Double Asteroid Redirection Test (DART) Lessons Learned

Elena Adams
DART Mission Systems Engineer
Johns Hopkins University Applied Physics Laboratory

Fireballs Reported by US Government Sensors

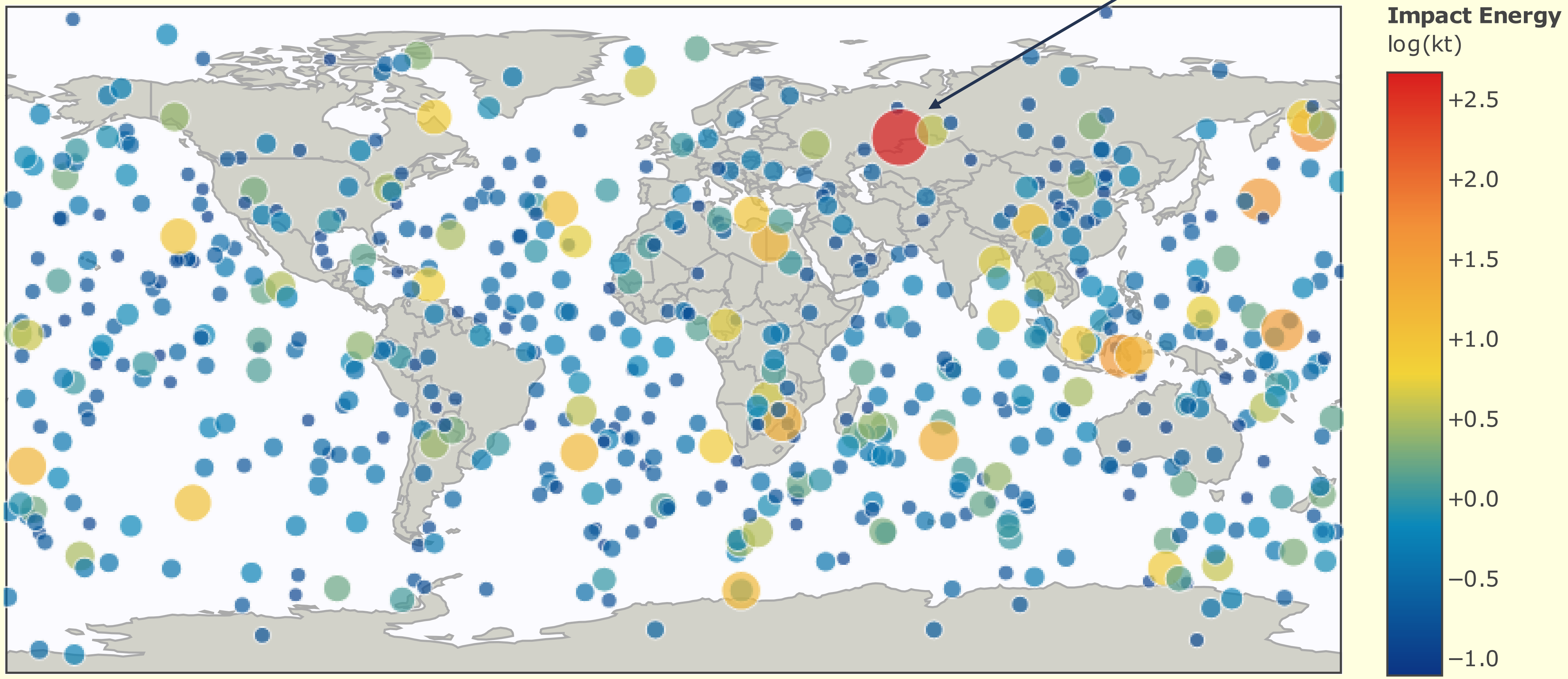
(1988-Apr-15 to 2022-Aug-21; limited to events >= 0.1kt)

Chelyabinsk

Year: 2013 **Diameter:** ~20 meters

Equivalent to: ~500 kilotons of TNT

Frequency: every few decades to centuries

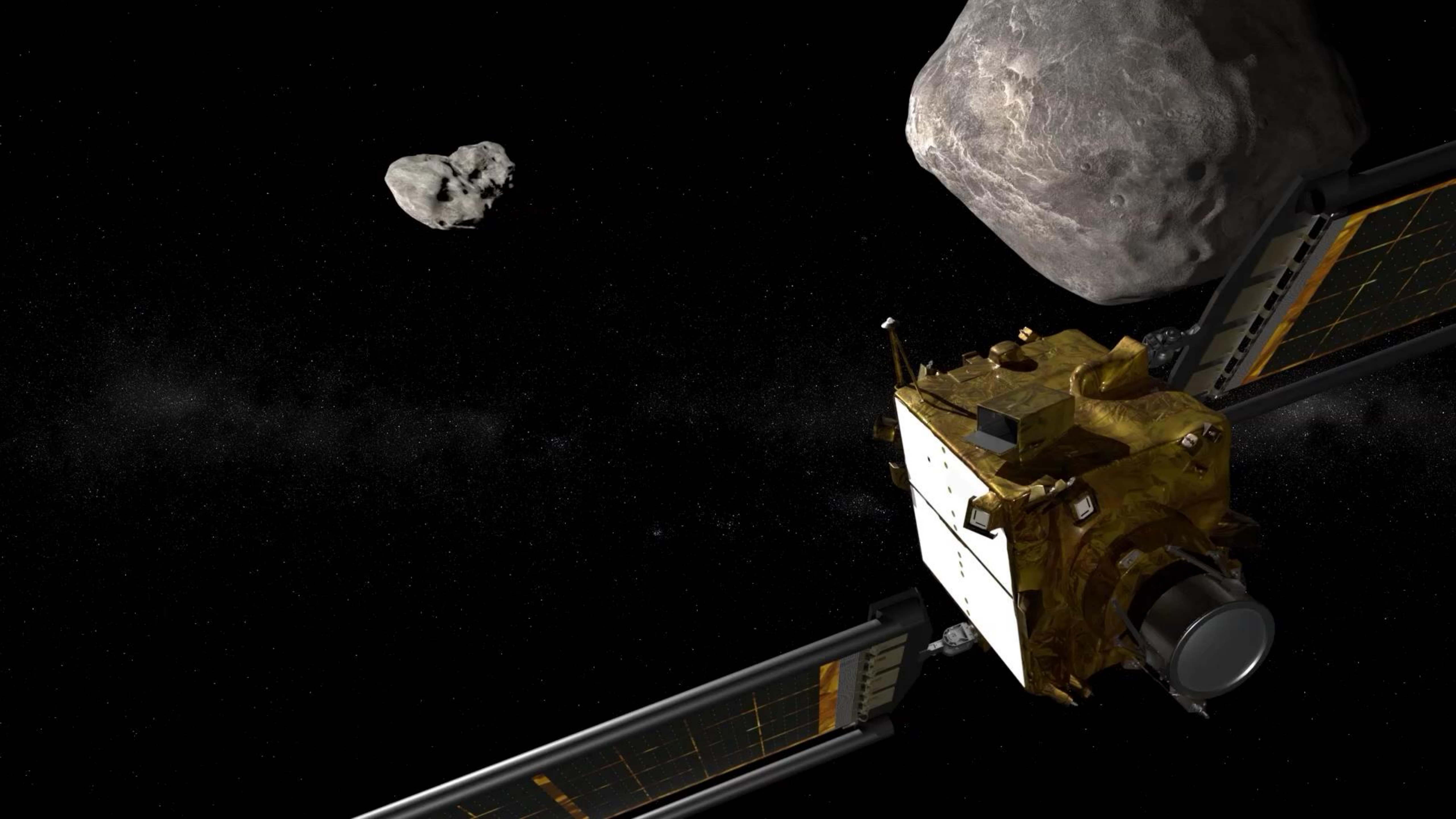


https://cneos.jpl.nasa.gov/fireballs/ Alan B. Chamberlin (JPL/Caltech)

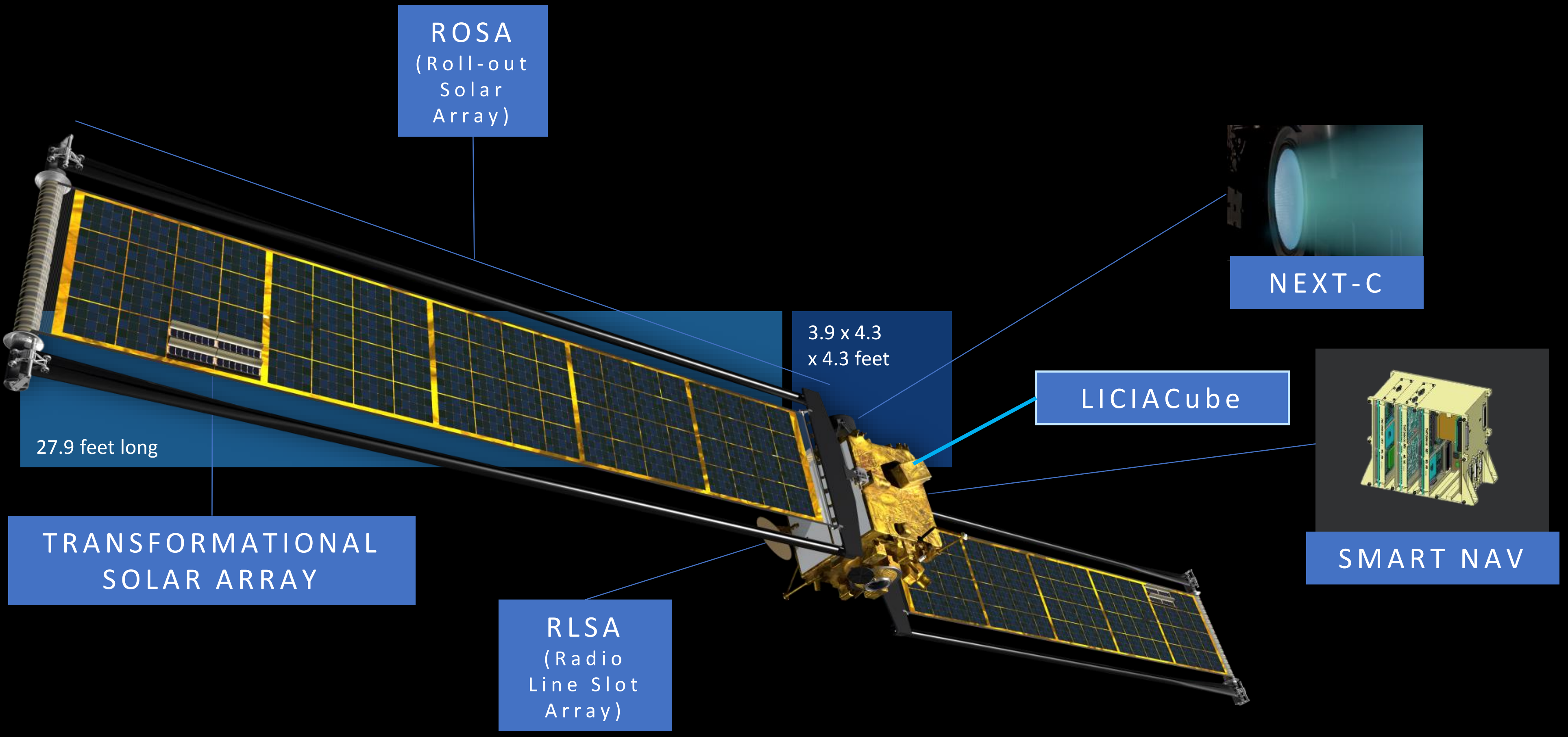
The Hazard by the Numbers

Asteroid Size	4 meters	25 meters	160 meters	1,000 meters	10,000 meters
Frequency	~1 per **year**	~1 per **100 years**	~1 per **25,000 years**	~1 per **500,000 years**	~1 per **100-200 million years**
Impact	Bright flash, no ground effects, but could leave meteorites	Air burst explosion, could cause widespread injuries if over populated area	Crater of 1-2 kilometer diameter, deadly over metro areas/states, mass casualties	10-kilometer crater, global devastation, possible collapse of civilization	100-kilometer crater, global devastation, mass extinctions of terrestrial life
# of NEOs	~500 million	~5 million	~20,000	~900	4
% Discovered	< 0.1%	0.4%	42%	> 95%	100%

NASA Planetary Defense Coordination Office (PDCO): established 2016



DART Technologies

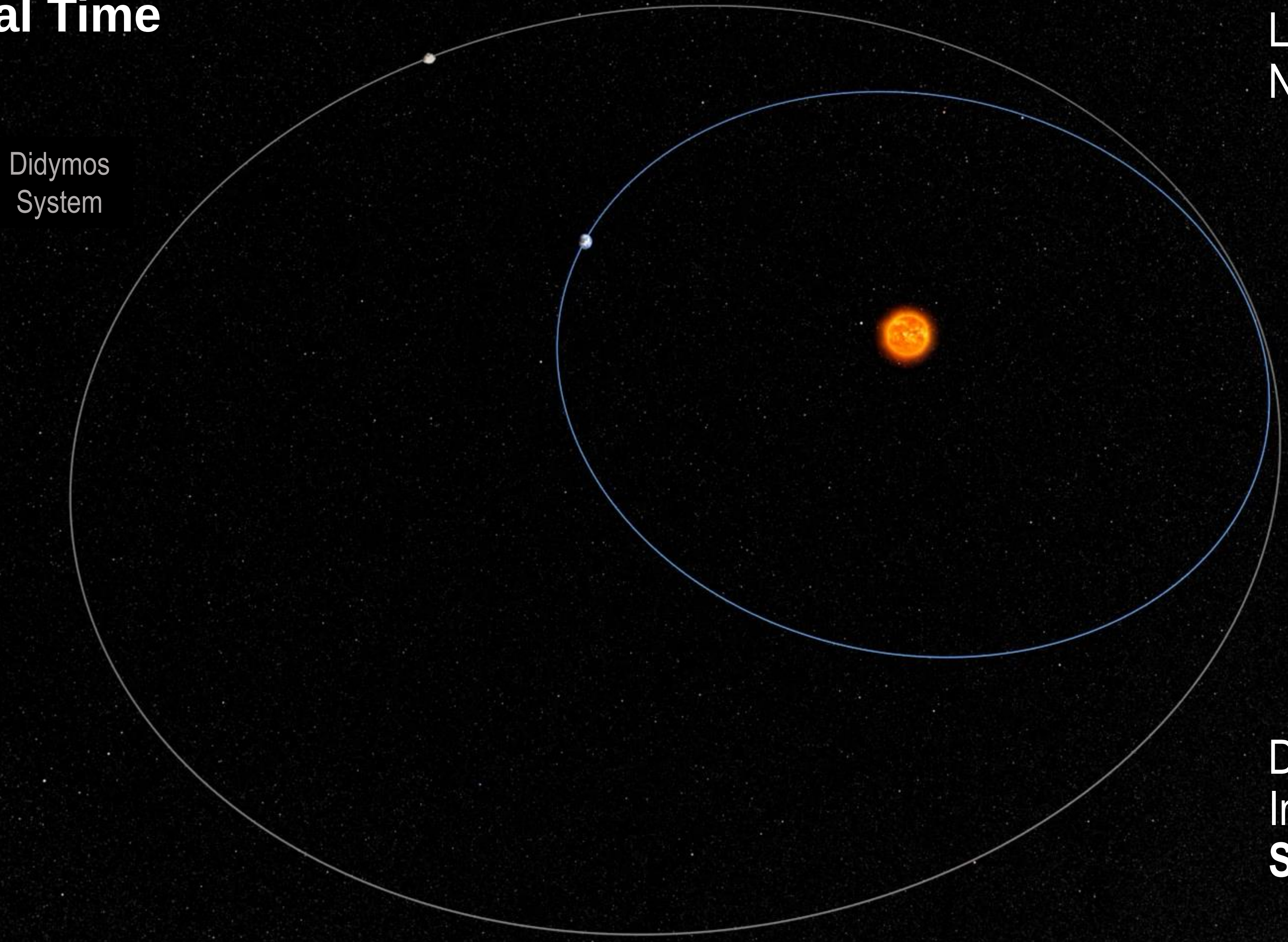


Bill Ingalls/NASA

Nov 2021
Vandenberg Space Force Base

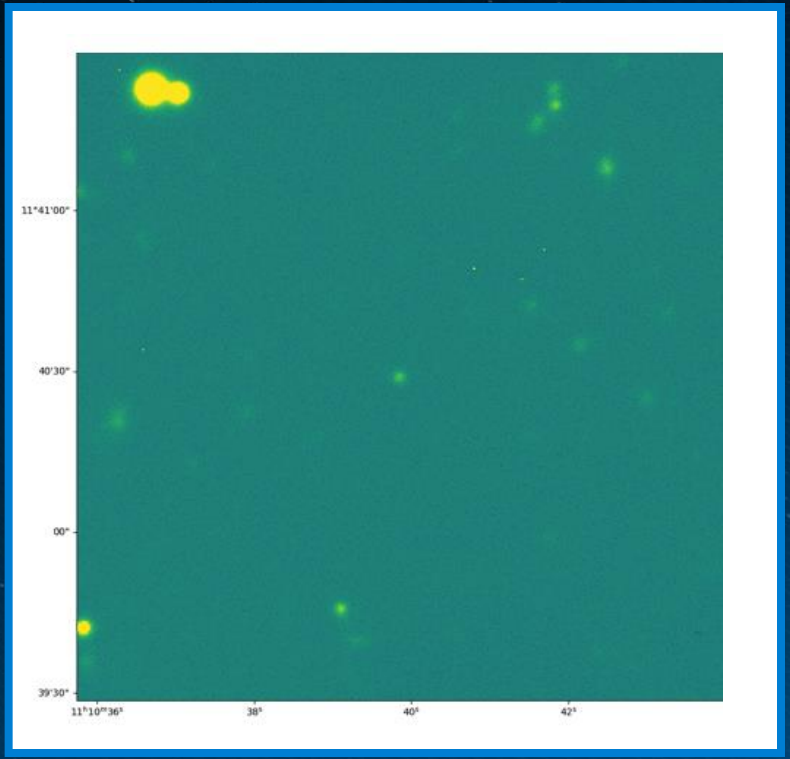
The Ideal Time

Launch:
Nov. 23, 2021

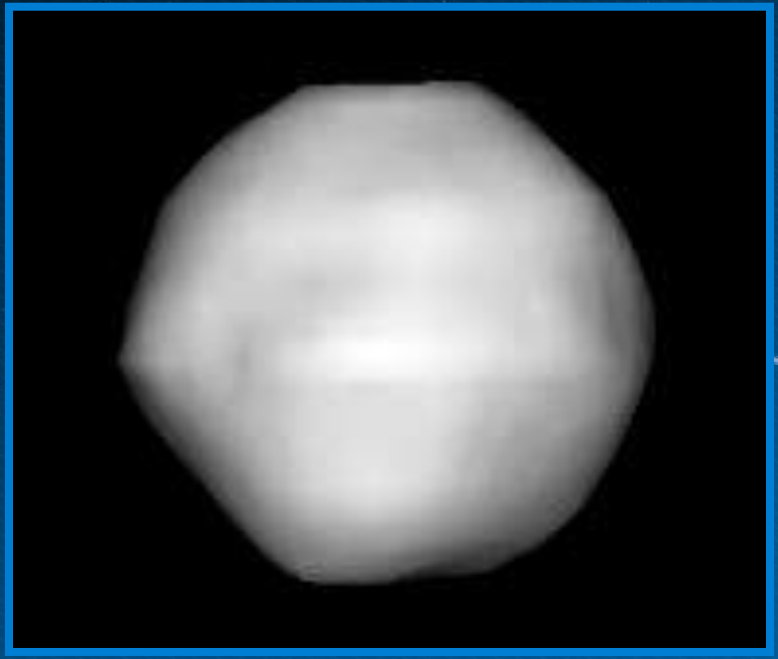


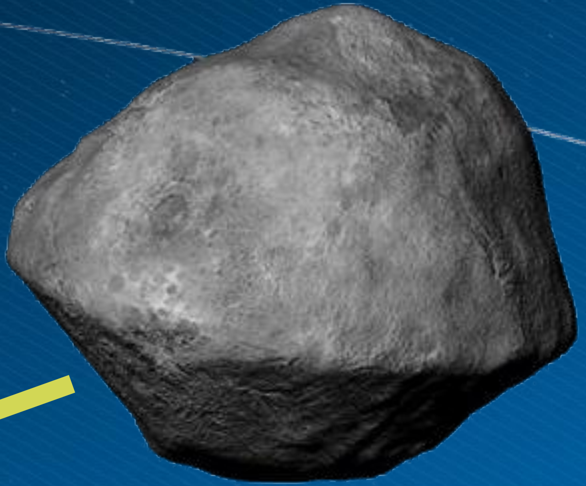
DART Kinetic
Impact:
Sept. 26, 2022

Knew little about the object we were going to hit



Images centered on Didymos, moving through star fields
Taken by Very Large Telescope, Chile, March/April 2019

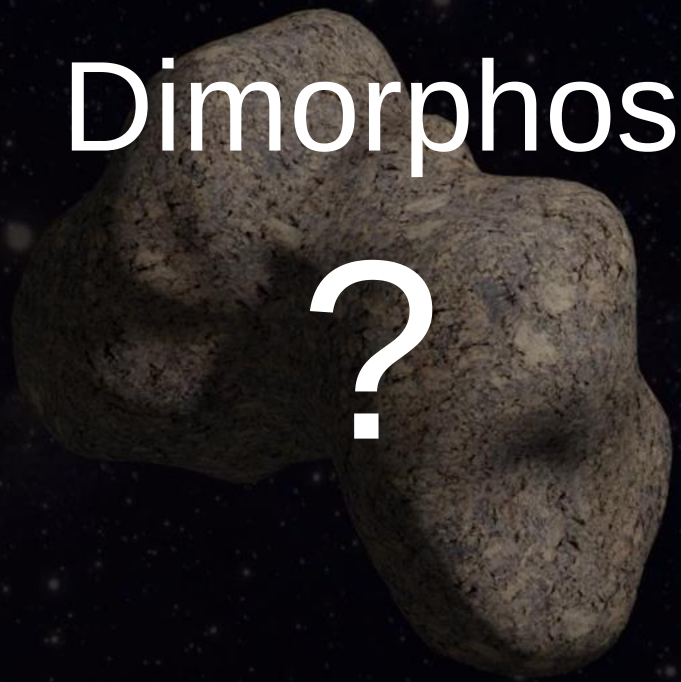




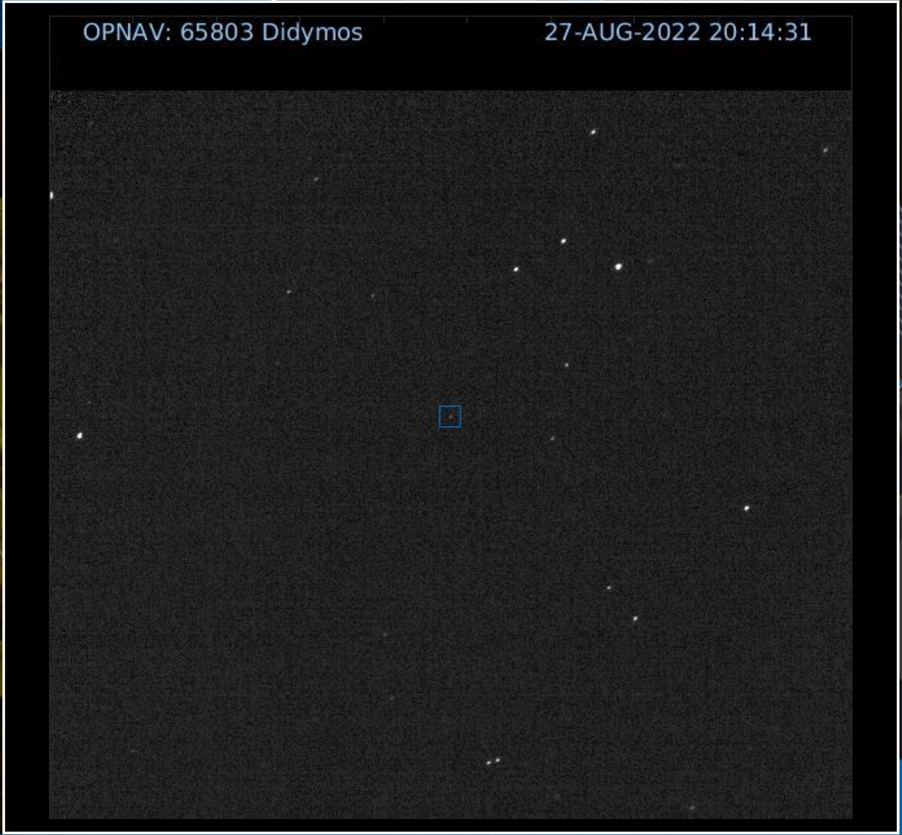
Radar shape model

Preliminary shape model of the Didymos primary asteroid from combined radar and light curve data, diameter ~780 m.

Knew little about the object we are going to hit



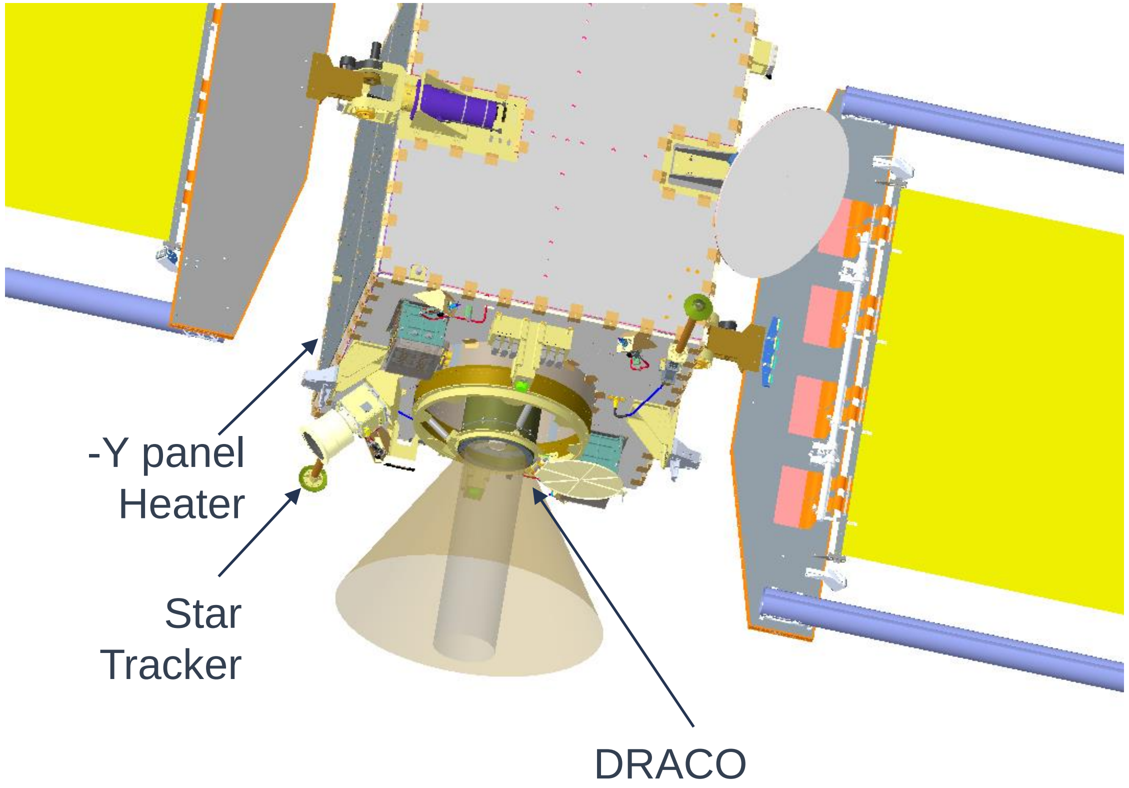
Our eyes:
DRACO Instrument



DRACO Optical Navigation Images in the last month prior to impact

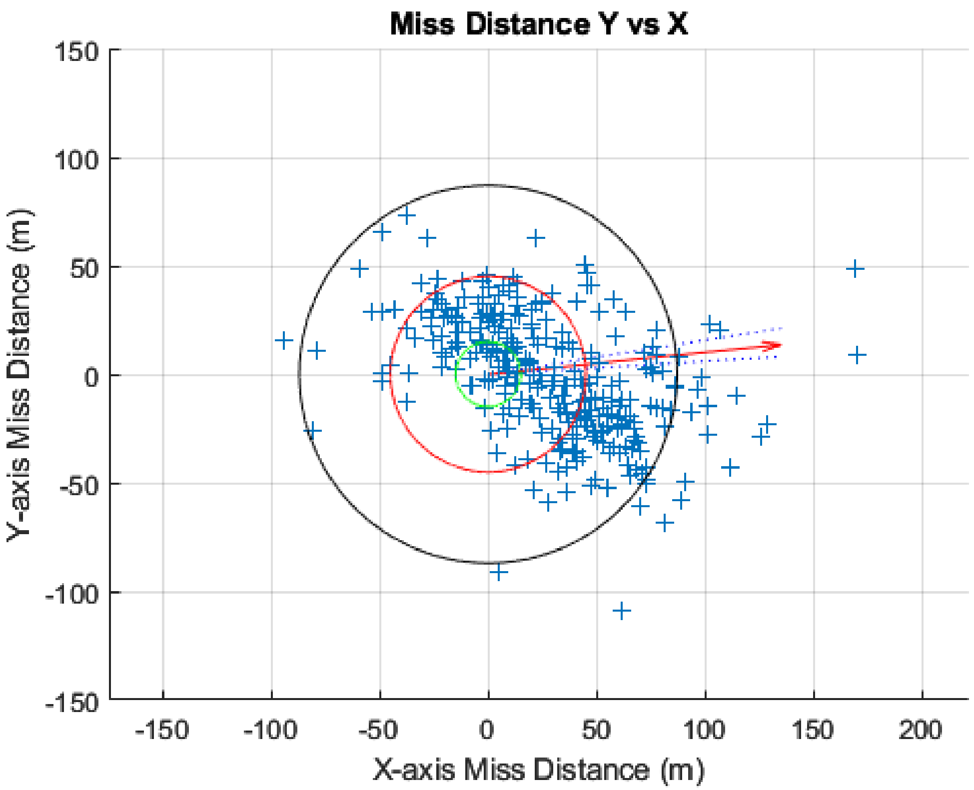
Star Tracker Alignment

- Star tracker characterization tests in flight revealed drifts in the alignment between the star tracker and the DRACO imager.
  - Drifts were believed to be caused by transient thermal environments caused by spacecraft slews (changing incident sun angle) in preparation for imaging tests.
- Subsequent thermal tests conducted after reaching thermal equilibrium revealed a secondary effect: heater cycling on a component near the star tracker and DRACO resulted in cyclical changes in the sensor alignment
- Over 100,000 images were captured and processed across 7 different characterization tests

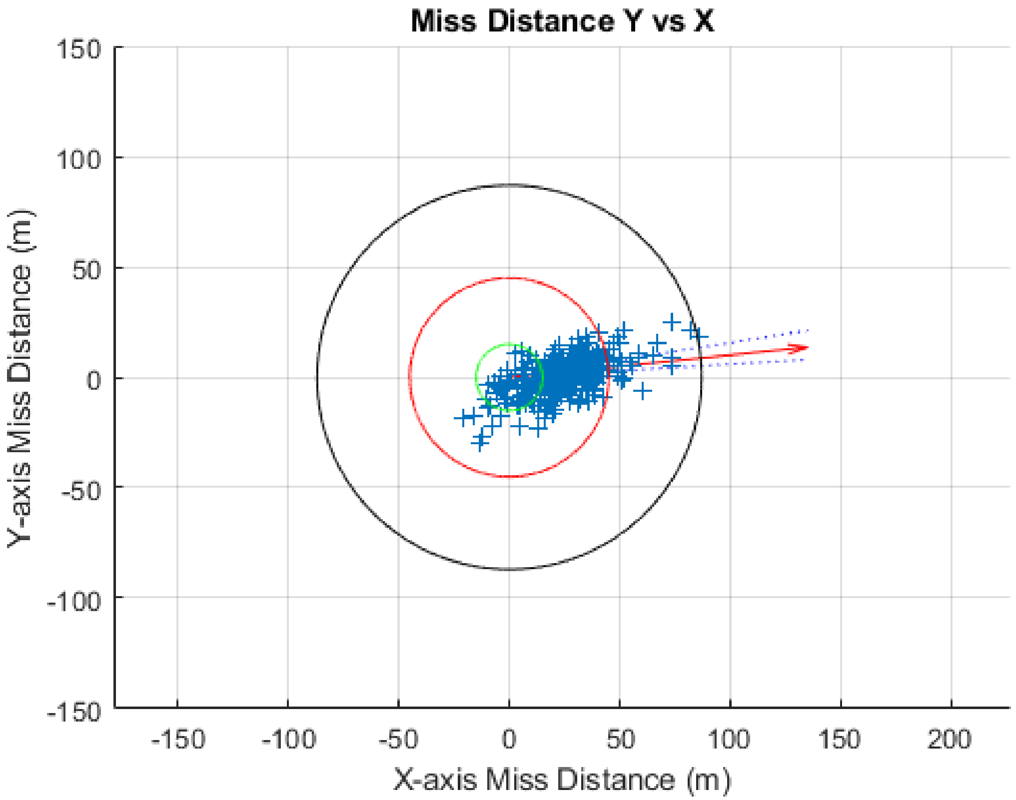


Expected Impact Performance

Without stable sensor alignment

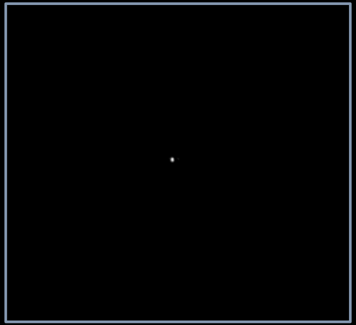


With stable sensor alignment



Monte Carlo Simulation results showing the distribution of miss distance from the center of Dimorphos at impact, with (right) and without (left) stabilized sensor alignment

Timeline to Impact



25,000 kilometers
Didymos – 8 pixel
Dimorphos – 2 pixel
Started tracking Dimorphos

920 kilometers
Didymos – 180 pixel
Dimorphos – 38 pixel
Final downlinked images to contain all of Didymos

76 kilometers
Didymos – N/A
Dimorphos – 470 pixel
Final images to contain all of Dimorphos

12 kilometers
Didymos – N/A
Dimorphos image– 31 meters across
Penultimate Image

68 minutes	2.5 minutes	12 seconds	2 seconds

4 hours · 71 minutes · **68 minutes** · 50 minutes · 20 minutes · **2.5 minutes** · **12 seconds** · **2 seconds**

Sept 26 7:10-7:15 pm EST

DRACO images streamed to Earth from 7 million miles away

10x speed

Sept 26 7:15 pm EST
Mission Operations Center, Laurel MD
"We have impact!"

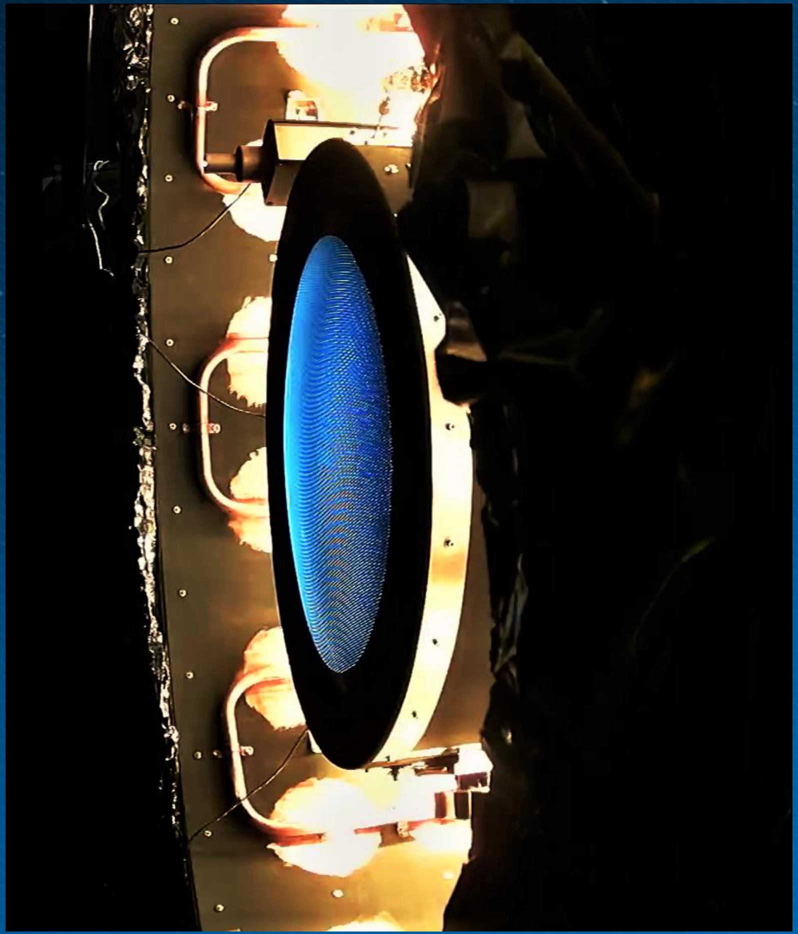
DART impacted Didymos within 25m of the geometric center, and within 2m of the center of the illuminated figure

Lessons Learned

- **Implement Flexible Heater Design** – Software programmable thermostat with power controllable at individual heaters. Enables fine control of alignment stability.
- **Optimize Star Tracker Orientation** – Align boresight as closely as possible with boresight of the payload and consider star scene during events with tight pointing requirements.
- **Consider Multiple Star Trackers** – Enables reduction in attitude uncertainty.
- **Consider High Accuracy Gyro** – Enables dead-reckoning instead of reliance on ST measurements
- **Be Wary of Model Applicability** – Applicability of empirical models limited to specific operating conditions. Rely on physics-based models for analysis of diverse conditions.
- **Consider Star Tracker Calibration** – Self-calibration features in some STs may improve performance
- **Ensure Representative Flight Tests** – Judicious test planning will alleviate Ops and Analysis burdens
- **Ensure Availability of Necessary Flight Data** – Early planning of flight data needs will enable more comprehensive analyses

NEXT-C Ion Propulsion System

- NEXT-C system was developed by NASA GRC and Aerojet Rocketdyne with support from ZIN Technologies for PPU development
- Single thruster and Power Processing Unit (PPU) were built and tested for DART
  - Testing included a system integration test where DART Flight Software was used to operate the system prior to delivery
- Spacecraft testing was focused on PPU tests during TVAC testing (an emulated electrical load bank was used in place of the thruster)
  - Simulated operation at the nominal DART throttle level were performed
  - Fault response tests were also completed during TVAC



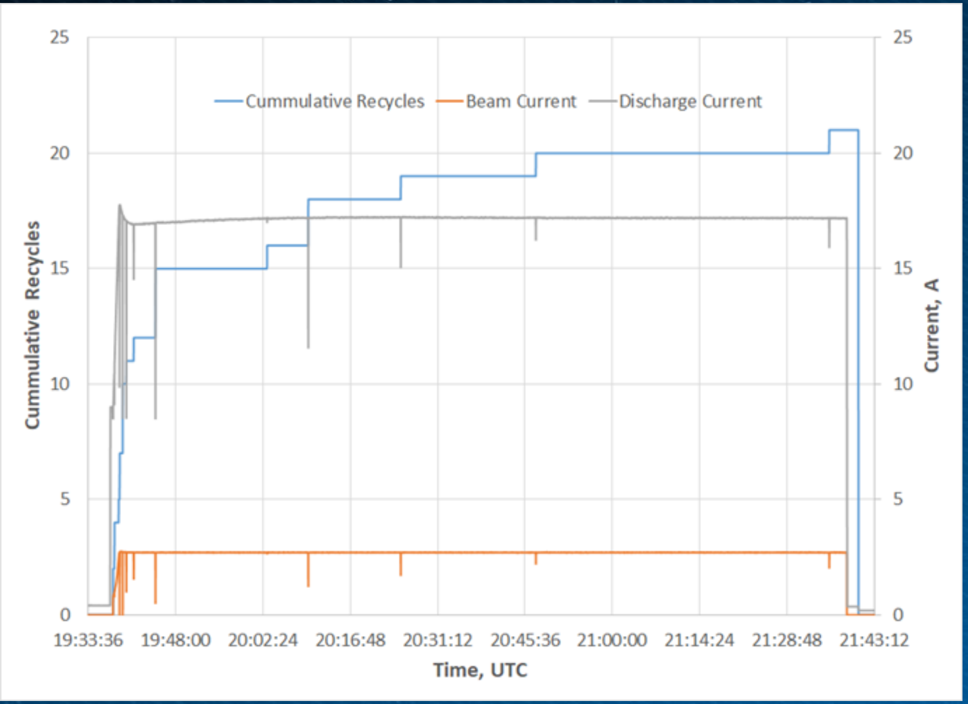
NEXT-C Firing in Component TVAC Test
Credit: Aerojet Rocketdyne/ NASA GRC

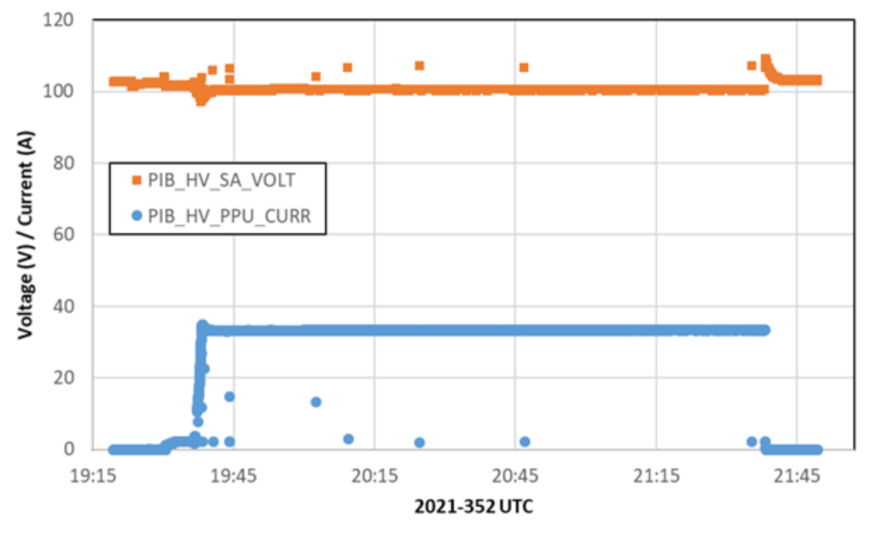
NEXT-C Operation

- NEXT-C Ion Propulsion System thruster went thru 4 stages of operation in flight
  - Xenon feed system conditioning prepared the flow system for operation
  - PPU aliveness and cathode conditioning confirmed operability after launch and prepared the cathodes for operation
  - Diode mode operation where both cathodes were operated at nominal DART operating conditions
  - Initial firing of the NEXT-C thruster
- Commissioning of the system was a limited duration firing at nominal power for 2 hours to demonstrate operability prior to longer duration operations that were planned for later in the mission
- Nominal operating point was at 3.5 kW input power, which was approximately half of the capability for the system
  - The input power was provided nominally throughout the operating period
  - Spacecraft thermal response was consistent with ground tests
- Anomalous interaction with the spacecraft power system electronics during the initial operation resulted in discontinuing use of the system during the remainder of the mission
  - Impacted hardware continued to operate in a nominal state but at an increased current draw

NEXT-C Operation

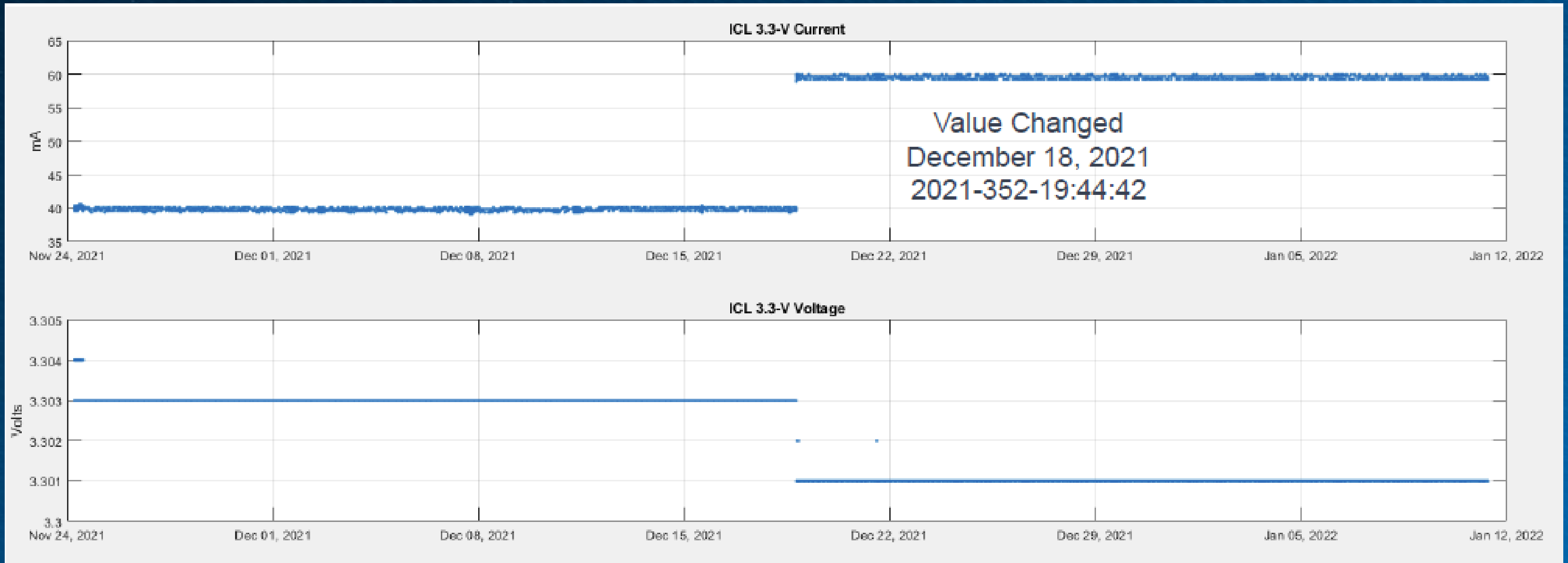
- During the operation time, the cathodes ignited nominally and the application of high voltage for beam extraction occurred nominally
- Spacecraft power response was consistent with the behavior observed in ground tests and was nominal during the operation time
- Thruster power was ramped up to the throttle level in less than 2 minutes and experienced several thruster recycles as expected
  - A recycle is a HV short at the thruster grid detected by the PPU as a high current condition. The PPU power cycles HV
  - Flight software controlled the ramp and performance was consistent with ground tests, including observing recycles
- Recycles continued intermittently through the operating period but did not impact NEXT-C performance, nor cause spacecraft resets or catastrophic faults
  - Recycles were observed both in the thruster data and spacecraft input power data





Electric Power System Response

- Anomaly observed in the Power System Electronics (PSE) was characterized by ~50% step increase of an internal secondary voltage current draw to the interface controller board not directly associated with NEXT-C operation
  - Prior to the anomaly, the current had been constant since launch
  - The current level remained constant at the elevated level for the remainder of the mission
- Current increase was found to coincide with the series of 3 thruster recycles approximately 7 minutes into the 2 hour operating window
- No further interactions were observed on the spacecraft



Anomaly Evaluation

- Anomaly evaluation investigated several possible root causes but was not able to definitively identify a primary root cause
  - One possibility was that there was an inductive EMI event on the solar arrays that allowed a current spike to progress through the low power bus
  - One possibility was that there was a large current spike that filtered through the spacecraft chassis that resulted in a ground voltage shift between panels
- Design of the spacecraft and its telemetry instrumentation do not support the full set of information needed on the ground to resolve these root causes.
- Ground tests with engineering model PSE hardware were used to identify potentially impacted circuits and identify possible mechanisms for increased current draw.
  - Testing revealed that a buffer/latch circuit can be toggled by directly applying a voltage pulse, which resulted in the same current increase as observed in flight
  - An EMI pulse that could toggle the buffer/latch would need to exceed the qualification test limits, as the circuit uses an isolation transformer to minimize coupling from ground voltage shifts and other EMI
- Mission operations with regards to NEXT-C operation were put on hold until further evaluations could made and a root cause could be identified

Lessons Learned

- Ensure that interface control documents (ICDs) for electric propulsion systems are matured enough to capture all possible interface paths between that system and the spacecraft
  - These need to be delivered as early as possible in the spacecraft development process
- Ensure that the EMC test program for components and the spacecraft include the types of interactions that can be produced by an electric propulsion system
- During spacecraft testing, a solar array wiring emulator should be used in conjunction with the array electrical simulators
- Early in a spacecraft development, a trade study should evaluate whether a single array bus should feed both the spacecraft and electric propulsion system or whether the array should be segmented
- Solar array design needs to consider shielding and/or separation of the EP and S/C sections
- Consider a trade study to evaluate implementing high rate telemetry on PSE current and voltage to the electric propulsion system
- Verify the intended state of FPGA I/O pins on spare/unused interface channels

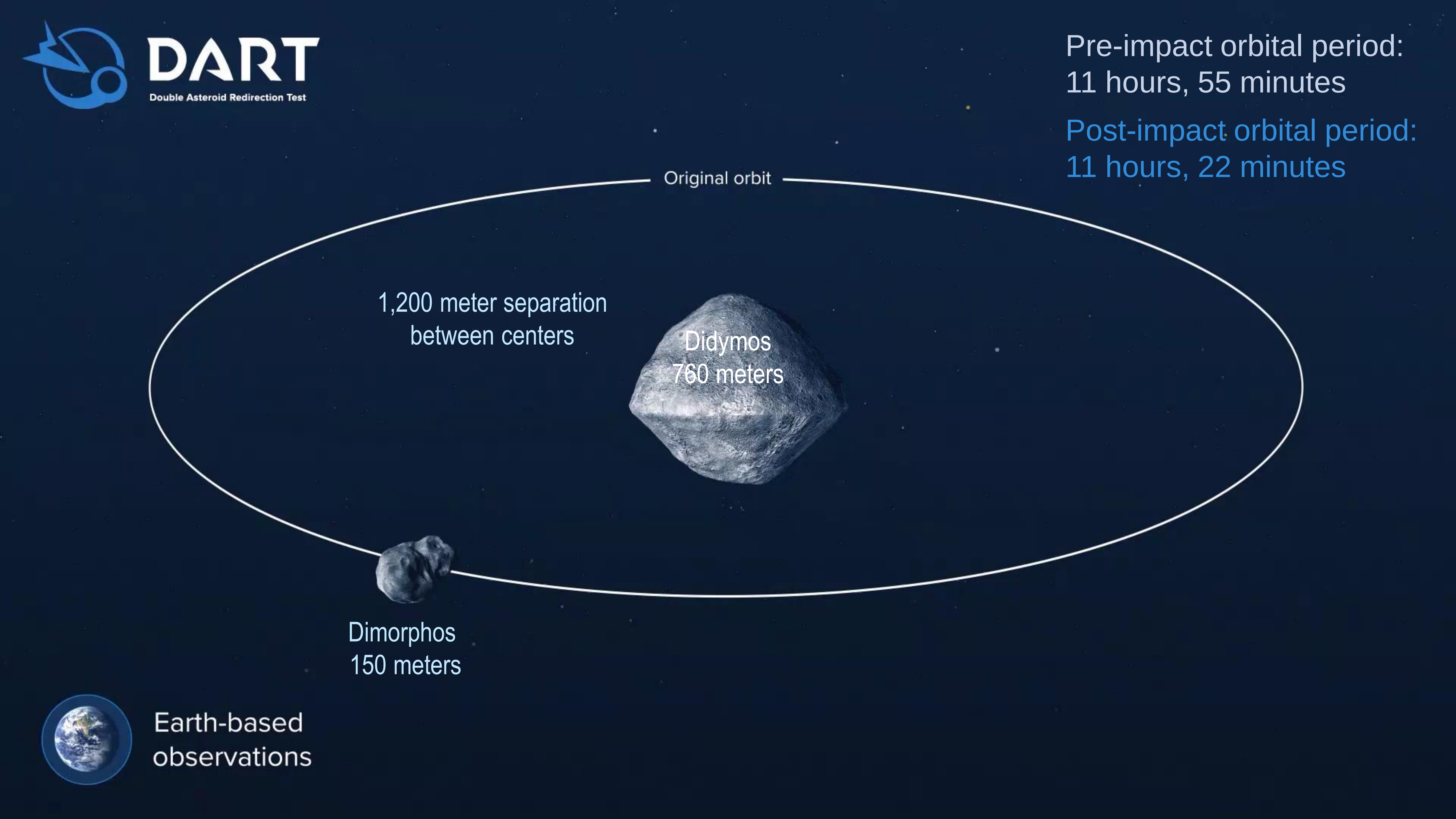
Mission Outcome

- DART spacecraft continued to operate nominal following the initial NEXT-C operation and PSE anomaly
- Spacecraft operation modes were not changed to avoid switching to alternate power configurations during the remainder of the flight
  - Spacecraft was already in an operation mode that allowed for the completion of the mission requirements
  - Solar array concentrators were not tested beyond the initial test during commissioning due to the need to switch power modes to conduct the tests
- No additional anomalies were observed during the remainder of the flight


September 26, 2022
Las Cumbres Observatory 1 m telescope in South Africa
4 minutes pre-impact to 37 minutes post-impact
Credit: Tim Lister, Joseph Chatelain, Rachel Street, Edward Gomez, Joseph Farah / Las Cumbres Observatory.

Credit: ASI/NASA

LICIACube


DART
Double Asteroid Redirection Test
Pre-impact orbital period:
11 hours, 55 minutes
Post-impact orbital period:
11 hours, 22 minutes
Original orbit
1,200 meter separation
between centers
Didymos
760 meters
Dimorphos
150 meters
Earth-based
observations