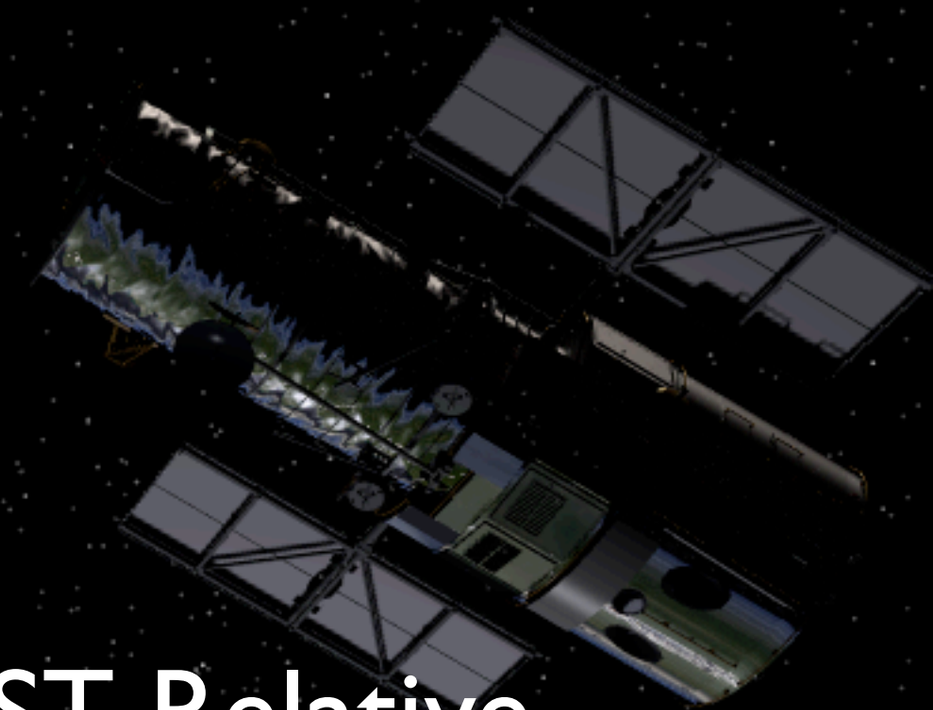


Flight Results from the HST Relative Navigation Sensors

Bo J. Naasz

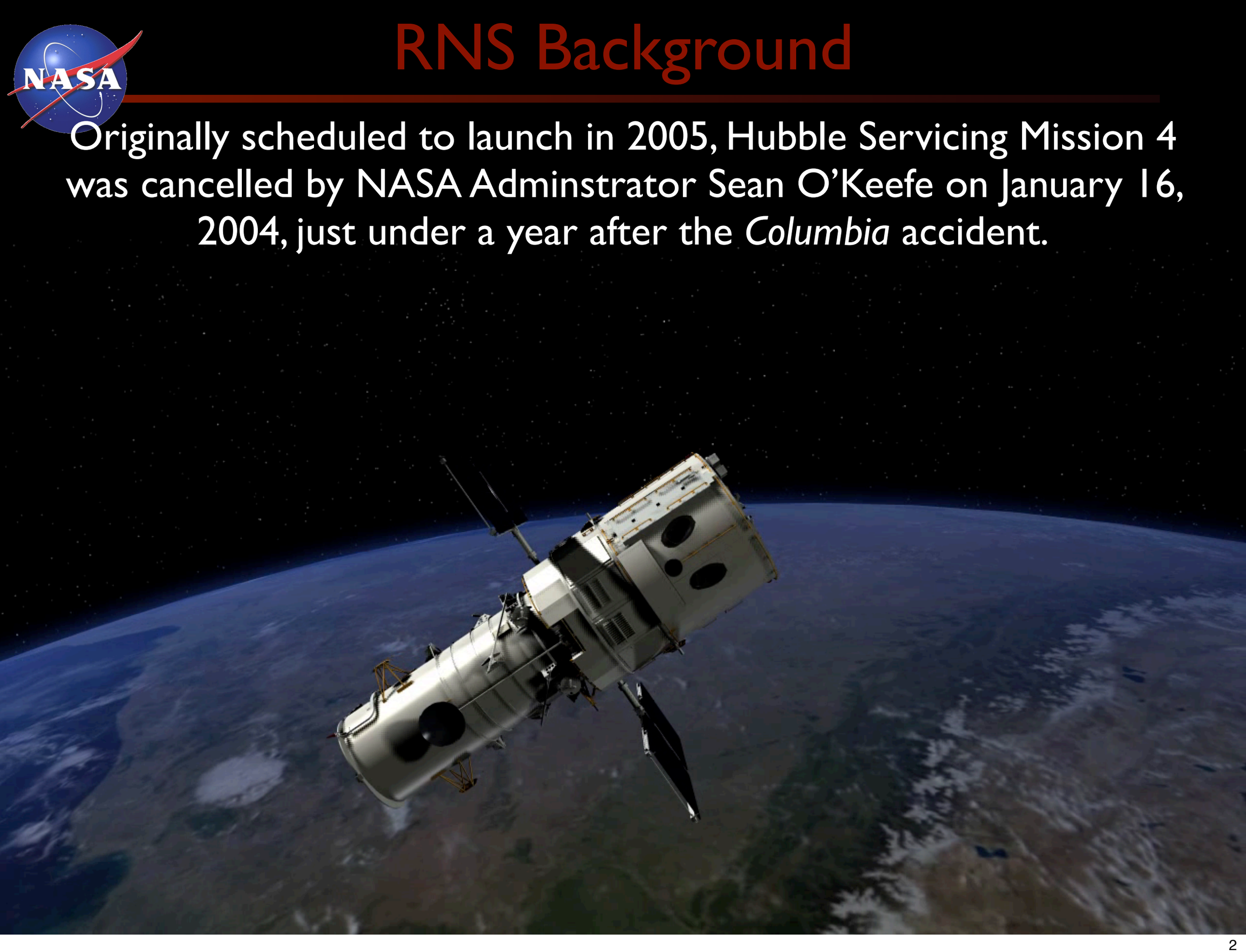
NASA Goddard Space Flight Center

Systems Engineering Seminar

August 4, 2009

RNS Background

Originally scheduled to launch in 2005, Hubble Servicing Mission 4 was cancelled by NASA Adminstrator Sean O'Keefe on January 16, 2004, just under a year after the *Columbia* accident.



RNS Background

In the wake of that decision, O'Keefe directed the HST Development Project at Goddard to investigate the possibility of executing a robotic servicing mission to HST.

RNS Background

The Hubble Robotic Servicing and Deorbit Mission (HRSDM) successfully completed its Preliminary Design Review. Relative navigation to HST, a non-cooperative target, was a major concern.

RNS Background

In April 2005 Dr. Michael Griffin took over as NASA Administrator and made the decision to proceed with Shuttle-based HST servicing, provided Shuttle Return to Flight proved successful.

RNS Background

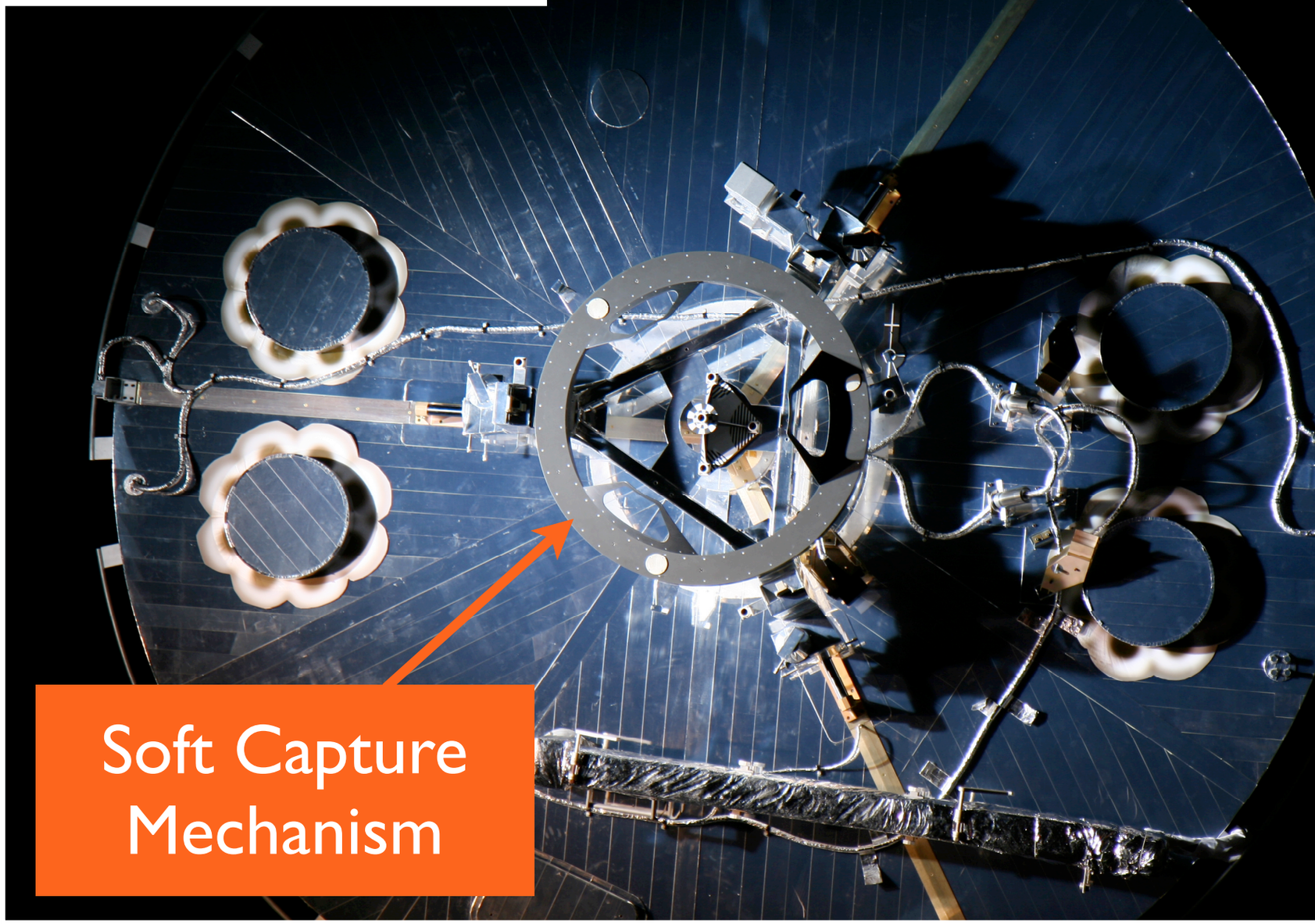
The robotic mission was totally cancelled.

RNS Background

The potential for a future rendezvous and docking with Hubble, perhaps to perform controlled reentry, led the Project to include a Soft Capture Mechanism and Relative Navigation System to the SM4 manifest.

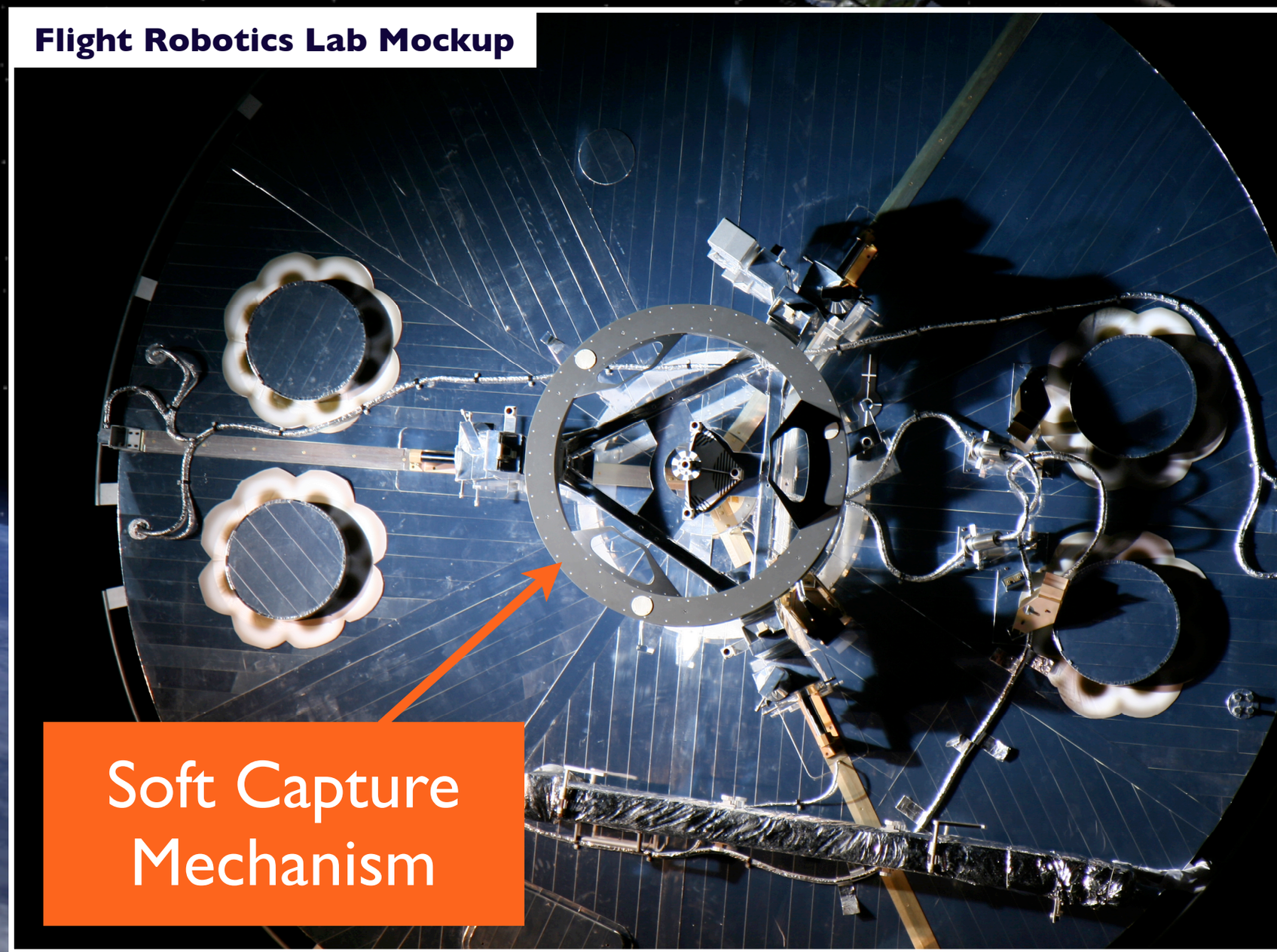
RNS Priorities

Flight Robotics Lab Mockup



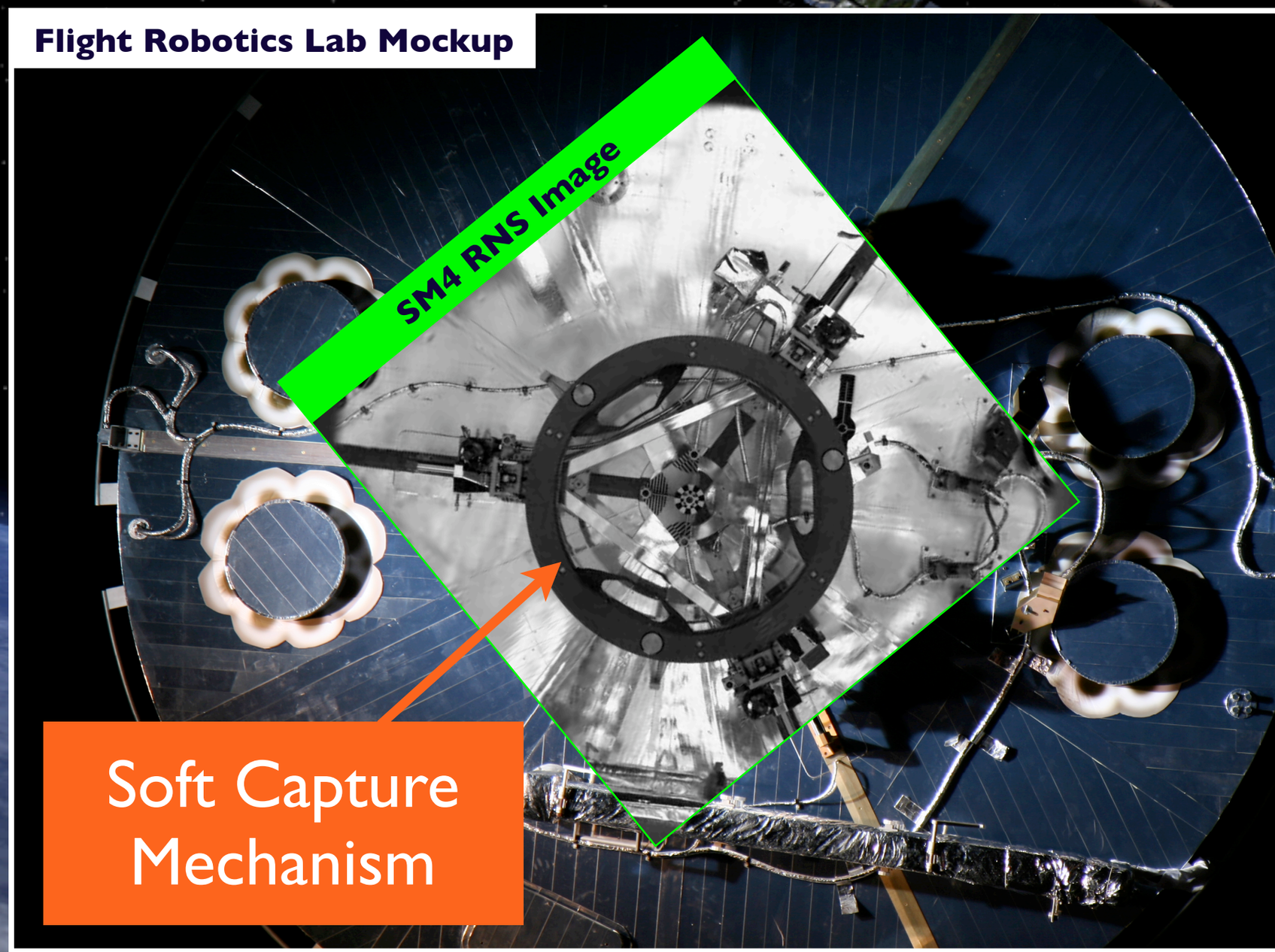
RNS Priorities

1. Do no harm, do not interfere with SM4 Mission Success
2. Image HST after installation of Soft Capture Mechanism (SCM)



RNS Priorities

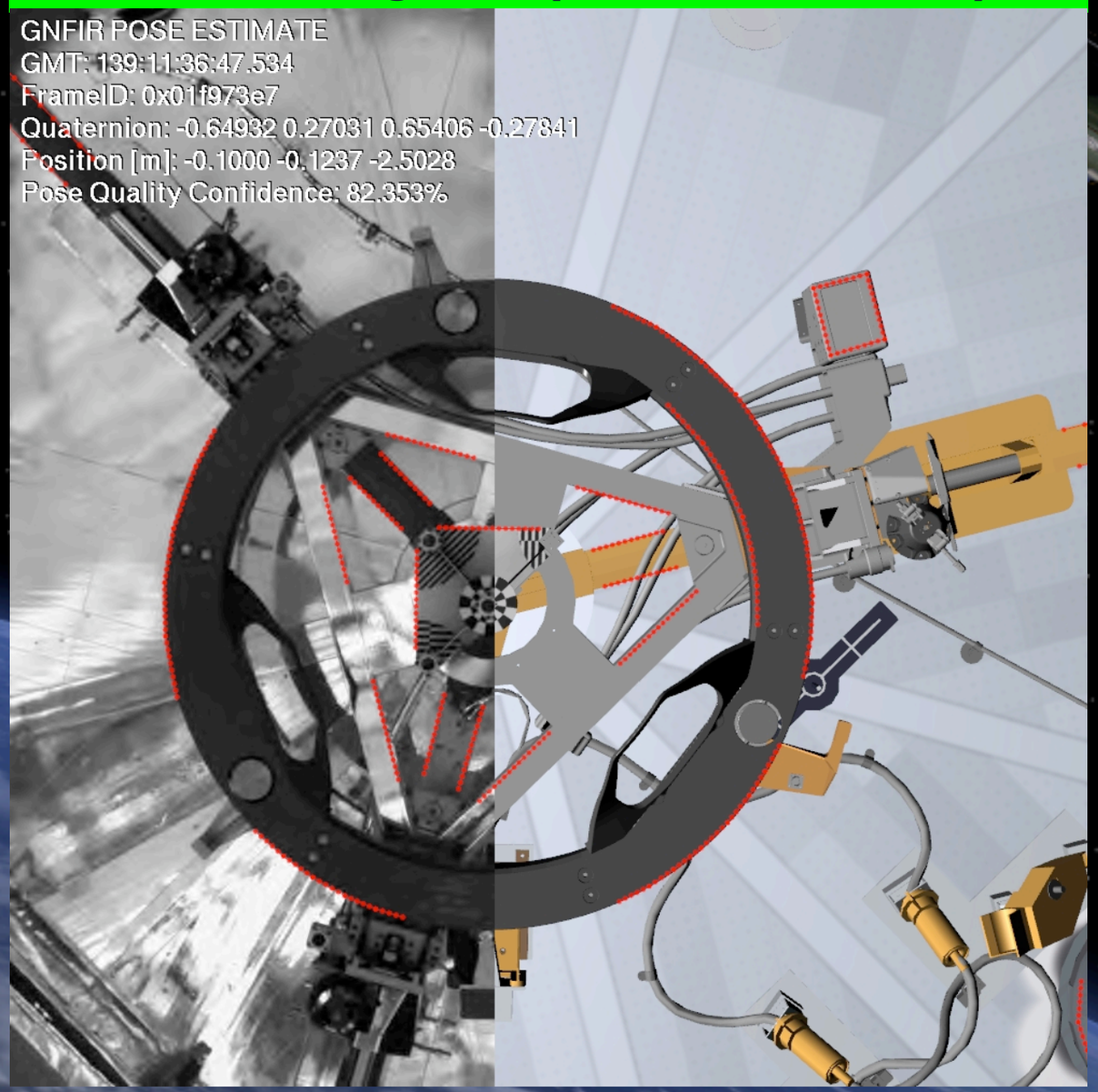
1. Do no harm, do not interfere with SM4 Mission Success
2. Image HST after installation of Soft Capture Mechanism (SCM)
3. Collect imagery and navigation data to facilitate (potentially automated) return to HST



RNS Priorities

1. Do no harm, do not interfere with SM4 Mission Success
2. Image HST after installation of Soft Capture Mechanism (SCM)
3. Collect imagery and navigation data to facilitate (potentially automated) return to HST
4. Demonstrate real-time, on-board pose estimation scalable for application to Autonomous Rendezvous & Docking

SM4 RNS image with pose solution overlay



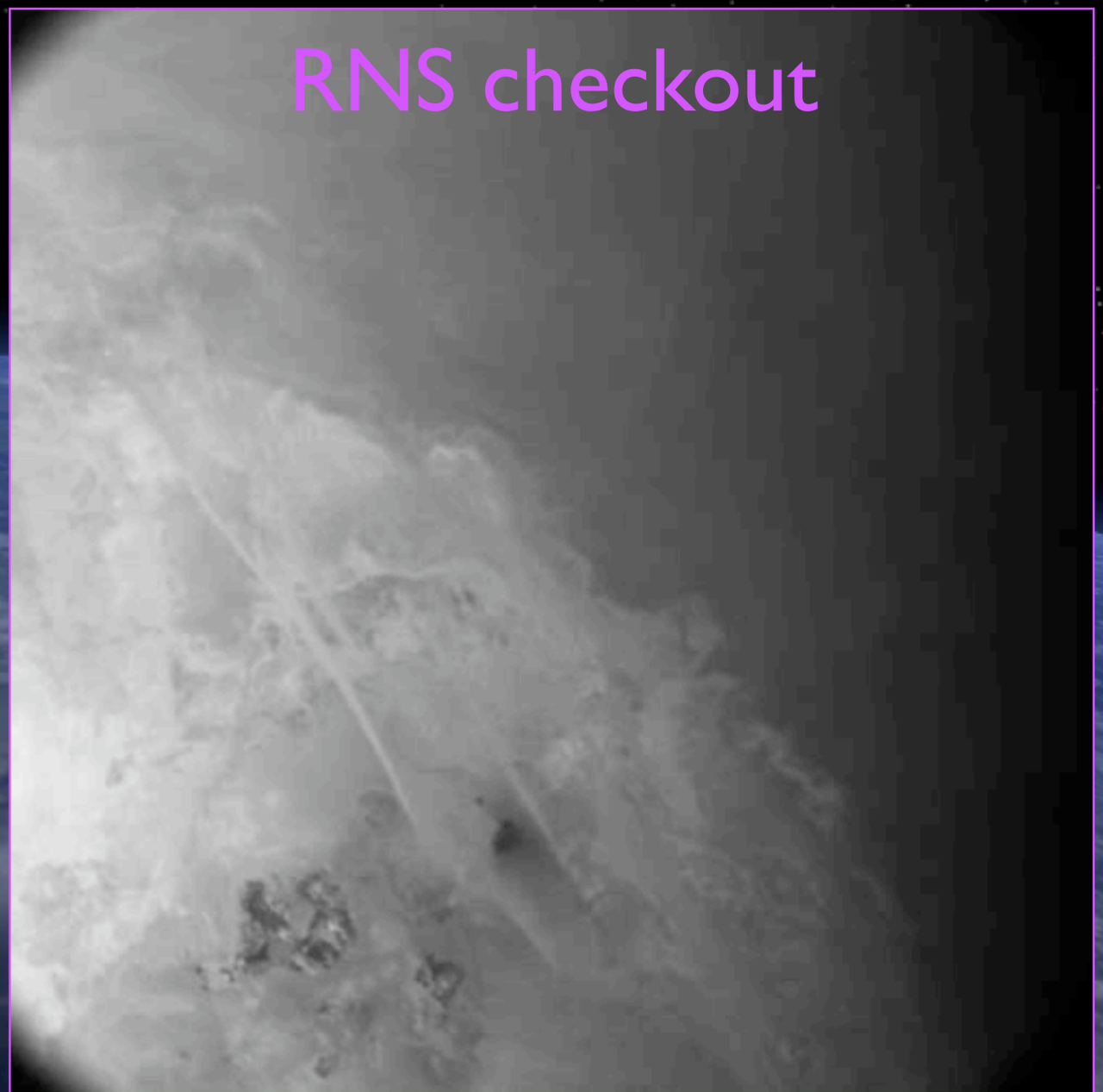
RNS Operations Summary

- Operated via ground terminal at JSC Payload Operations Center
  - Commanding and telemetry via Shuttle PDI (S-band)
  - Image downlink via Shuttle Ku-band (not available when Rendezvous Radar active)

JSC Payload Operations Center

RNS Operations Summary

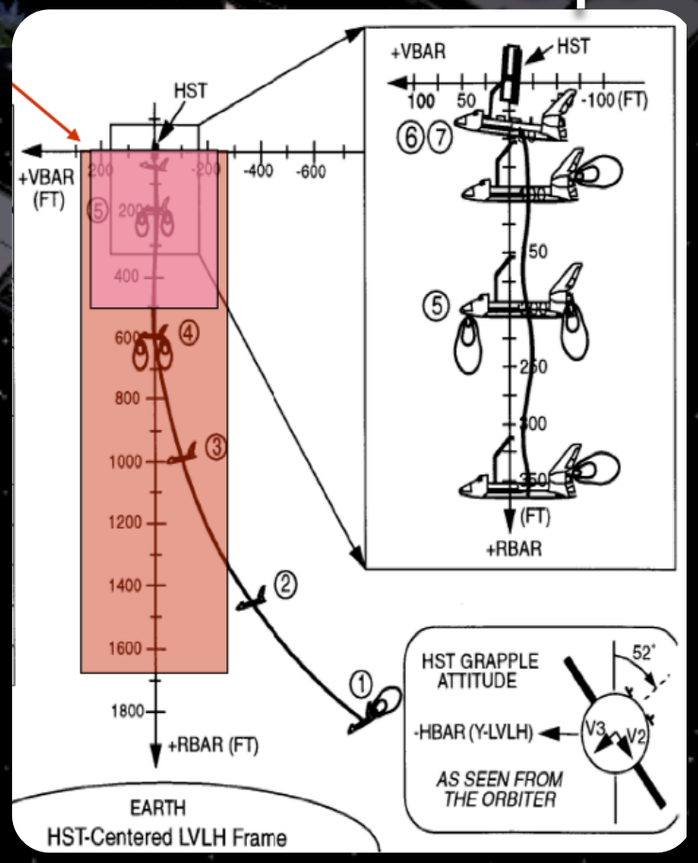
- Flight Day 2: System checkout
  - Verified commanding, sensors, and ability to record images
  - Verified Ku-playback, and live Ku downlink



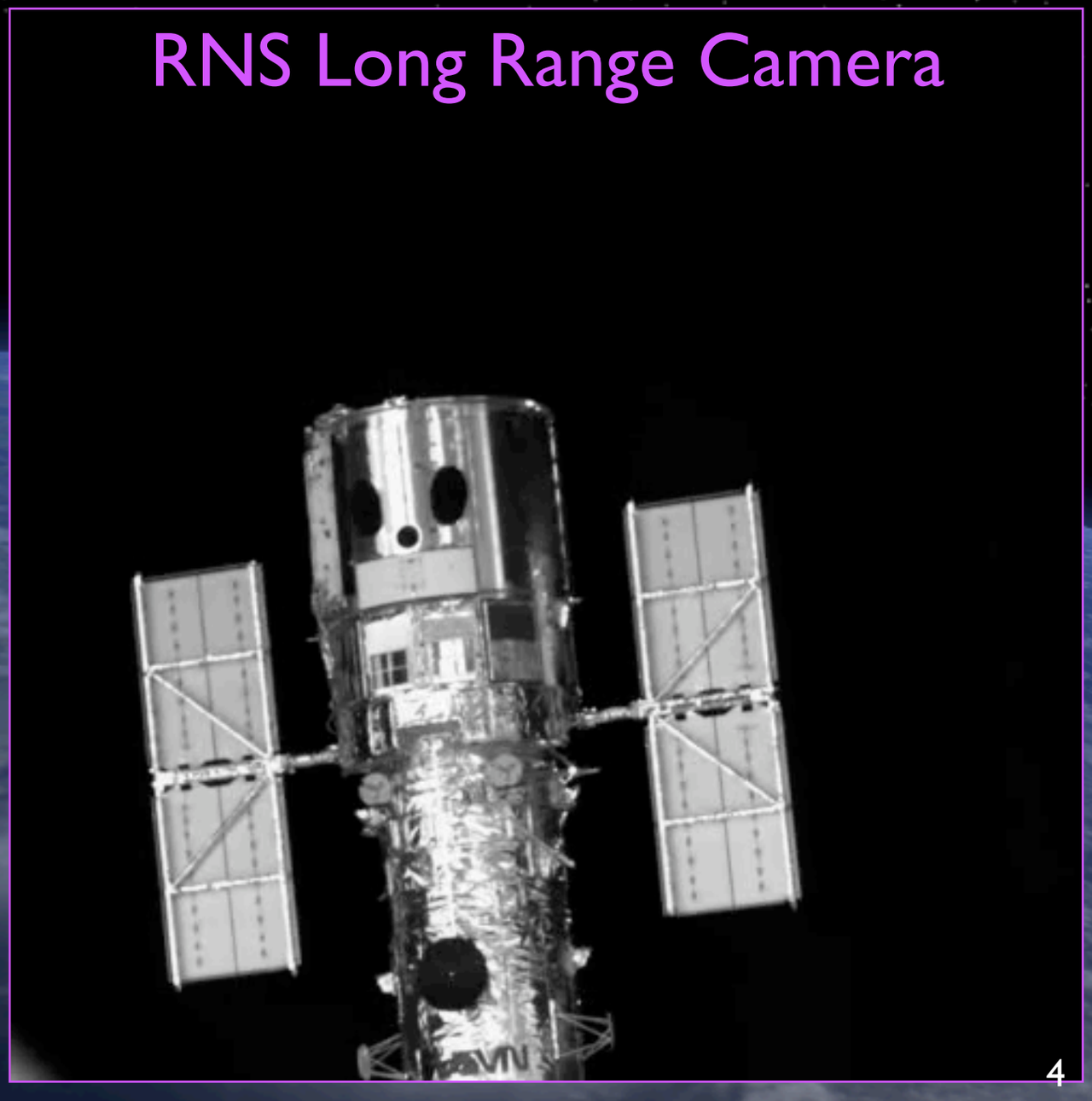
RNS Operations Summary

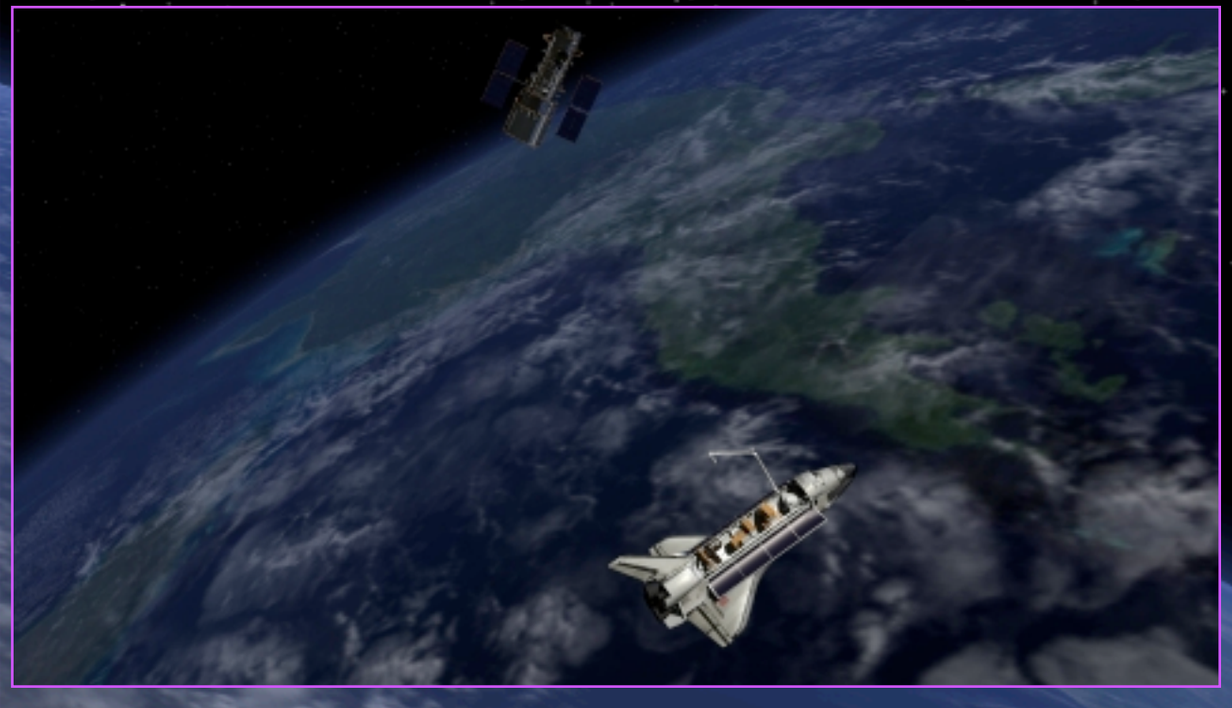
- Flight Day 3: Rendez, Prox Ops, Grapple, and Berth
  - RNS active and recording for about 2.5 hours
  - Start recording images at about 600 ft range, GPS at 1600 ft

Rendezvous Ops



RNS Long Range Camera

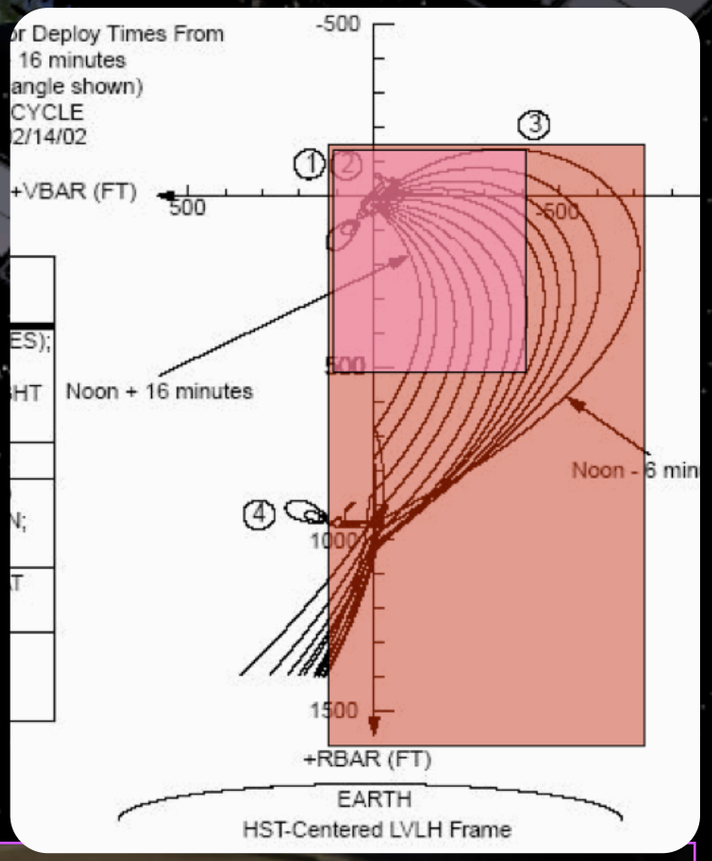


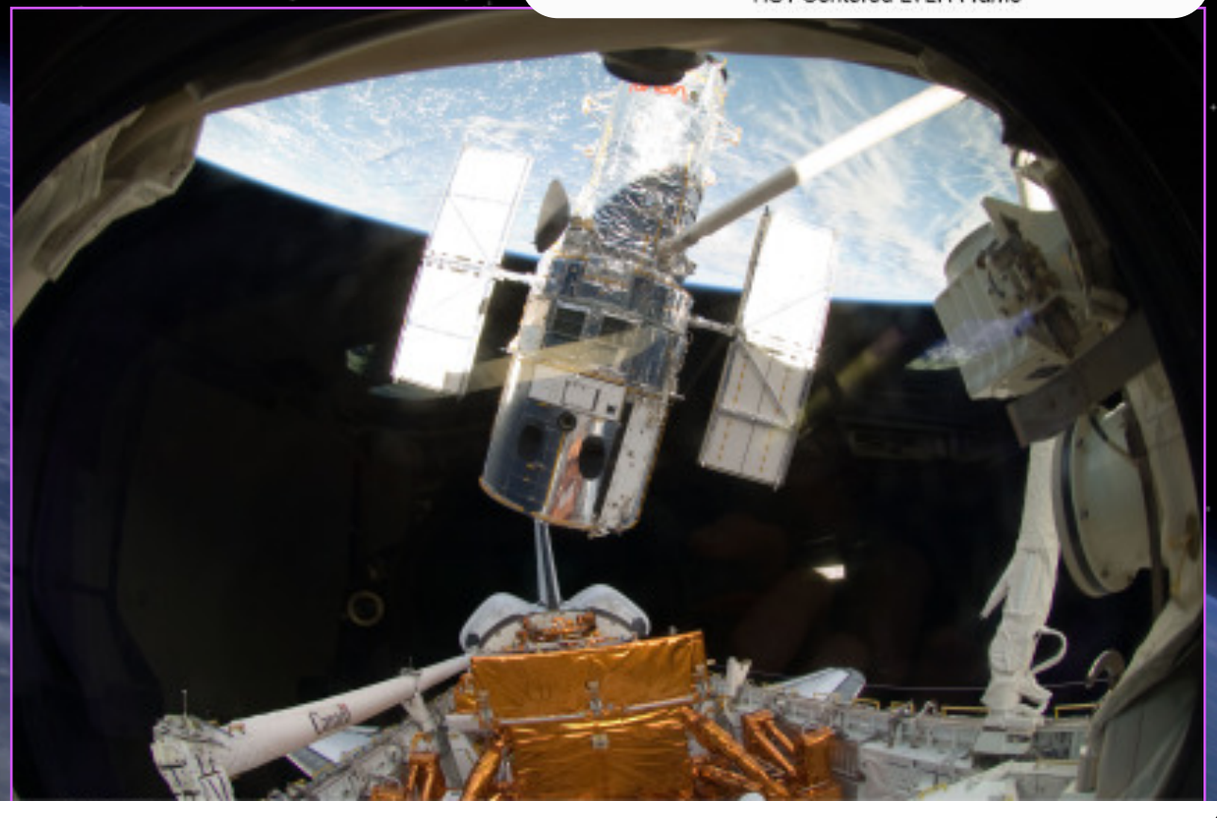


RNS Operations Summary

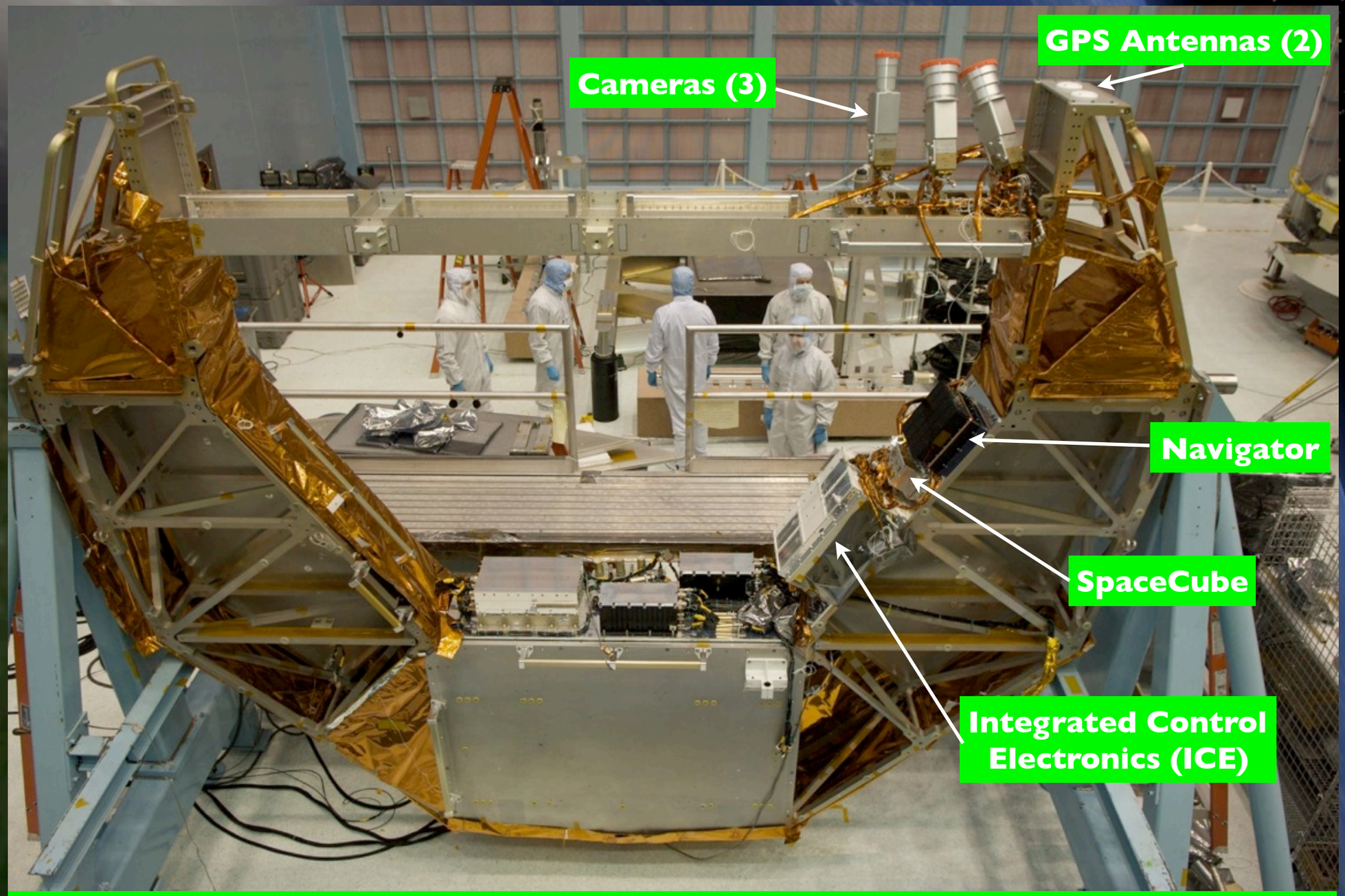
- Flight Day 9: Unberth, Release, and Departure
  - RNS active and recording for about 2.5 hours
  - RNS Intermediate Position (RIP) - pause with HST on RMS - best view of SCM

Deploy Ops



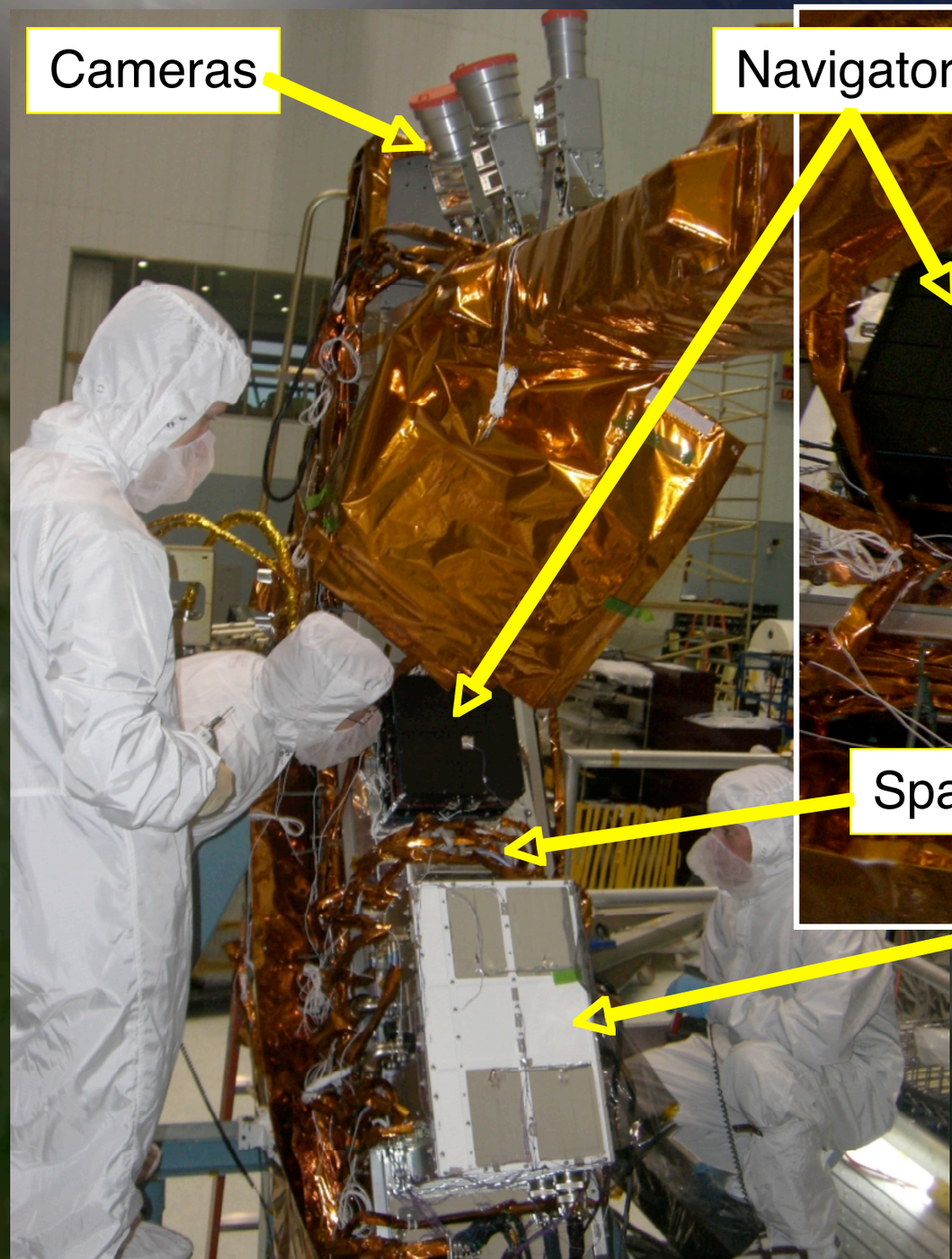


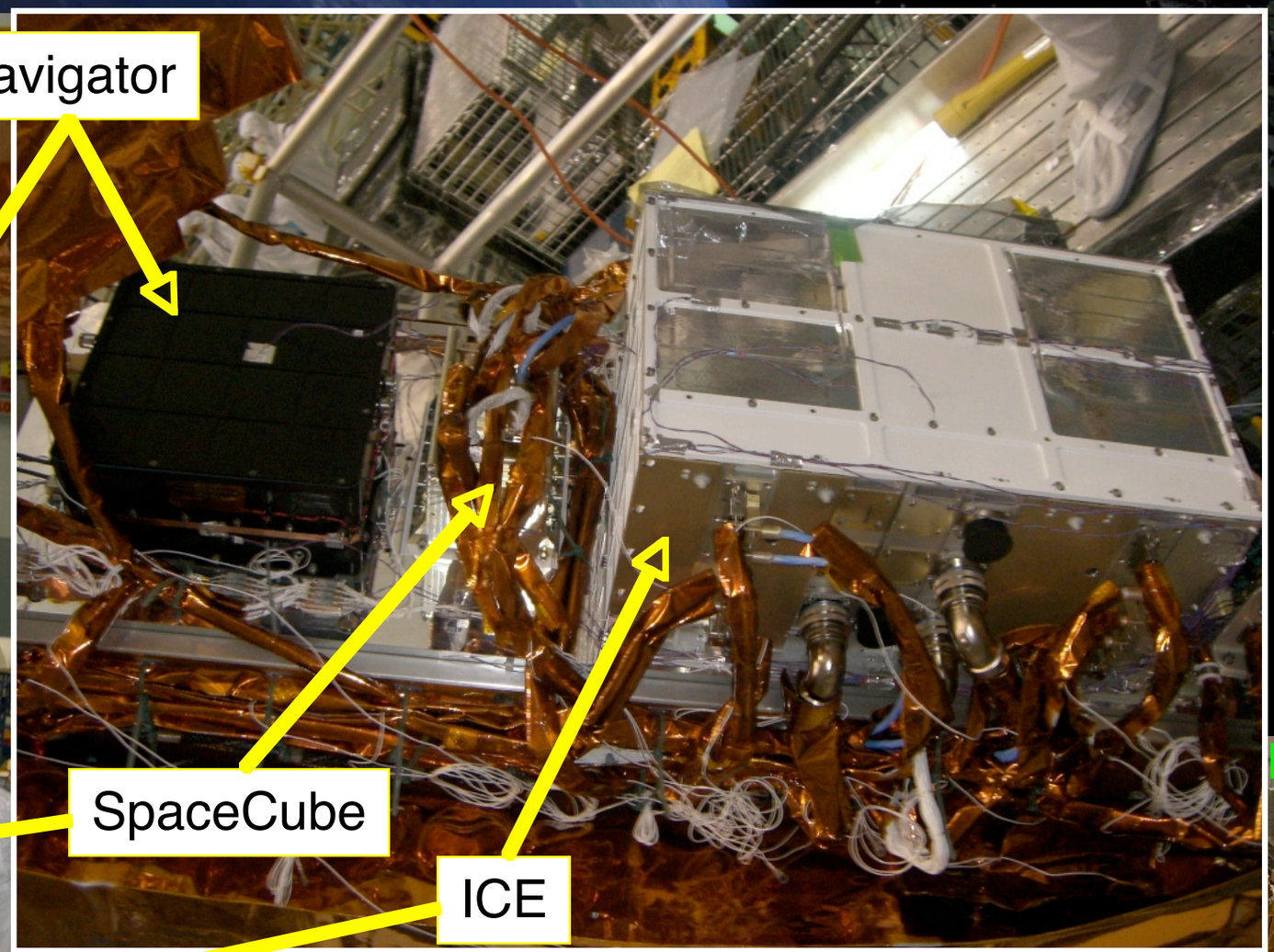
RNS Hardware

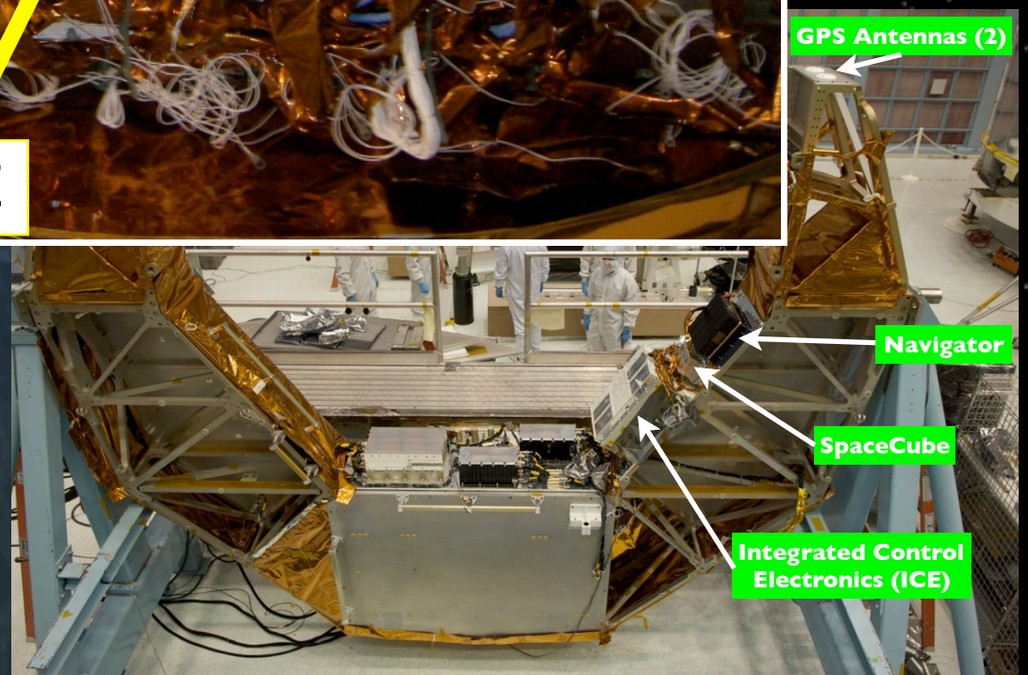


RNS System on Multi-Use Logistics Equipment (MULE) Carrier

RNS Hardware







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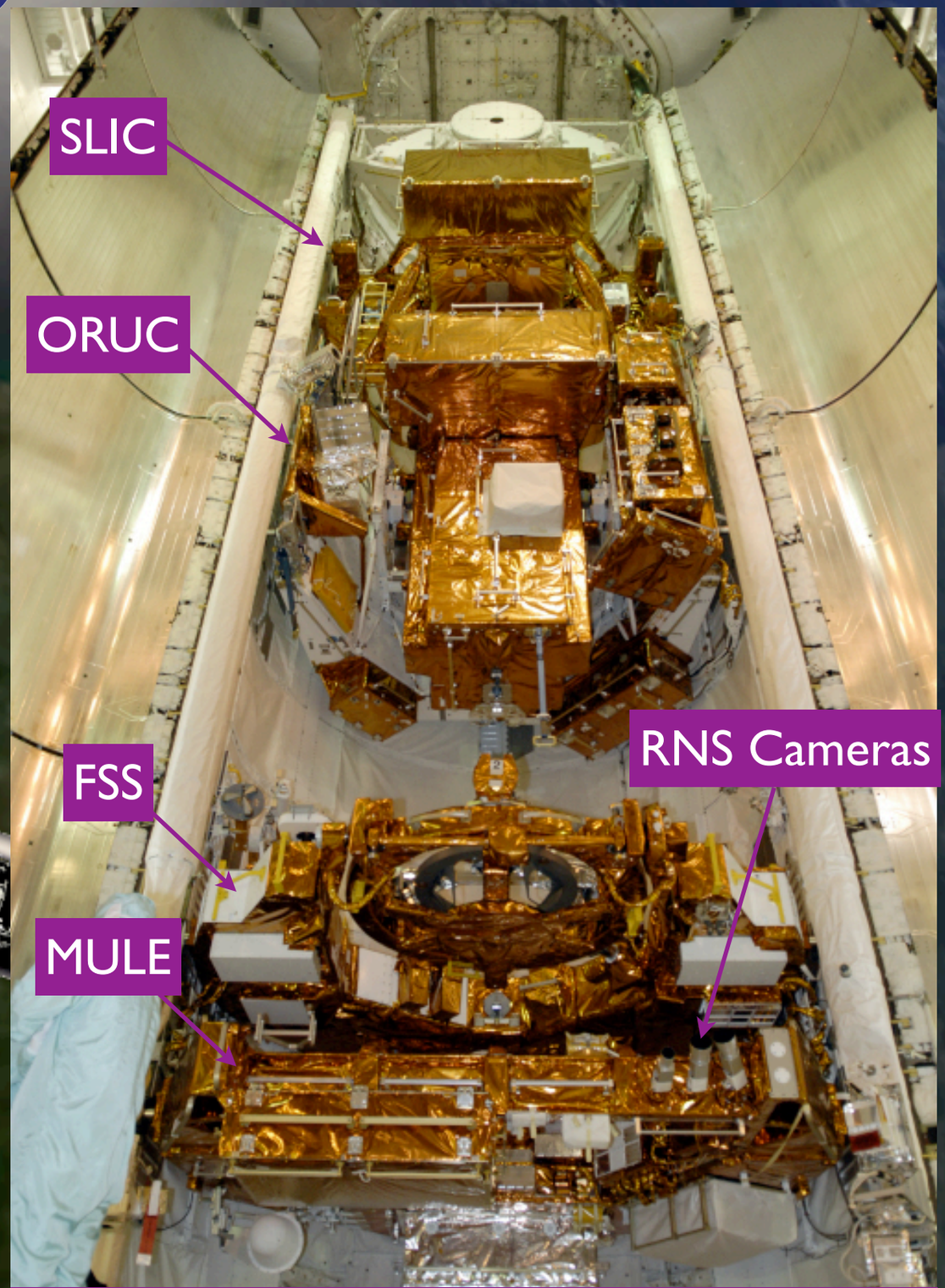
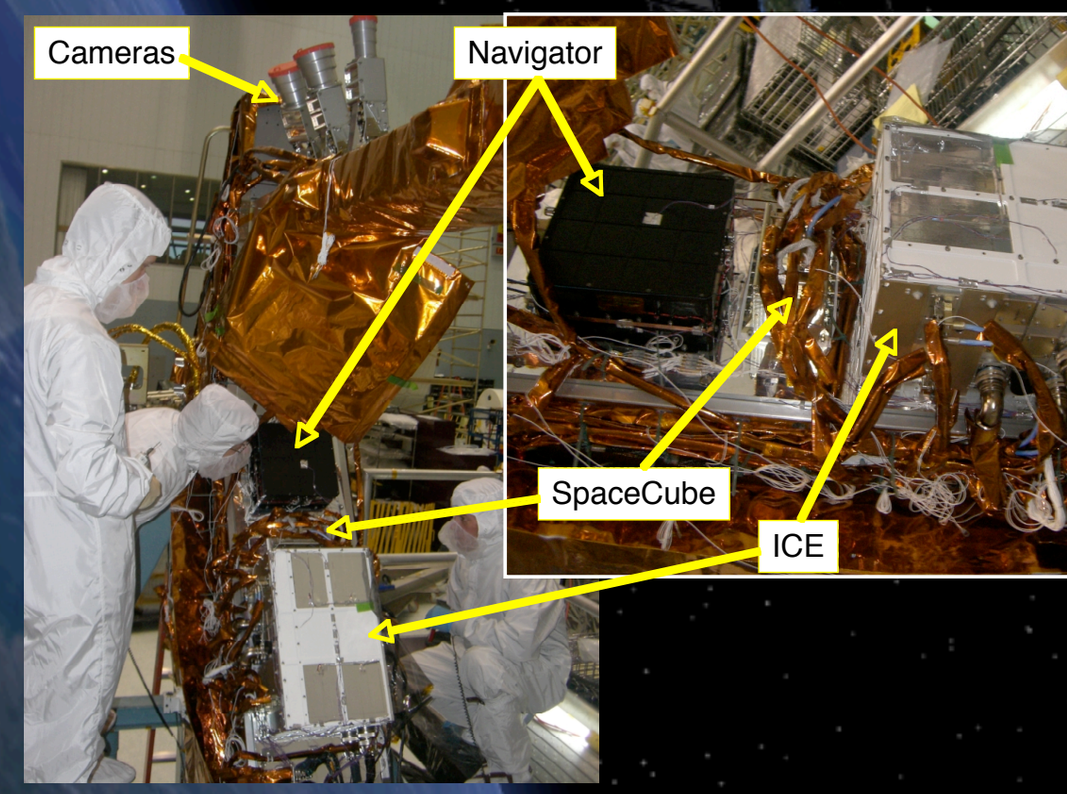
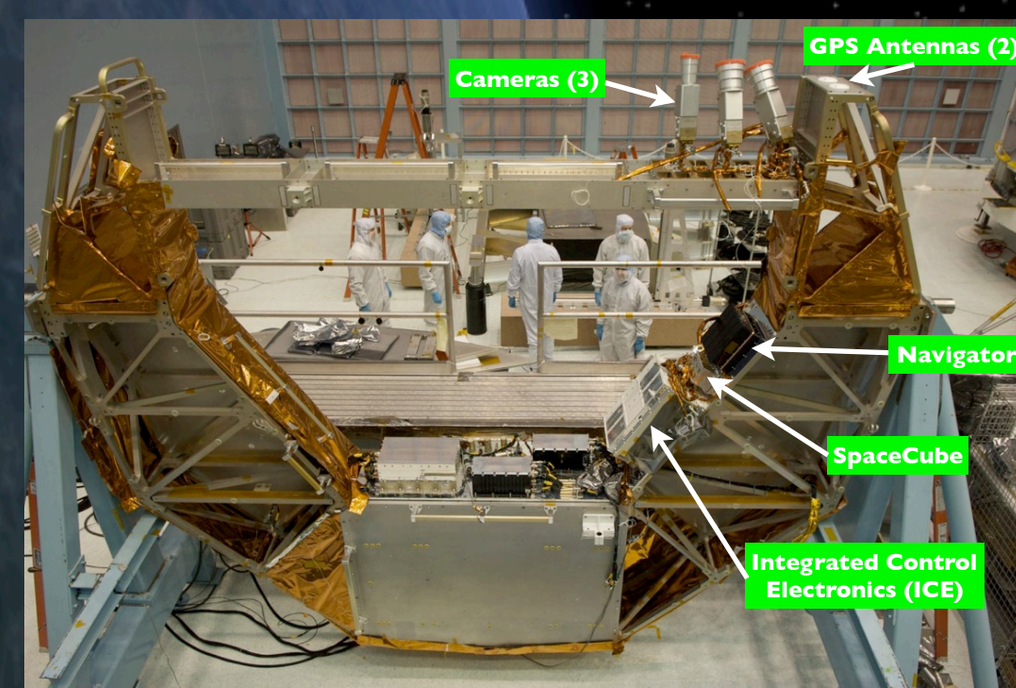
RNS Hardware



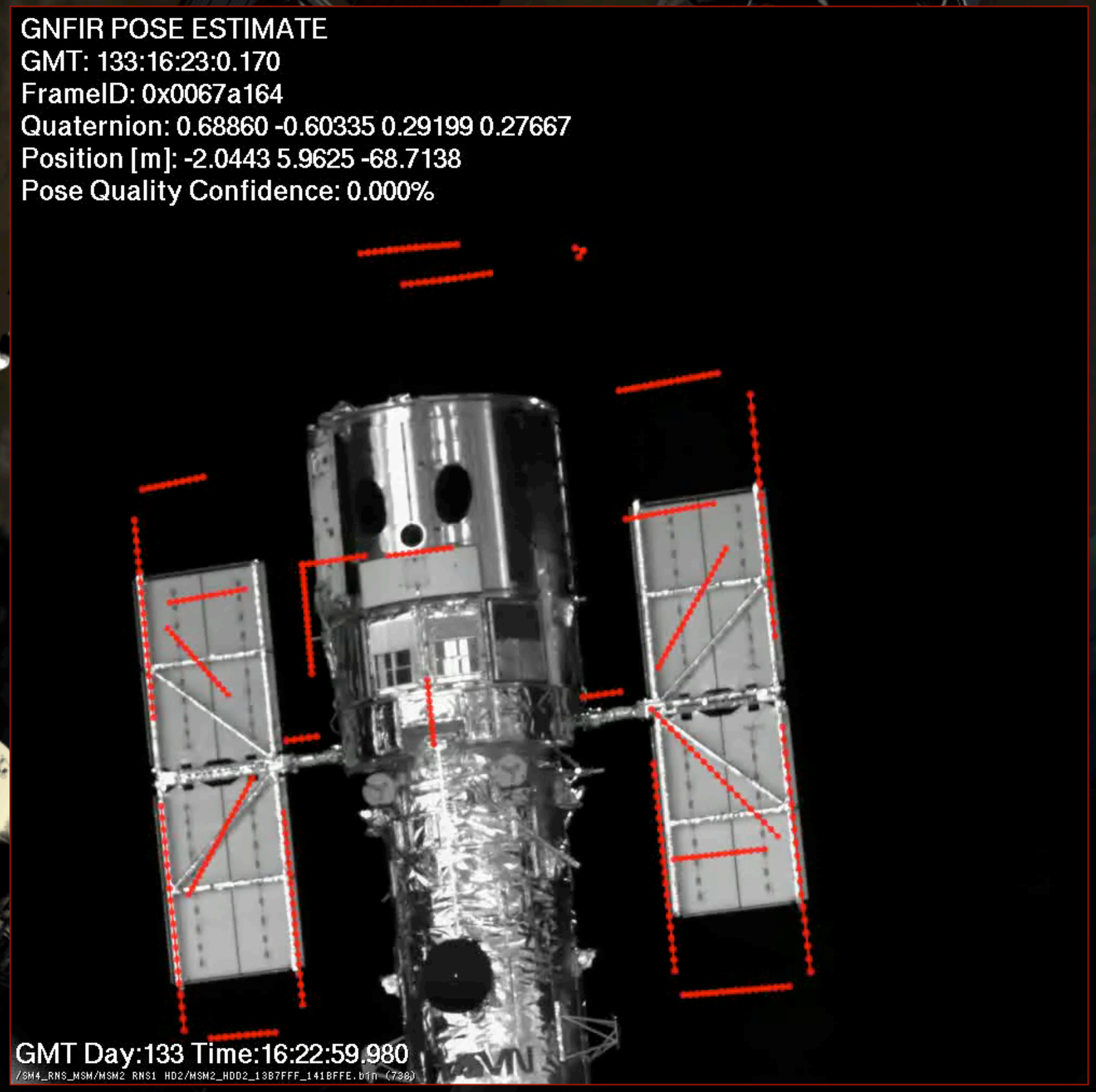
Space Shuttle Atlantis at KSC
Pad 39A with HST SM4 Payload





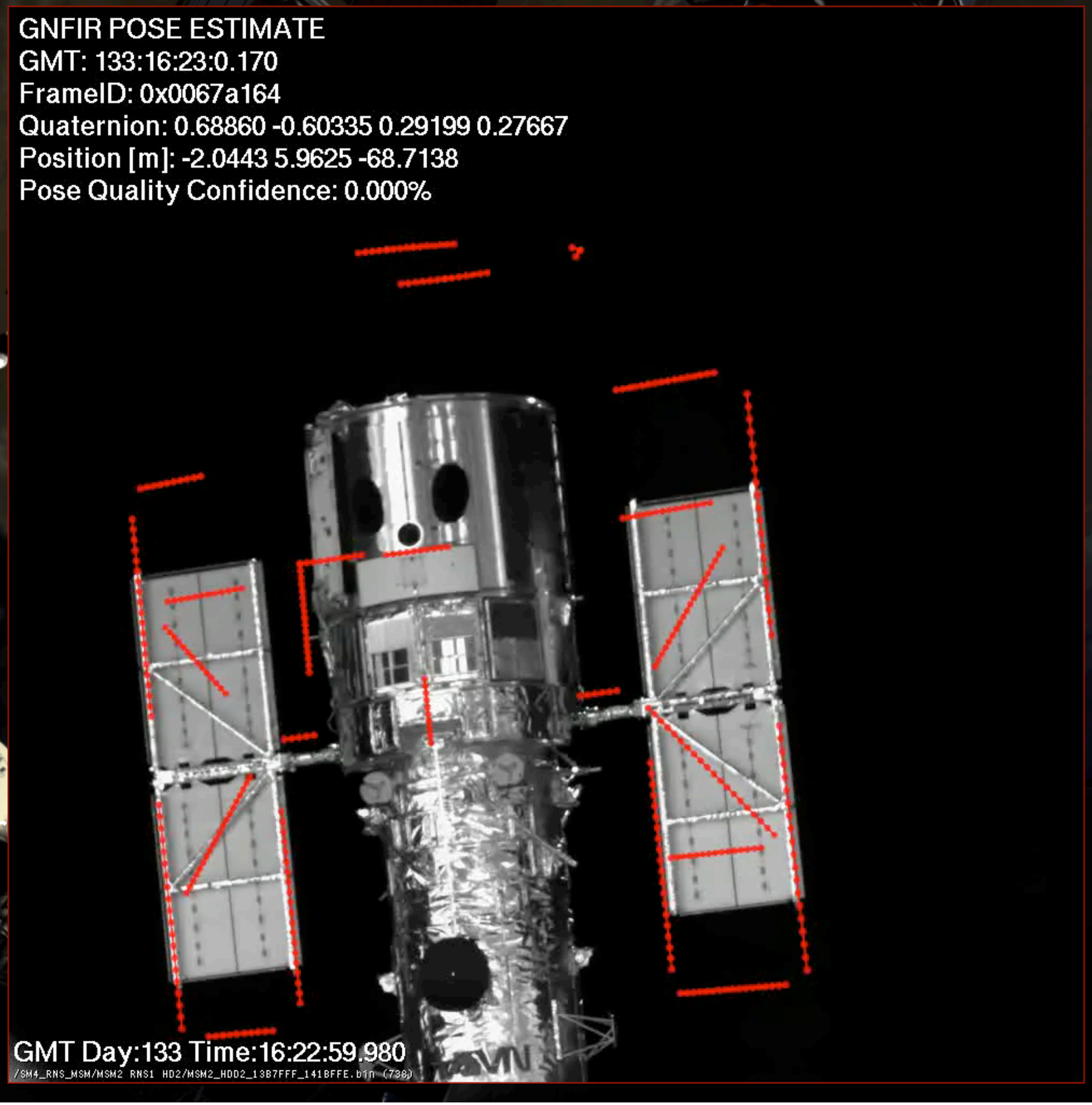
RNS System on Multi-Use Logistics Equipment (MULE) Carrier

Pose Algorithms



Pose Algorithms

- Pose is 6 DOF attitude and translation of a target relative to the camera frame
- Identify and locate 3D objects from 2D camera frames
- RNS pose algorithms:
  - GNFIR - Goddard Natural Feature Image Recognition
  - ULTOR P^3E - ULTOR Passive Pose and Position Engine
- Algorithms are monocular and passive (no fiducials or cooperative targets)
- Implemented in SpaceCube, w/ significant FPGA utilization



Goddard Natural Feature Image Recognition

- Based on RAPiD algorithm (Drummond and Cipolla):

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Edge detect a gray scale image using a standard gradient filter (e.g. Sobel 3x3)

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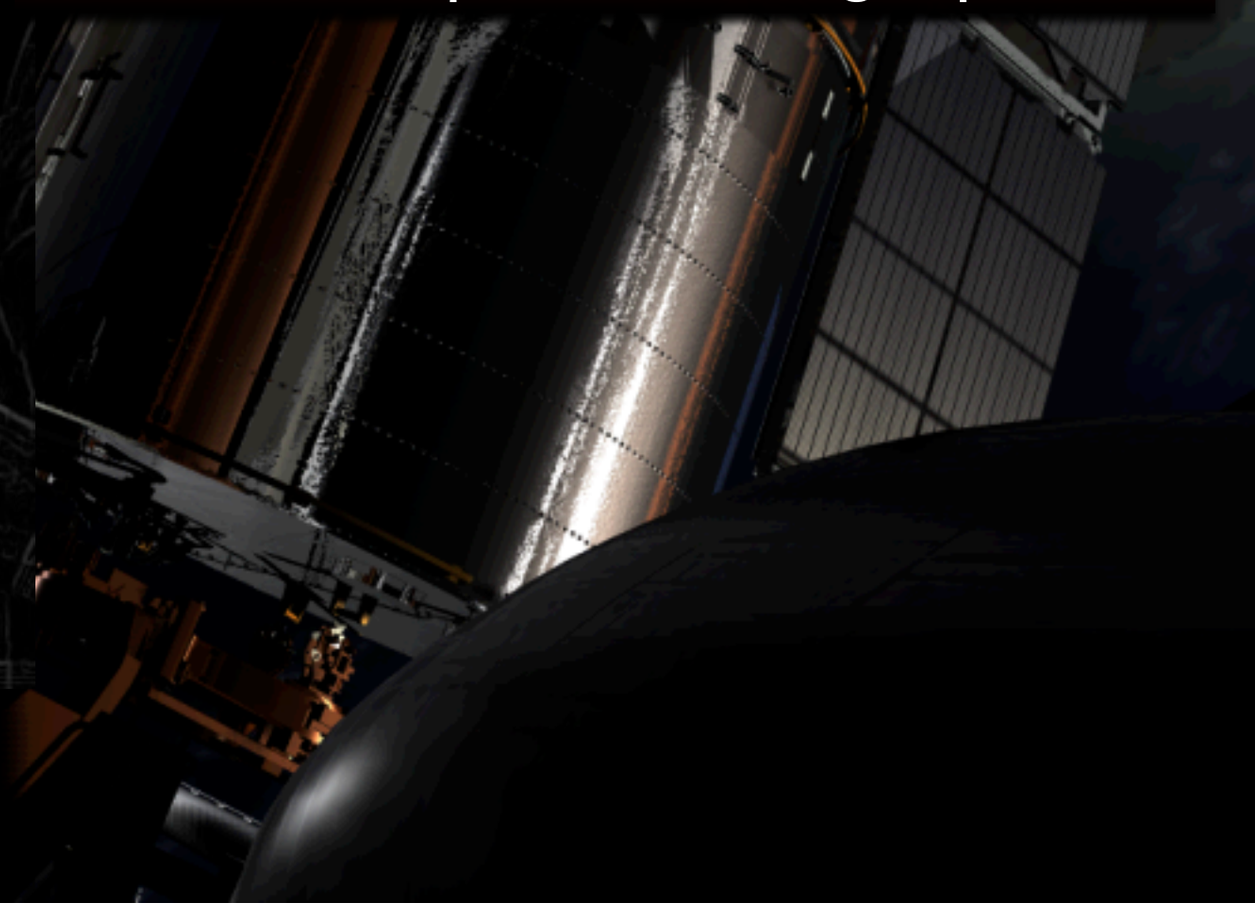
Use *a priori* pose estimate and camera matrix to project end points of an edge in model space into image space



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Segment the line into a number of control points

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Segment the line into a number of control points

Perform a 1D search in the direction of the predicted edge normal

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Use *a priori* pose estimate and camera matrix to project end points of an edge in model space into image space

Segment the line into a number of control points

Perform a 1D search in the direction of the predicted edge normal

Perform a least squares fit to minimize the edge search error

Goddard Natural Feature Image Recognition

- Updates in the Goddard version include
  - Removed optical flow
  - Drummond-Cipolla edge tracker re-implemented
  - Sobel Edge Detect implemented in SpaceCube firmware
  - Added trajectory/centroid acquisition search
  - Outlier editing

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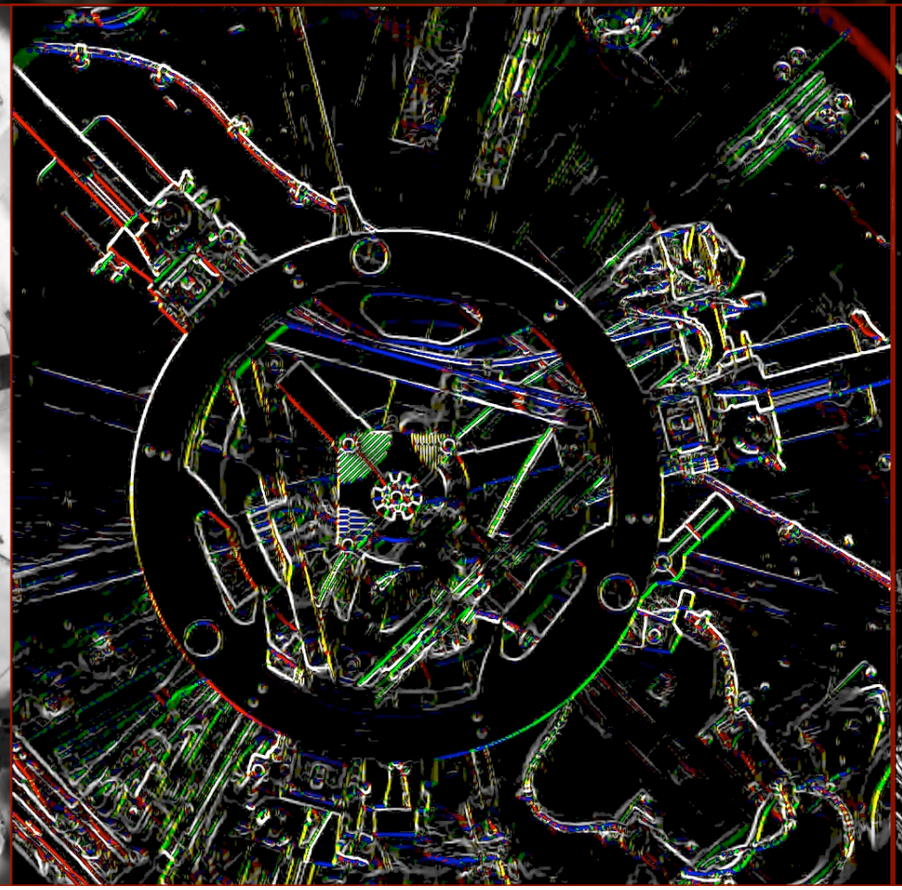
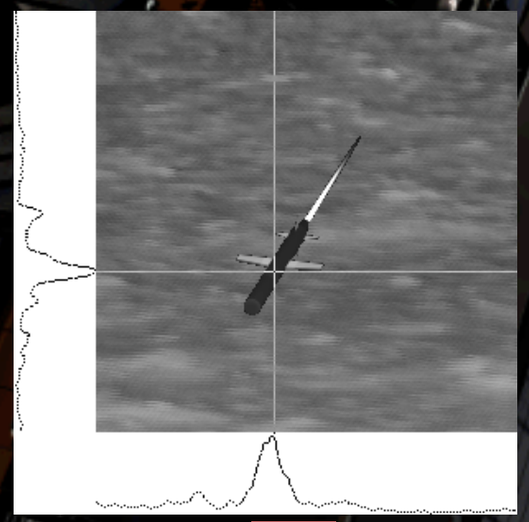
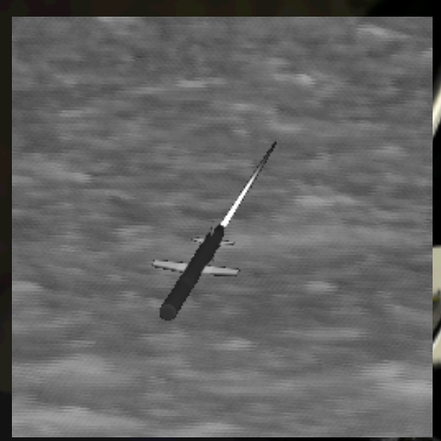


ULTOR P³E

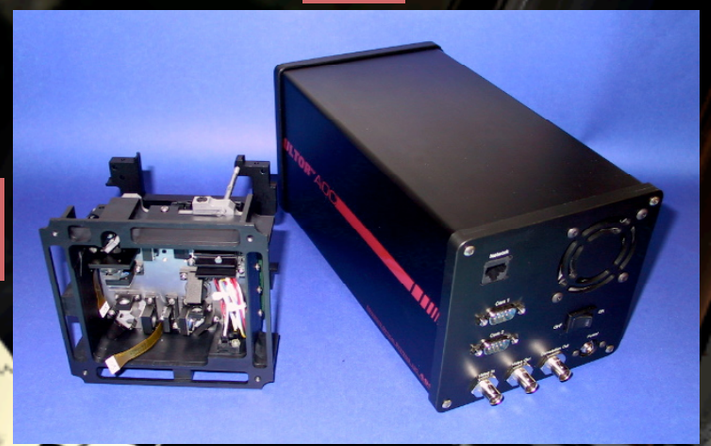
Reference

Filter

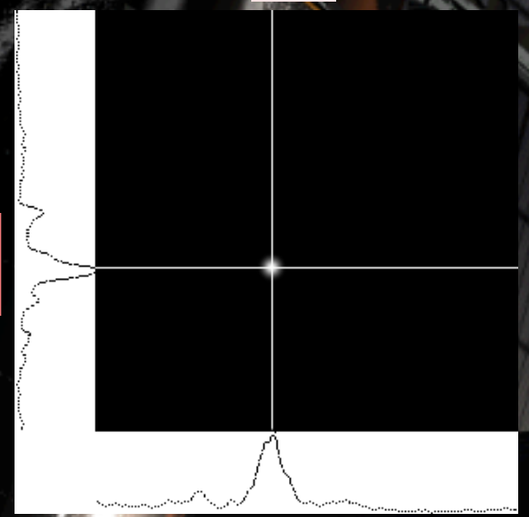




Target



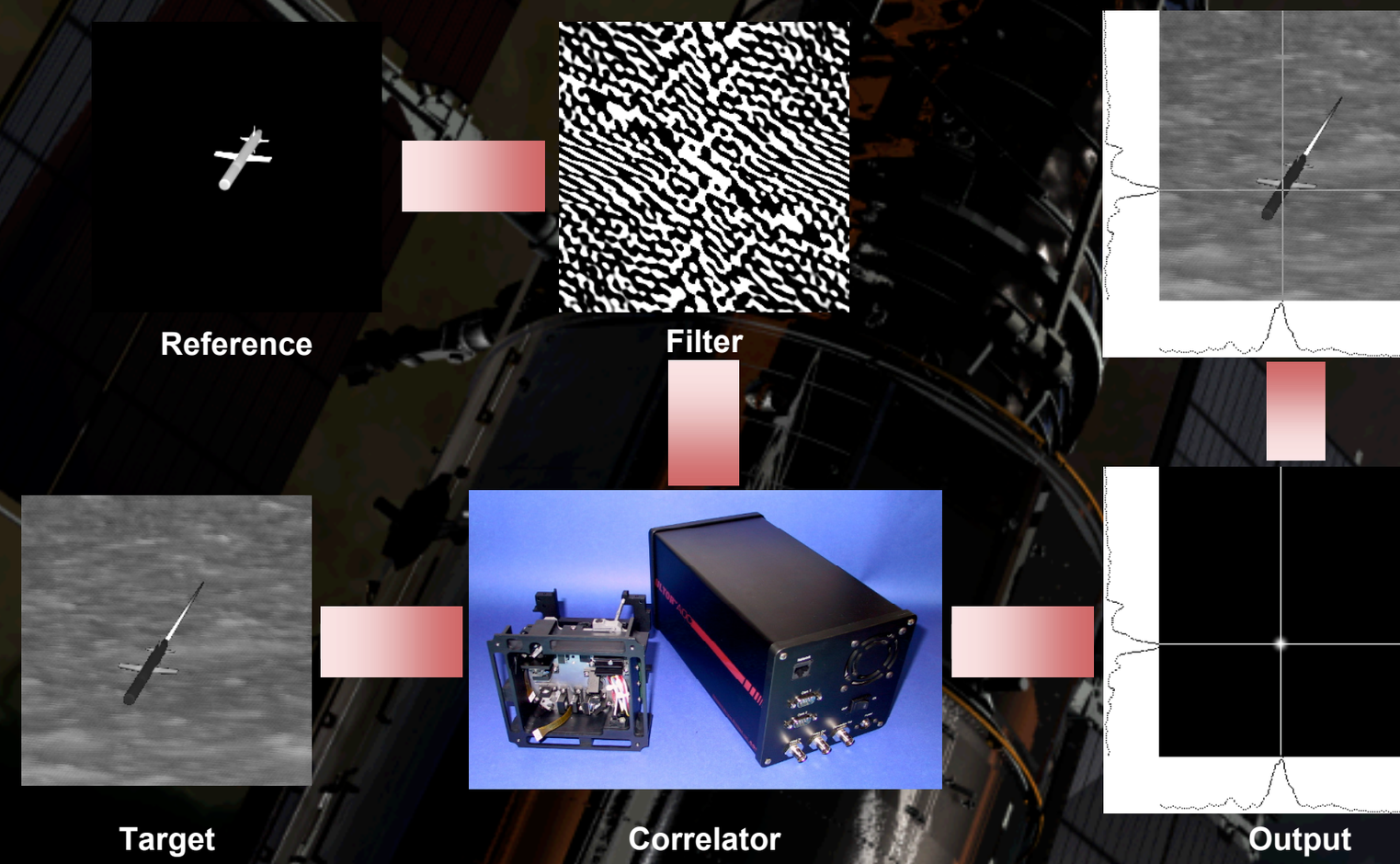
Correlator



Output

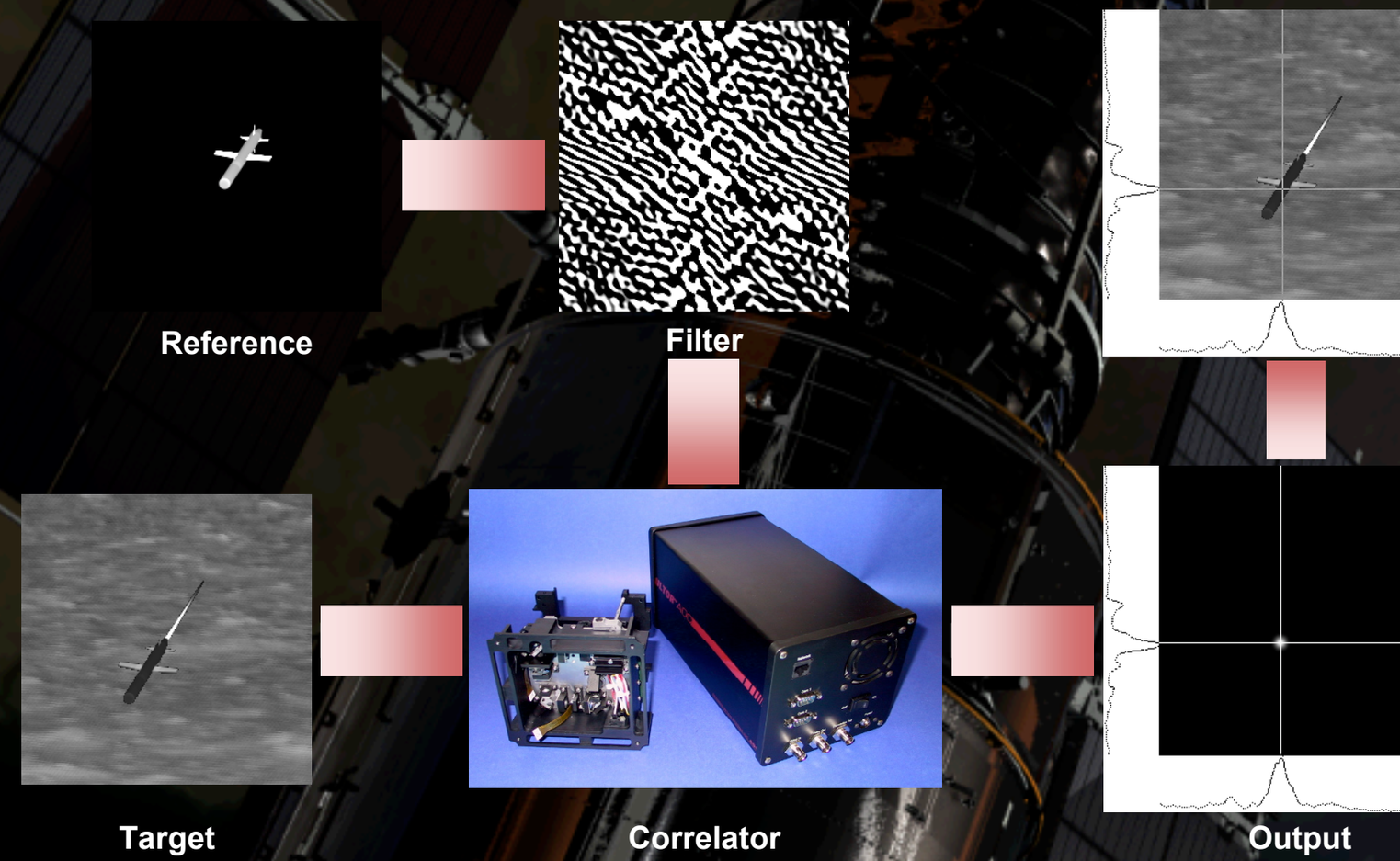
ULTOR P³E

- ULTOR Passive Pose and Position Engine
- Developed by Advanced Optical Systems for missile based Automatic Target Recognition applications
- Correlation image processing technique based on analysis of spatial frequencies of two dimensional image data
- AOS originally developed ULTOR® based on high speed optical processing technology

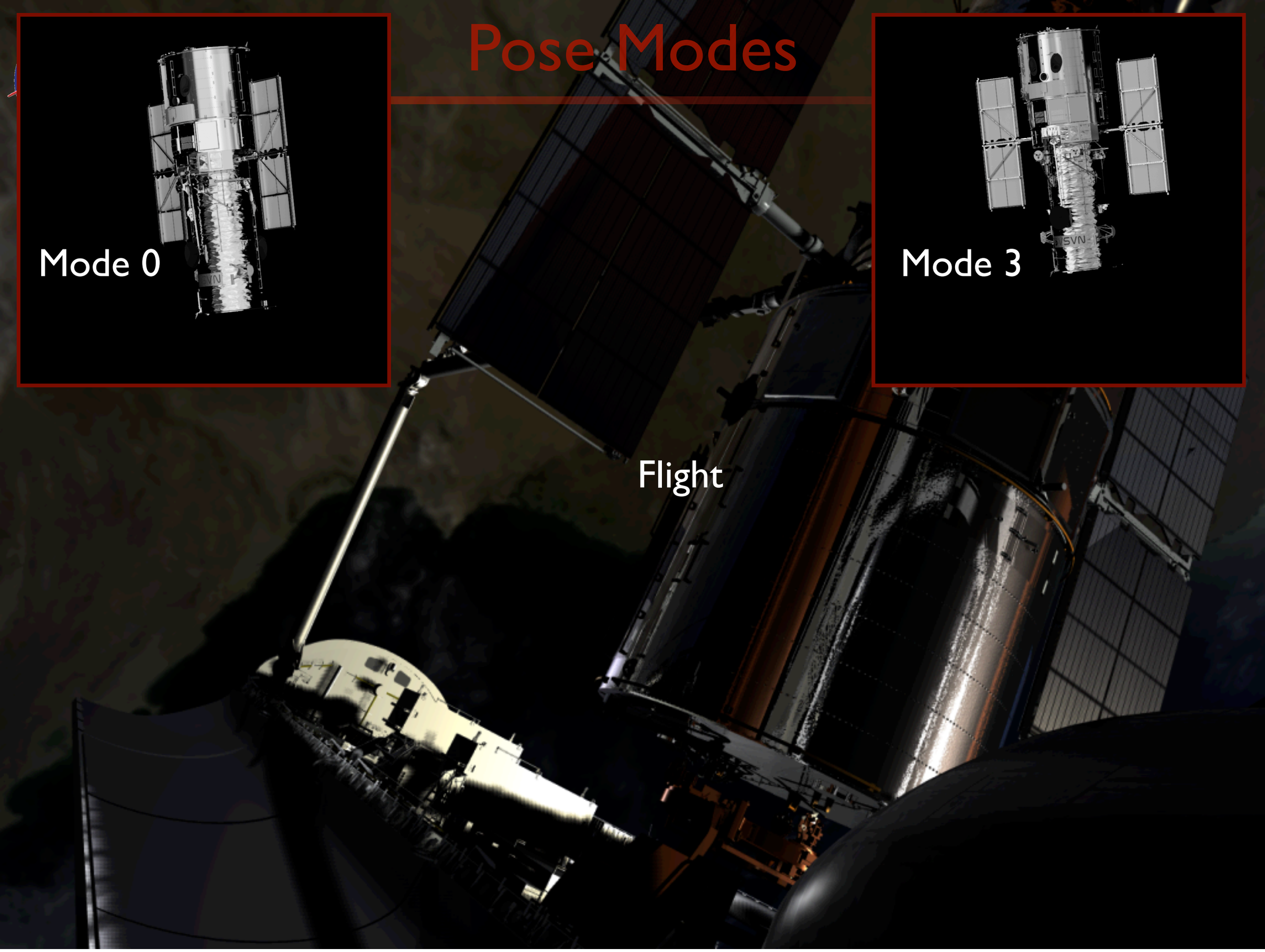


ULTOR P³E

- Rendezvous results
  - Acquired briefly, but failed to track
  - Provided a seed to GNFIR, enabling GNFIR to track for 21 minutes
  - Post processing shows that ULTOR would have tracked for ~15 minutes if either:
    - HST had performed roll to grapple as expected,
    - ULTOR mode had been changed by ground command to compensate for the roll offset
  - HST commanding issue precluded both of these
- Deploy results
  - Failed to acquire and track
  - SCM features and lighting did not correlate well to ground training data

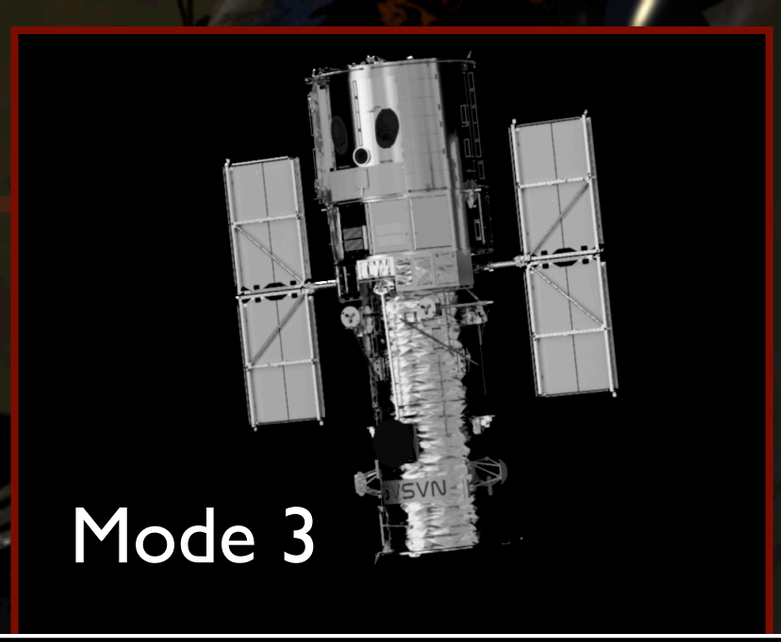


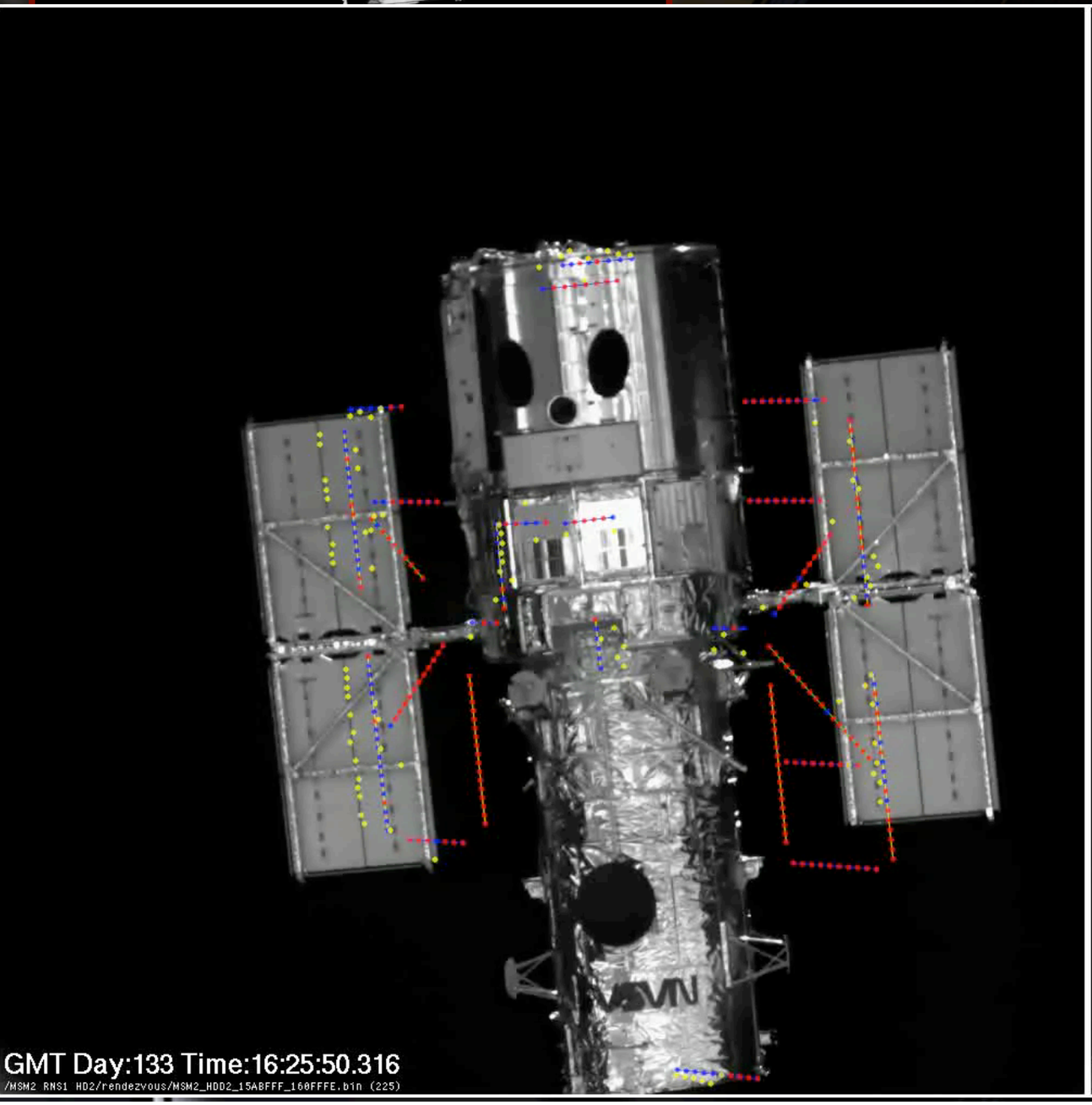
Pose Modes



Pose Modes

Mode 0


Mode 3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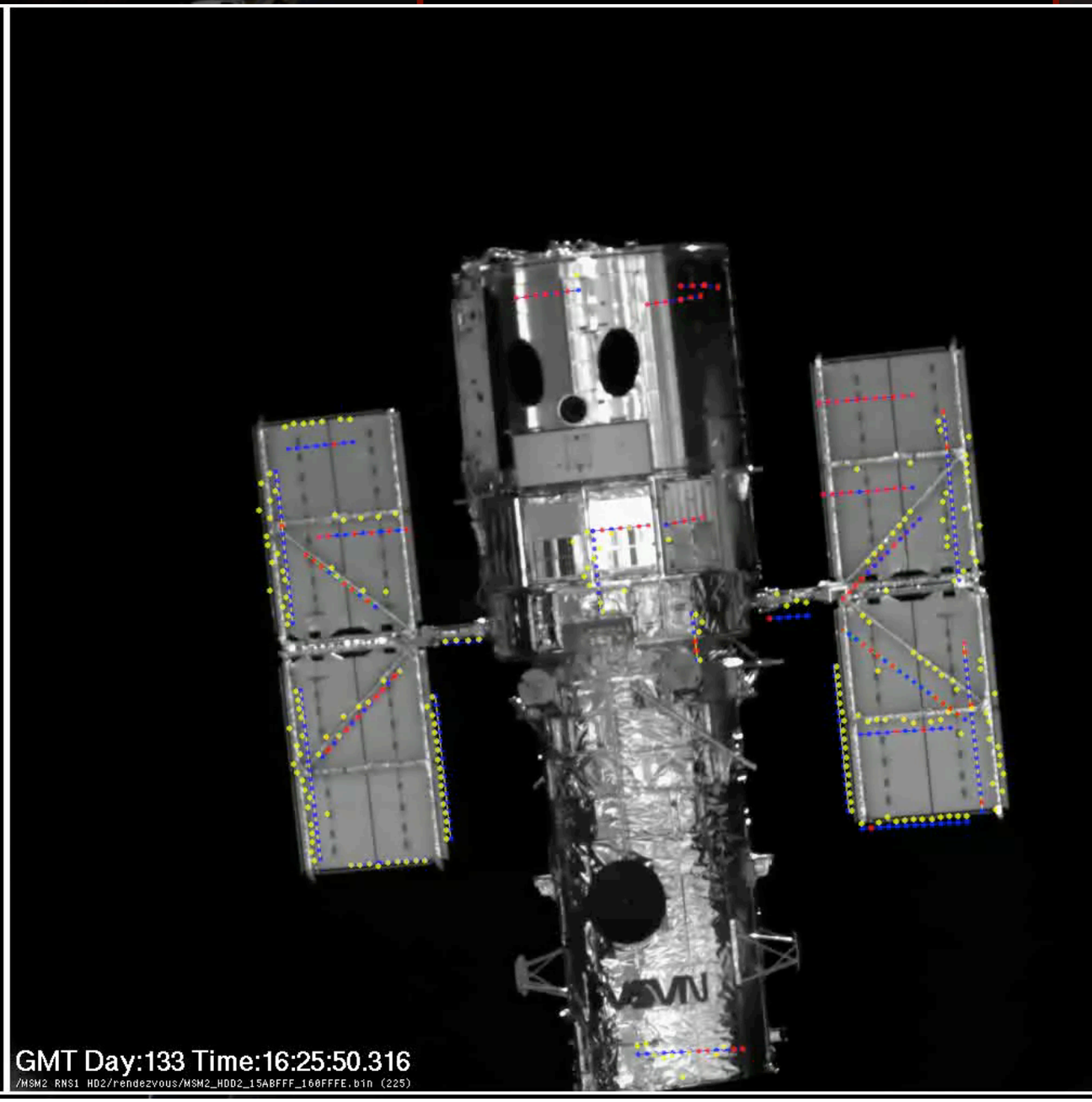
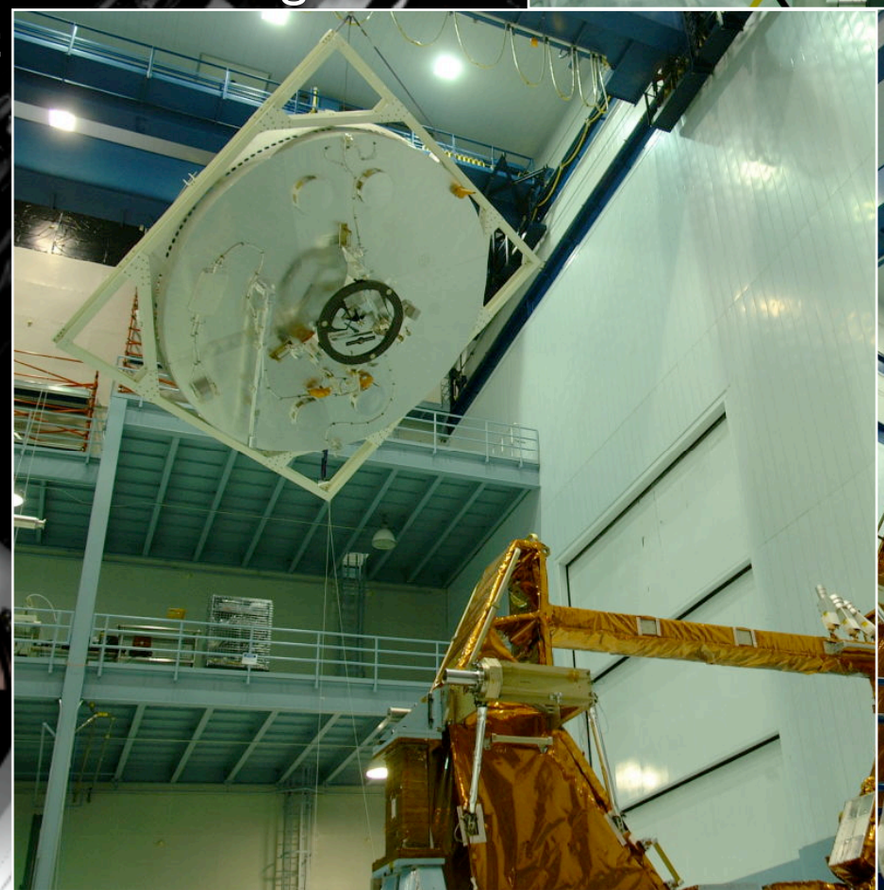

GMT Day:133 Time:16:25:50.316
/MSM2_RNS1_HD2/rendezvous/MSM2_HDD2_15ABFFF_160FFFE.bin (225)

Testing

- Pose and AGC testing
  - 3 EDU system test phases at the MSFC Flight Robotics Lab (FRL)
  - Flight System Pose End-to-End Test in the GSFC SSDIF (B29 "Hubble Clean Room")
  - **Most exhaustive pose and AGC testing used synthetic imagery generated by Freespace/Geomod (in-house SW) suite**
    - Processor hardware stimulated using sensor emulators and synthetic imagery
    - B28 CASS/RNS Lab
- Hardware/System testing
  - Software "flatsat" testing
  - Box-level thermal vacuum and vibe tests
  - ESTL/SAIL tests
  - System-level environmental testing



Flight Robotics Lab Testing

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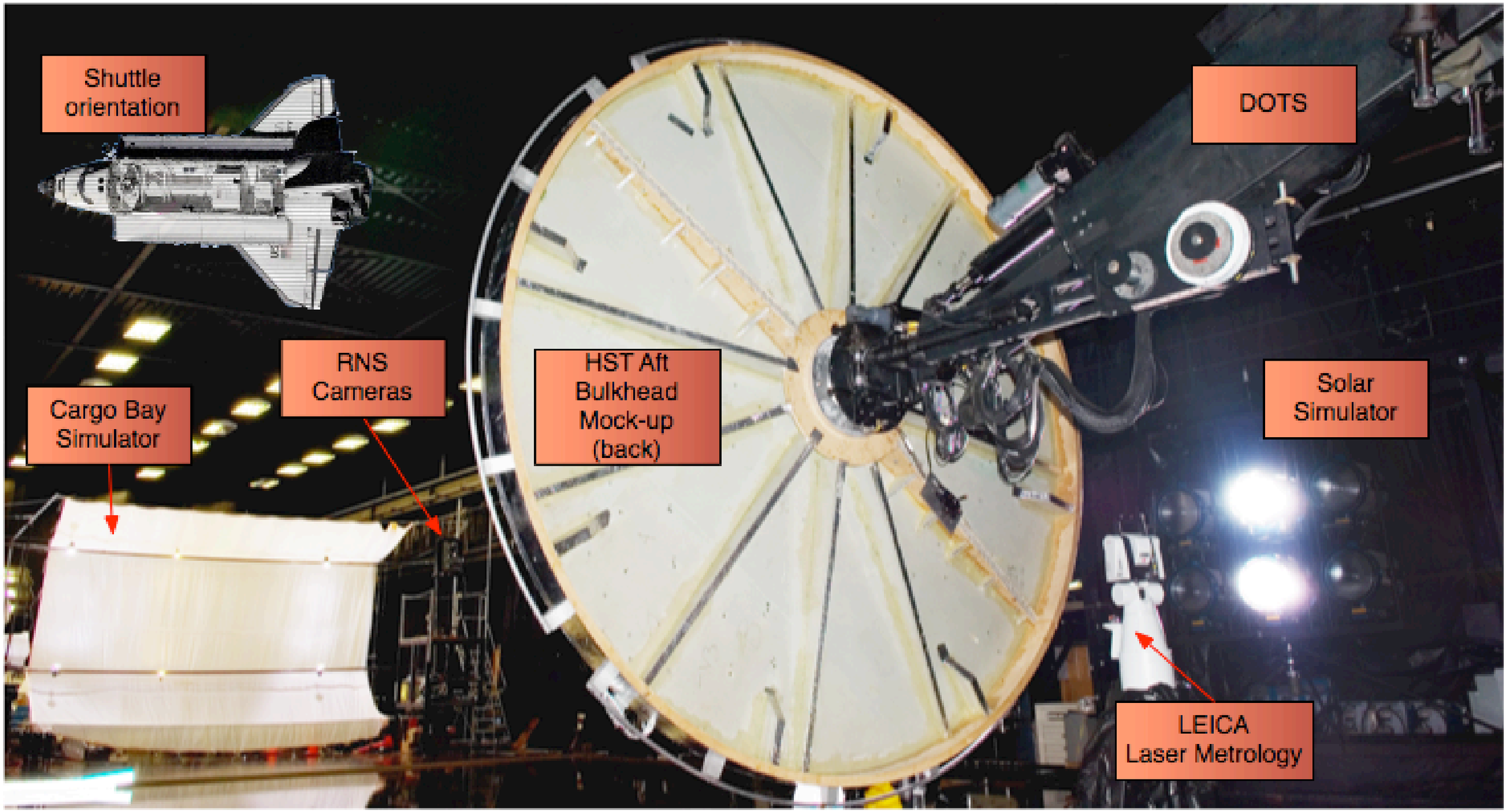
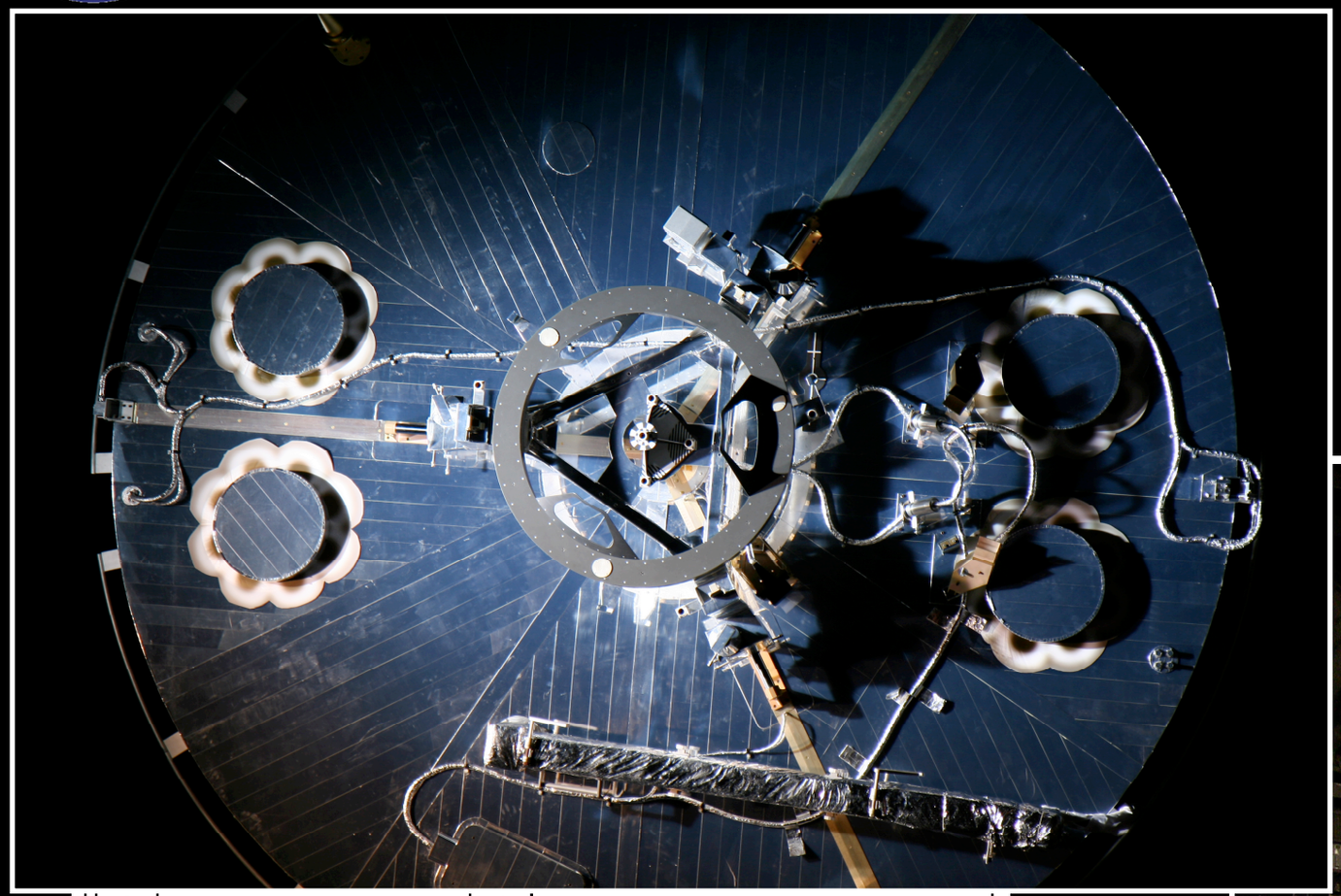
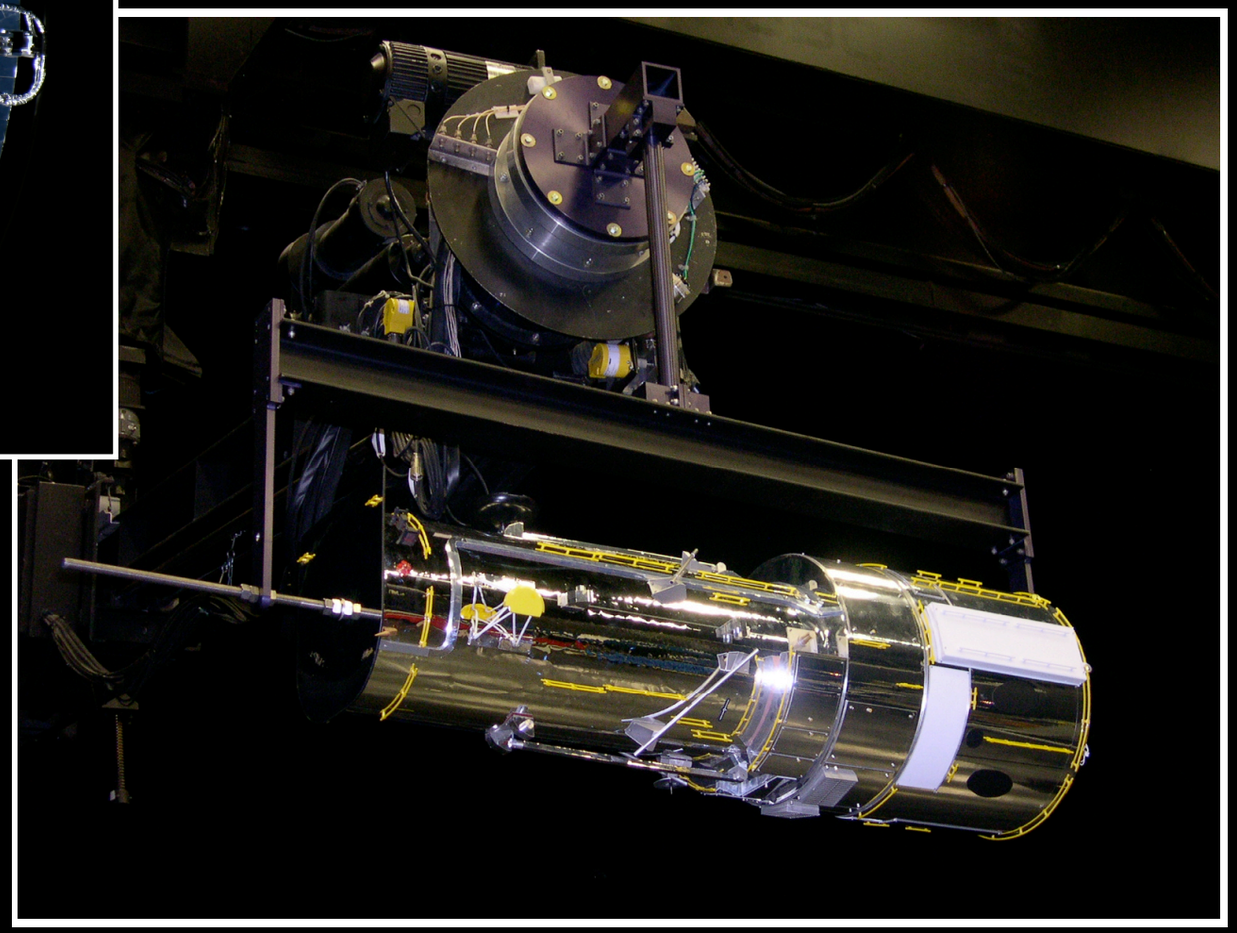
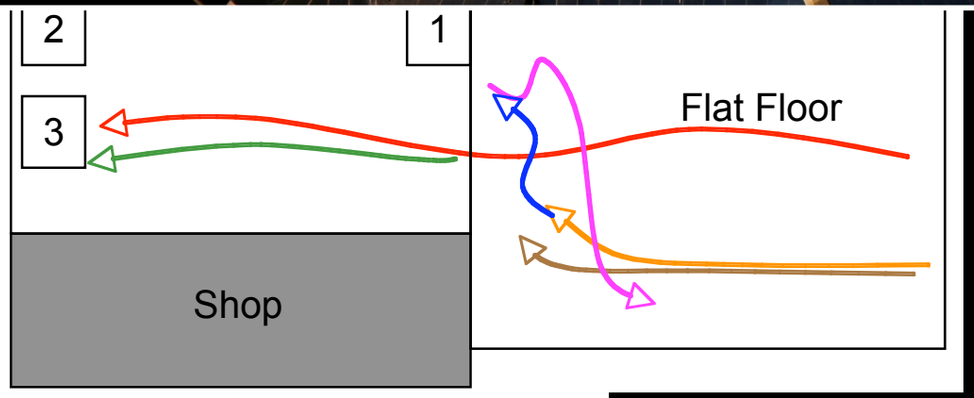


Flight Robotics Lab Testing



- Exercise end-to-end RNS interfaces
- Test trajectories for all 3 cameras
- Comprehensive traj. & lighting study
- Evaluate pose performance
- Long-range test with scale model

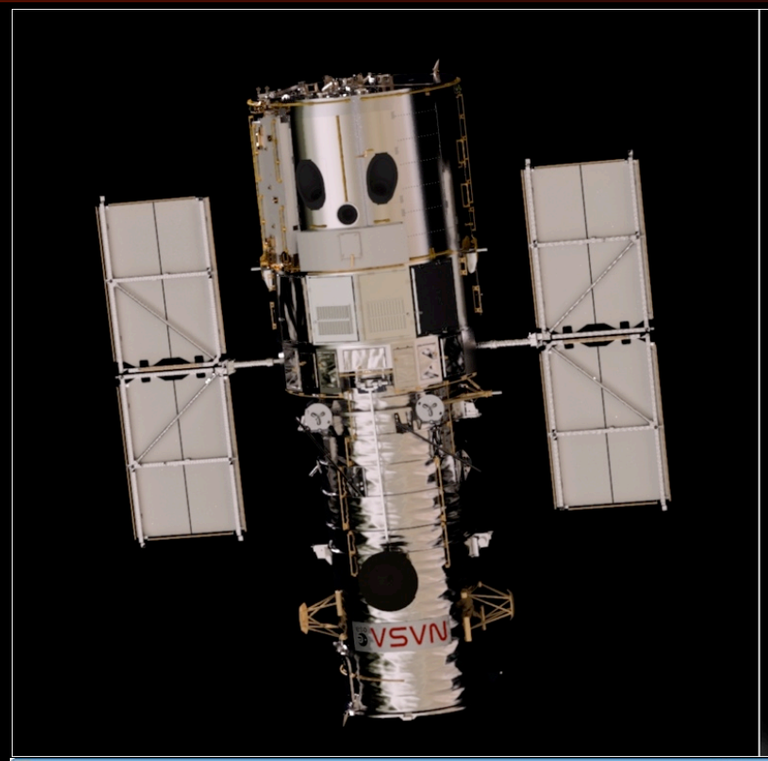


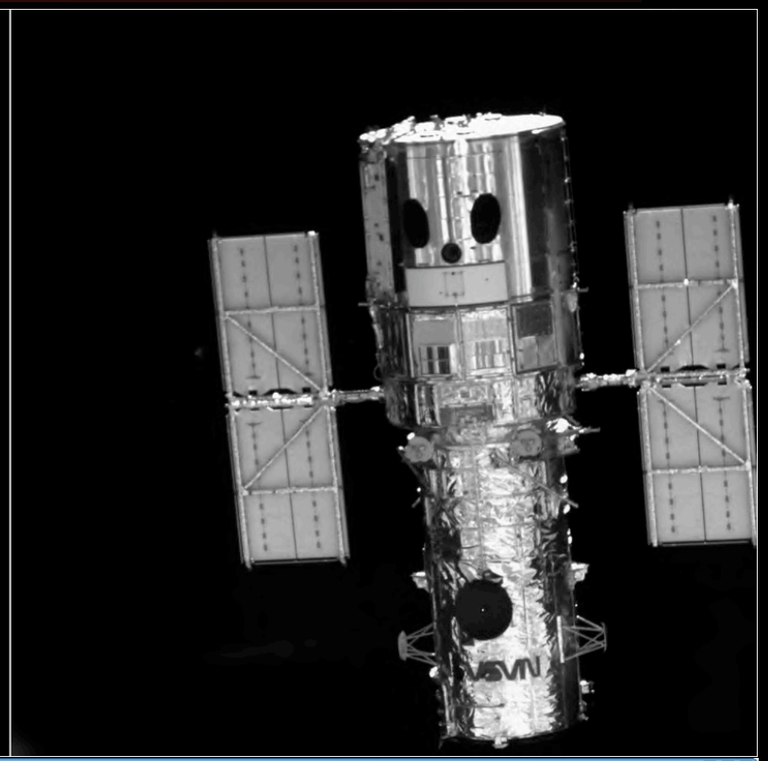


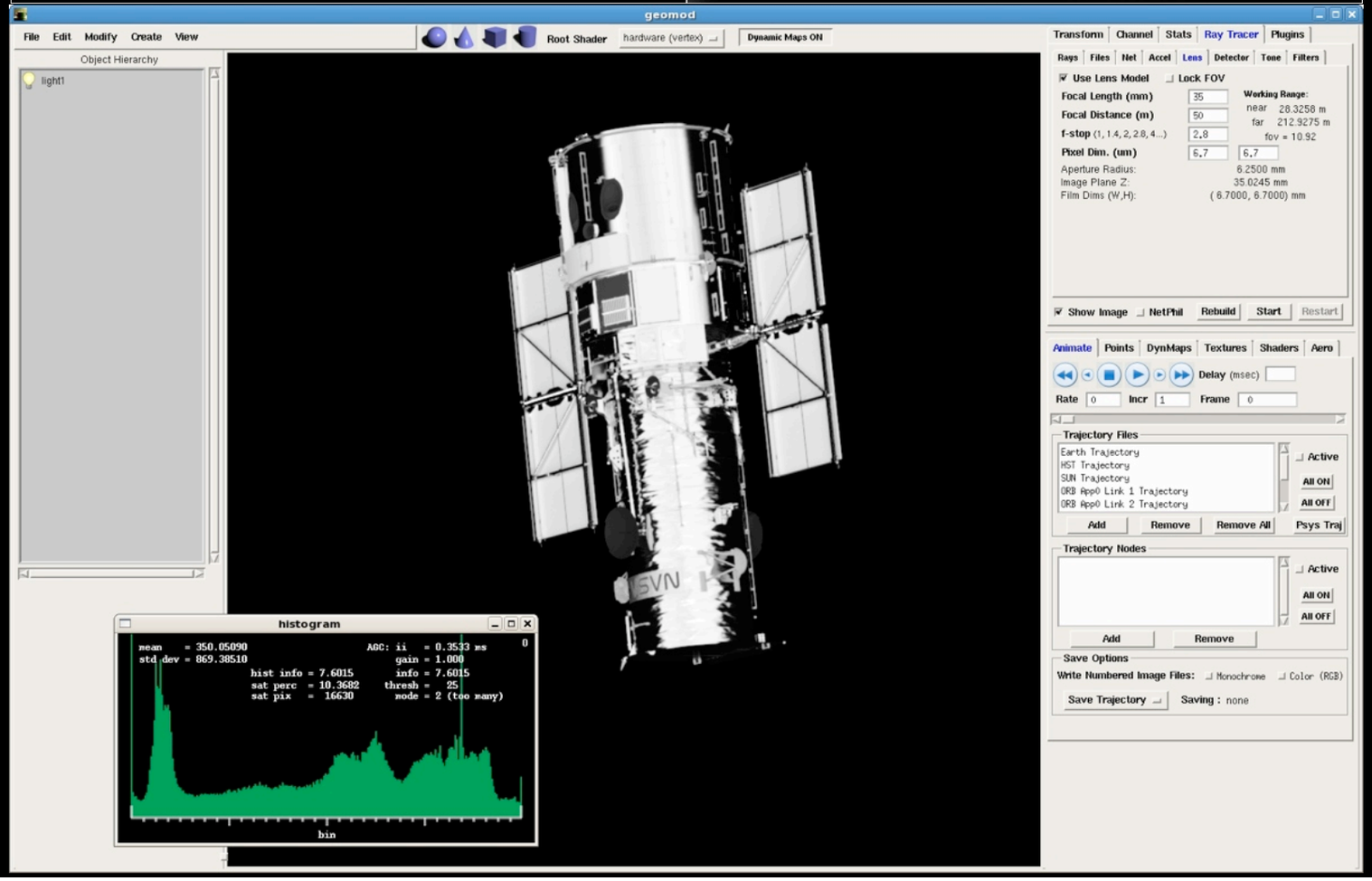
Trajectories:
R-Bar to Grapple
Grapple to Berth
Deploy (with RIP)
RNS1 Full Scale Rendezvous
SM5 Rendezvous
10th Scale Rendezvous

High Fidelity Synthetic Imagery

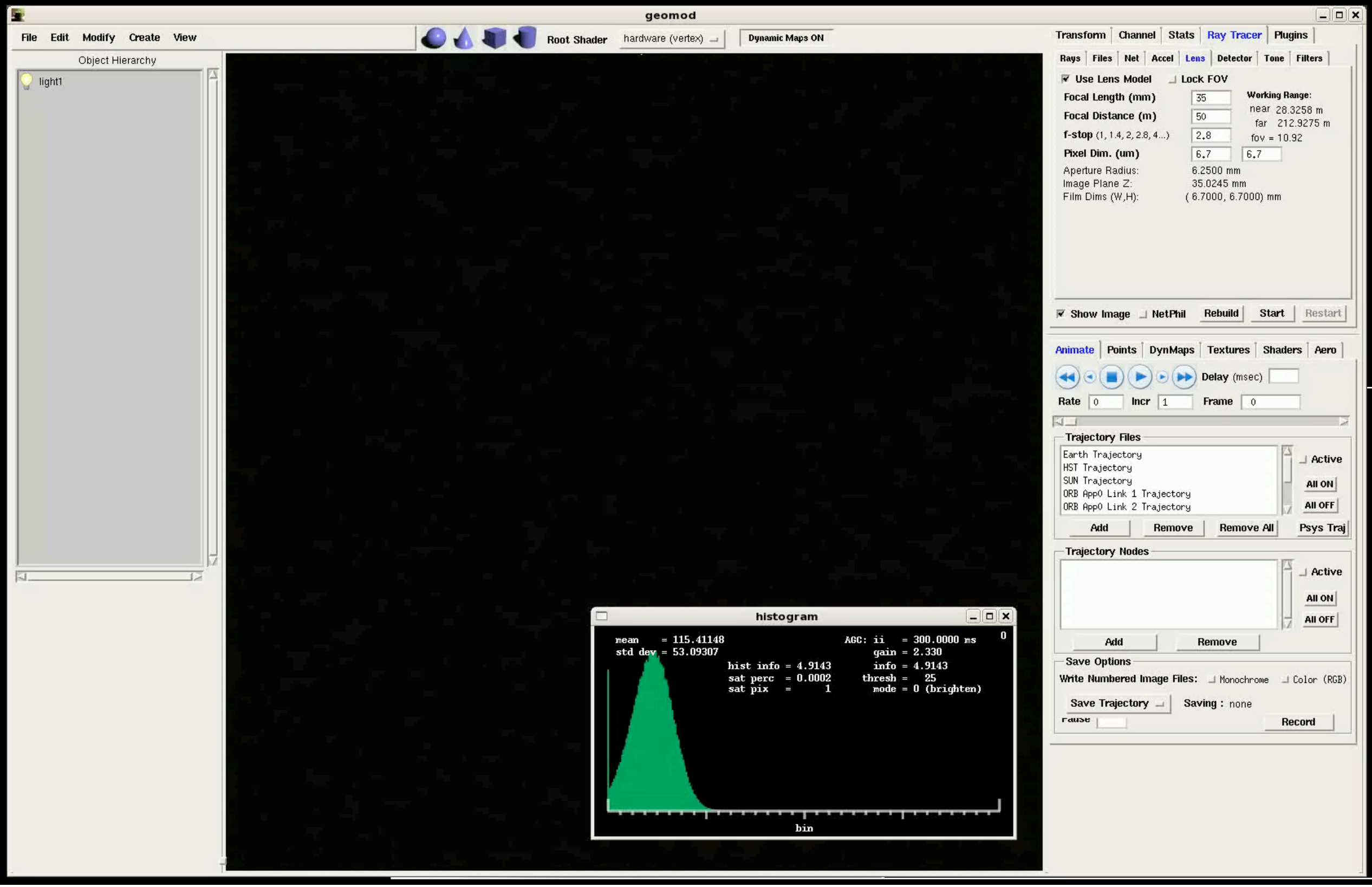
- Synthetic imagery generated using in-house tools:
- Vehicle dynamics simulation (**Freespace**)
  - Orbit
  - Attitude
  - Shuttle robotic arm
- Geometry Modeling (**Geomod**)
- Physical Illum. (**Phillum**)
  - Stochastic ray tracer
  - Detector and lens models for CCD cameras
  - Light source models
  - Closed loop AGC
- Heavy utilization of the NASA Center for Computational Sciences (NCCS) "Discover" Cluster







Synthetic Imagery for AGC Testing



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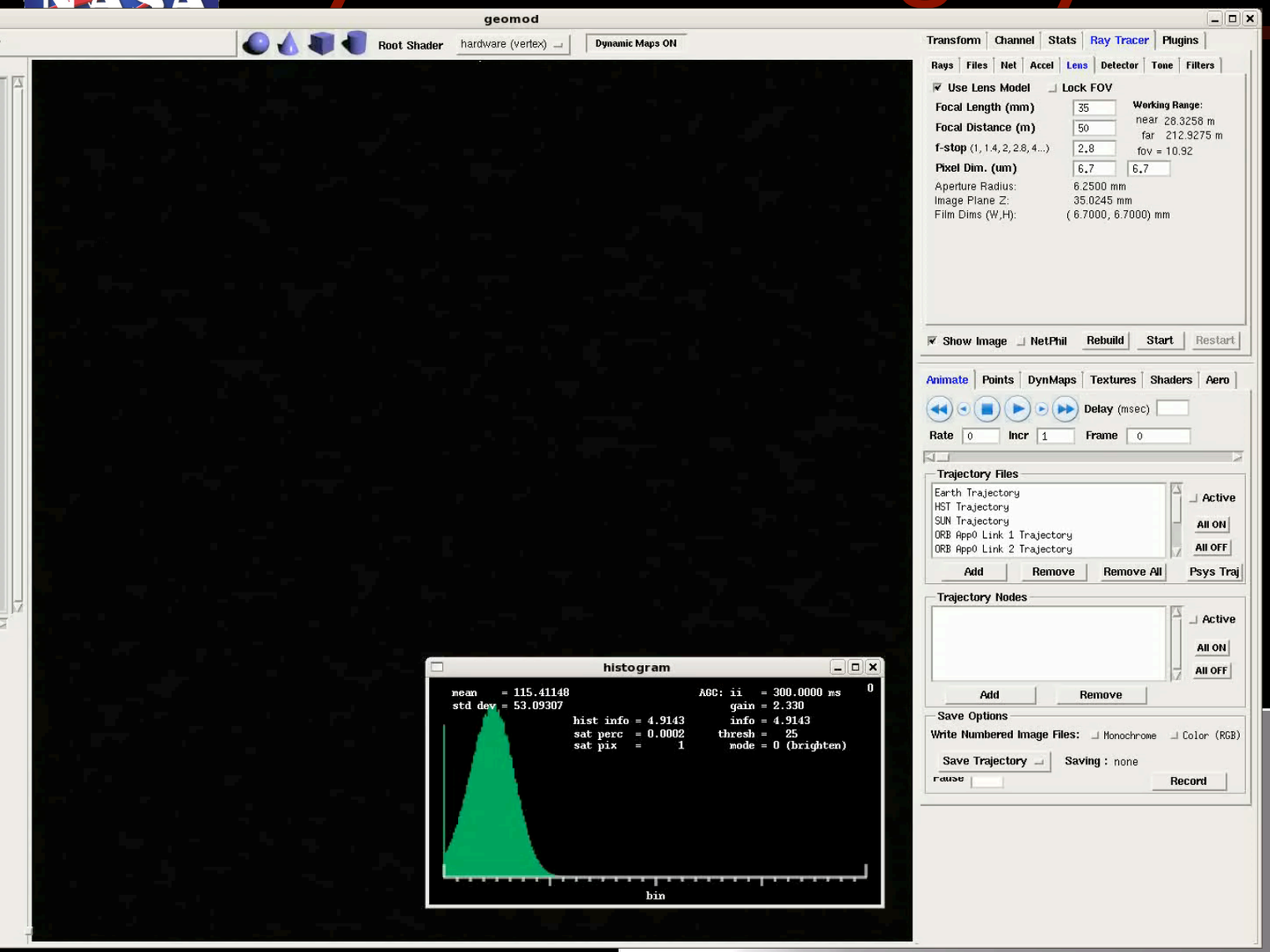
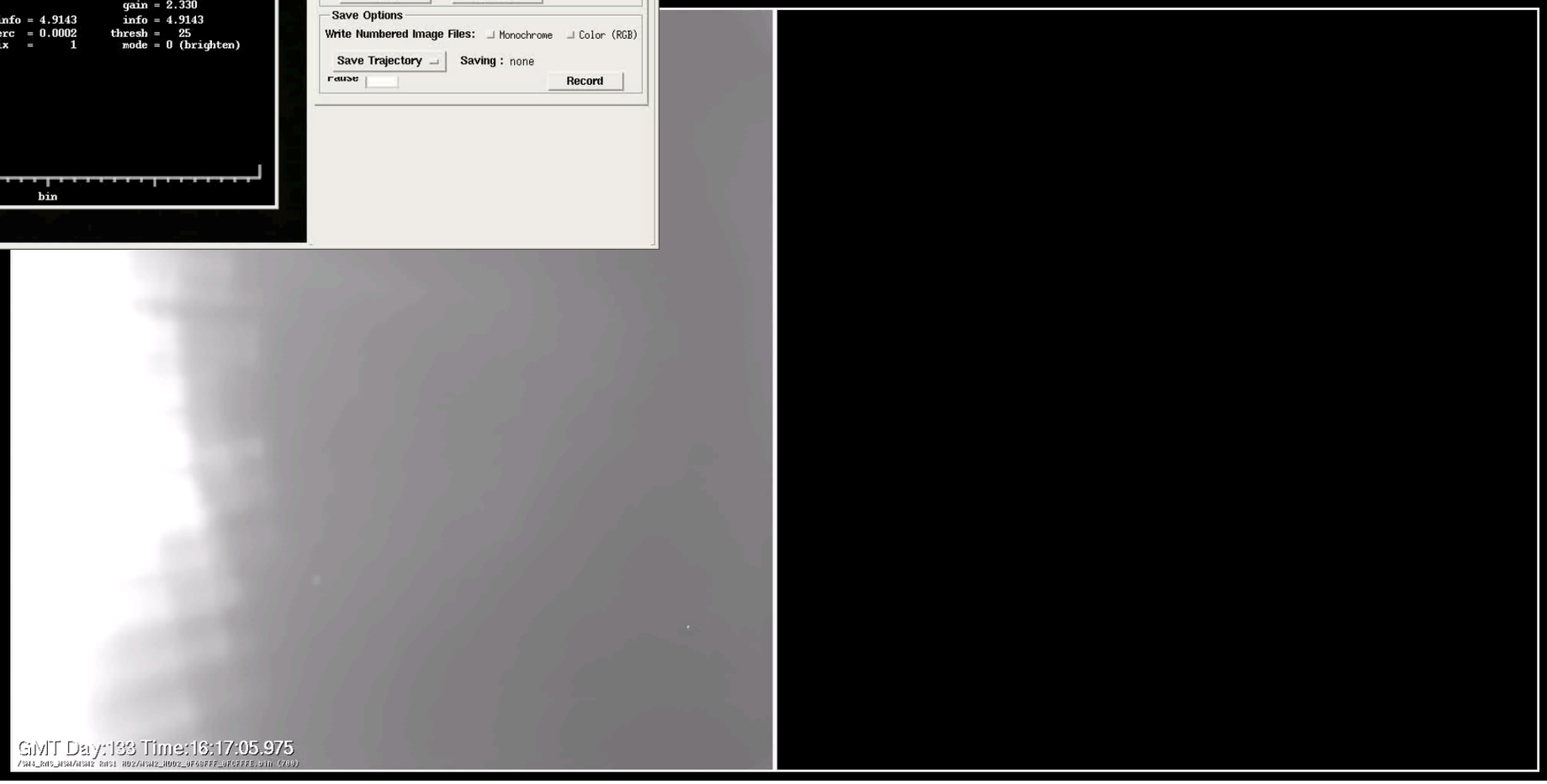
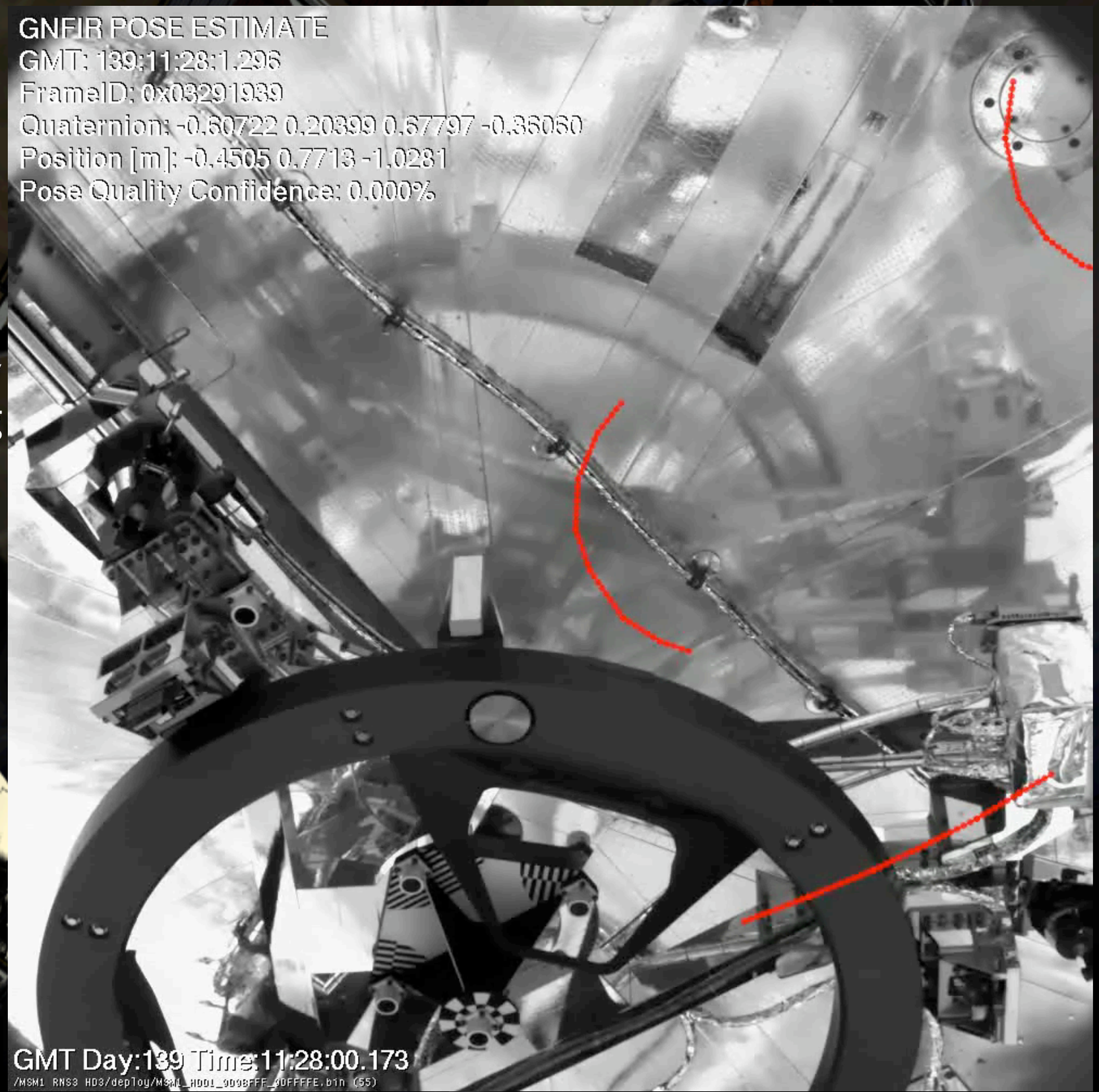




Goddard Natural Feature Image Recognition

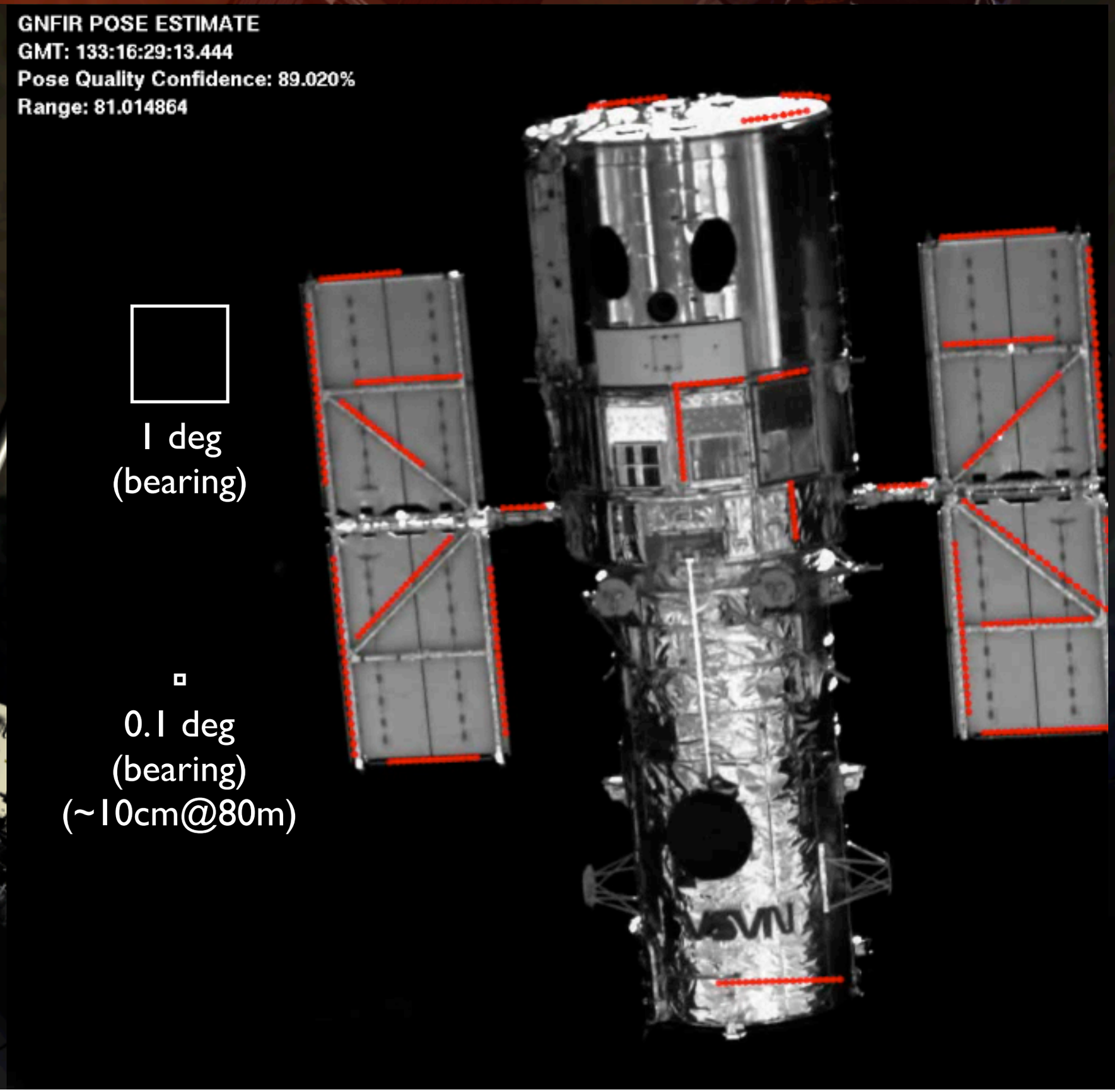
Goddard Natural Feature Image Recognition

- Rendezvous results
  - Acquired and tracked on long range camera for 21 minutes
  - Ranges from 50 - 100 meters
  - Maximum pose quality of 99% during tracking
- Deploy results
  - Acquired and tracked on short range camera for ~15 minutes at ranges of 2-3 meters
  - Average pose quality of 83%
- Pose accuracy results pending Shuttle RELBET



Full quantitative performance results pending Shuttle RELBET availability

11 deg

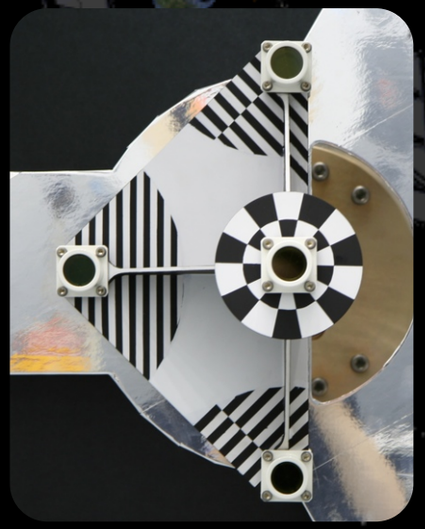


What's next?

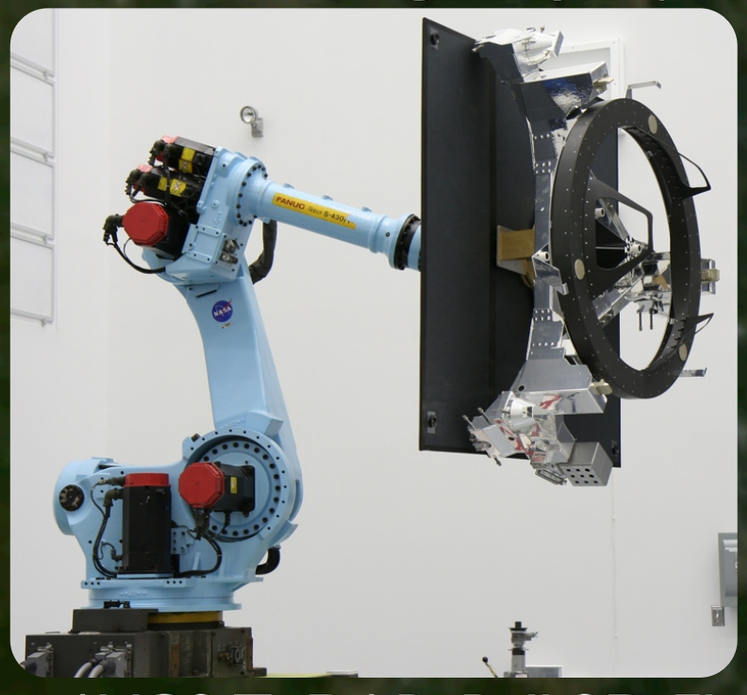
- SM4 Post Processing
- National Servicing Capabilities Office proposed FY09 tasks
  - 3.1.4 - Evaluate current flight-ready or near-flight relative navigation systems technology
  - 3.2.1 - Defining a strawman navigation system for rendezvous, proximity operations, and docking with a non-cooperative (potential spinning, GEO) vehicle
  - 3.2.2 - Developing relative navigation system technology to fill in the technology gaps
  - 3.2.3 - Conduct relative navigation system hardware-in-the-loop testing
  - 3.4.2 - Develop a precision pointing package for use on robotic arms, such as Canada's Special Purpose Dexterous Manipulator, Dextre that reduce the on-orbit movement, vibration, and jitter of the arm
- Future missions
  - Station demonstration (Servicing Study FY10 funding?)
  - Sample return, autonomous rendezvous, or precision landing mission?
  - Hubble de-orbit mission?

Active Relative Navigation Sensors

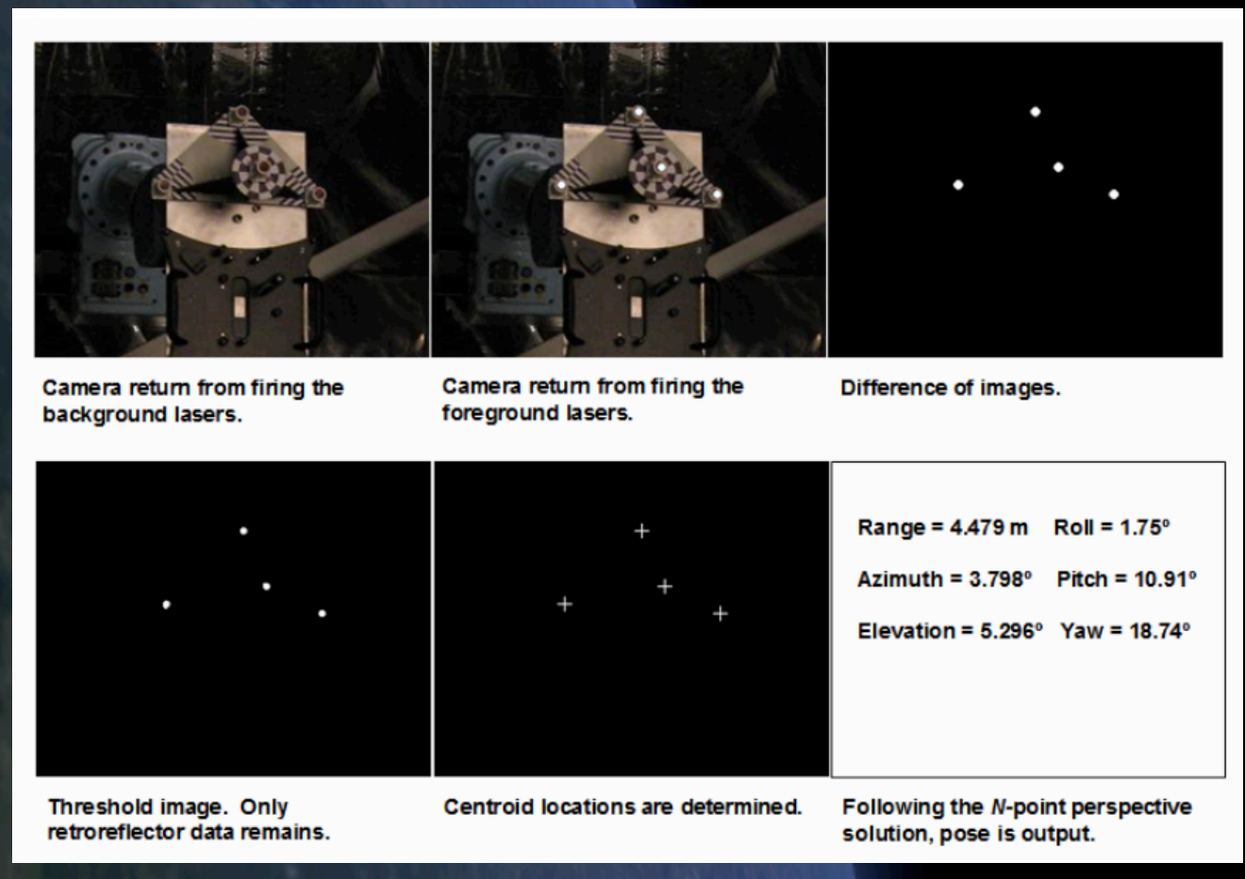
- Advanced Video Guidance System (AVGS)
  - Flew on DART, Orbital Express
  - Hubble Soft Capture Mechanism retro-reflectors are AVGS-compatible
- Laser Radar
  - Ball 3D Flash Ladar (Orion)
  - Neptec TriDAR (scanning)
  - Optec (scanning, XSS-11)
  - DragonEye (ASC, SpaceX)



HST SCM Short Range Target



AVGS, TriDAR, Ball 3D Flash Ladar testing in GSFC "White House"



AVGS processing flow

Relative Navigation IRAD

Continue development of GN&C capabilities for Autonomous or Automated Rendezvous, Proximity Operations, Docking, and Undocking (ARPODU), and to expand these capabilities to new science missions requiring ARPODU, precision landing, and onboard surface navigation capabilities

Current Capability:

Rendezvous Navigation
(vehicle-relative nav)
2D Optical sensors

Future Capability:

Precision Landing/ Surface Navigation
(terrain-relative nav)
3D Laser Range Sensors

- Laser Radar Simulation and Processing
- Terrain Modeling
- Continue sensor and processor hardware-in-the-loop testing

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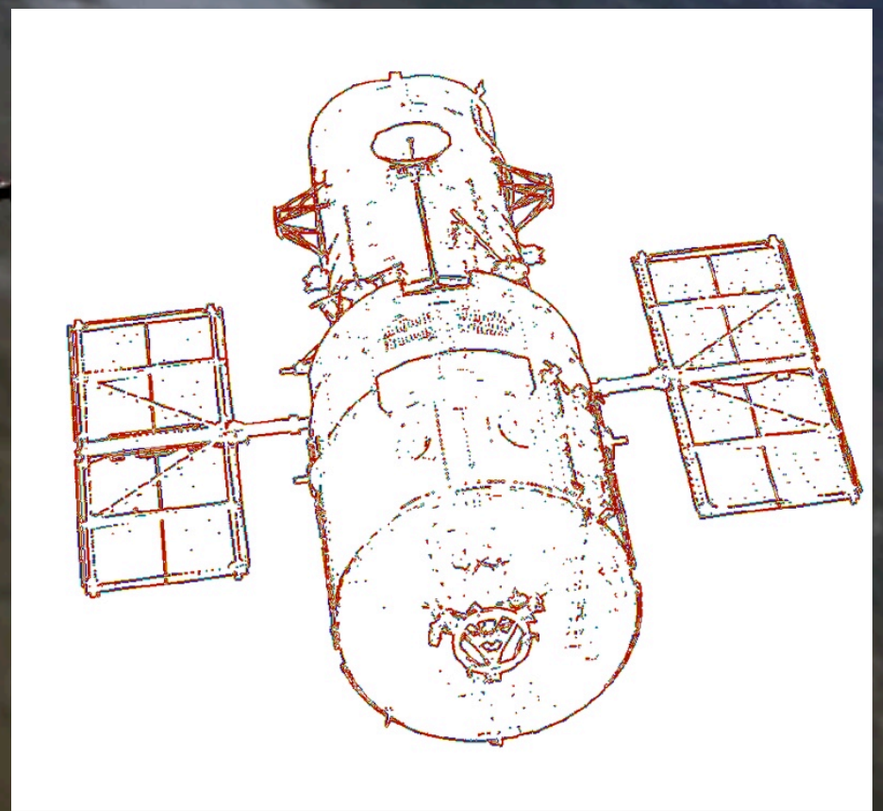

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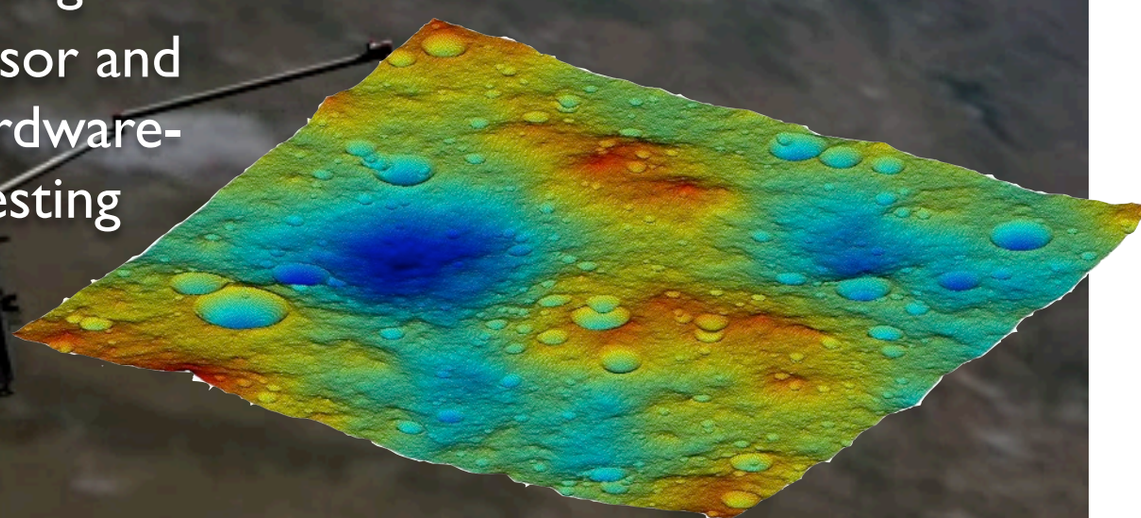
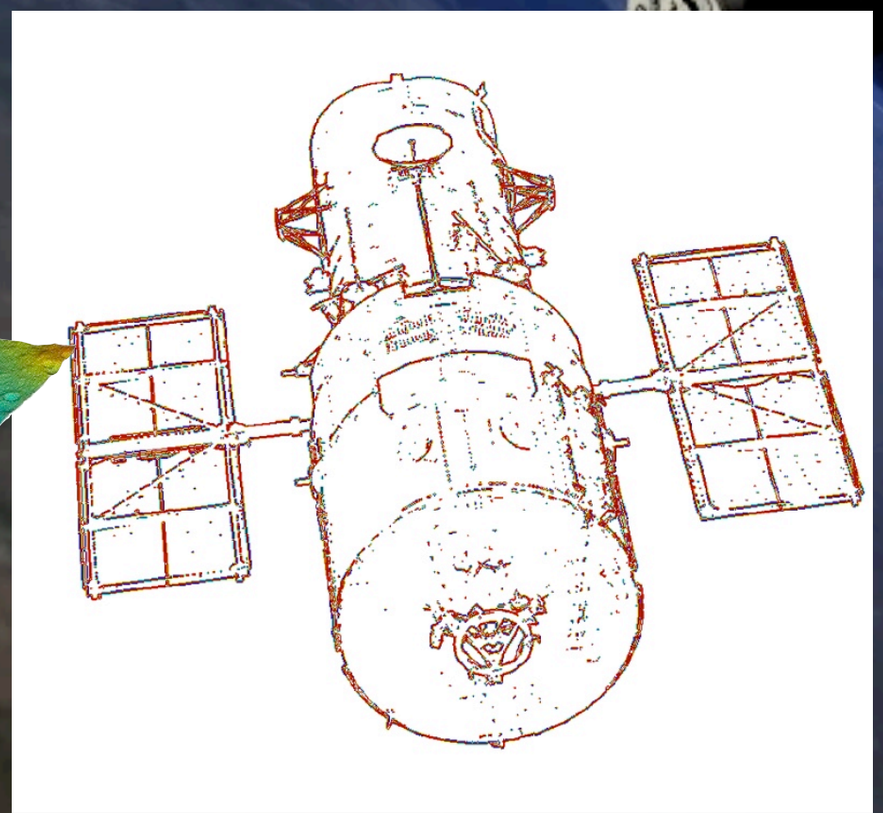
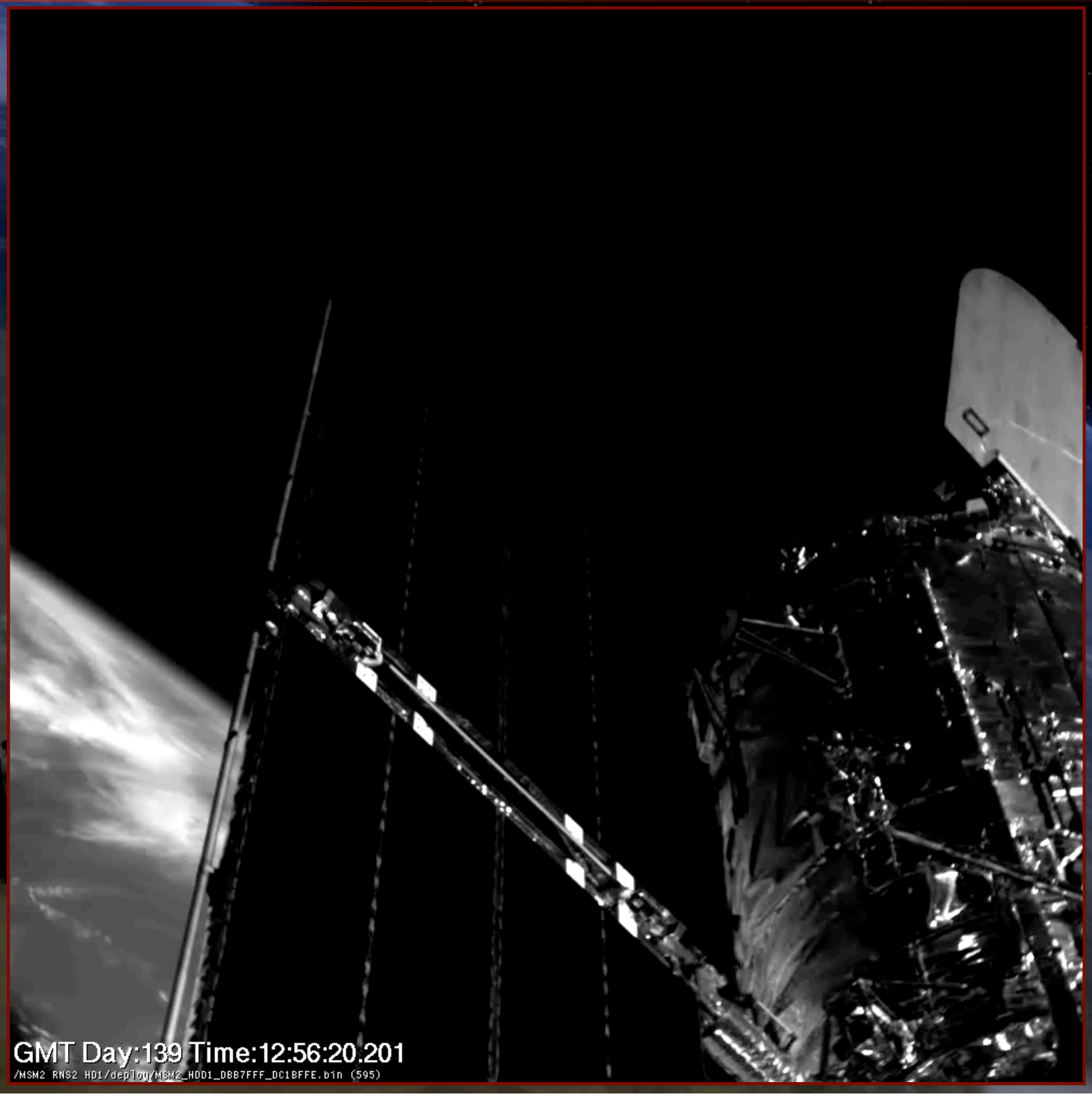


Simulated Terrain



QUESTIONS?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