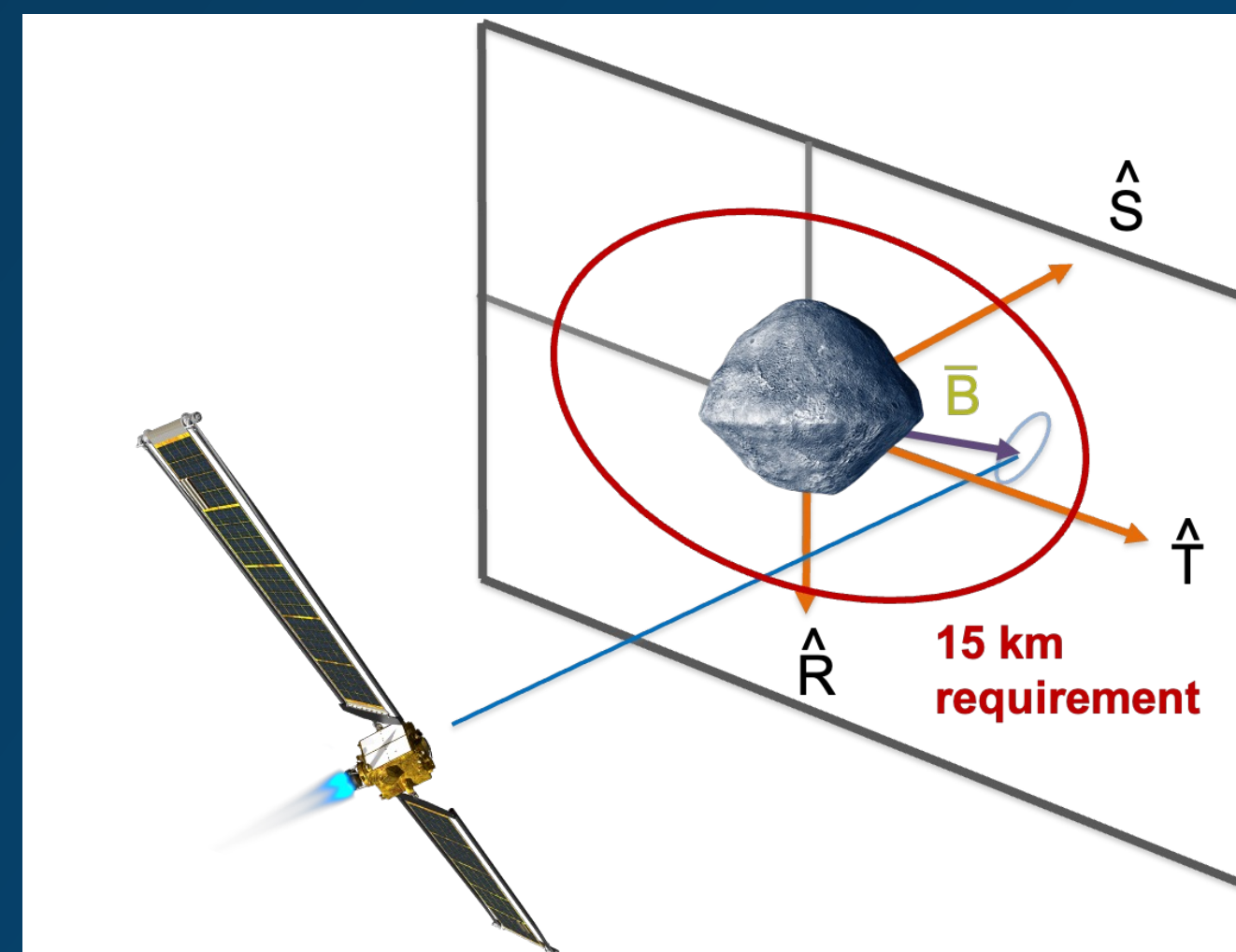
- Launch:
- 24 Nov 2021
  - Vandenberg SF Base
  - Falcon 9
- Maneuvers (TCMs):
- 7 executed using chemical fuel to correct errors.
  - 1 demonstration burn executed using the ion-propulsion system (NEXT-C).
- Impact:
- 26 Sep 2022
  - 6.14 km/s relative velocity to target Dimorphos.



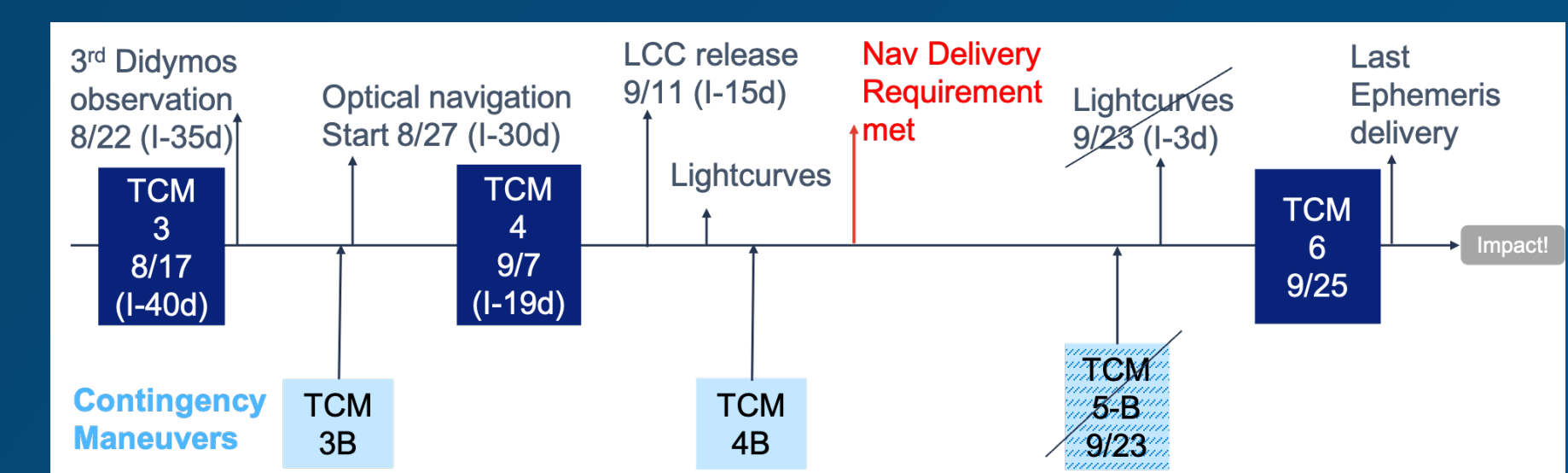
DART had the following Mission Design and Navigation requirement:

- Provide sufficient targeting to achieve at a 67% confidence level (1 sigma):
- 15 km projected on the B-plane.
  - 3 seconds error in B-plane passage [time].

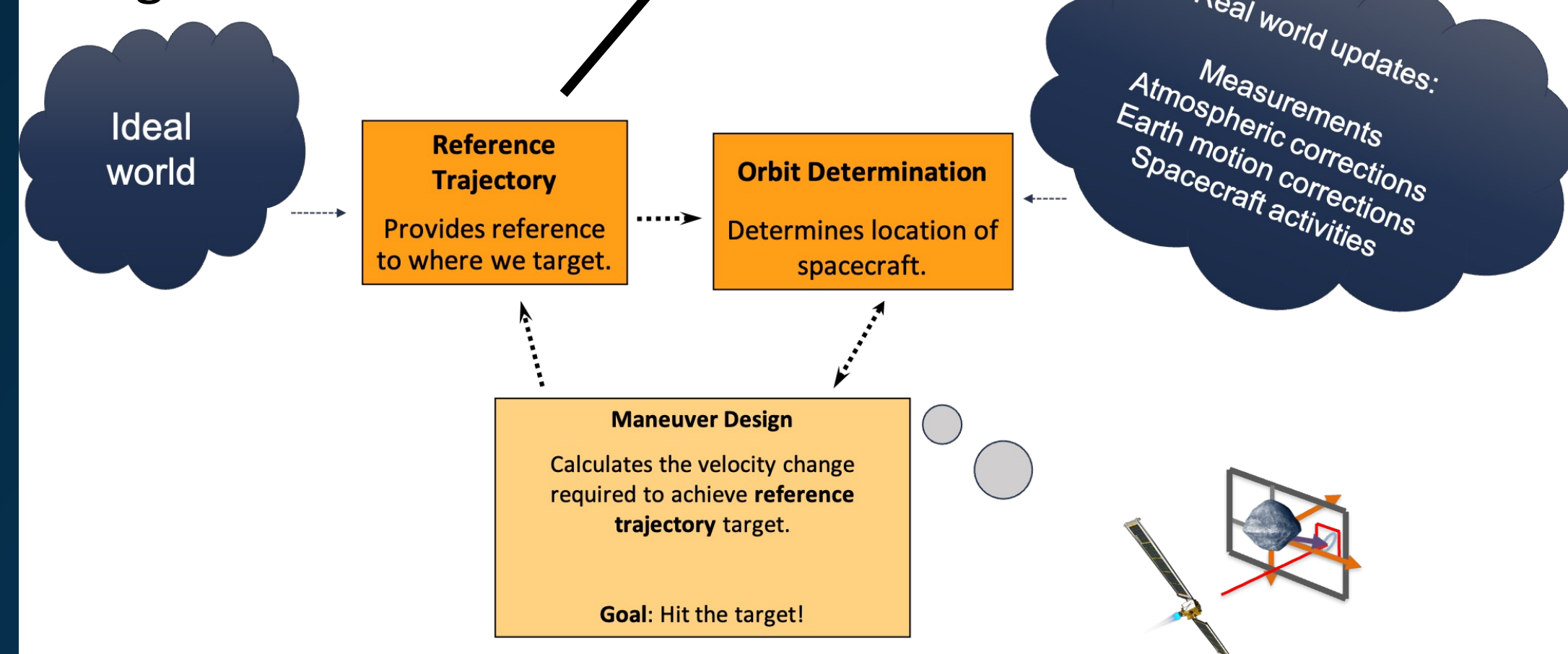
The B-plane passes through the center of the target body, and is perpendicular to the incoming asymptote of flyby trajectory.



Approach Timeline to meet SMARTNav handoff requirement



## Navigation in a Nutshell



The GNC software included control modes dictating the required pointing accuracy.

- Tighter pointing → more thrusting activities.

Misalignments caused residual translational delta-V outside our line of sight. See [2] for a complete description of the processing, analysis and modeling of the thrusters' delta-V output.

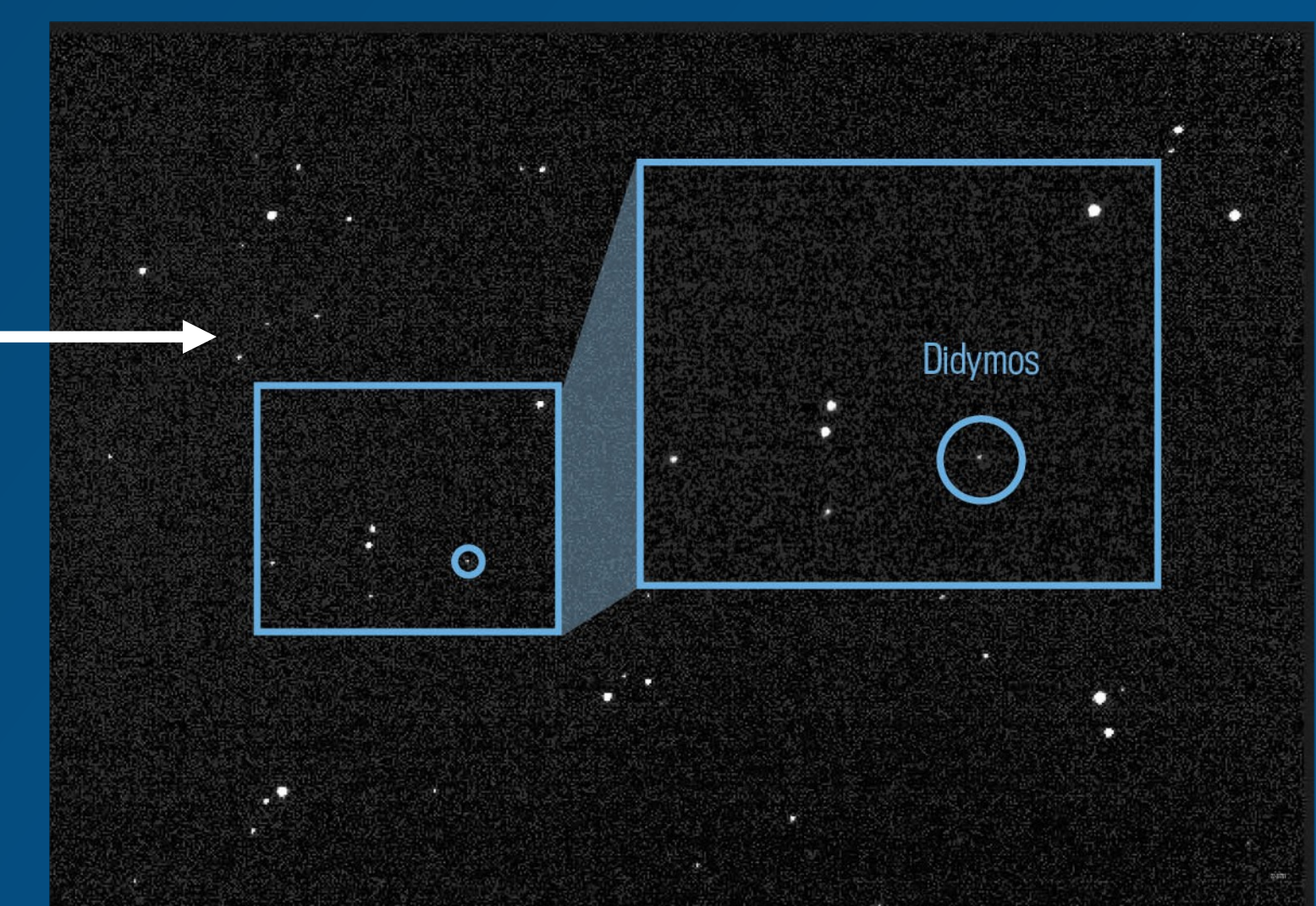
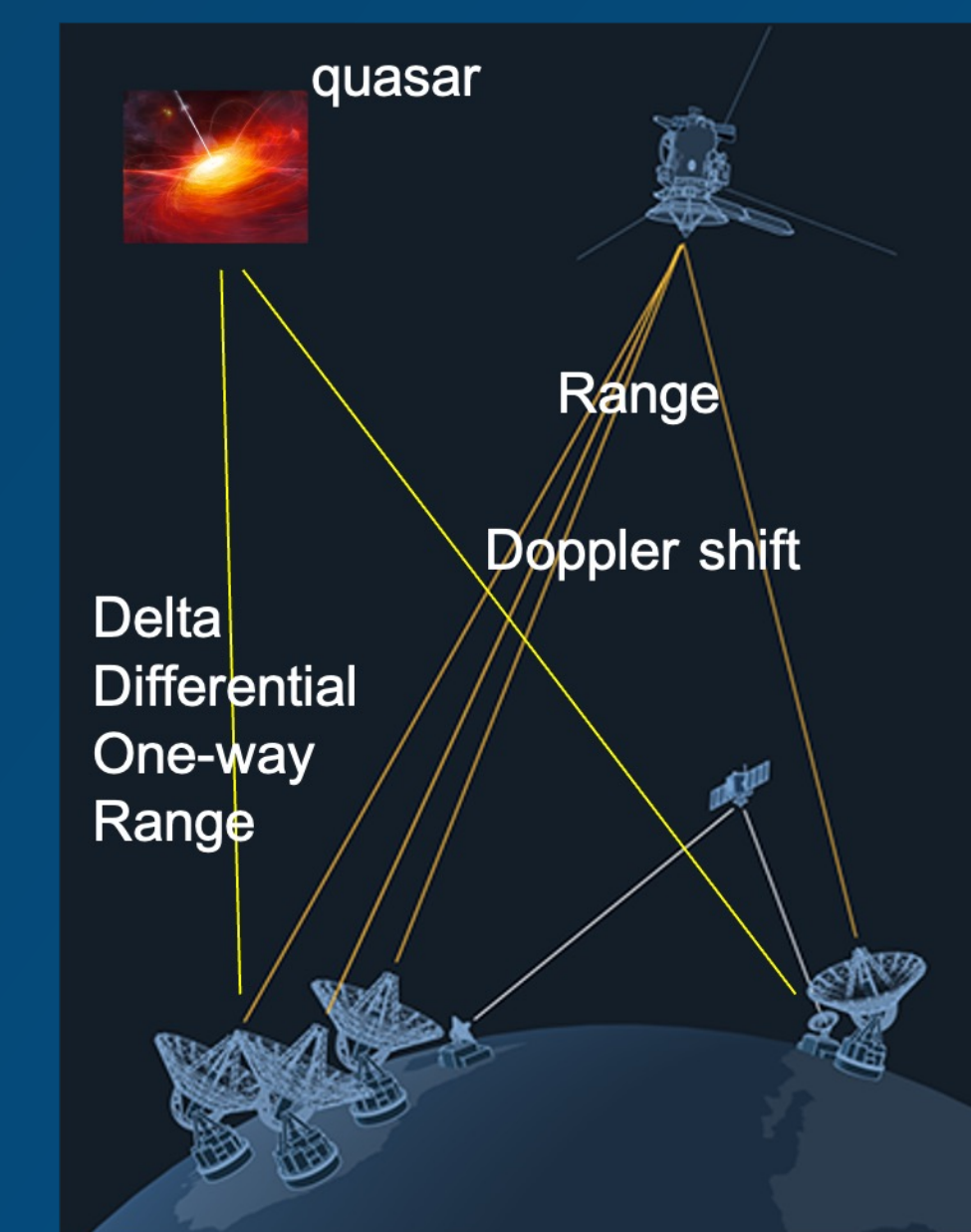
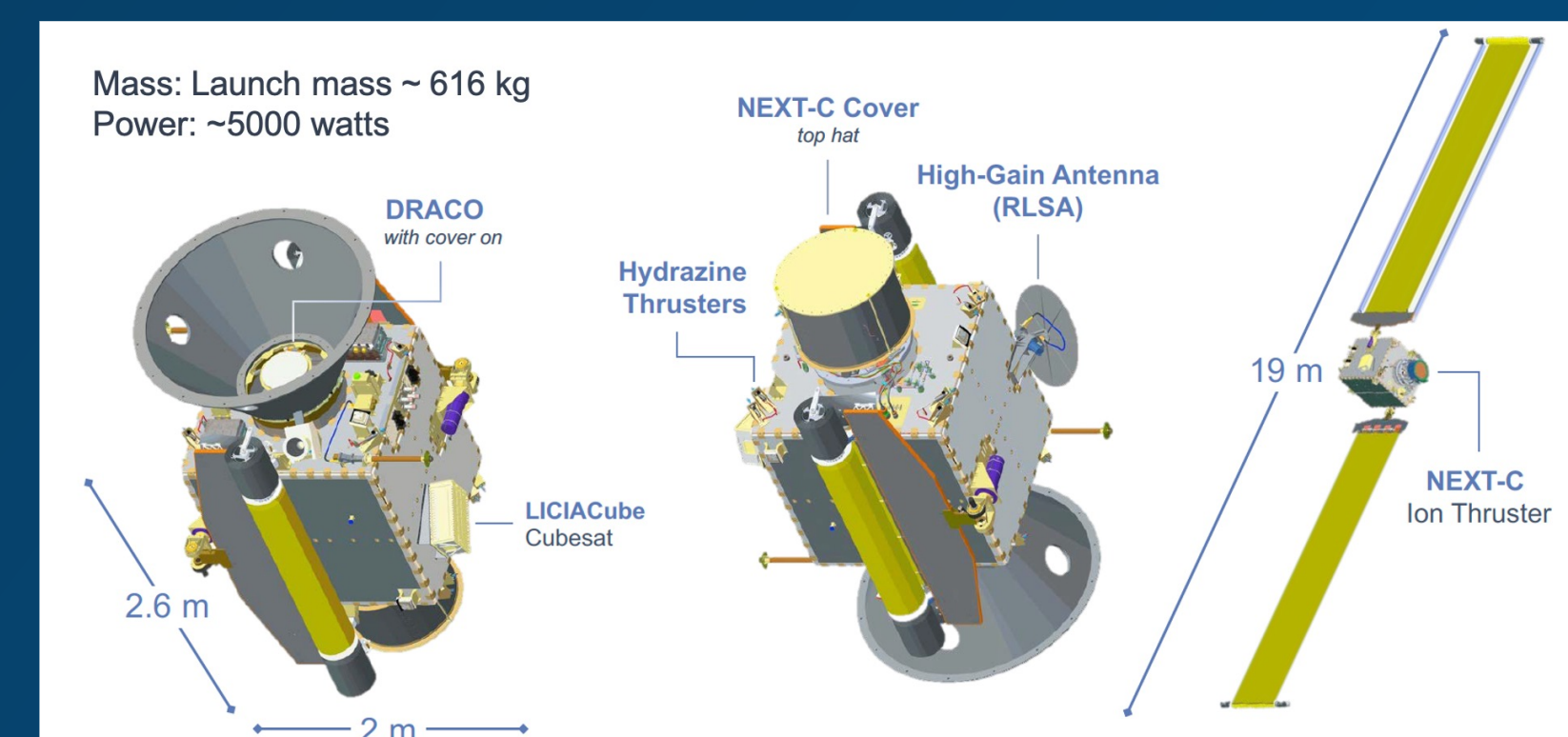
Also find DART MDNav lessons learned in IAA-PDC-23-154! [4]

## Optical navigation (Opnav)

Radiometric measurements

Line of sight: Doppler & Range  
Angular: DDOR  
→ Critical to provide off line of sight change in spacecraft velocity due to unbalanced thrusters.

Spacecraft activities included all thrusting events due to no reaction wheels.



First sight of Didymos!  
Composite of 243 images taken by the onboard camera two months prior to impact.

- Didymos system is very faint at 20 million miles away.

The uncertainty on the Didymos system position at the impact time was initially ~25 km (1 sigma).

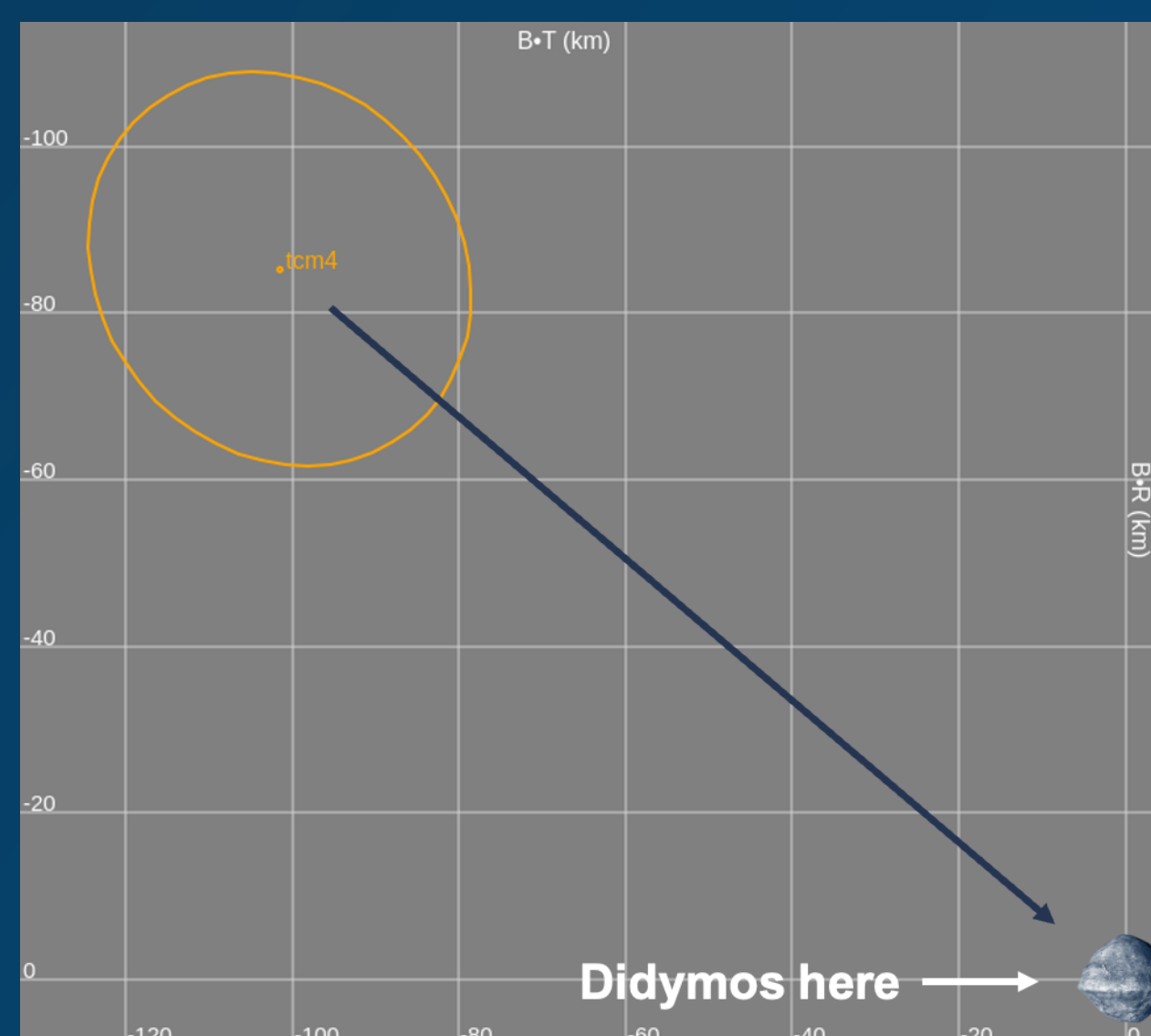
- Didymos: ~ 800 m in diameter
- Dimorphos: ~160 m in diameter

The images allowed refining both the spacecraft and Didymos trajectories. See [3] for a complete description of DART's optical navigation.

In Approach, the spacecraft thrusting activities caused concerning delta-V biases, leading to a software control update 10 days prior to impact.

TCM4, Sept 7<sup>th</sup>  
Final solution for designing TCM4

This solution incorporated Opnav data for the first time even though the Didymos system had been detected earlier than anticipated.

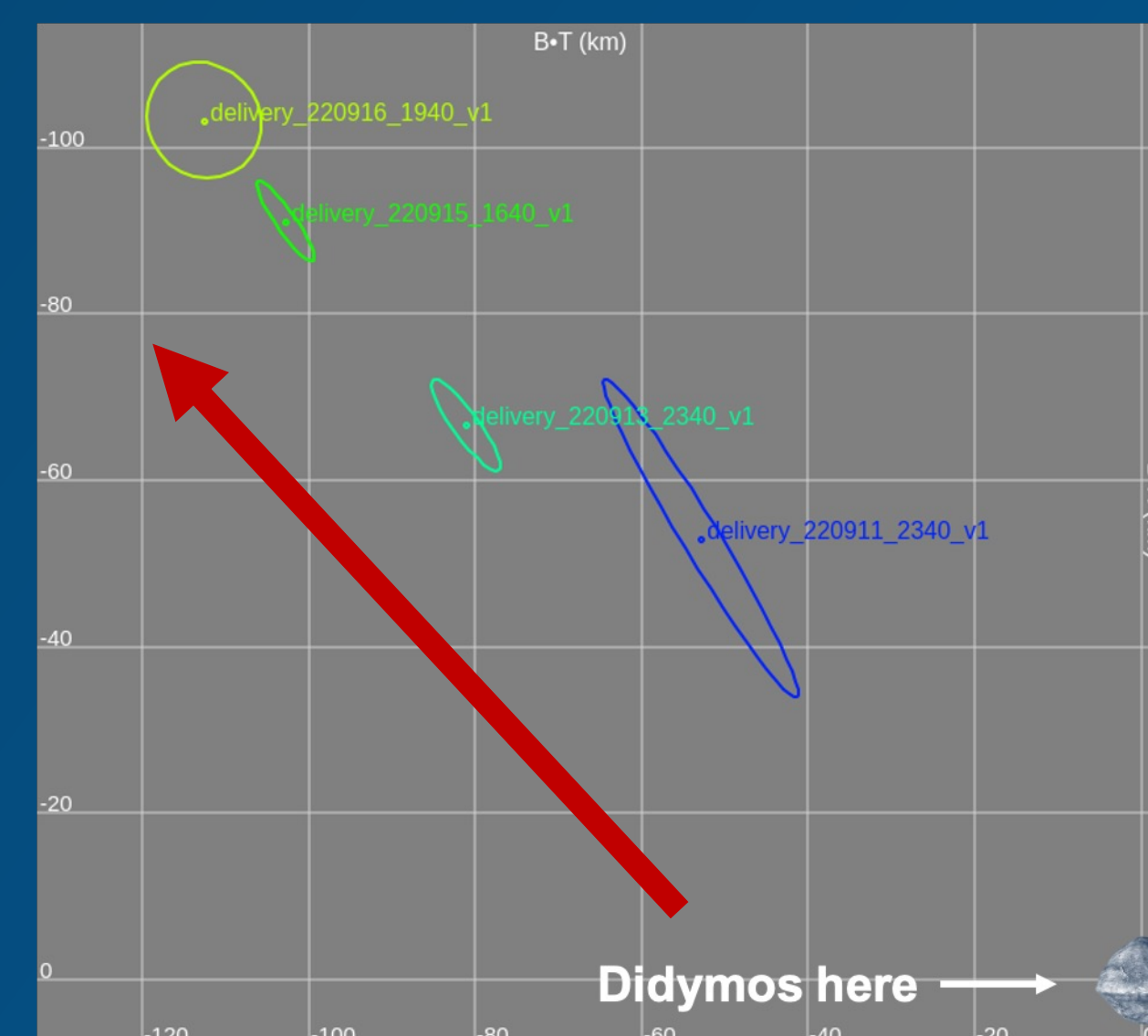


These intermediate solutions indicate DART is slowly getting away caused by:

- Thrusters misalignment.
- Accentuated by the amount of thrusting due to tighter pointing requirements in the final month.

The software that controls the spacecraft thrusters has a big impact on how the various pointing control modes behaved.

- Many discussions and investigations occurred to reduce the amount of thrusting.

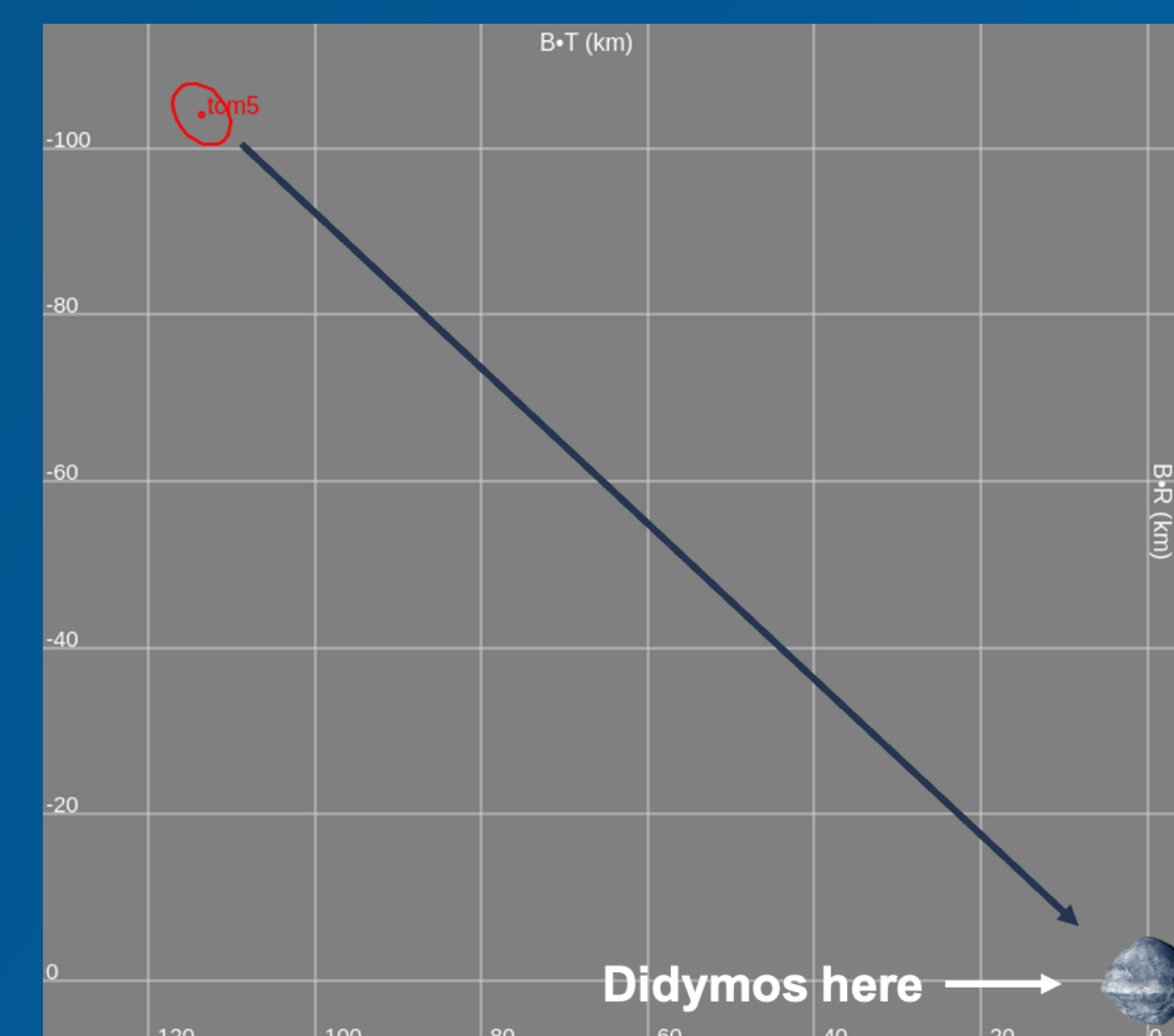


TCM5, Sept 7<sup>th</sup>  
Final solution for designing TCM5

This solution corrected for:

- A slight bias from the spacecraft thrusting.
- Errors from a science imaging observation.
- Errors from deployment of LICIAcube.

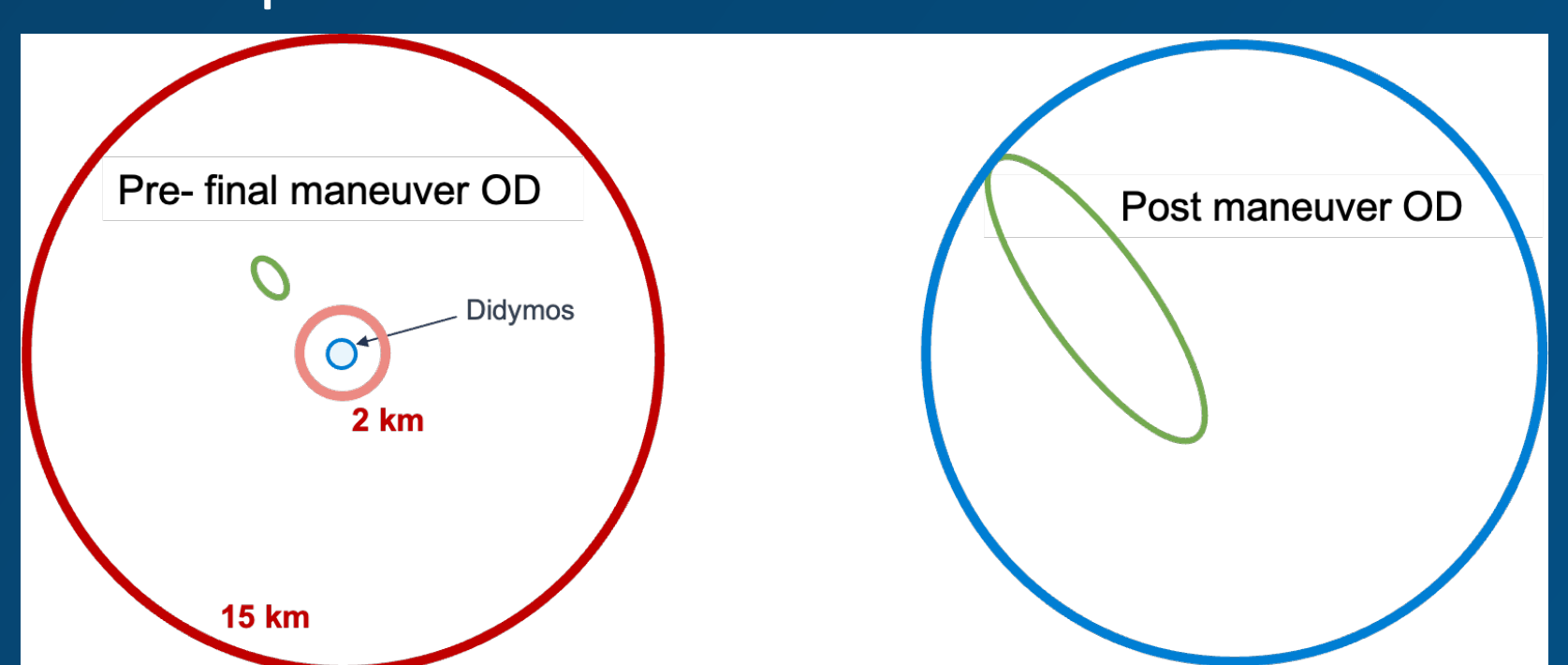
But a much quieter spacecraft...



TCM6, Sept 26<sup>th</sup>

The last DDOR used helped determined out of plane velocity biases and stabilized the TCM5 estimation. The OD was situated just 4 km away from Didymos on the B-plane.

Nav performance for the SMARTNav handoff



The 3-sigma OD error ellipse shown to be entirely within the (blue) Didymos body size.

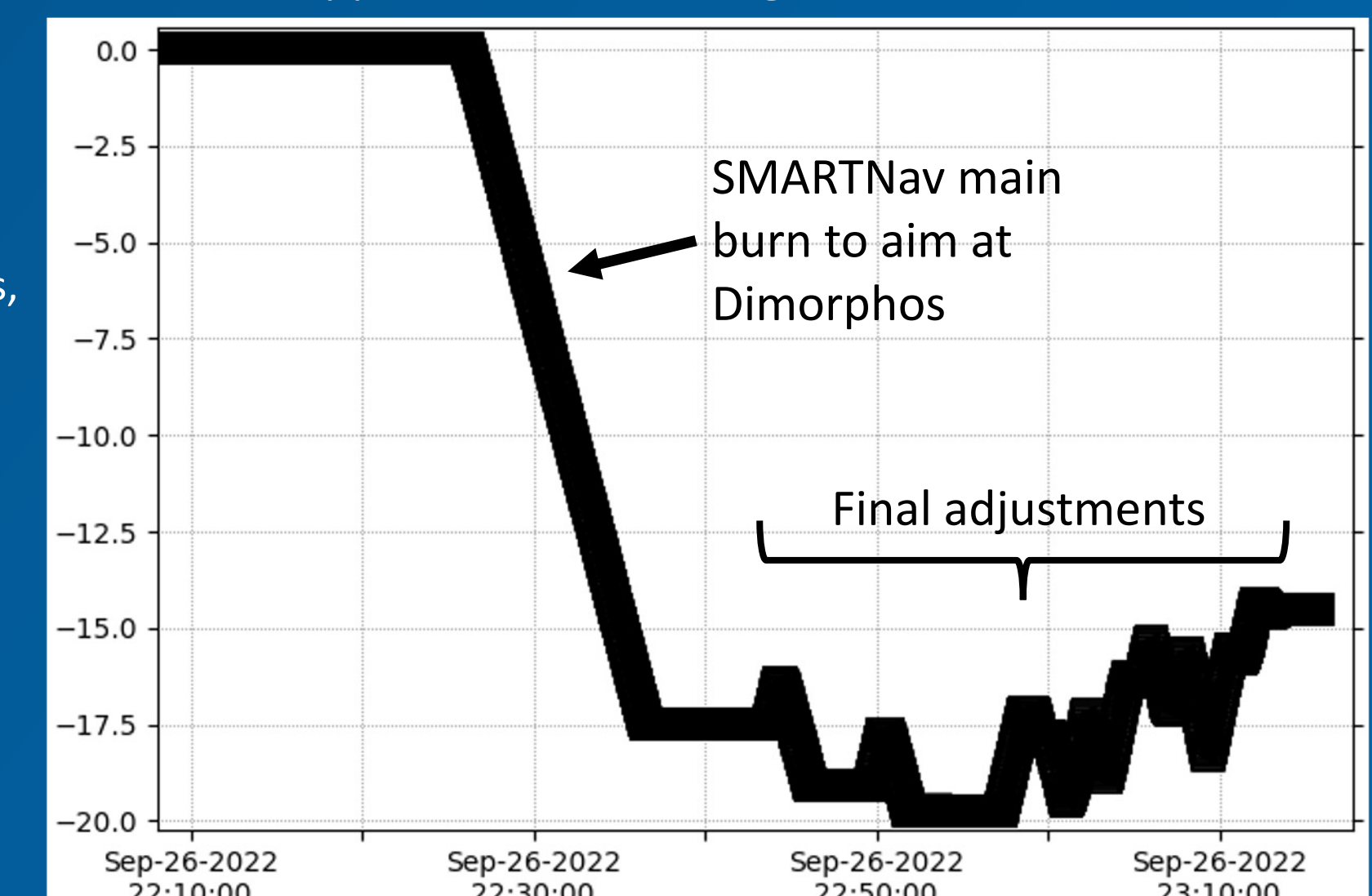
## Last Hour Reconstruction

DART successfully impacted Dimorphos on September 26, 2002 at 23:14:24 UTC, based on the spacecraft clock time stamps inserted into each downlink frame by the spacecraft radio. SMARTNav started operating four hours prior to impact, where its initial conditions were to be aligned with Dimorphos. The main maneuver, near 45 cm/s, happened when Dimorphos exceeded SMARTNav's brightness threshold.

The reconstruction of DART's trajectory in the final hour required a slightly modified OD process. We elected to fix the spacecraft trajectory relative to Dimorphos, so the spacecraft's path relative will not change. The computed centroids of Dimorphos provide the target relative information, while the Doppler helps resolve the velocity changes from the thrusters. We account for attitude errors through a bias parameter estimated in the two boresight angles and the twist around the boresight, and used the telemetered small forces for SMART Nav burns.

Note this reconstruction method impact time has much higher uncertainty due to no downtrack information, but it produces a highly accurate result in terms of the B-plane and impact location.

## Doppler residuals during SMARTNav activities



[1] J. Atchison, F. Laipert, M. MacQuaide, and J. Bellerose, "Double Asteroid Redirection Test (DART) Final Mission Design and Flight Path Control", 33rd AAS/AIAA Space Flight Mechanics Meeting, Austin, TX, 23-260, 2023.  
[2] D. Velez, J. Bellerose, D. Holzberger, I. Murphy, T. McElrath, "Double Asteroid Redirection Test (DART) Mission: Processing, Analysis, and Modeling of the Reaction Control System Thruster Delta-V for Orbit Determination", 33rd AAS/AIAA Space Flight Mechanics Meeting, Austin, TX, 23-110, 2023.  
[3] 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, 23-238, 2023.  
[4] J. Atchison, J. Bellerose, S. Bhaskaran, F. Laipert, D. Mages, T. McElrath, M. McQuaide, N. Mottinger, B. Rush, Z. Tarzi, A. Vaughan, and D. Velez, "DART Mission Design and Navigation Lessons Learned for Future Planetary Defense Missions", IAA Planetary Defense Conference, Vienna, Austria, IAA-PDC-23-154, 2023.

