DART

JOHNS HOPKINS APPLIED PHYSICS LABORATORY

NASA

# Ground System Real-time Image Processing of DRACO Observations for the DART Mission

## NASA's First Planetary Defense Mission

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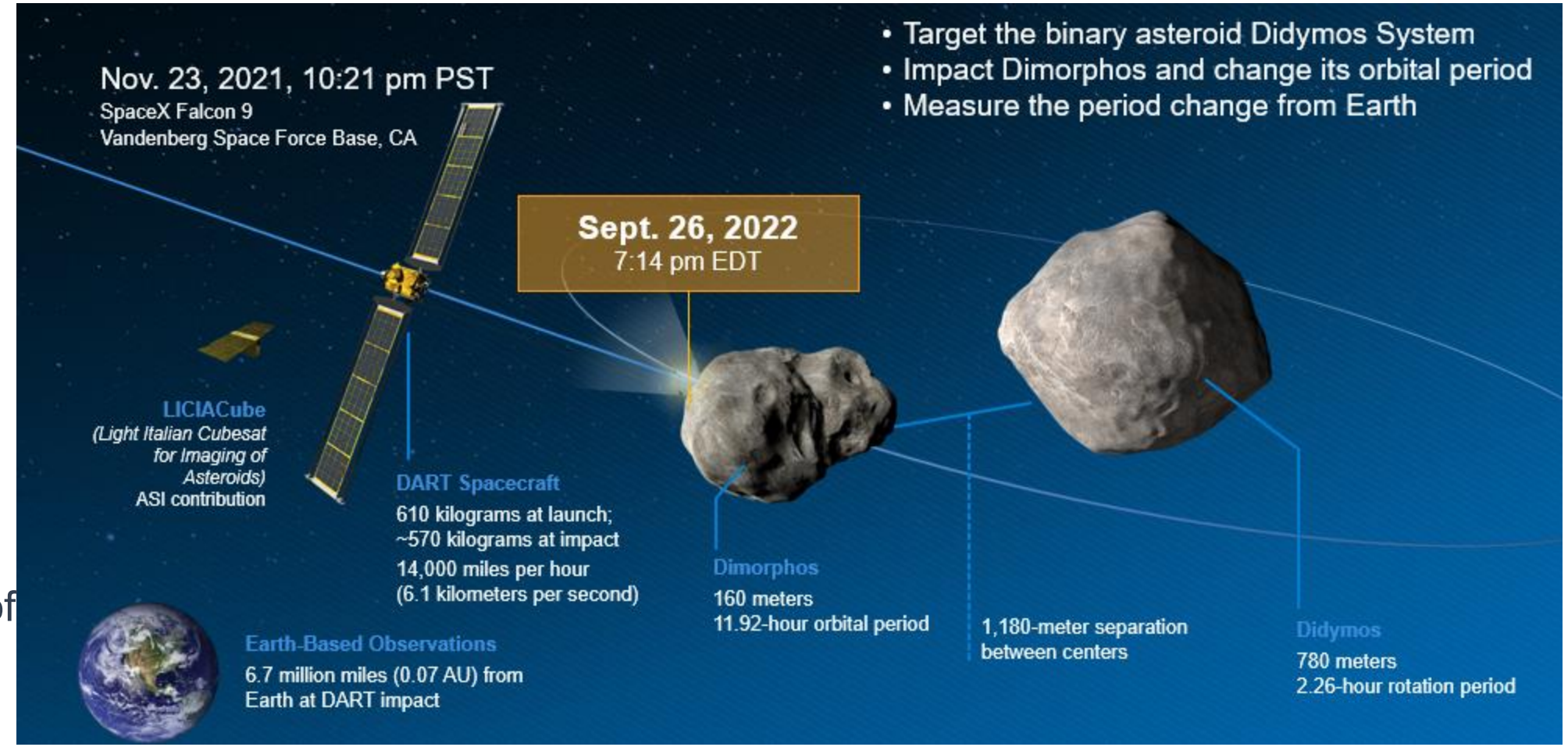
# DART – Double Asteroid Redirection Test

## The first mission to demonstrate asteroid deflection with a kinetic impactor

Mission success for NASA:

DART spacecraft successfully impacted Dimorphos and reduced its orbit by 33 minutes (mission objective was 7.3 second change).

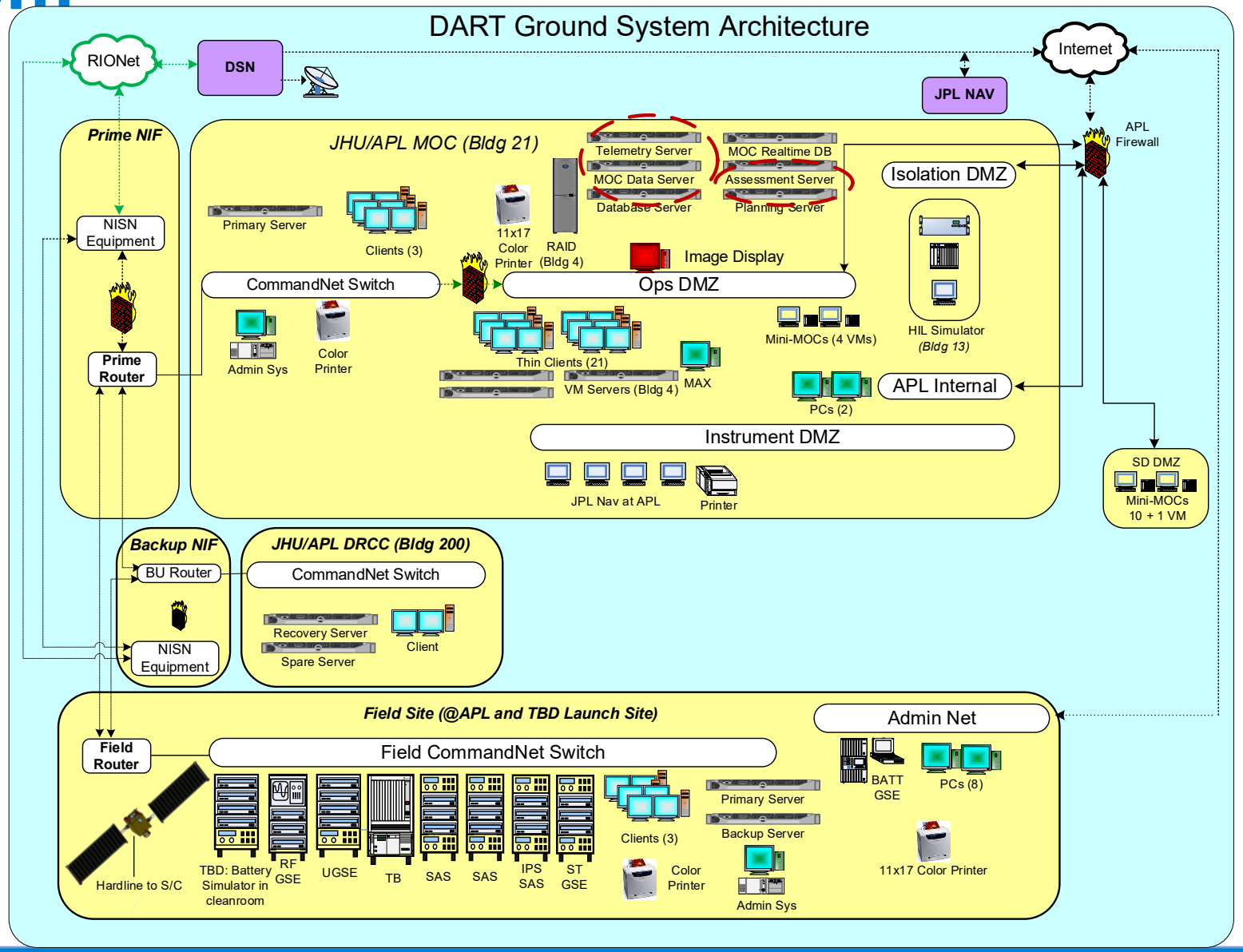
Proof of concept of kinetic asteroid deflection for planetary defense



# Ground System

Similar architecture to other APL-managed NASA missions

Red indicates hosts supporting DRACO image processing (software processing, FITS files storage or GUI display)

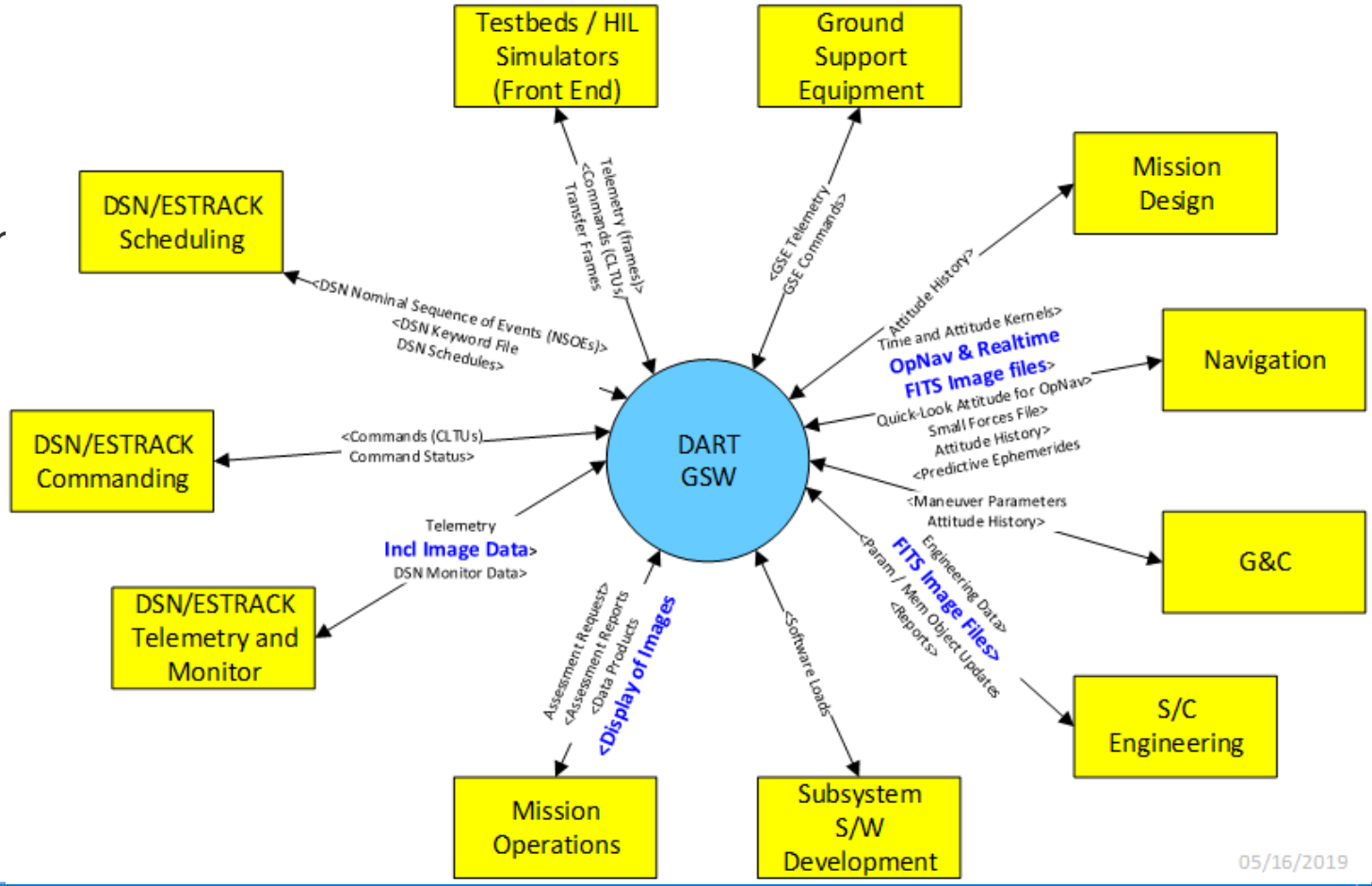


# DART Ground System Contributions

Ground Data System and Ground Software supported pre-launch as well as post-launch testing, rehearsals, and mission operations

Image processing required for:

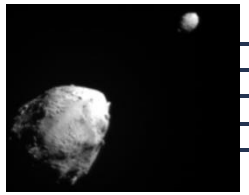
- I&T testing and imager characterization
- Hardware-in-Loop (HIL) simulatior runs
- Post-launch commissioning of DRACO
- In-flight tests including Jovian Moons tests of SMART Nav targeting
- Op Nav image observations
- DRACO images during Approach and Terminal



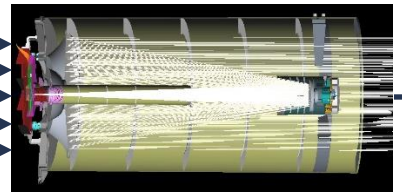

05/16/2019

# Image Flow from Telescope to Ground

Didymos/Dimorphos



DRACO Telescope



Focal Plane Array captures digital image

2161 rows x 2576 columns x 11 bits/pixel (58.4 Mbits)

High Speed Data Link (SerDes)

Images @ 1.04 Hz

Firmware and Software on Spacecraft's Single Board Computer

Step 1. Trim edges

2048 x 2048 pixels

Step 2. 2 x 2 binning

1024 x 1024 x 12 bits/pixel (lsb of 2 x 2 sum is dropped)

Step 3. Send Region Of Interest (always 512 x 512) to Radio (full 1024 x 1024 image is used for onboard navigation)

Mismatch between these two rates necessitated skipping about 1 image in every 8 to prevent falling behind real-time. That is, latest available image, not next image, is always downlinked.

NASA's Deep Space Network

DSS-35 Canberra shown – 34m antenna

**Actual antenna used during Terminal**

1.116 s/image or image rate of 0.896 Hz

3,000,000 bits/s
OWLT = 39 s

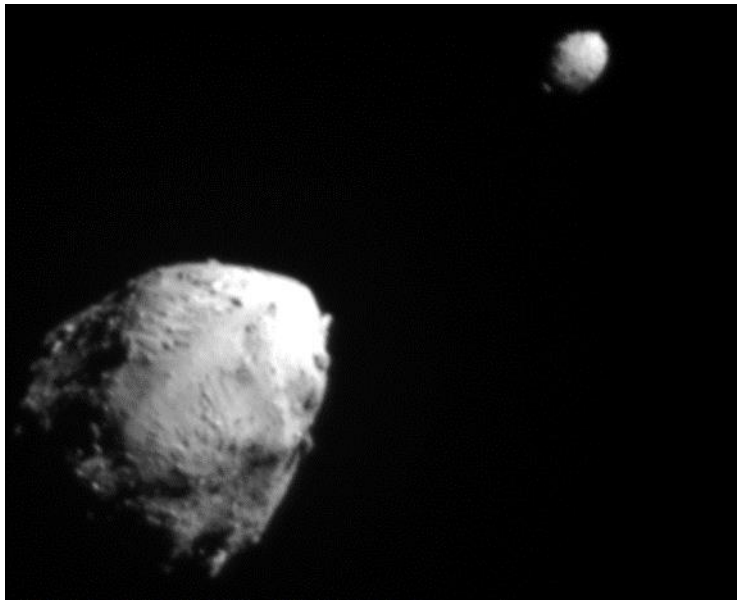
High Gain Antenna

Spacecraft Radio

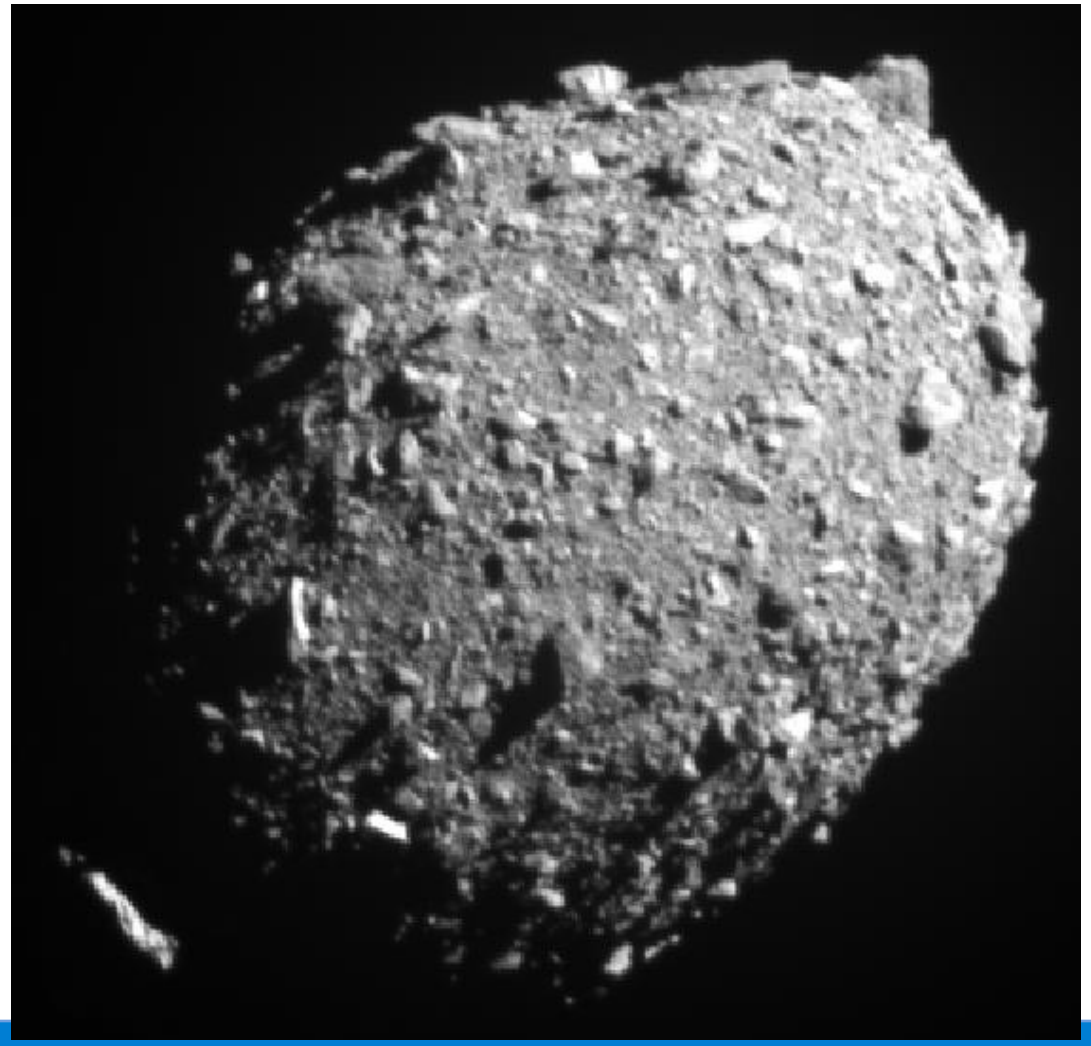
3,304,764 bits/image (with packet and frame overhead)
One packet per frame
8920 bits per frame
369 frames per image (including "header" row)

# DART images from final few minutes (512 x 512 pixels, 12 bits per pixel)

- T-minus 162 seconds (~1,000 km away)
- Final image showing BOTH Didymos and Dimorphos



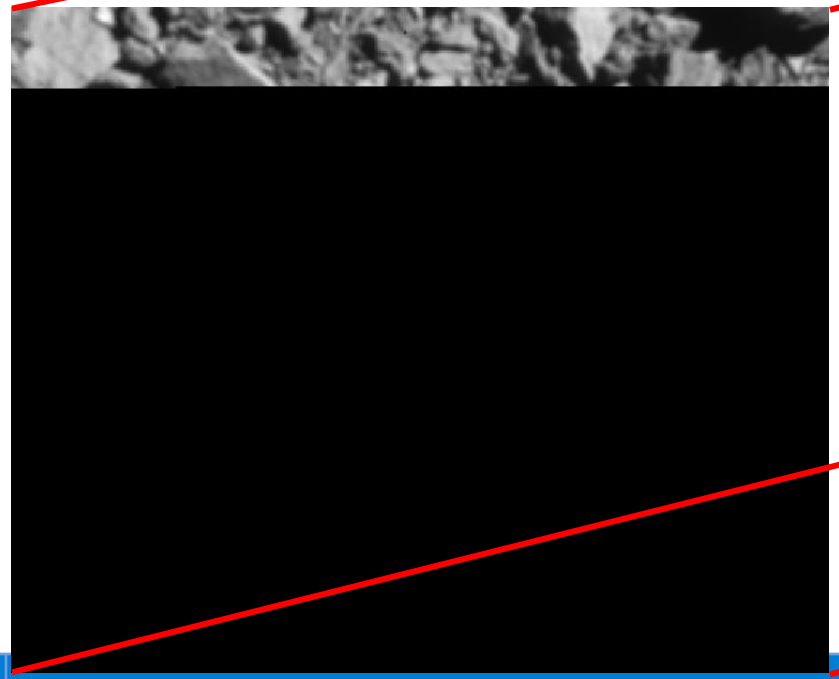
- T-minus 13 seconds (80 km away); final full Dimorphos

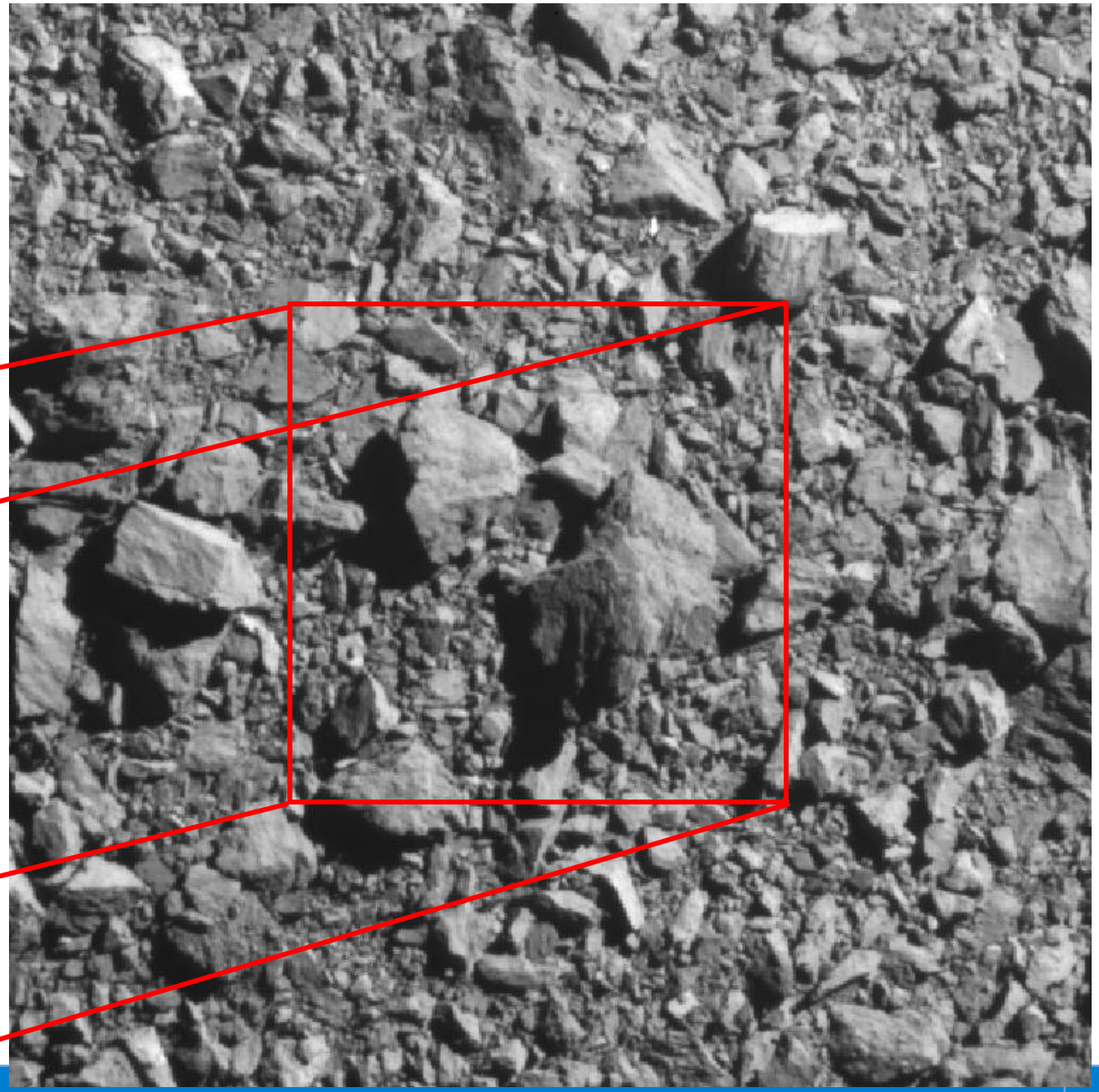


# Last Two Images

- T-minus 1.8 seconds (last complete image, 11 km away, showing approximately a 28 x 28 meter portion of the surface)

- T-minus 0.86 seconds. Image transmission was interrupted by impact. Image processing recognized the incomplete image data and processed what it had.





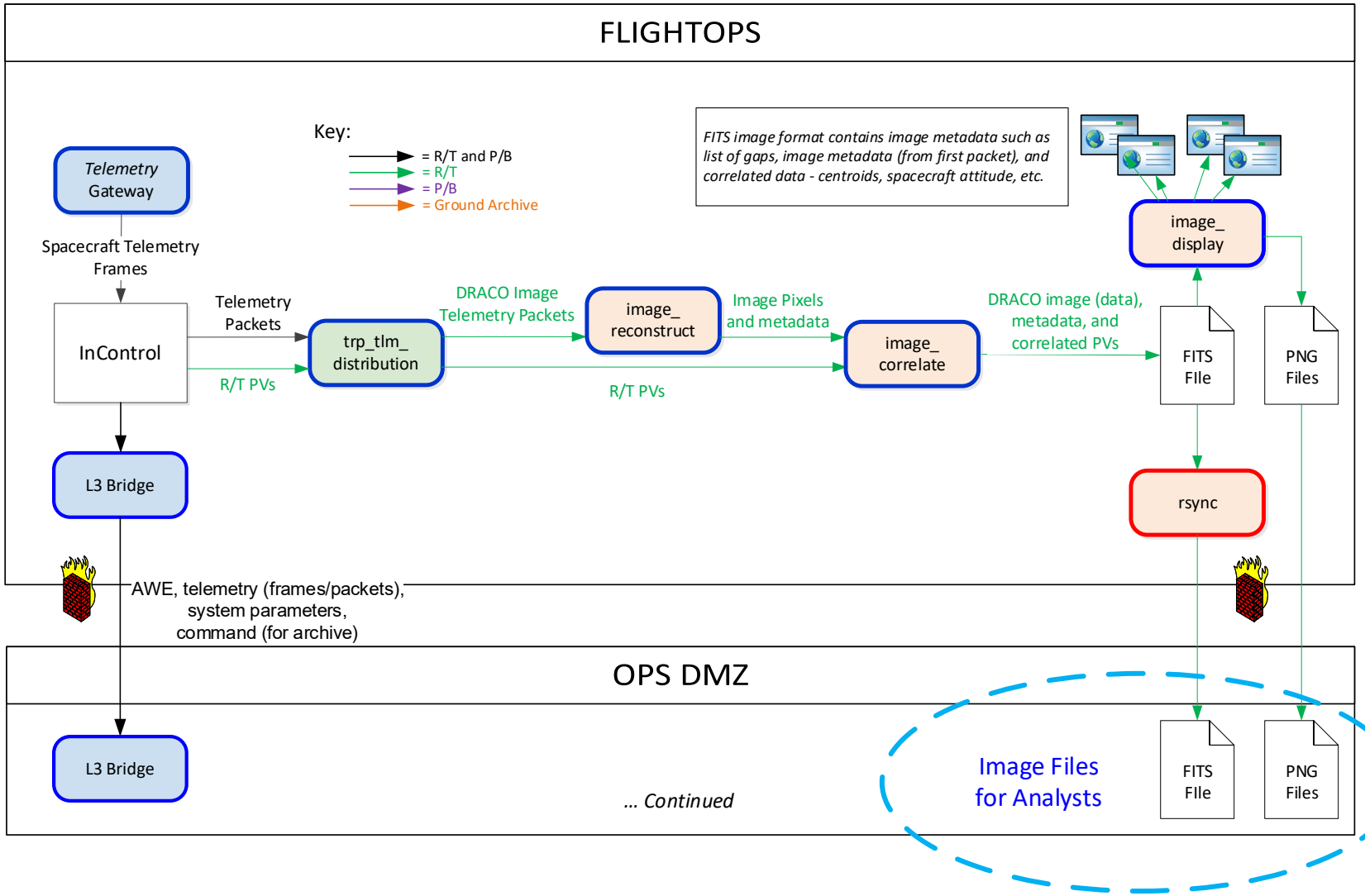
# Ground Image Processing Pipeline

## Not just pretty pictures!

Ground Pipeline

1. Reconstruction of images from raw DRACO CCSDS packets (**Image_Reconstruct** service)
2. Correlation of reconstructed images with telemetered spacecraft housekeeping and navigation data. Results written to Flexible Image Transport System (FITS) formatted files (**Image_Correlate** service)
3. Rapid FITS file delivery to analysts, ImageDisplay, and other users (via immediate rsync and **MOC Data Server**)
4. Visualization and display of images with navigation indicators, used for evaluating real-time SMART Nav (autonomous guidance and navigation algorithm) performance (**ImageDisplay webservice**)
   - Supported simultaneous browser access by users on demand from MOC servers, laptops, remote VPN
5. Modes for both realtime images and images played back from the DRACO recorder, as well as an offline means to update incomplete correlation data (post-pass)

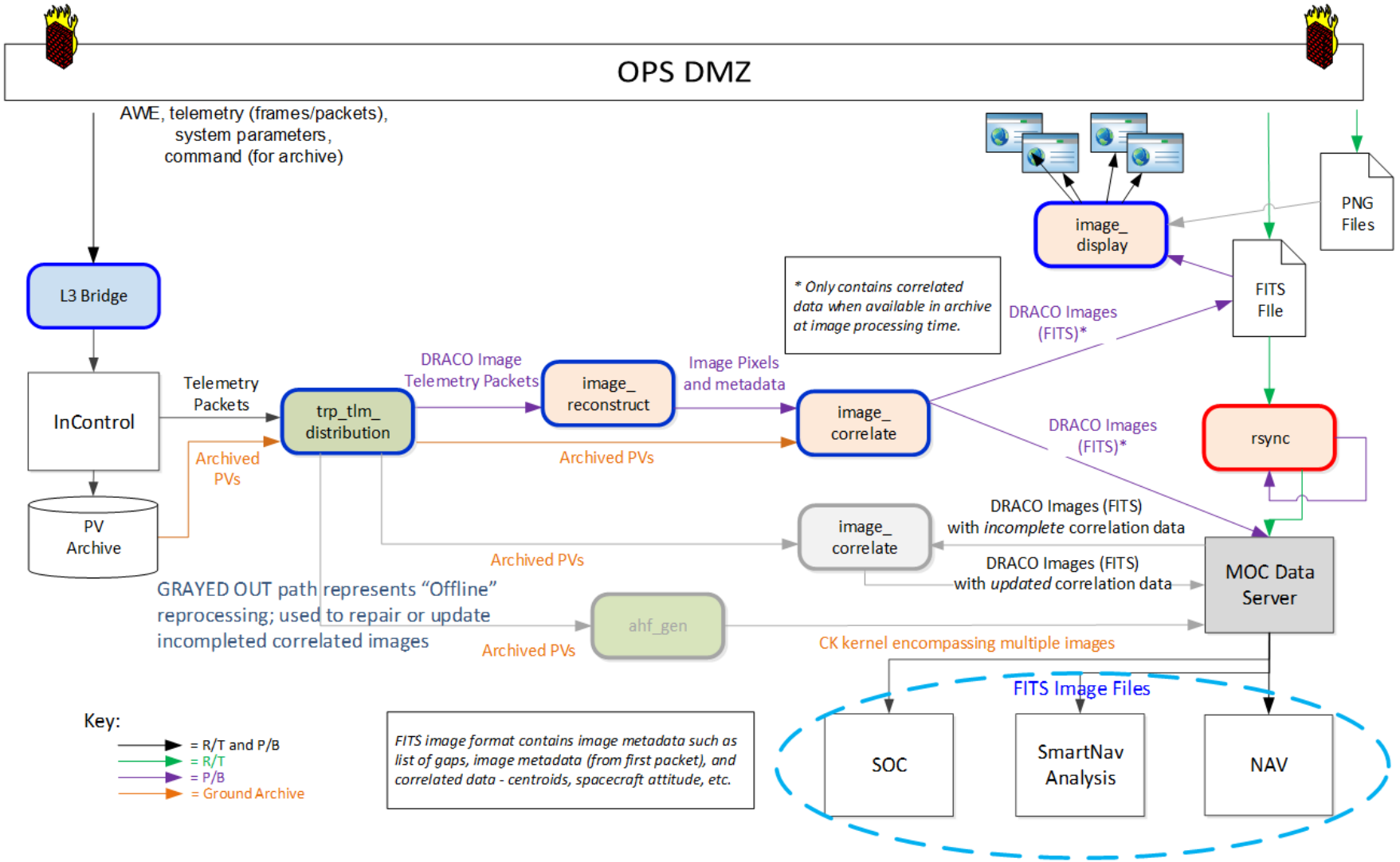
# Image Processing Data Flow – *Realtime* Images




Realtime: DRACO images **streamed immediately** to ground, transmitted during contact with spacecraft (with contemporaneous telemetry)

- Image header packet
- GNC packet

# Image Processing Data Flow – *Playback* Images

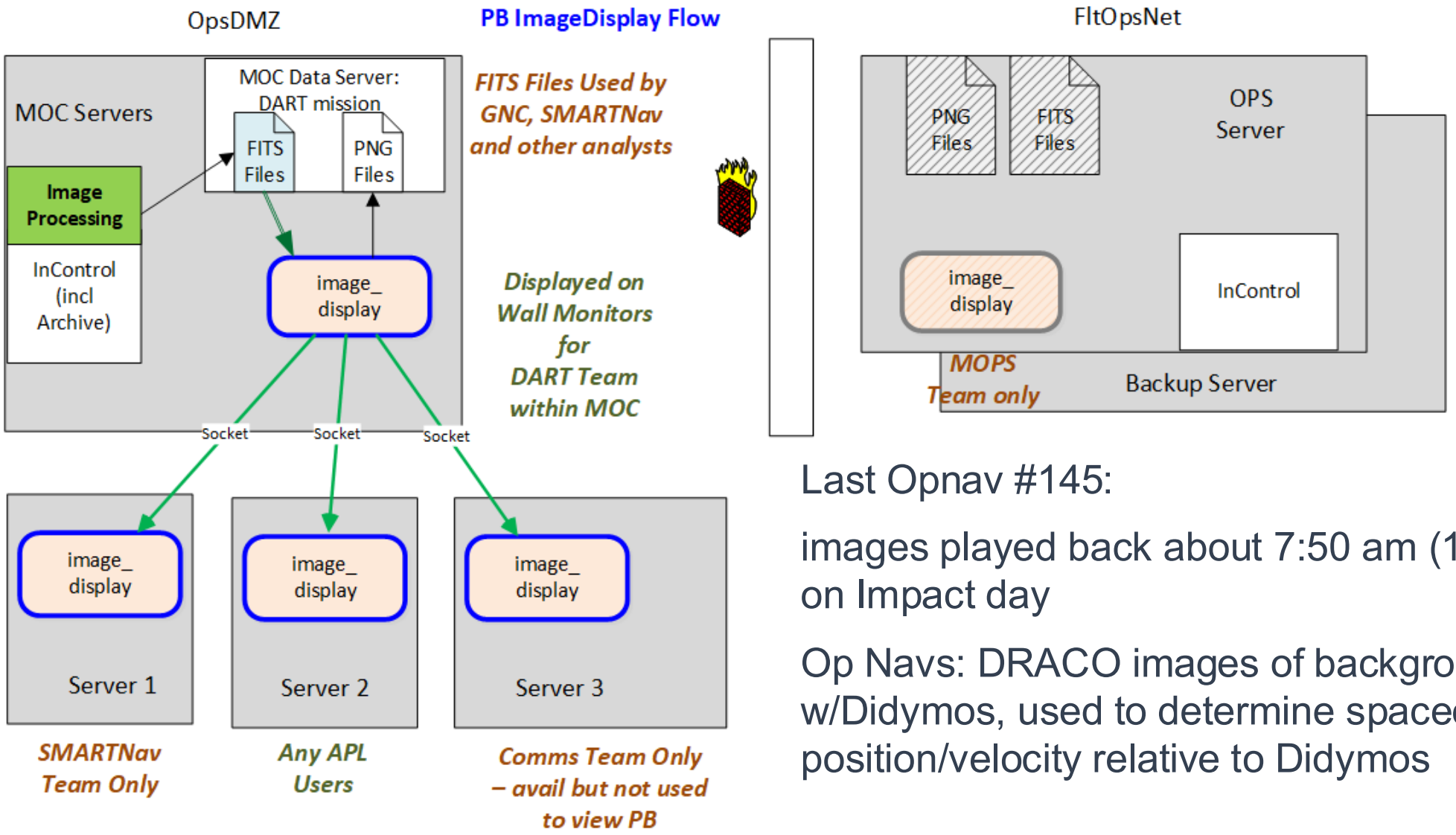



Playback: Images saved during observations made out of contact, **later transmitted** to ground (must transmit associated telemetry **before** the images, to permit correlation)

# Technologies Used

- Technologies used in ground software's image processing and display pipeline
  - TRP (Telemetry Request Protocol), a client-server protocol using the Google Protocol Buffers language
  - TCP/IP connection to TRP Tlm Distribution service
  - XML configuration files
  - NASA ***nom-tam-fits*** library for FITS file writing/reading/updating (imageCorrelate only)
  - Java Serialization for passing images and metadata over TCP from imageRecontruct to imageCorrelate
  - Java Threads
    - Receiving/queueing incoming data
    - Processing data
  - Spring Boot (web server, back-end)
  - Angular II Typescript (front-end web application UI)
  - Java 1.8
  - Gradle, Maven (build, dependency management)
  - Bamboo (continuous integration, push-button deployment)

# ImageDisplay Data Flow – Op Navs

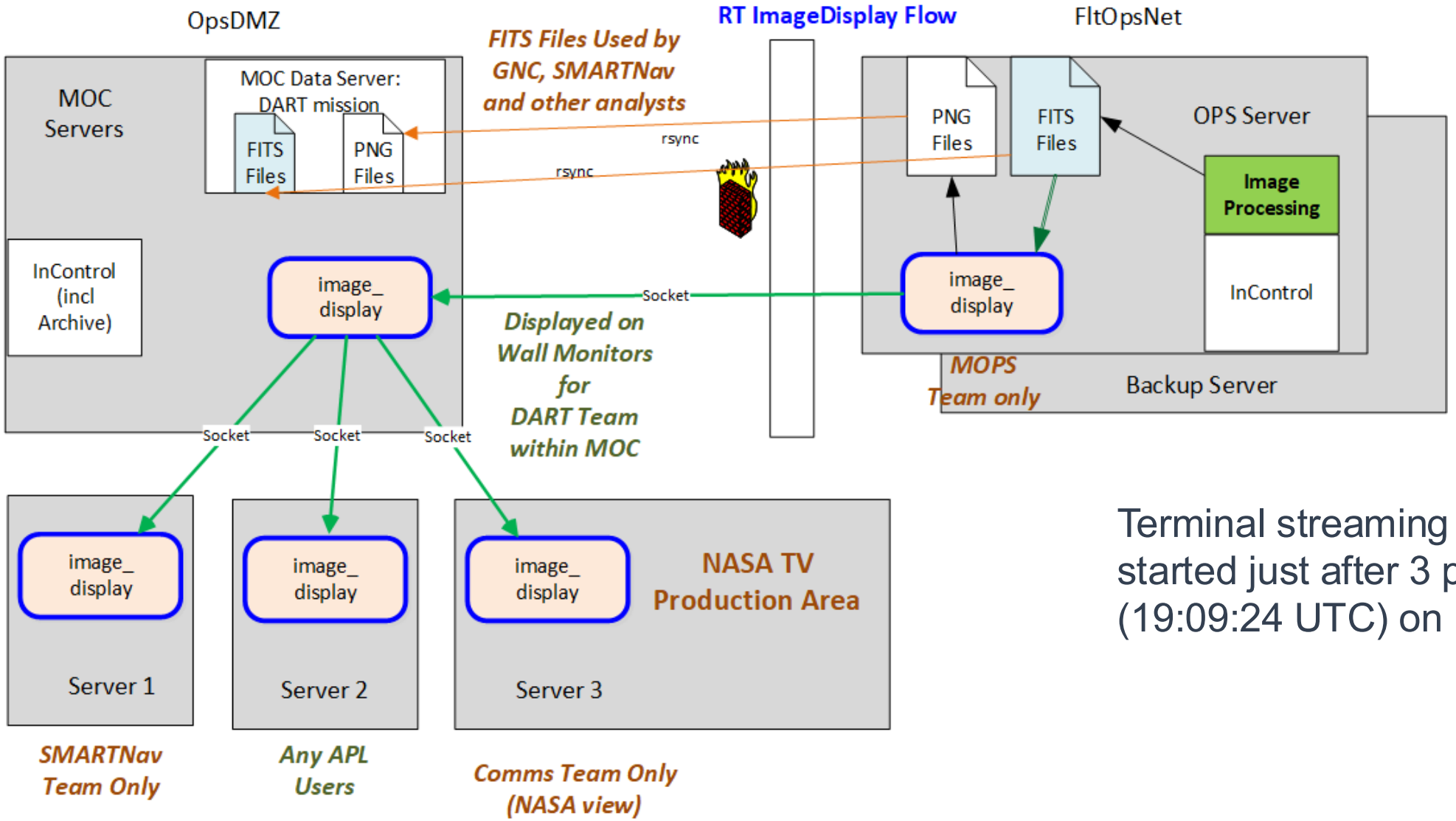



Last Opnav #145:

images played back about 7:50 am (11:50 UTC) on Impact day

Op Navs: DRACO images of background stars w/Didymos, used to determine spacecraft position/velocity relative to Didymos

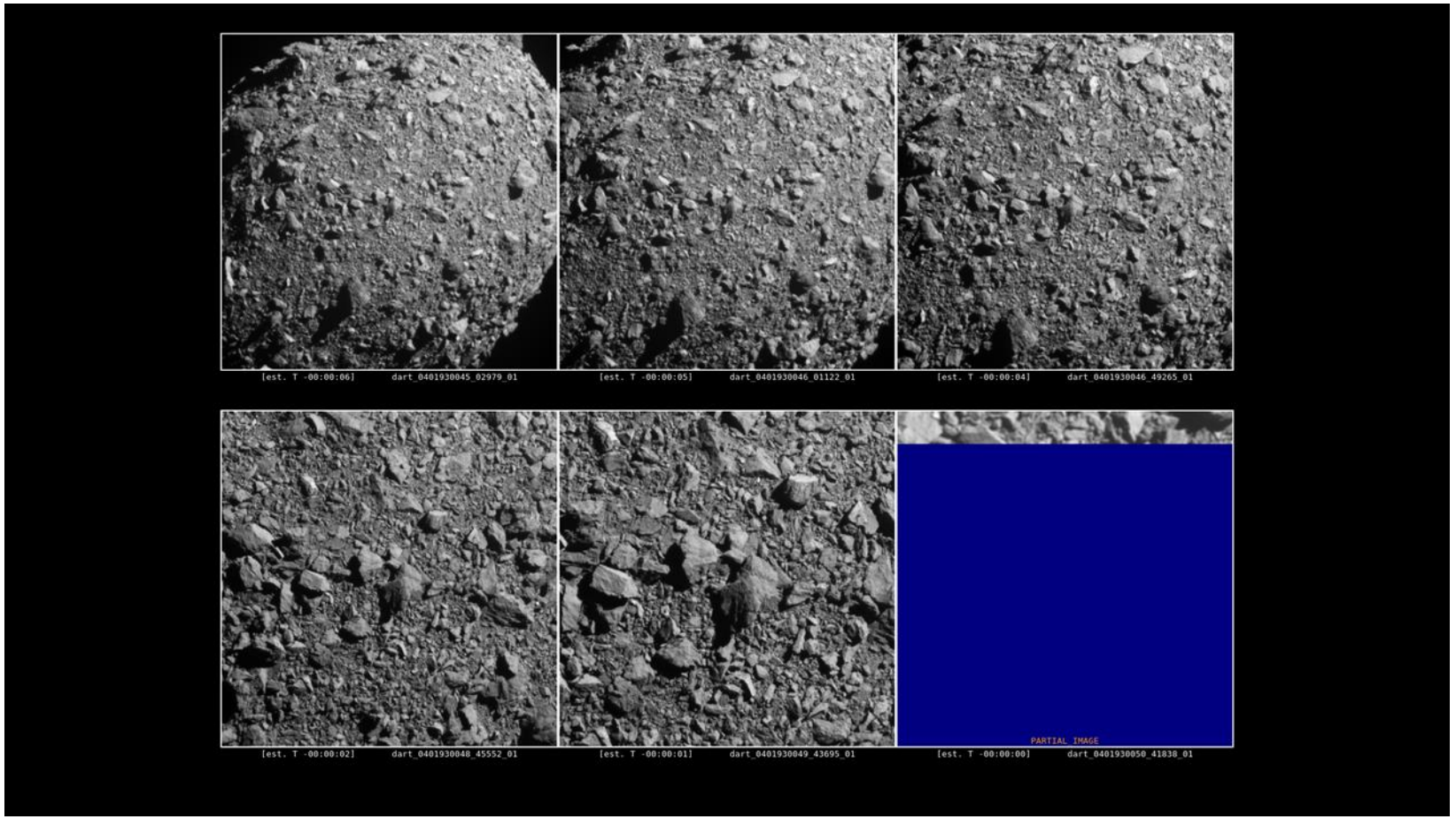
# ImageDisplay Data Flow – Terminal RT Stream




Terminal streaming of RT images started just after 3 pm EDT (19:09:24 UTC) on Impact day

# Feed into DRACO Engineering Mosaic Display

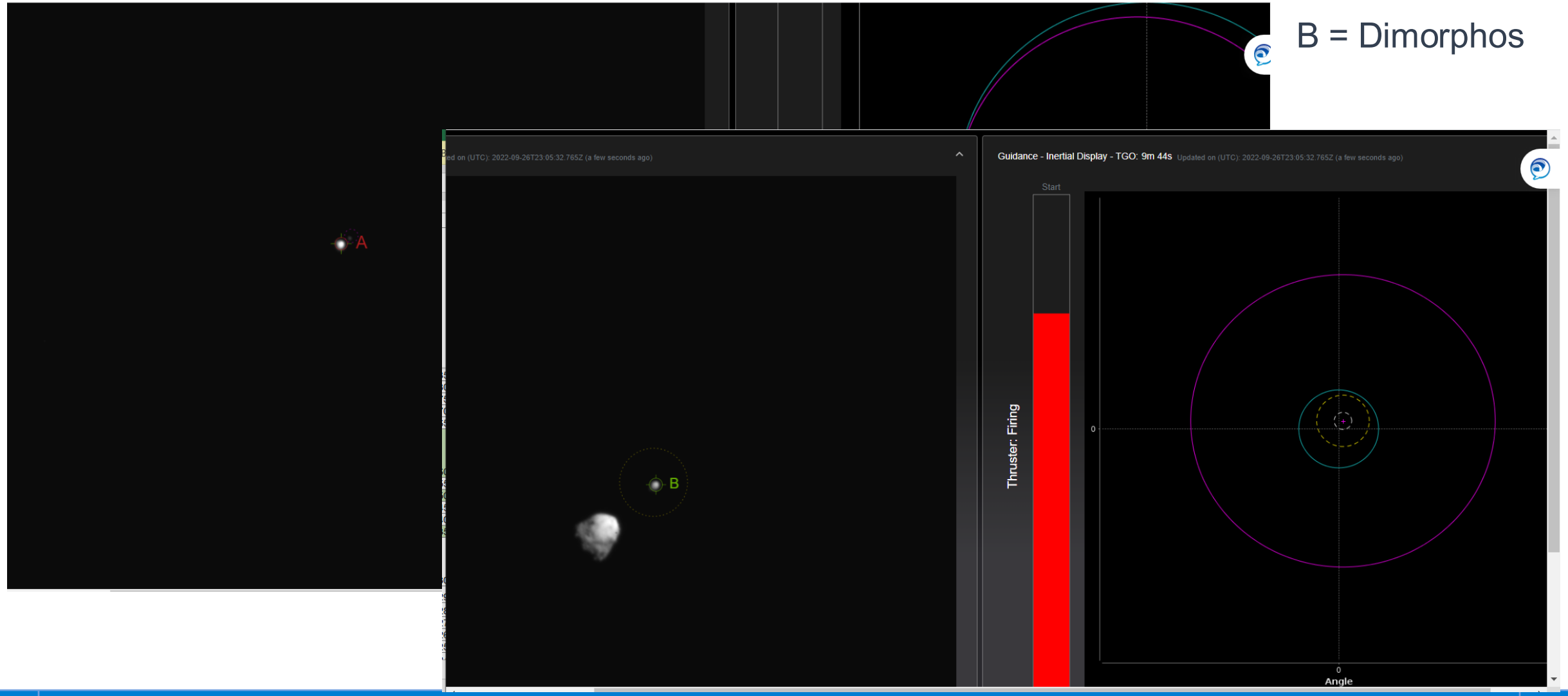
- Engineering Team devised a customized mosaic (last 6 images, rotating)
- Updating from the FITS files as fed from Ground Software pipeline
- Displayed alongside the ImageDisplay view



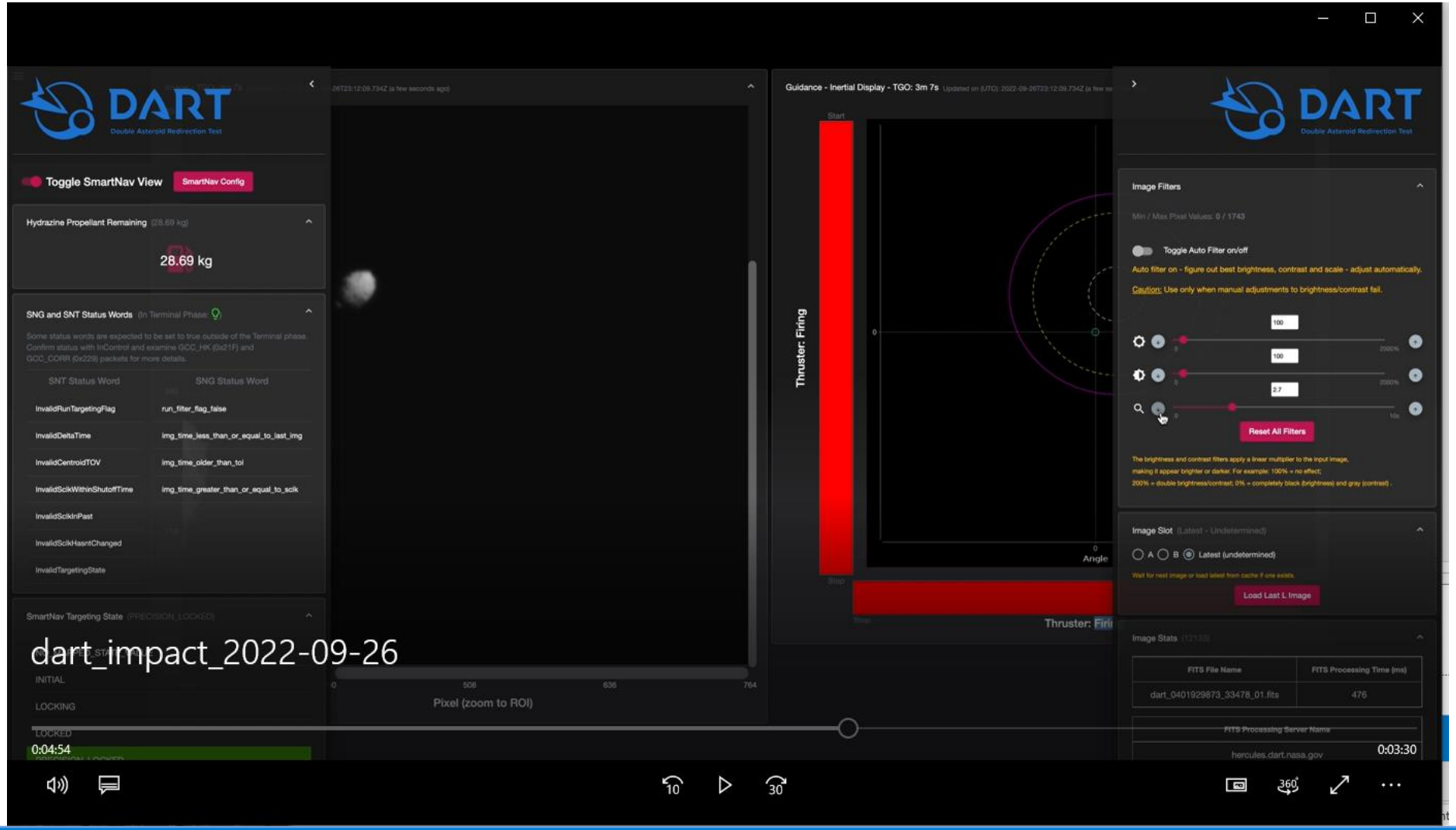
# Informal Snap from GSW Instance

A = Didymos

B = Dimorphos

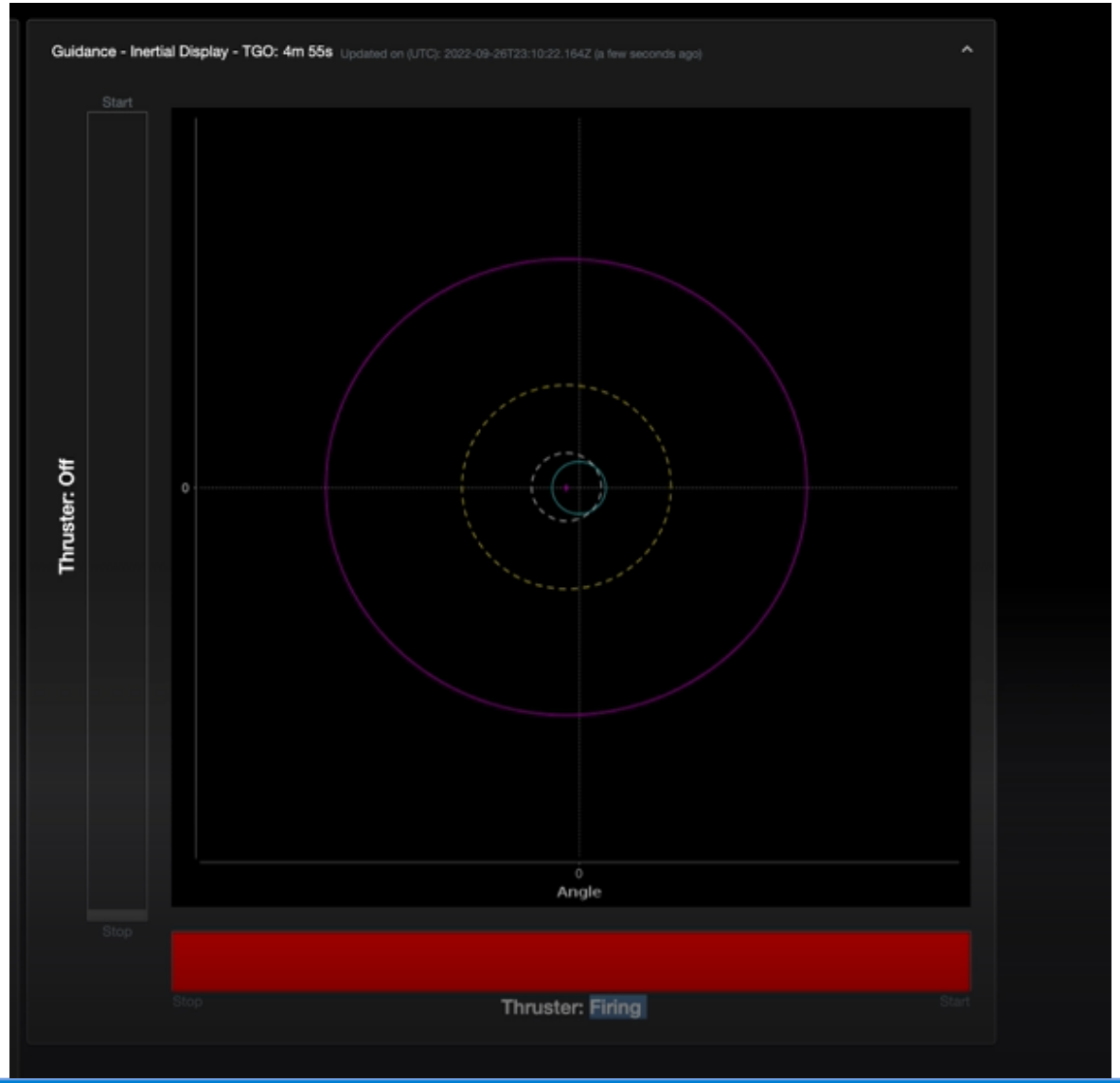


# GSW Image Display During Terminal – Showing Configuration Panels




Showing the side panels for configuration of the viewer and which overlays to show/ hide.

# What Did the Circles Mean?



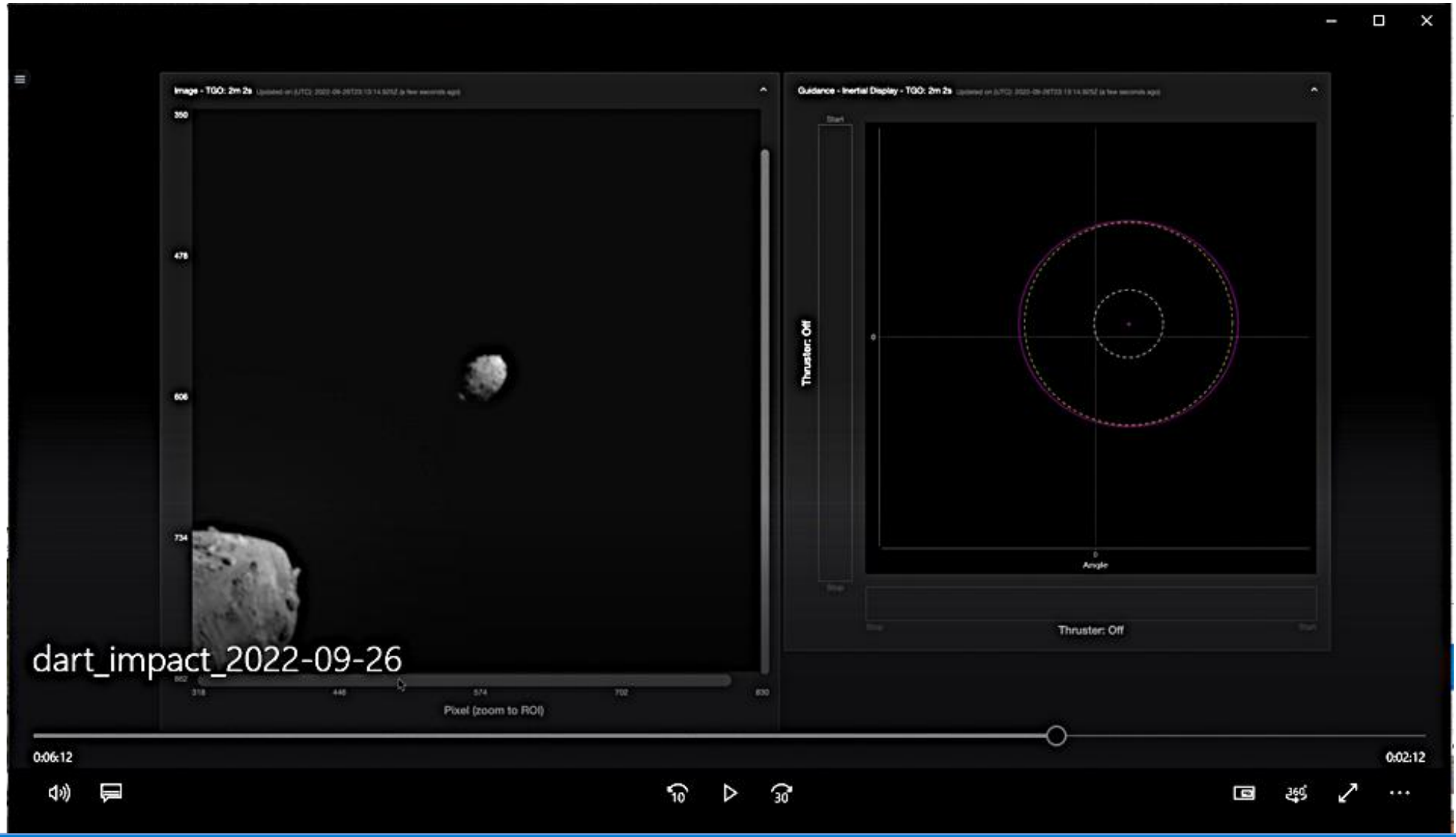

Overlays

Toggle All Image Overlays On/Off

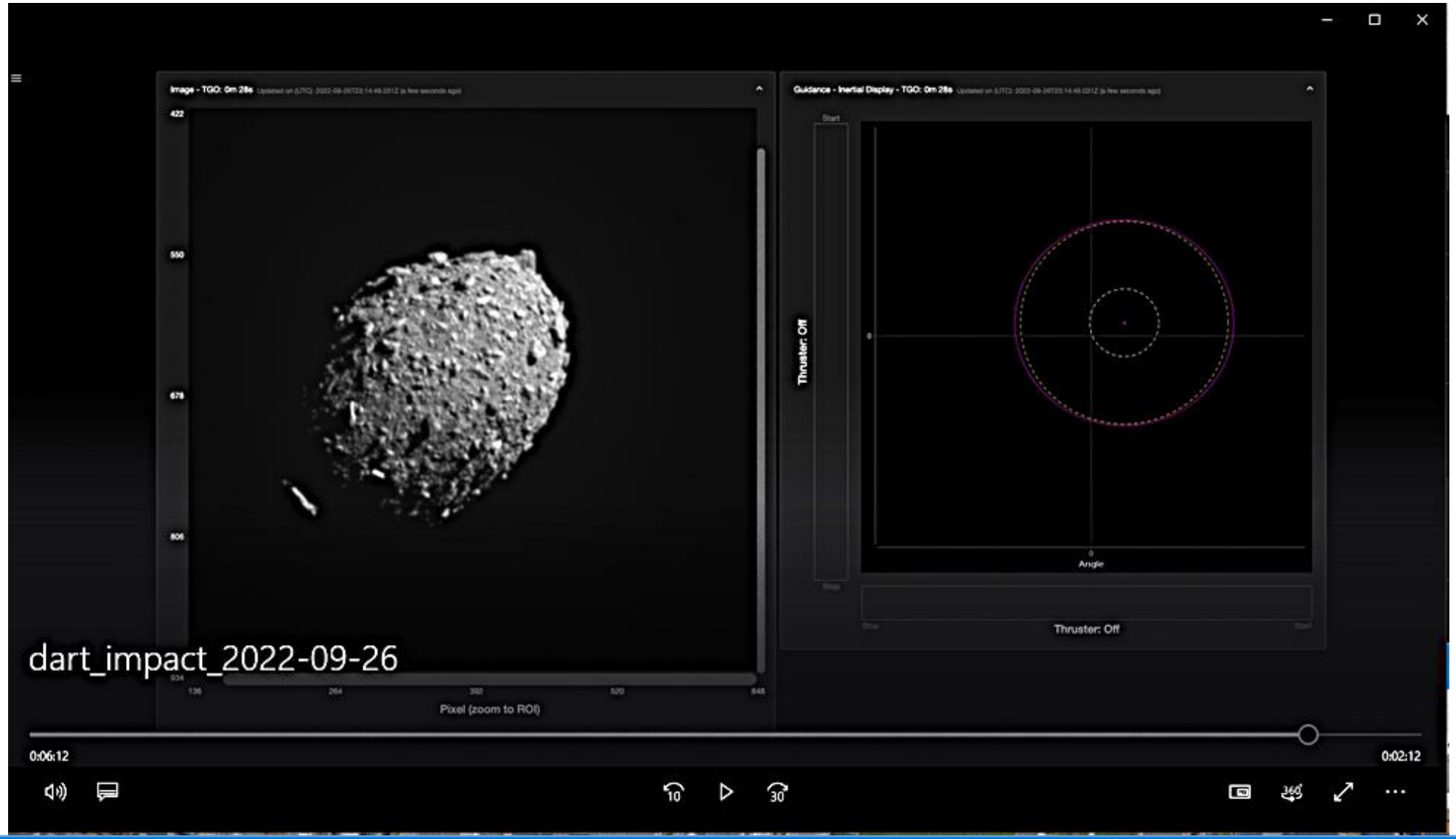
| Image Overlay | | |
|---|---|---|
| | A | Didymos Label |
| Label Placement | | Left / Right / Top / Bottom |
| | B | Dimorphos Label |
| Label Placement | | Left / Right / Top / Bottom |
| | | Didymos Blob |
| | | Dimorphos Blob |
| | | Didymos Aimpoint Active |
| | | Didymos Aimpoint InActive |
| | | Dimorphos Aimpoint Active |
| | | Dimorphos Aimpoint InActive |
| | | TIA Initial (InActive) |
| | | TIA Locking/Locked |
| | | TIA Precision Locked |

| Guidance - Inertial Display Overlays | |
|---|---|
| | Didymos Blob |
| | Dimorphos Blob |
| | 15m Miss Distance |
| | 45m Miss Distance |
| | Maneuver Capability |
| | SNG solution |

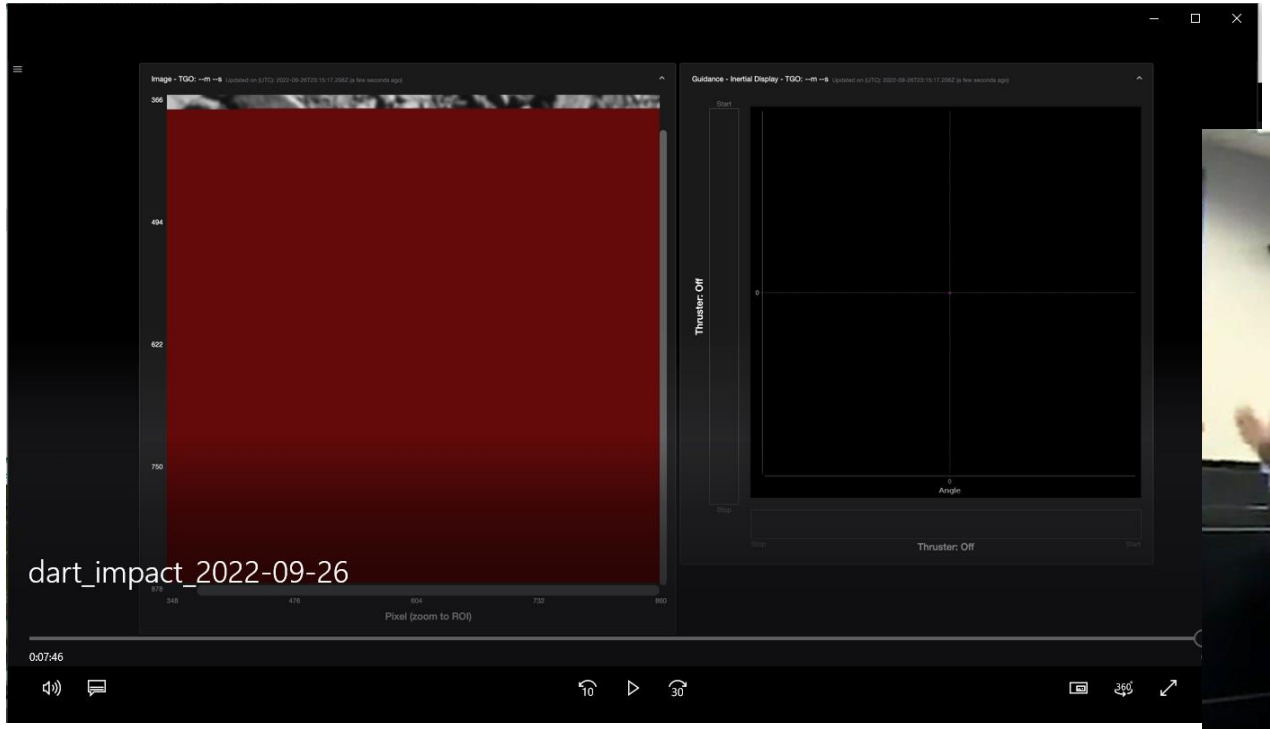
# Closing In on Dimorphos



# Full Speed Ahead



# Final, Partial Image was Expected




# Ground System Perspective: Terminal By the Numbers

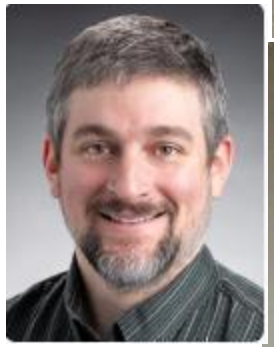
- **15 million** hits on dart.jhuapl.edu website during final 12 hours
  - Between 7 – 8 pm: **2.7 million hits** – Planetary Defender turn-out!
- **13,636** Terminal images processed and provided to MOC Data Server
- **78** Voice comm boxes located around APL campus
- **60+** DART OPS DMZ client users supported simultaneously
- **42** Analog dial-in numbers active
- **26** DART OPS DMZ VMs running InControl client software
- **5** instances of ImageDisplay supporting browser views, including for NASA broadcast
- **1** repaired image during Terminal (split FITS file recombined)
- **1** final, partial image properly reconstructed and rendered
- **0** telemetry frames dropped until impact

**. . . and One Smacked Asteroid!**

# References


- 2020 GSAW Proceedings, Dean Sibol, Double Asteroid Redirection Test (DART): NASA's First Planetary Defense Mission
- D. Bekker, R. Smith and M. Q. Tran, "Guiding DART to Impact — the FPGA SoC Design of the DRACO Image Processing Pipeline," *2021 IEEE Space Computing Conference (SCC)*, Laurel, MD, USA, 2021, pp. 122-133, doi: 10.1109/SCC49971.2021.00020.
- Daly, R.T., Ernst, C.M., Barnouin, O.S. *et al.* Successful kinetic impact into an asteroid for planetary defence. *Nature* **616**, 443–447 (2023). https://doi.org/10.1038/s41586-023-05810-5
- D.L. Bekker, R.T. Daly, C.M. Ernst, *et al*. Real-time monitoring of onboard image processing performance during DART terminal approach. LPSC, 54 (2023), abstract no. 2511

# The Team

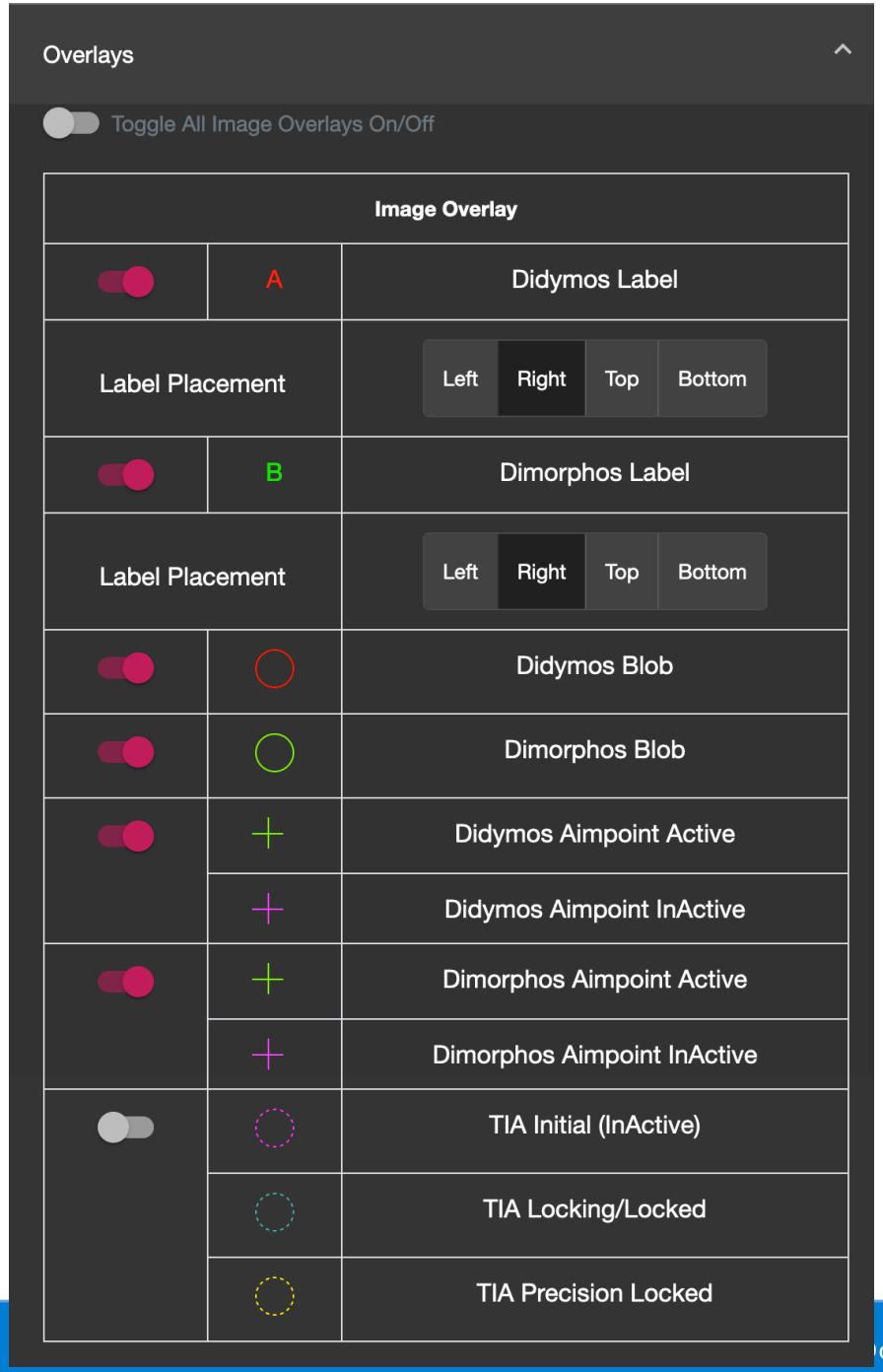

- David Carl, GSW Engineer for Image Reconstruct / Image Correlate services
- Patricia Harrington-Duff, DART GDS and Ground Software Lead
- Jonathan Labin, GSW Engineer for Image Reconstruct service
- Michael Malinowski, GSW Engineer for ImageDisplay webservice
- Andrew J. Smith, DART Deputy Ground Software Lead
- Daniel Wilson, DART Data System Engineer

# BACKUP SLIDES

# Close-up of Configuration

- Users could toggle on or off the entire set of overlays, or individual elements; change positioning of labels
- Image could be zoomed in or out
- Timing of view refreshes could be modified
- Users could force re-load of prior image

- TIA = Target Inclusion Area

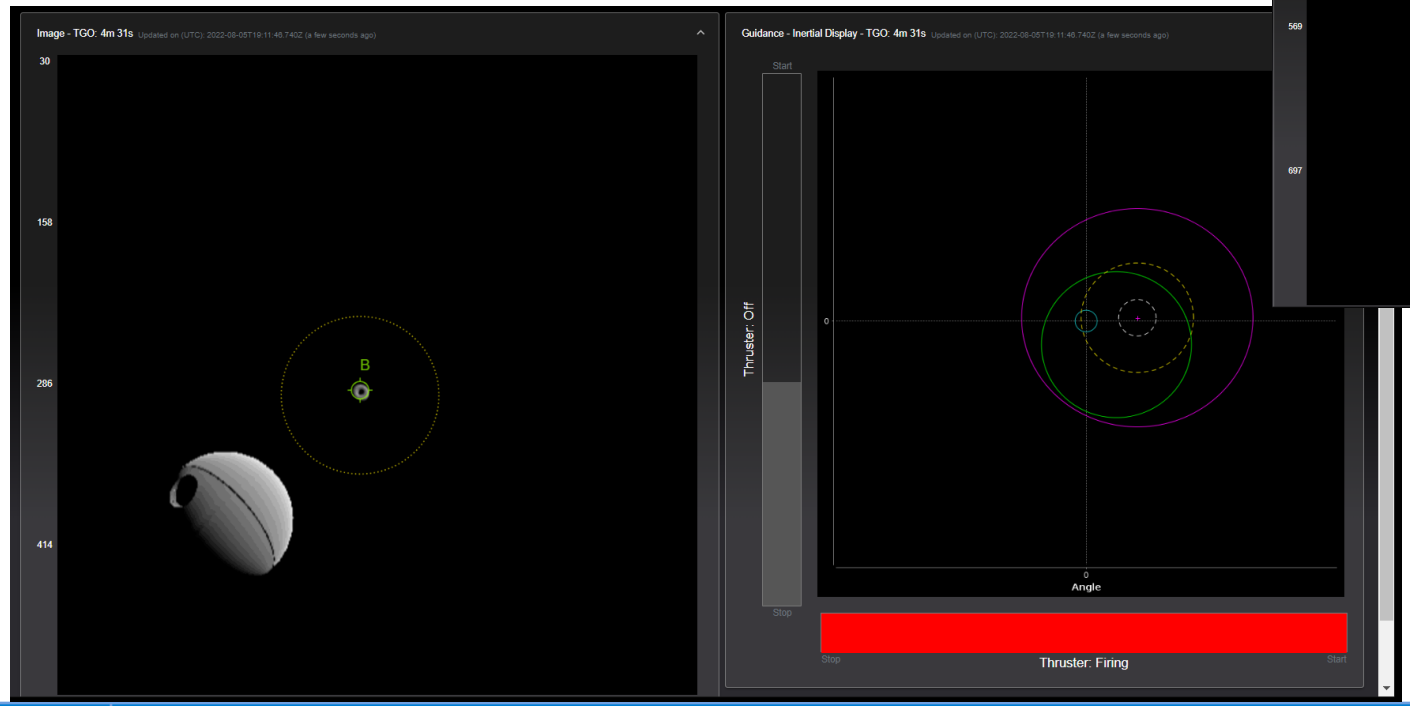


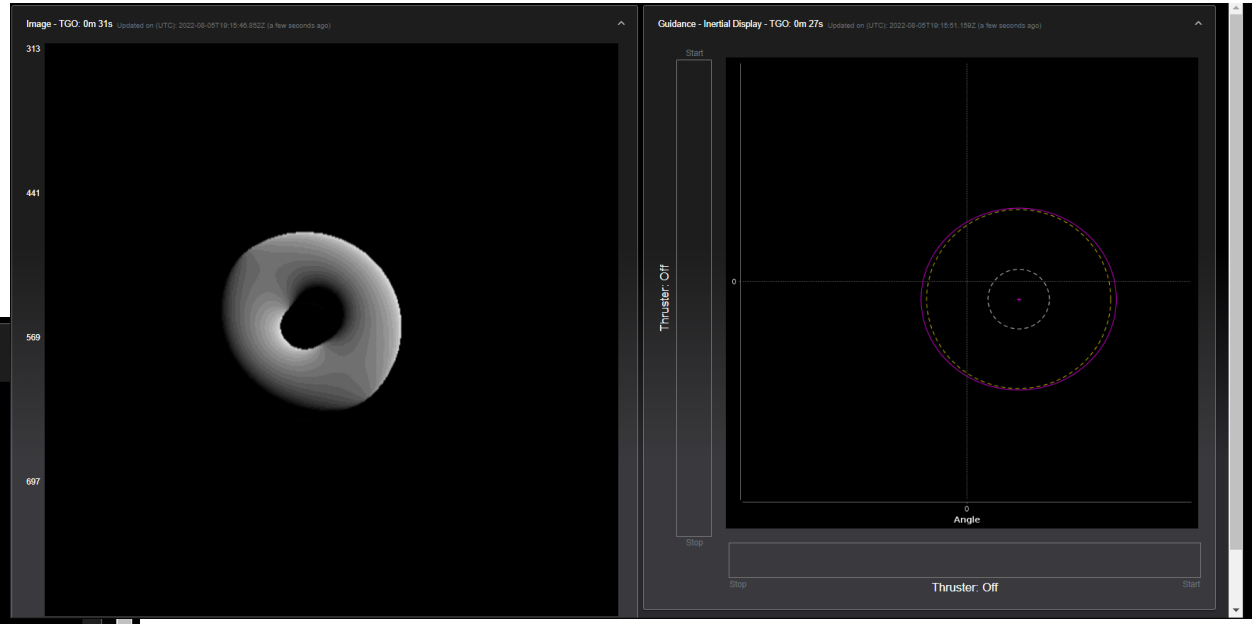
# Guidance for Inertial Display Overlays

- Light Blue: Maneuver Capability (in angle space: future delta V capability / closing velocity)
- Magenta: The 3-sigma uncertainty region encompassing the required maneuver to reach the target (how much delta V is required / closing velocity)
- Red circle: Didymos detection, as mapped to the inertial angle from the estimated velocity vector. Circle size scaled with number of pixels in detection, as mapped to angle space. These jump around as the body-to-inertial frame rotations are estimates themselves.
- Green circle: Dimorphos detection, as mapped to the inertial angle from the estimated velocity vector. Circle size scaled with number of pixels in detection, as mapped to angle space. These jump around as the body-to-inertial frame rotations are estimates themselves.
- Yellow dashed line: Represents 45m 3-sigma zone in inertial angle space. The filter estimate should be inside this by the very end.
- White dashed line: Represents 15m 1-sigma zone in inertial angle space. It is desirable that the filter estimate be inside this by the very end.

# Display from Rehearsal with Contingencies

- Rehearsal with successful targeting, combined with a missed impact scenario – by assuming a donut-shaped Dimorphos



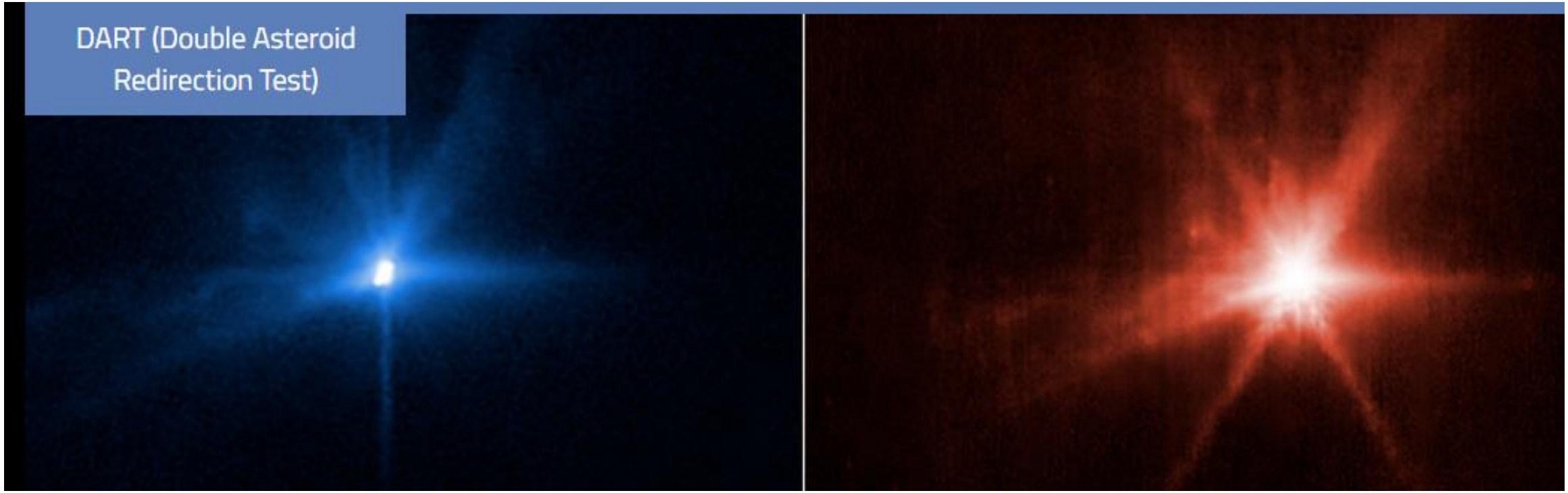



# The Italian View from LICIACube

Credit: ASI/NASA

LICIACube = Light Italian CubeSat for Imaging Asteroids,
i.e., a mini-spacecraft that DART carried with it until it was ejected 15 days before impact

# Impact at 6.14 km/second! (~4 x speed of a bullet)




From Hubble Space Telescope

From James Webb Space Telescope

https://www.nasa.gov/feature/goddard/2022/webb-hubble-capture-detailed-views-of-dart-impact

# DART Impact Movie

- Last 8 minutes of DART as viewed with Image Display, leading up to Impact and final, partial image