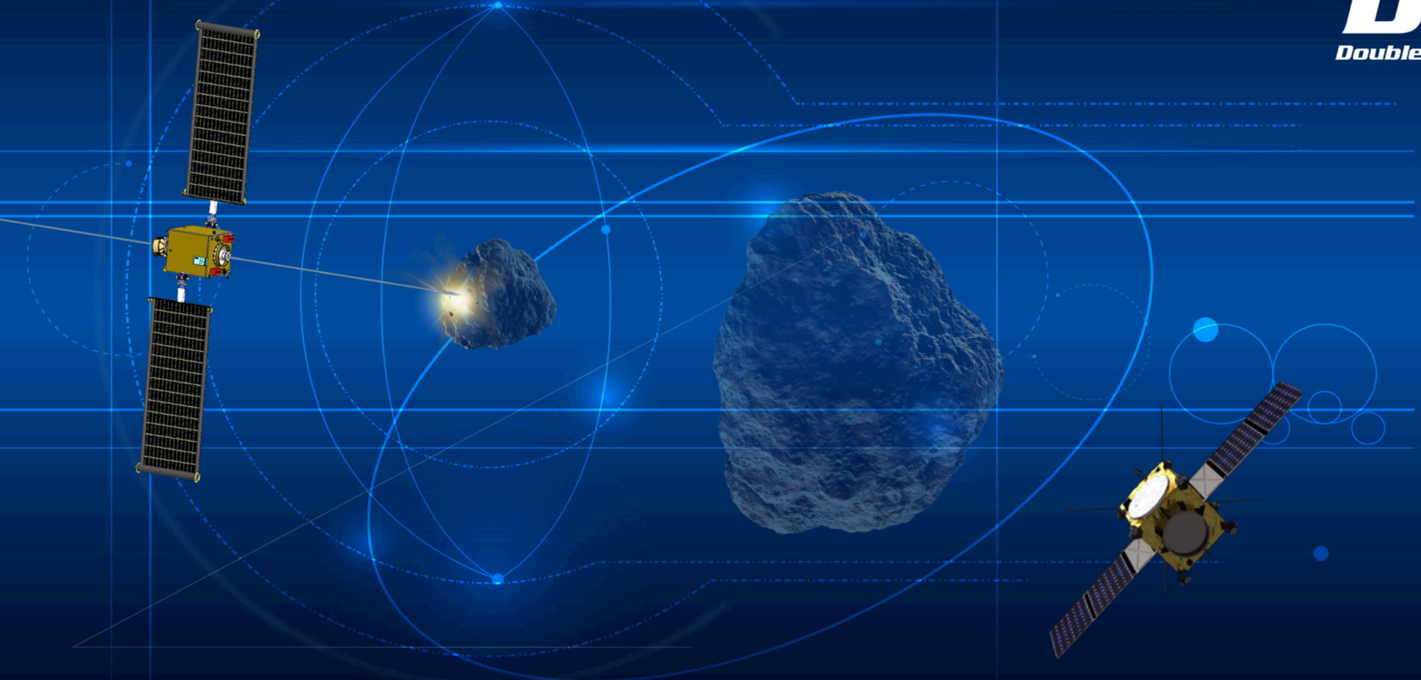
Approved for Public Release IAC, September 2016

Asteroid Impact & Deflection Assessment (AIDA)

DART

Double Asteroid Redirection Test



AIDA-DART Mission Overview

Cheryl Reed, APL DART Project Manager
Drs. Andy Cheng, Andy Rivkin, Co-Investigation Leads
Dr. Brian Kantsiper, DART Mission System Engineer

IWAN/SMPAG Meetings; 14 October 2016

Goddard Space Flight Center
Johnson Space Center
Langley Research Center
Glenn Research Center

NASA HQs., Planetary Defense Coordination Office, PDCO

Johns Hopkins Applied Physics Laboratory

Jet Propulsion Laboratory
California Institute of Technology

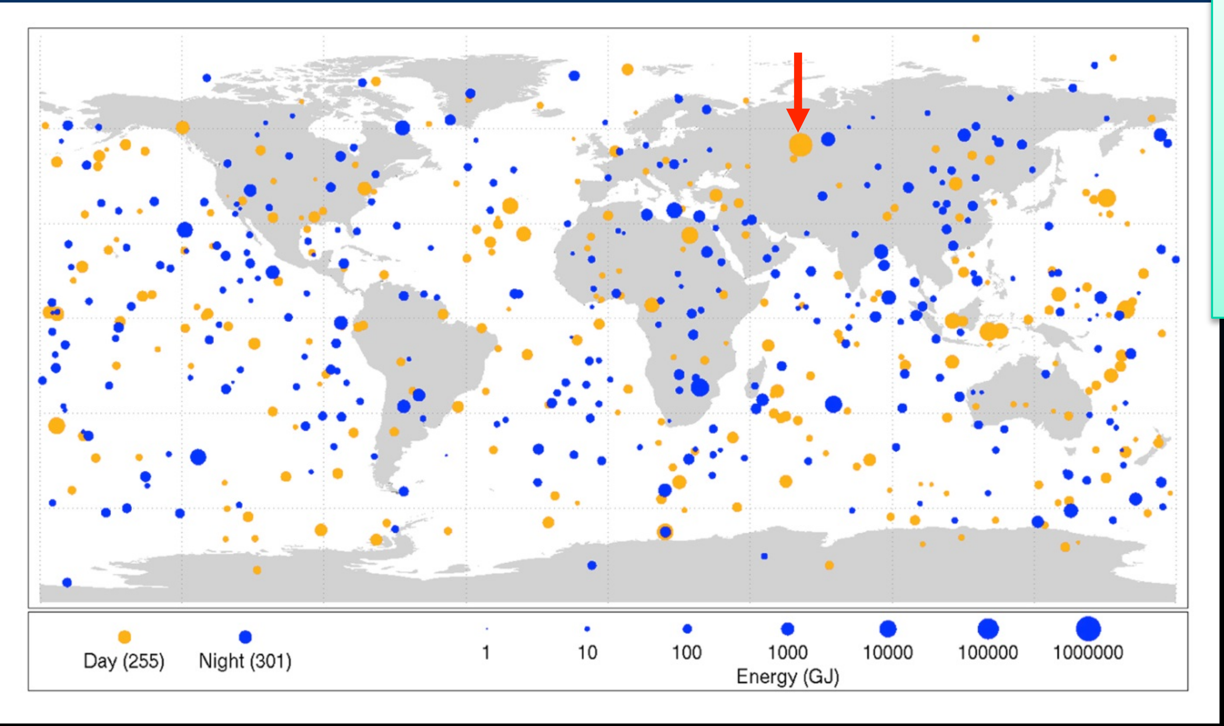
University of Colorado Boulder

University of Maryland

Lawrence Livermore National Laboratory

Planetary Defense: Asteroid Mitigation, a Global Concern

Small asteroids that hit the Earth, 1994-2013



Mitigation Techniques:

- ➢ **Kinetic Impactor**
- Energetic Explosion
- Gravity Tractor
- Directed Energy

Chelyabinsk-sized impacts (500 kilotons TNT) every few decades
Tunguska-sized impacts (5 megatons TNT) every few centuries

Regimes of Primary Applicability of the Four types of Mitigation

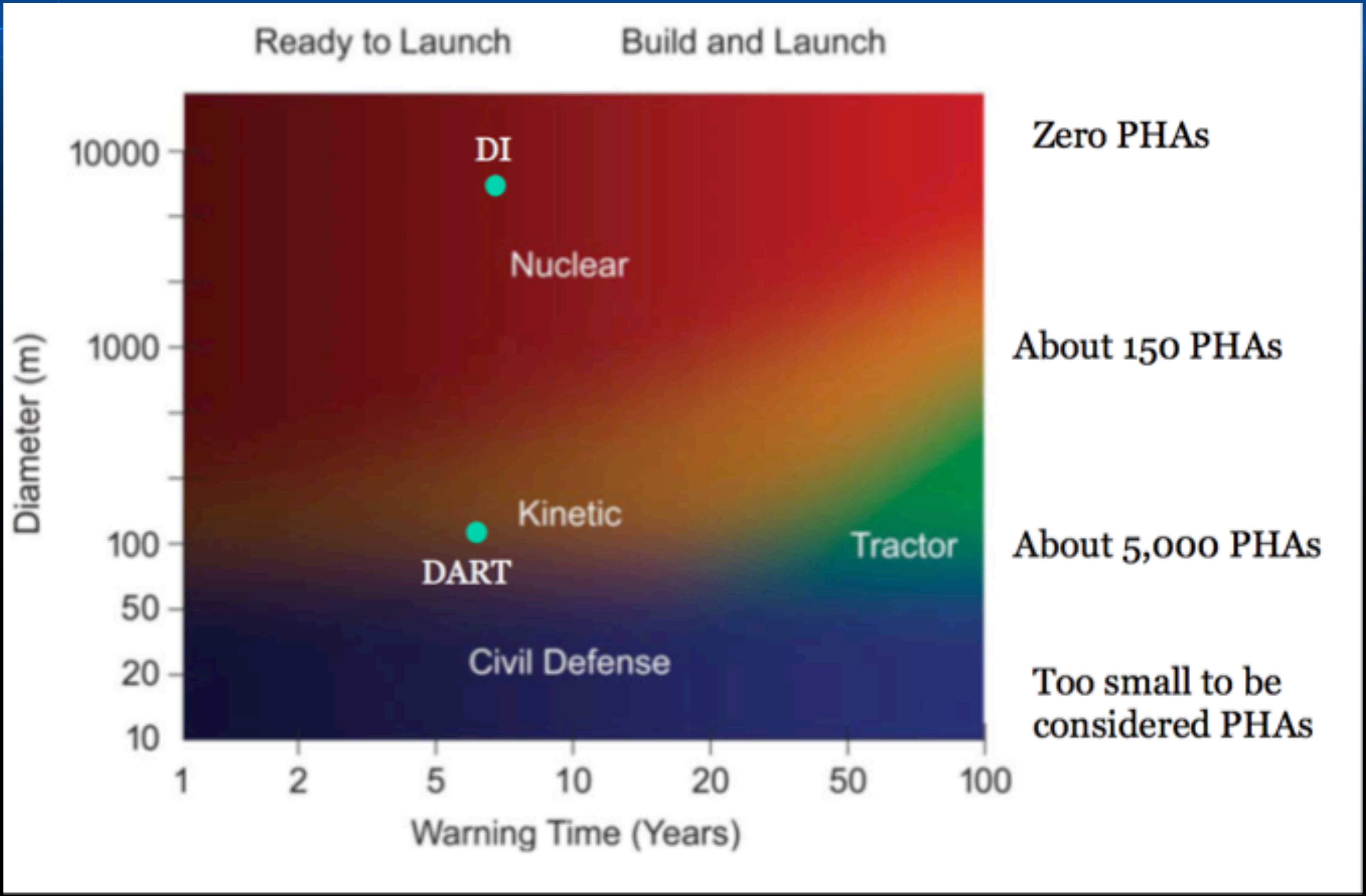
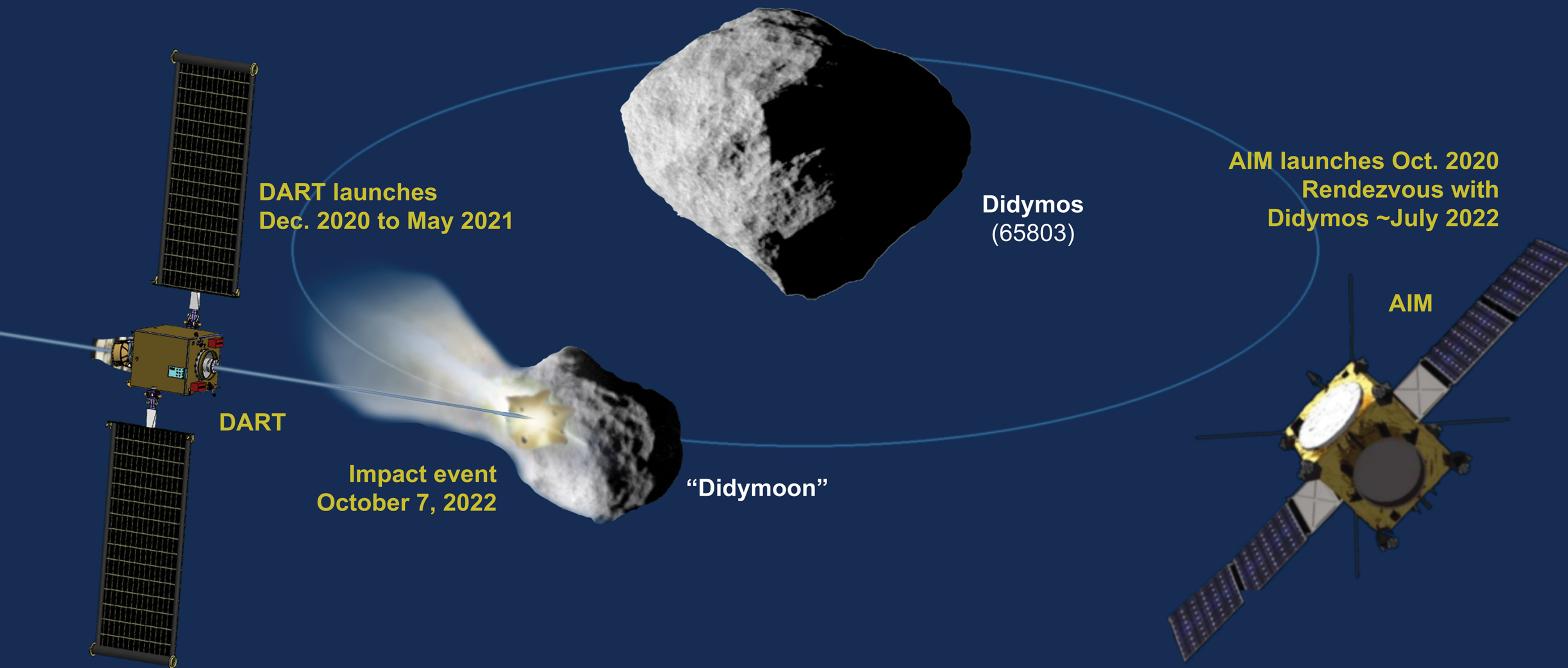


Image courtesy of Tim Warchocki

Asteroid Impact & Deflection Assessment (AIDA)

NASA's Double Asteroid Redirection Test (DART)

ESA's Asteroid Impact Mission (AIM)



Radar and Telescope Observations

Goddard Space Flight Center
Johnson Space Center
Langley Research Center
Glenn Research Center

Johns Hopkins Applied Physics Laboratory

Jet Propulsion Laboratory
California Institute of Technology

University of Colorado Boulder

University of Maryland

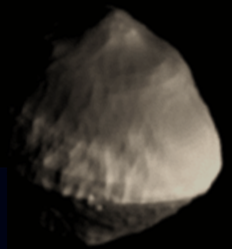
Lawrence Livermore National Laboratory

DART

- DART is an element of AIDA , a joint, **international mission collaboration** to demonstrate asteroid impact threat mitigation with a kinetic impactor spacecraft to deflect an asteroid, and assess the deflection result. AIDA consists of:

AIDA = AIM+DART

  - ESA's rendezvous and monitoring spacecraft, the Asteroid Impact Monitor (AIM) mission
  - NASA's kinetic impactor spacecraft, the Double Asteroid Redirection Test (DART) mission
- **DART is a compelling opportunity:** The spacecraft will intercept the secondary member of the binary Near-Earth Asteroid Didymos binary system ~October, 2022 (using autonomous guidance with proportional navigation to hit the "center" of the 160m target body).
- **DART is a strategic technology demonstration.**
  - **DART is a full scale test of a kinetic impactor (an independent mission)**
  - **DART will also demonstrate SMD's NEXT Solar Electric Propulsion System**
- DART leverages many other NEO Observation Program investments, space-based missile technology and APL's DoD capabilities and investments
- **A comprehensive DART project includes ground-based observations**
- **DART is a Class D, Cat. III mission**



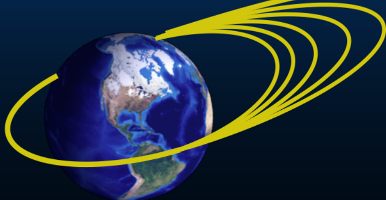
DART
Double Asteroid Redirection Test

DART Mission Design - Path To Terminal Guidance

Autonomous Navigation and Targeting (SMARTNav)

@2022 Intercept (~10.9M km; 6.8M miles from Earth)

1. Ascent / Boost



Direct Launch
or Low-Thrust Spiral*

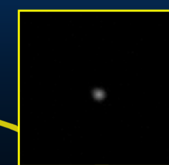
<6-9 months for EP>
<10^8 km from target>

2. Cruise / Calibration

Flyby of PHA allows sensor calibration and control-gain tuning

<7 months until impact>
<10^8 km from target>

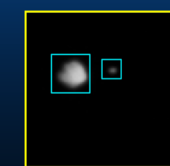
3. Target Detection / Coarse Acquisition



Weeks prior to impact, seeker detects primary

<2 months until impact>
<10^7 km from target>

4. Scene Classification



Seeker counts and classifies closely spaced objects

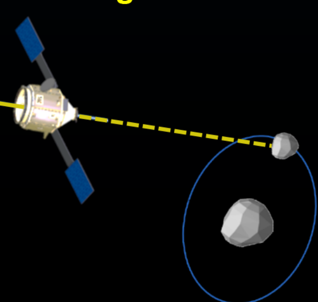
<3 hours until impact>
<76,000 km from target>

5. Target Selection

With sufficient confidence, seeker selects target and locks on.

<1.5 hours until impact>
<38,000 km from target>

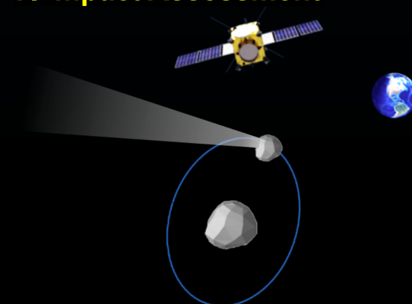
6. Homing Until Intercept



Pro-Nav executes precision engagement and is robust to target uncertainties

<Executed until final 2 minutes>
<~6.0 km/s Impact>

7. Impact Assessment



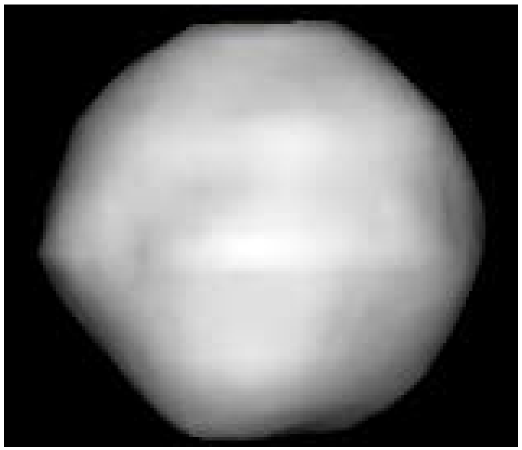
Earth tracking and AIM quantify intercept success.

<3 months>

*15-18 months total flight time

DART
Double Asteroid Redirection Test

DART is targeting the Didymos system in October, 2022



Preliminary shape model of the Didymos primary from combined radar and light curve data, diameter ~780 m. The secondary (not imaged) may be more elongated.

Primary Diameter	780 m ± 10%
Secondary Diameter	163 m ± 18 m
Total System Mass	$(5.278 \pm 0.54) \times 10^{11}$ kg
Component Bulk Density	2,100 kg m^{-3} ± 30%
Primary Rotation Period	2.2600 ± 0.0001 h
Component Separation	1180 +40/-20 m
Secondary Orbital Period	11.920 +0.004/−0.006 h
Spectral Class	S

- Didymos is a well-characterized asteroid that approaches close to Earth, enabling ground-based observations of impact demonstration
- The secondary ("Didymoon") is realistic scale
  - Small enough to deflect kinetically and measure result
  - Smaller NEOs represent a more frequent threat to Earth

Cheng AF et al. (2015) Acta Astron., 115: 262

Cheng AF et al. (2016) Planet. Space Sci., 121:27

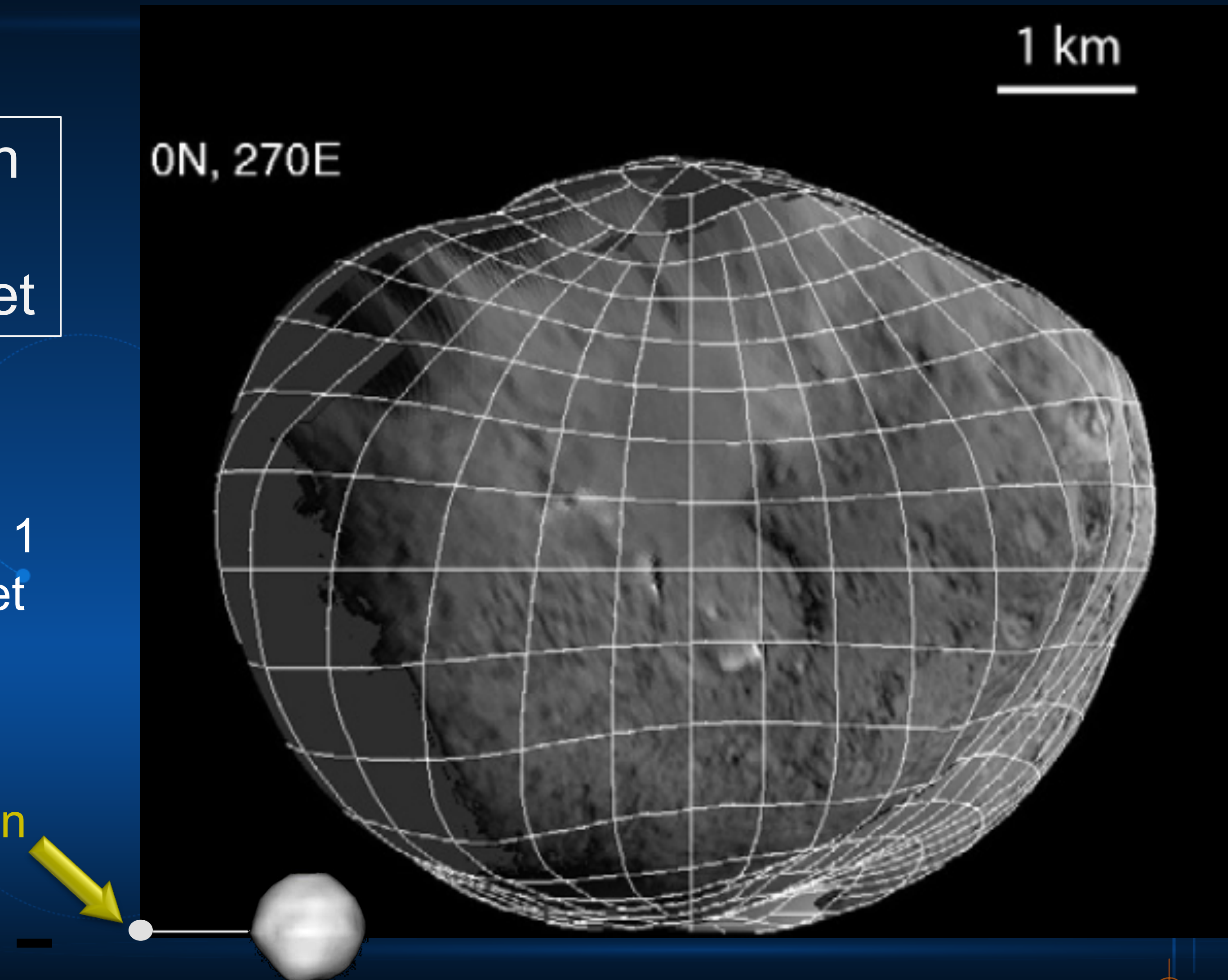
Michel P et al. (2016) Adv. Space Res., 57:2529

First Kinetic Impact Test at Realistic Scale for Planetary Defense

DART target much smaller than the Deep Impact target

Comet 9P/Tempel 1
Deep Impact target

DART target
Didymos moon



DART
Double Asteroid Redirection Test

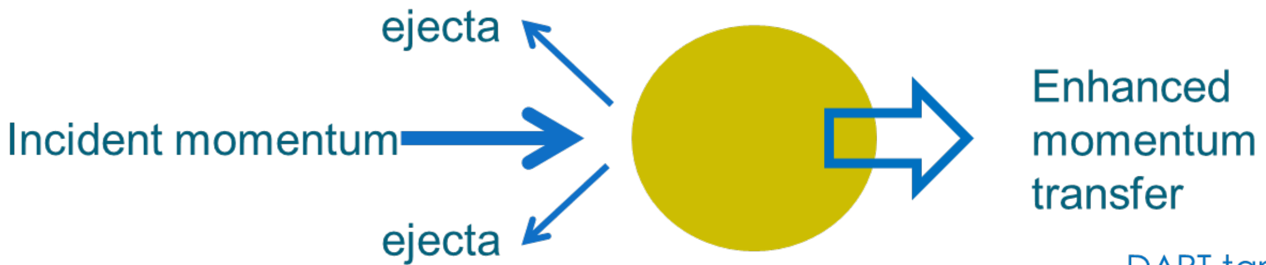
DART Level 1 Requirements (Updated 09-28-16)

	ID	Requirement	Implications
Threshold	DART-1	DART shall intercept the secondary member of the binary asteroid 65803 Didymos as a kinetic impactor spacecraft during its September to October, 2022 close approach to Earth.	Autonomous navigation; optimal ground-based observing opportunities
	DART-2	The DART impact on the secondary member of the Didymos system shall cause at least a 73 s change in the binary orbital period.	Ideal impact time to maximize deflection
	DART-3	DART shall measure the change in the binary orbital period to within 7.3 s (1-σ).	Measurement of orbital period change to 10% precision corresponds to 6.7% measurement precision in orbital energy transfer.
	DART-4a	The DART project shall characterize the binary orbit with sufficient accuracy by obtaining ground-based observations of the Didymos system before and after spacecraft impact to allow determination of the velocity change imparted to the target within 10% precision, and through an independent estimate of the target mass obtain a measure of the momentum transfer enhancement parameter referred to as “Beta”.	Localize and characterize impact site to support modeling and simulation reconstruction of event
Baseline	DART-4b	The DART project shall obtain data, in collaboration with ground-based observations and data from the AIM spacecraft, to constrain the location and surface characteristics of the spacecraft impact site and to allow the estimation of the dynamical changes in the Didymos system resulting from the DART impact, and in particular the coupling between the body rotation and the orbit.	Localize and characterize impact site to support modeling and simulation reconstruction of event

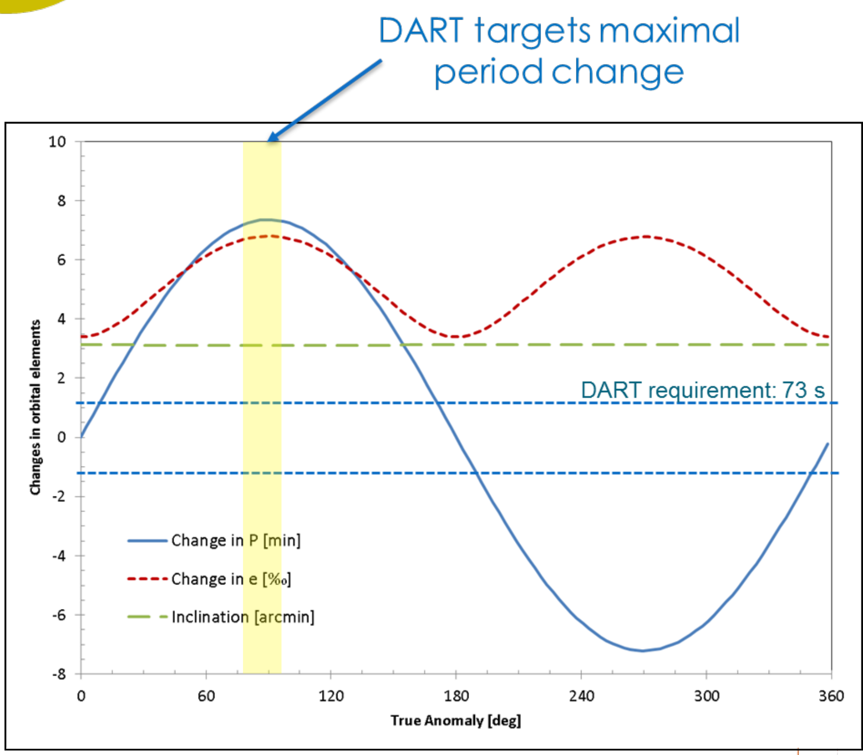
DART Investigation Plan documents all aspects of the DART Investigation and data management

DART

First Measurement of Momentum Transfer Efficiency at an Asteroid



- Momentum transfer from kinetic impact is enhanced by impact ejecta
- is defined as momentum transfer divided by momentum input
  - **If no ejecta, then $\beta = 1$**
  - **Ejecta release *enhances* momentum transfer, $\beta > 1$**
- Estimation of is critical for deflection performance. How large a kinetic impact is needed, or how many kinetic impacts are needed, depend on



JHU/APL Proprietary

DART Primary Objective: Improve and Validate Impact Models with kinetic impact experiment

- DART impact on Didymos secondary is a controlled experiment
  - High-speed impact on an asteroid with known projectile and impact conditions
  - DART images the target site and geology
- DART telescopic observations determine the amount of target deflection by measuring the period change of the Didymos binary system before and after the DART impact
  - With AIM data, if AIM is present at Didymos, further measure the momentum transfer and vector velocity change of the target
- Validate and improve performance models of kinetic impact by calibrating model predictions with results of the DART experiment
  - Modeling and numerical hydrocode simulations of the DART impact predict momentum transfer and ejecta distributions
  - Benchmark numerical hydrocode simulations with each other and with laboratory experimental data
- Independent analyses at GSFC, JPL, and U. Colorado confirm that DART can determine the deflection magnitude with ground-based observations despite the complex dynamics of the Didymos system

DART

Double Asteroid Redirection Test

Investigation Team and Working Groups

DART Core Team		AIM Team Leadership	
Andrew Cheng (APL)	AIDA Coordination lead	Patrick Michel* (CNRS)	AIM Investigation Team Lead
Andrew Rivkin (APL)	DART Investigation Team Lead; DART Investigation 2 lead	Steve Schwartz* (Obs. Cote d' Azur)	AIM Investigation 1 lead
Steven Chesley (JPL)	Dynamics lead	Peter Pravec* (Ondrejov Obs.)	AIM Investigation 2 lead
Brent Barbee (GSFC)	V&V lead	Kleomenis Tsiganis* (U. Thessaloniki)	AIM Investigation 3 co-lead
Angela Stickle (APL)	DART Investigation 1 lead	Adriano Campo Bagatin* (U. Alicante)	AIM Investigation 3 co-lead
Derek Richardson (UMD)	DART Investigation 3 lead	Stefan Ulamec* (DLR)	AIM Investigation 4 lead
Olivier Barnouin (APL)	DART Investigation 4 lead; shape model development		

Investigation 1: Modeling and Simulations of Impact Outcomes	
Megan Bruck Syal (LLNL)	impact modeling using spheral and SPH
Paul Miller (LLNL)	planetary defense interpretation and applications
Emma Rainey (APL)	impact modeling using CTH
Collaborators: Dan Durda (SWRI), Galen Gisler (LANL); Keith Holsapple (UW); Kevin Housen (Boeing); Daniel Jontof-Hutter (Penn St); Naor Movshovitz (UCSC); J. Michael Owen (LLNL); Cathy Plesko (LANL); KT Ramesh (JHU); James Richardson (Arecibo); Pete Schultz (Brown)	
Investigation 2: Remote Sensing Observations	
Paul Abell (JSC)	Strategic Knowledge Gap (SKG) and human exploration applications
Lance Benner (JPL)	radar observations
Collaborators: Michael Busch (SETI); Ellen Howell (UofA); Matthew Knight (Lowell/UMD); Emily Kramer (JPL); Jian-Yang Li (PSI); Tim Lister (LCOGT); Amy Mainzer (JPL); Nicholas Moskovitz (Lowell); Shantanu Naidu (JPL); Michael Nolan (UofA); Dagmara Oszkiewicz (Lowell); David Osip (LCO); William Ryan (NMT); Eileen Ryan (NMT); Amanda Sickafoose (MIT/SAAO); Jessica Sunshine (UMD); Audrey Thirouin (Lowell); Cristina Thomas (PSI); Padma Yanamandra-Fisher (JPL)	
Investigation 3: Dynamical and Physical Properties	
Julie Bellerose (JPL)	gravity and dynamics
Eugene Fahnestock (JPL)	ejecta dynamics
Daniel Scheeres (U Colorado)	geotechnical properties
Douglas Hamilton (UMD)	orbital dynamics
Collaborators: Eric Asphaug (ASU); Bill Bottke (SWRI); Christine Hartzell (UMD); Toshi Hirabayashi (Purdue); Jay McMahon (U Colorado); Paul Sánchez (U Colorado); Gal Sarid (UCF); Simon Tardivel (JPL); Kevin Walsh (SWRI)	
Investigation 4: Science Proximity Observations	
Nancy Chabot (APL)	DRACO Instrument Scientist
Carolyn Ernst (APL)	impact site morphology characterization

Working Group 1: Modeling and Simulations of Impact Outcomes		
Gareth Collins	Nilda Oklay	Mark Price
Frank Schaefer	Gonzalo Tancredi	Martin Jutzi
Juergen Blum	Yang Yu	Kai Wünnemann
Jean-Baptiste Vincent*		
Working Group 2: Remote Sensing Observations		
Marco Delbo*	Elisabetta Dotto	Petr Scheirich
David Polishook	Julia de León	Javier Licandro
Working Group 3: Dynamical and Physical Properties		
Jens Biele*	Derek Hestroffer	Fernando Moreno
Siegfried Eggl	Rosemary Mardling	Alessandro Rossi
Seth Jacobson	Naomi Murdoch	Paolo Tanga
Antii Penttila	George Voyatzis	Pascal Rosenblatt
Working Group 4: Science Proximity Observations		
Ian Carnelli	V Ciarletti*	Kieran Carroll
Andres Galvez	Simon Green*	K Mellab
B Grieger	A Herique*	M Kueppers

* AIM Investigation Team members

Investigation Team WGs (4)

Impact Modeling & Simulation

- Benchmark codes and determine the sensitivity to impact models and to impact conditions.
- Initial comparisons show promising comparisons between codes. Use of similar strength models yields consistent results for different codes.
- From the magnitude of the deflection, determine the momentum transfer efficiency and beta and its relation to the target properties.
- From the impact event, investigate the ejecta mass and the predicted size of the resulting crater.
- Support mission design studies.

Remote Observation

- Refine the properties of the binary system
- Constrain the composition and spectral properties of the Didymos system
- Measure the change in the orbital period due to the DART impact and characterize the dynamical evolution of the satellite and impact ejecta
- Team of planetary astronomers obtaining telescope time for 2017 apparition, advance planning for subsequent apparitions
- DART impact during excellent apparition: Didymos at V ~ 14-15, very well placed for Chile, easily observable from other observatories

Dynamical & Physical Properties

- Supply and maintain jointly with AIM team a reference model for the Didymos system.
- Determine the long-term dynamics and stability of the system to assess expected changes in measured post-impact quantities. The current focus is that solar tides may cause important variation in orbital period.
- Predict physical properties based on pre-encounter modeling.
- Investigate dynamical effects of impact, including ejecta evolution. Impact may induce libration, and material exchange between components.

Science Proximity Operations

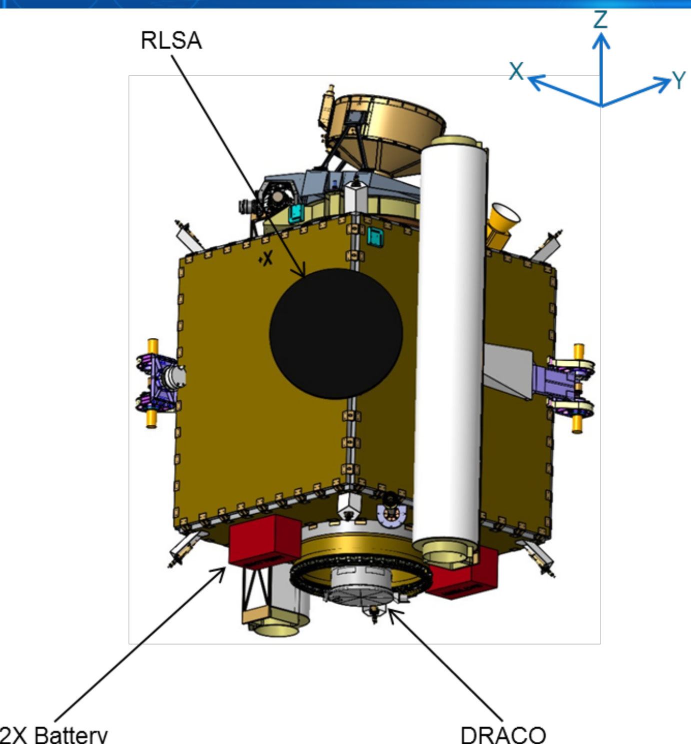
– Complete a detailed imaging plan (including for when to downlink binned and unbinned data) for DRACO calibration and observations prior to impact

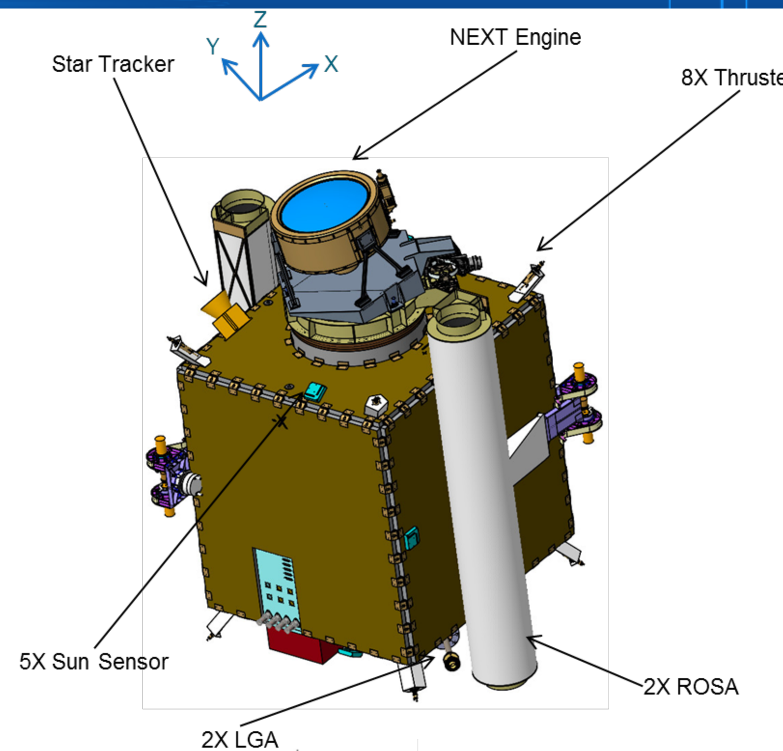
– Develop detailed plan for SOC architecture, including tools for uplink, DRACO calibration pipeline, and implementation of scientific analyze tools.

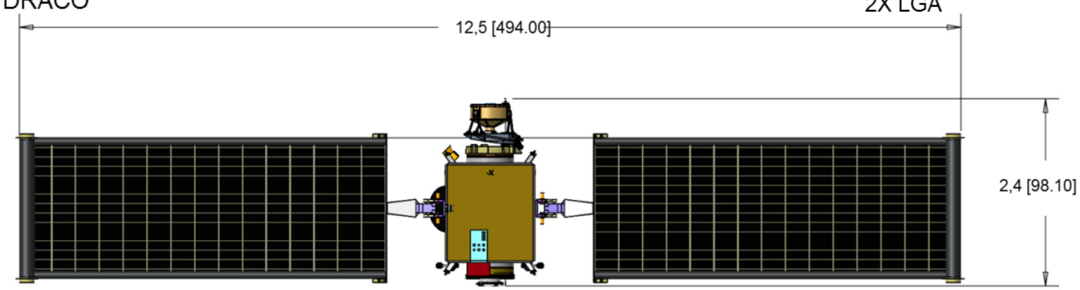
– Develop the interface requirements document needed between the virtual SOC/science team and MOC, for observation planning and DRACO data delivery.

– Develop document describing the data products to be produced by the proximity observation team.

DART Spacecraft Overview

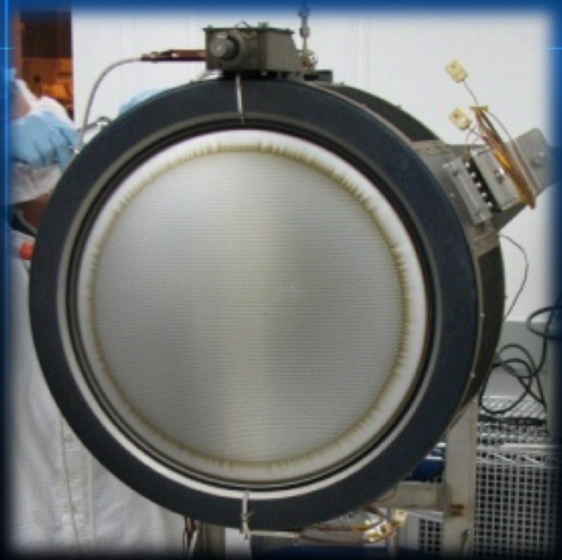


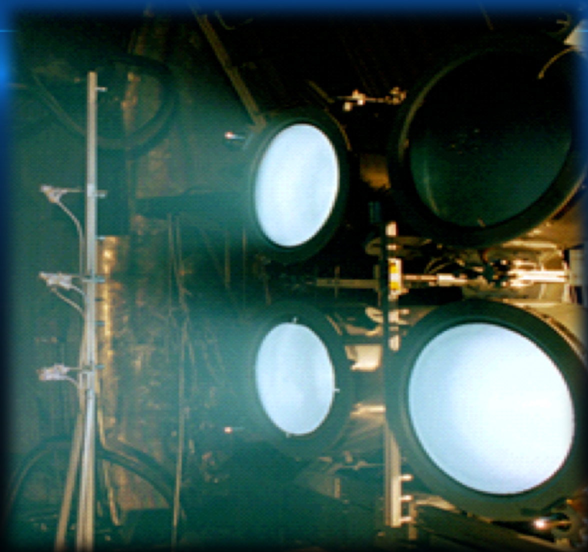




Dimensions are Meters [Inches]

NEXT-C Project: DART Collaboration





Performance Characteristics	
Thruster Power, kW	0.5 – 6.9
Specific Impulse, sec	2500 - 4200
Thrust, mN	25 - 235
Thrust –to-Power, mN/kW	32 - 48
Thruster Efficiency	0.32 – 0.7
Lifetime - Xenon Throughput, kg	> 600

- NASA's Evolutionary Xenon Thruster (NEXT) began as a technology development project
- NEXT-C project's objective is to transition the NEXT technology to flight and create a commercially available product (Managed by NASA GRC)
- The NEXT-C project is producing two flight qualified thrusters and two Power Processing Units (PPUs)
- Flight project preparing to support a mission(s) with GFE flight hardware delivery in early 2019

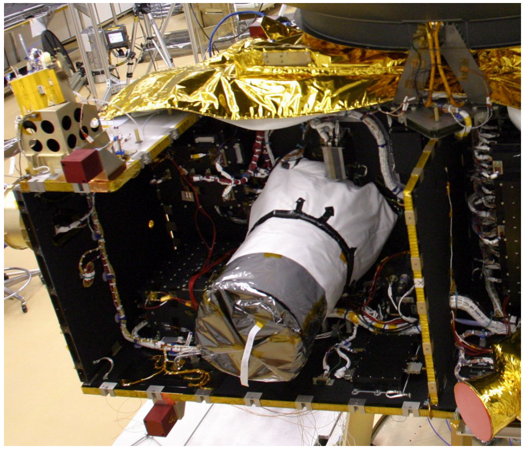
DART is the first flight of NEXT and will fully qualify it for future deep space missions

DART Double Asteroid Redirection Test

DART: Didymos Reconnaissance and Asteroid Camera for OpNav (DRACO) Imager

- **Design Summary**
  - Heritage design based on LORRI from New Horizons mission
    - Uses of a CMOS 2k x 2k (BAE sCMOS) detector instead of LORRI CCD
    - Data Processing functions implemented in Avionics IEM instead of LORRI DPU
  - Visible narrow angle camera with a large aperture (200 mm) and good optical performance
  - Build to print LORRI optics, with in-progress trade of switching to Al optics from SiC

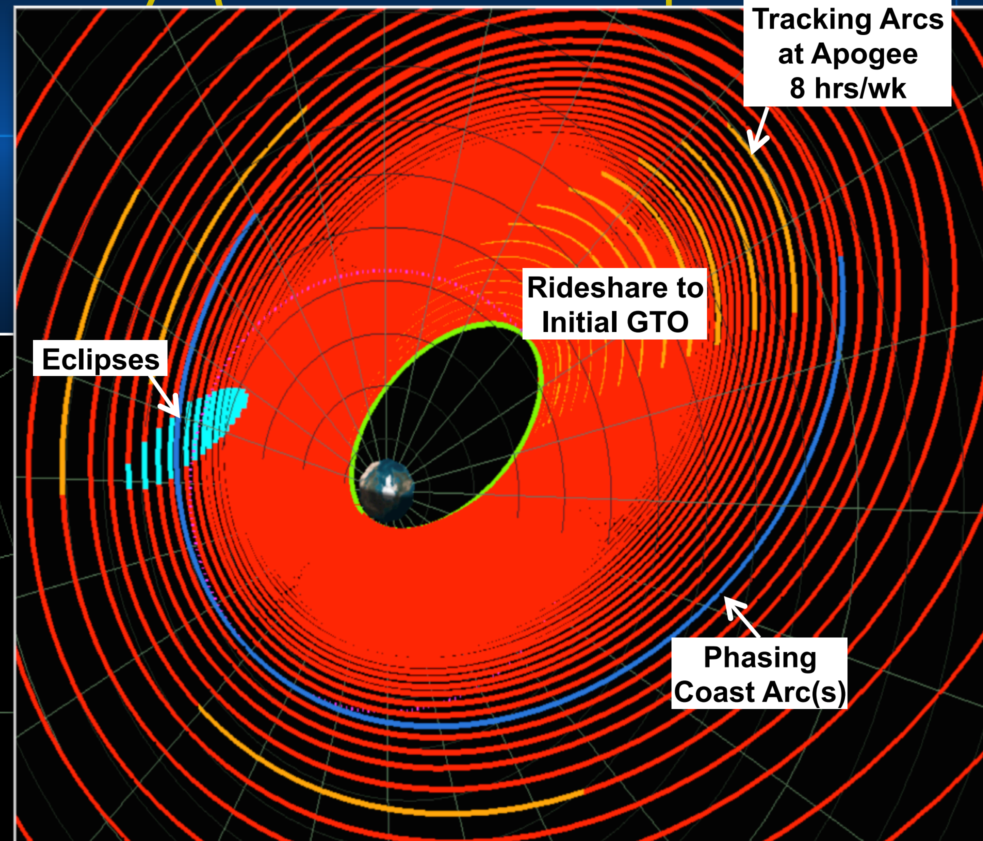
- **Instrument Uses**
  - Provides images used for distant, 30-day out, ground-based optical navigation to Didymos
  - Provides images and centroids for close, autonomous guidance to Didymos (SMARTNav)
  - Provides final images of the surface used for determining impact location and impact site morphology. These are used for impact modelling and understand effectiveness of impact.

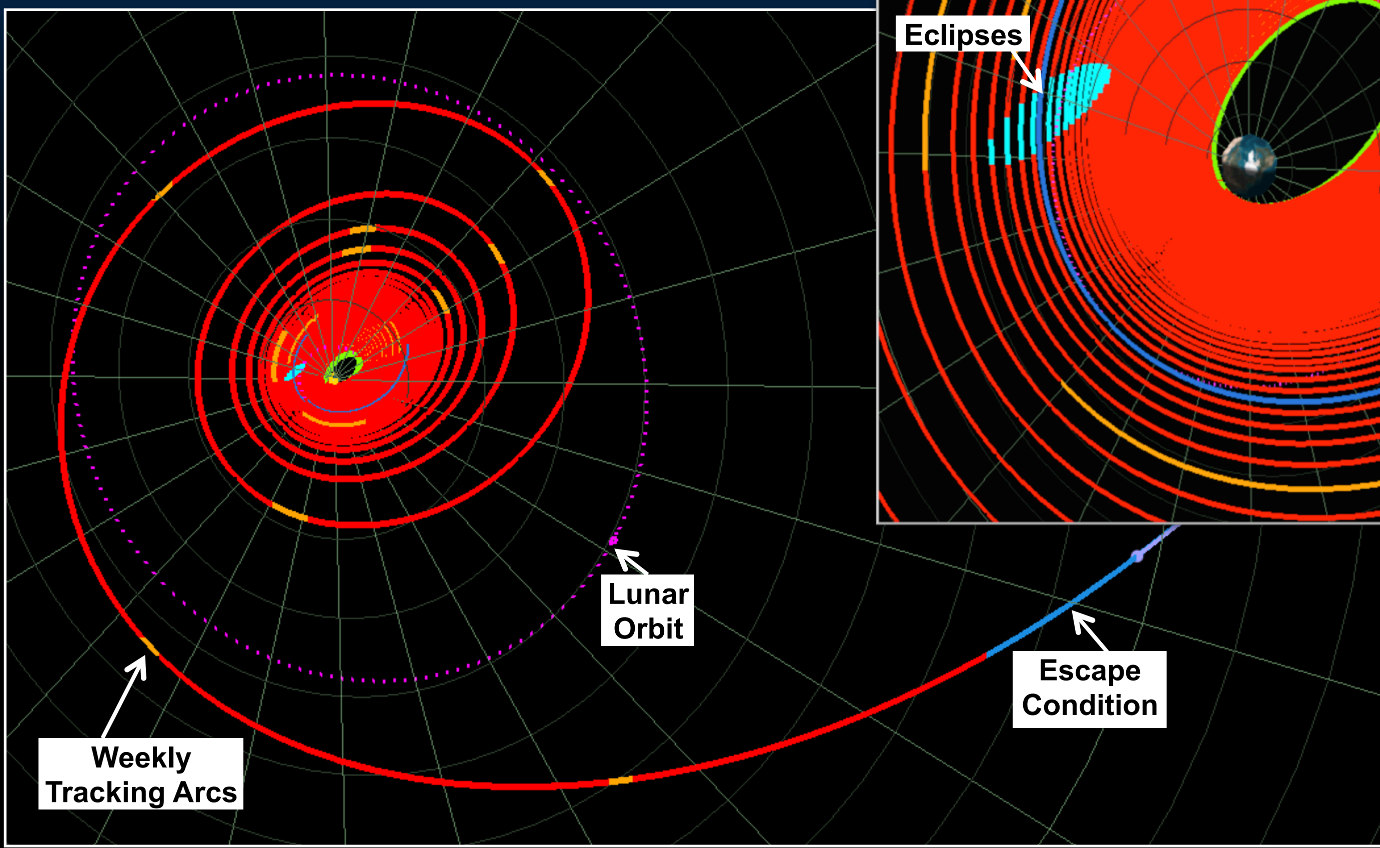


DART Double Asteroid Redirection Test

DART Baseline Trajectory (Earth Escape)

- Launch Jan 26 2021, 640 kg (1 case within launch period)
- Clear GEO Altitude, May 26 2021, 600 kg (120 day)
- Clear Upper Van Allen Belts, June 18 2021, 592 kg (143 day)
- Escape Aug 28 2021, 568 kg (214 day)
- Continuous tangential thrusting, except for eclipses, tracking and phasing arcs.



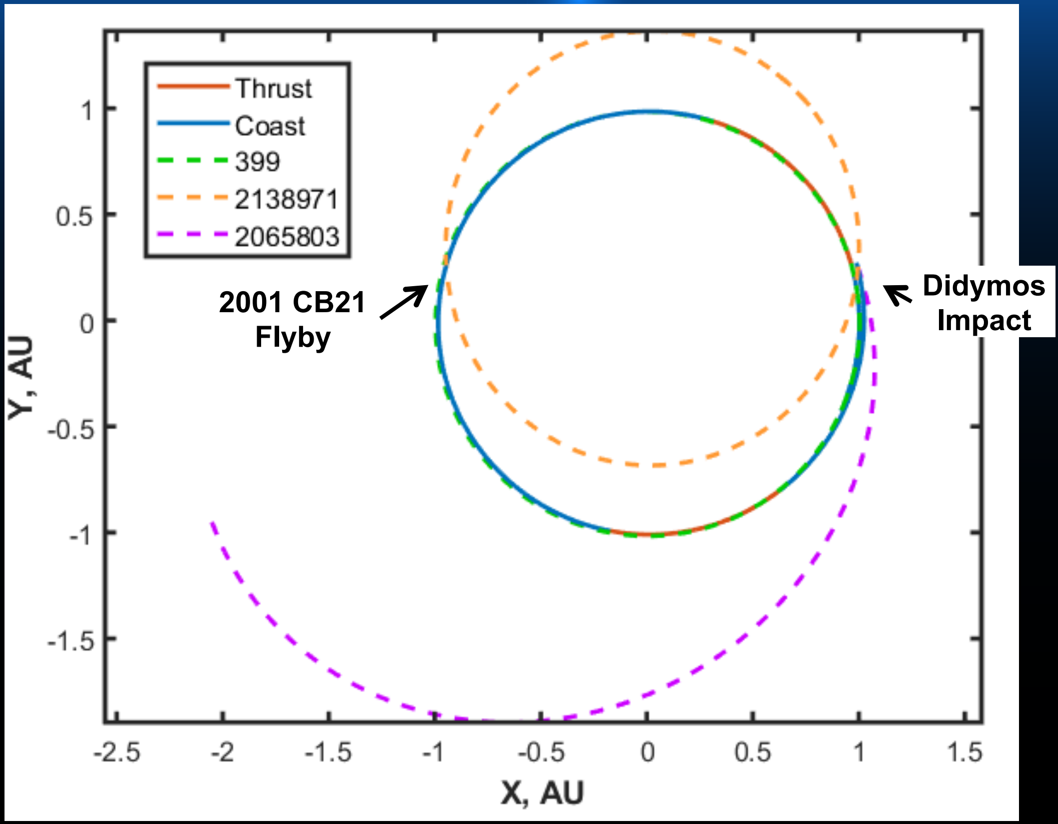


IPS restarts (spiral and cruise)

- Eclipse On/Off cycles: 15 (worst-case launch: 180)
- Other On/Off cycles: 36
- Total On/Off cycles: 51
- Minimum eclipse restart:30 min. (min. design - 30 min.)
- Maximum eclipse restart: 71 min. (max. allowable - 150 min.)

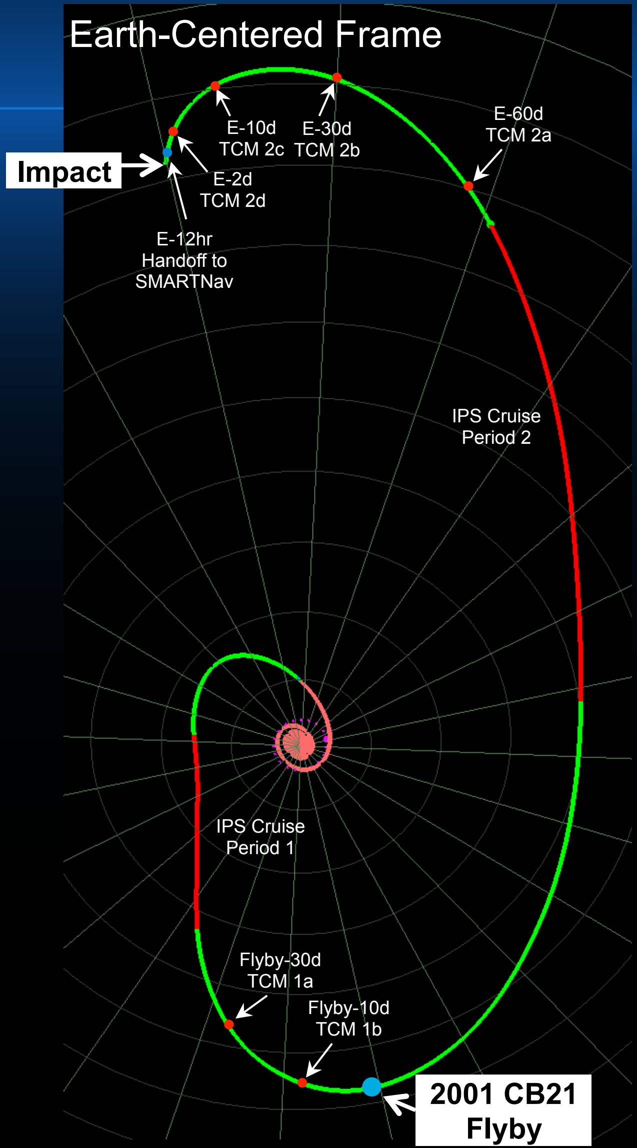
DART Baseline Trajectory (Deep Space)

Flyby: Mar 03 2022, 640 kg, 11.37 km/s (67 day coast arc)
Impact: Oct 07 2022, 529 kg, 5.92 km/s (82 day coast arc)



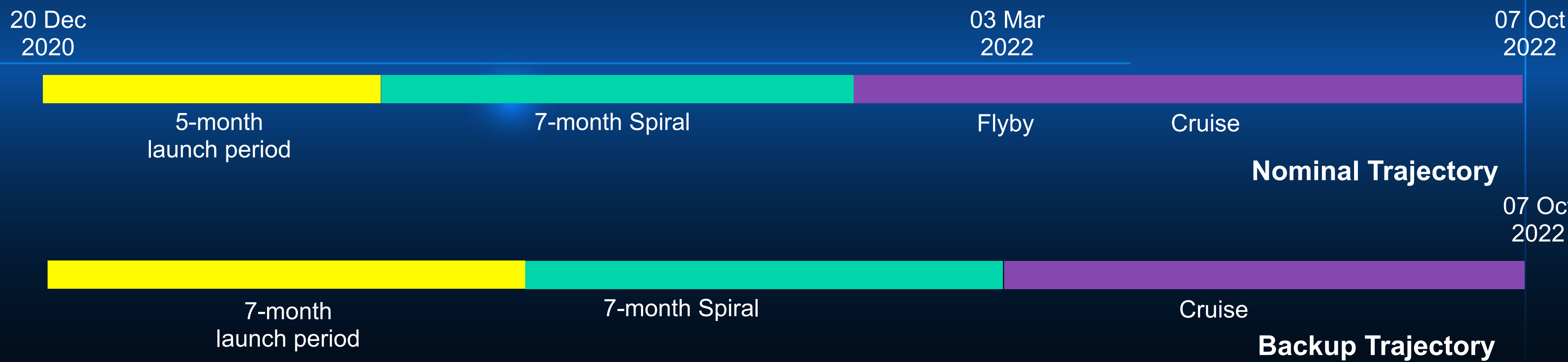
Sun-Centered Inertial Frame

*All planned, deterministic maneuvers are accomplished with IPS
*Zero planned, deterministic, impulsive ΔV by mission design in baseline reference trajectory



DART
Double Asteroid Redirection Test

DART Baseline Launch Schedule (Commercial Rideshare)



- Baseline includes
  - **5-month launch period**
  - **7-month spiral**
  - **Asteroid 2001 CB21 flyby**
  - **Impact in Oct 2022**
- Backup trajectory eliminates the flyby
  - **Launch window extended to 7 months**
  - **Spiral duration and impact date unchanged**
- Additional power for the EP system can extend launch period further by shortening the spiral time

What will DART achieve?

Before DART

- Theoretical understanding of kinetic impactor mitigation
- Impact codes necessary for mitigation planning untested in relevant physical regime
- Realistic-sized hazardous asteroid response to impact mitigation poorly constrained in important ways

After DART

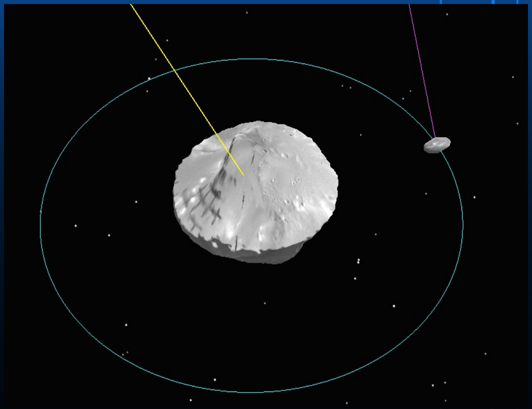
- "Dress Rehearsal" on appropriately-sized object of most common NEO composition (representative threat), demonstrating ability to intercept
- Impact models validated and cross-referenced, allowing confident predictions in relevant situations
- Improved understanding of important asteroidal physical parameters

DART Firsts

First mission to **measure asteroid deflection** by determining the "ejecta momentum amplification factor" of a kinetic impactor, **as well as the initial conditions** (impact conditions, target's properties)

First mission (with AIM) to **study a binary asteroid,** its **origins** and **interior structure**

First mission to fly **NASA's NEXT** solar electric propulsion technology.



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