Optical Testing of the James Webb Space Telescope

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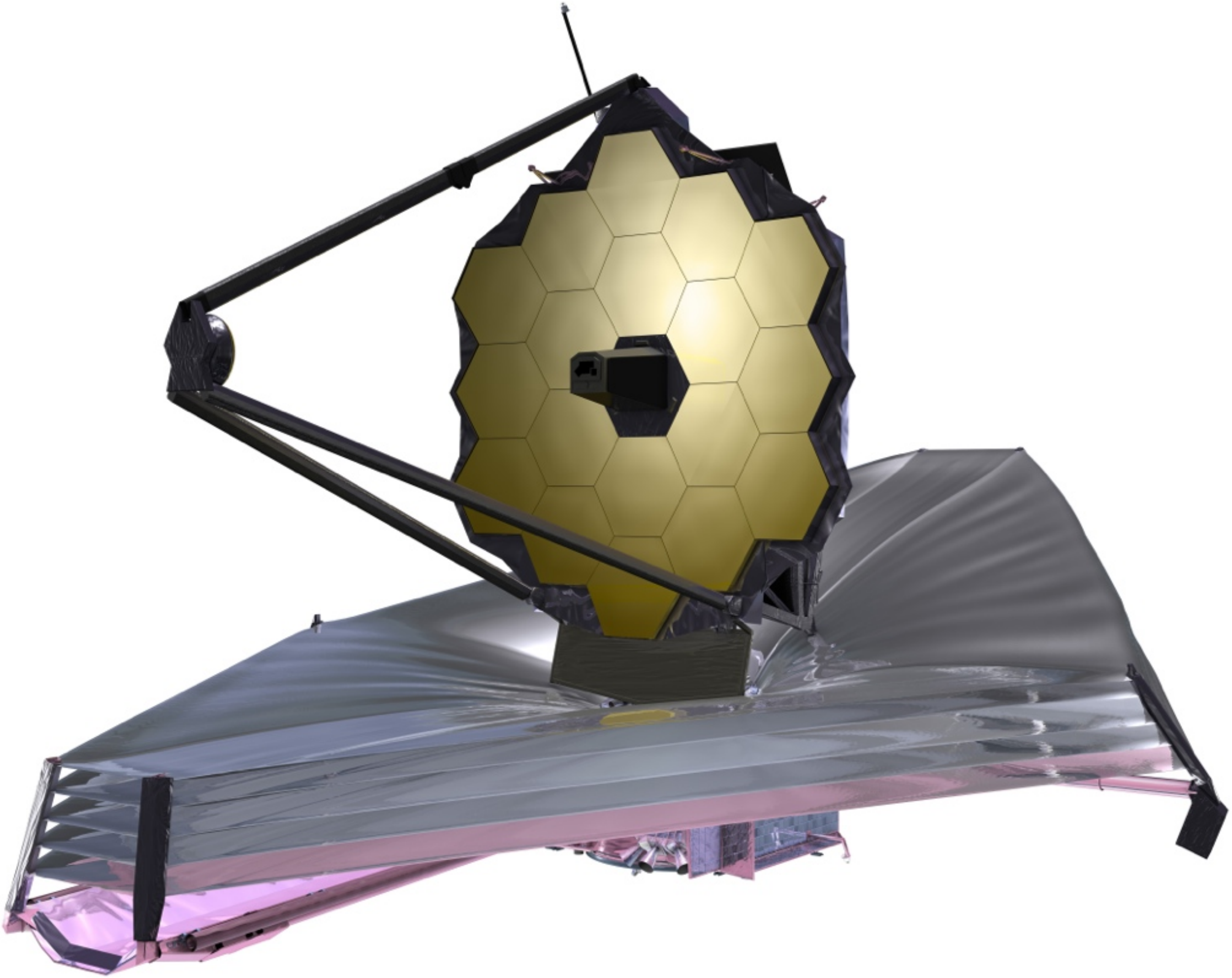
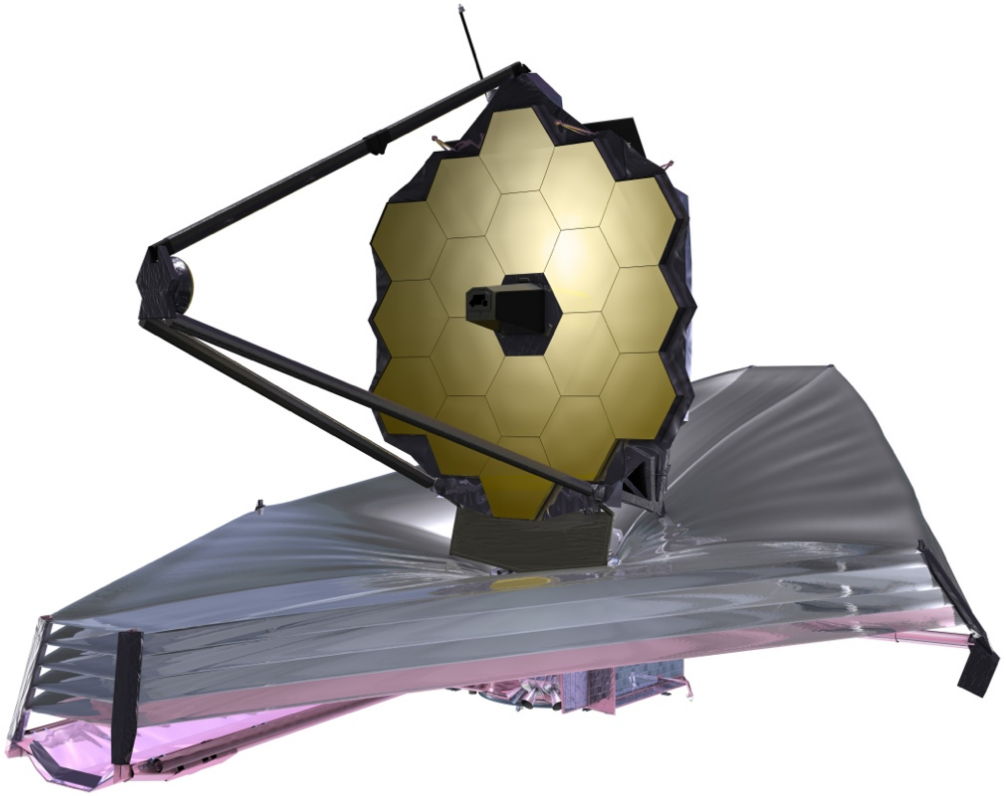
22 September 2017

The James Webb Space Telescope (JWST)

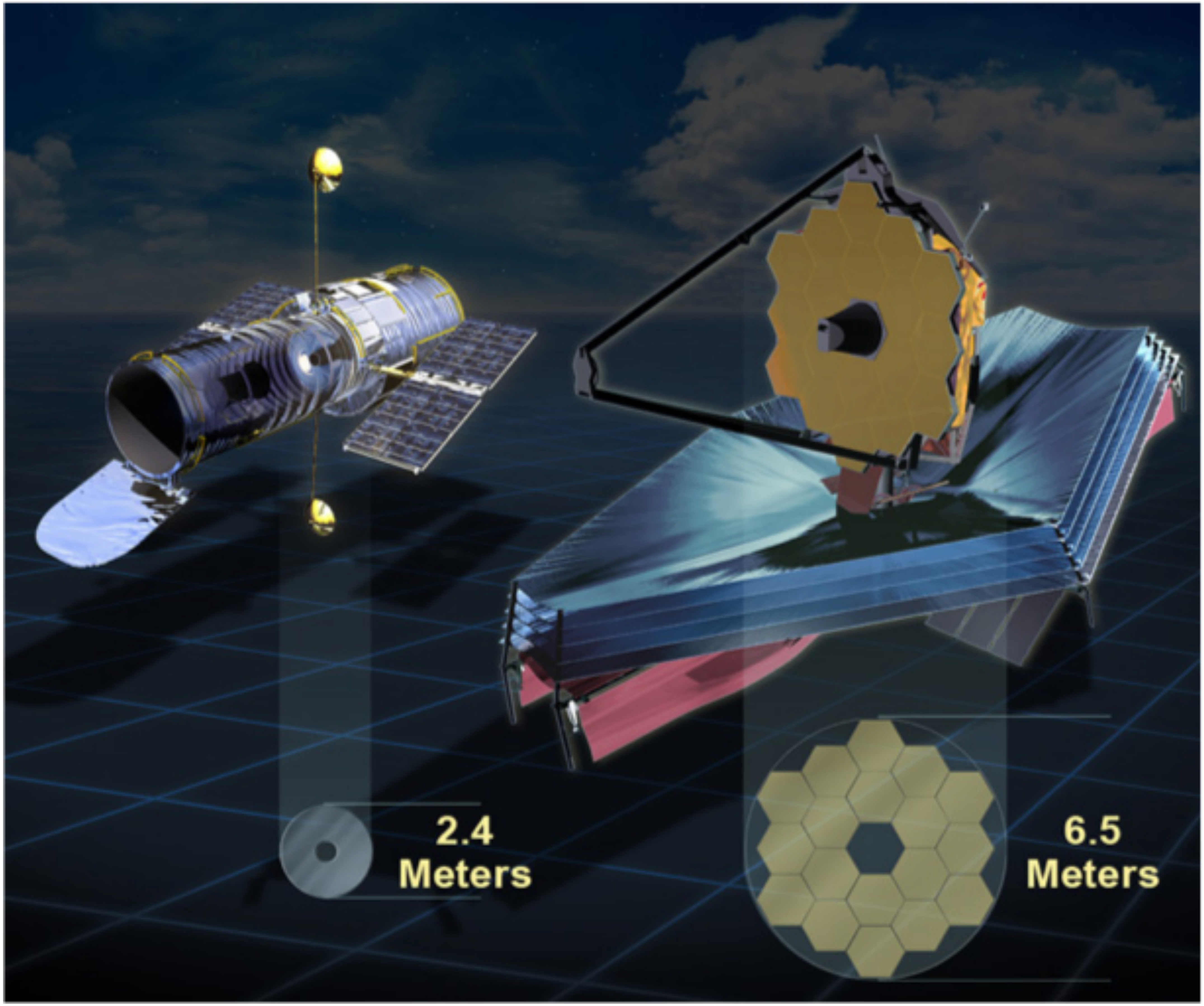


The James Webb Space Telescope (JWST)



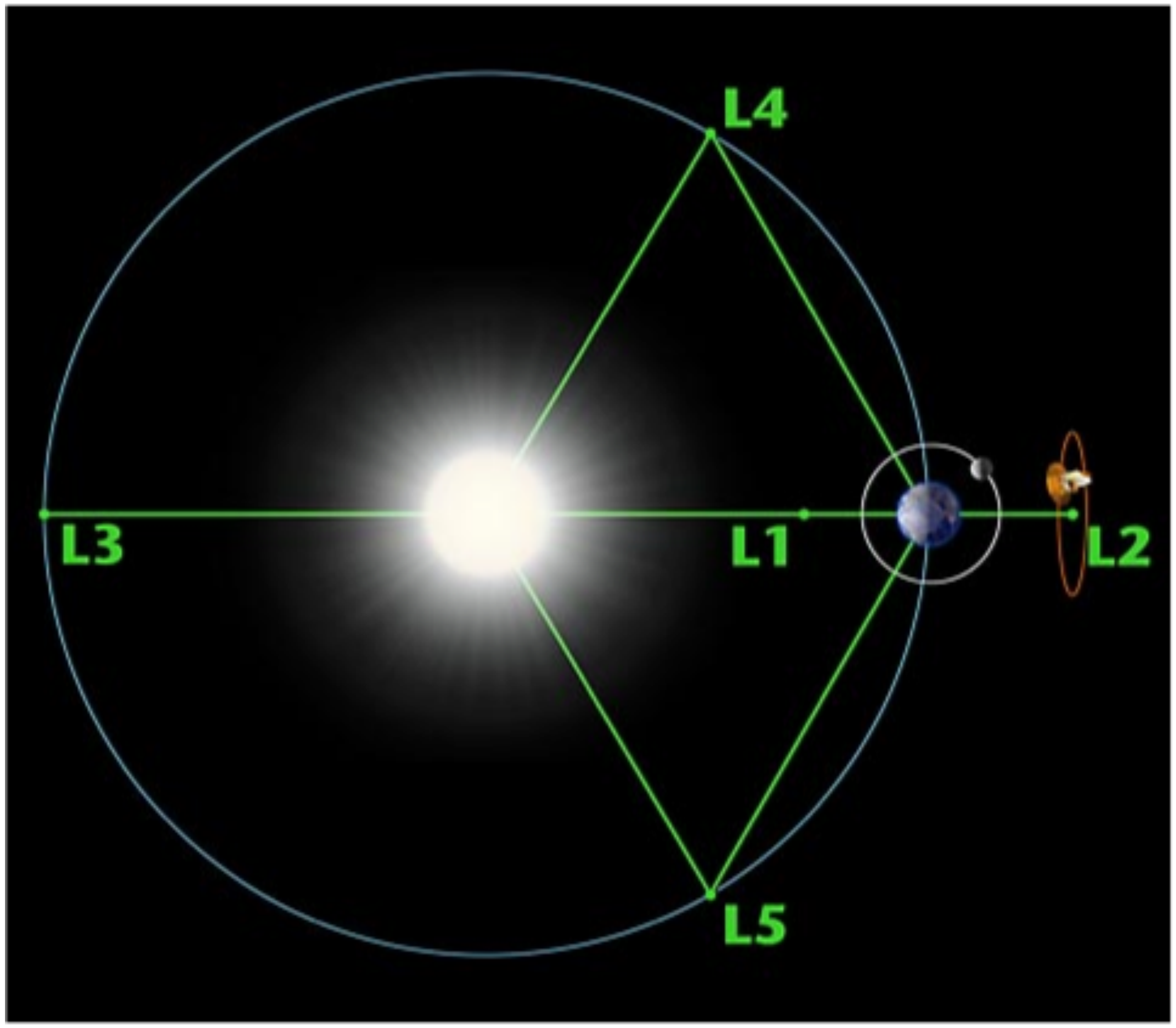
- **A space-based observatory, operating at infrared wavelengths.**
- **Science themes:**
  - First Light & Reionization
  - Assembly of Galaxies
  - Birth of Stars & Protoplanetary Systems
  - Planets & Origins of Life
- **Named in honor of James E. Webb, NASA's second administrator.**
- **Planned to launch in an Ariane 5 rocket from French Guiana in October 2018.**
- **Total cost is ~ $8.8 billion.**

Size Comparison with the Hubble Space Telescope



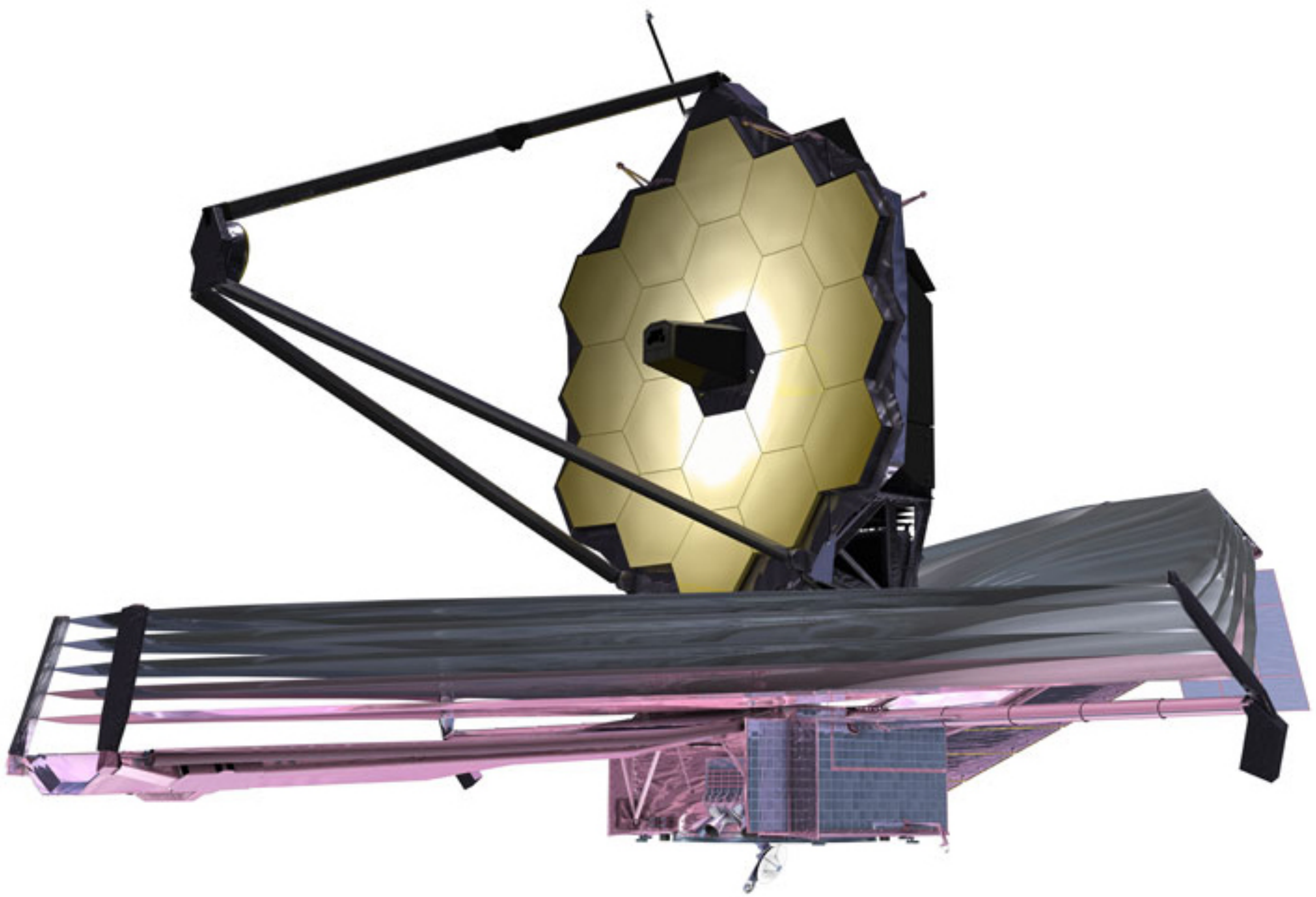
L2 Orbit

- **The JWST will orbit about the 2nd Lagrange point between the Sun & Earth, about 4X further away than the moon (~1.5 million km from Earth)**

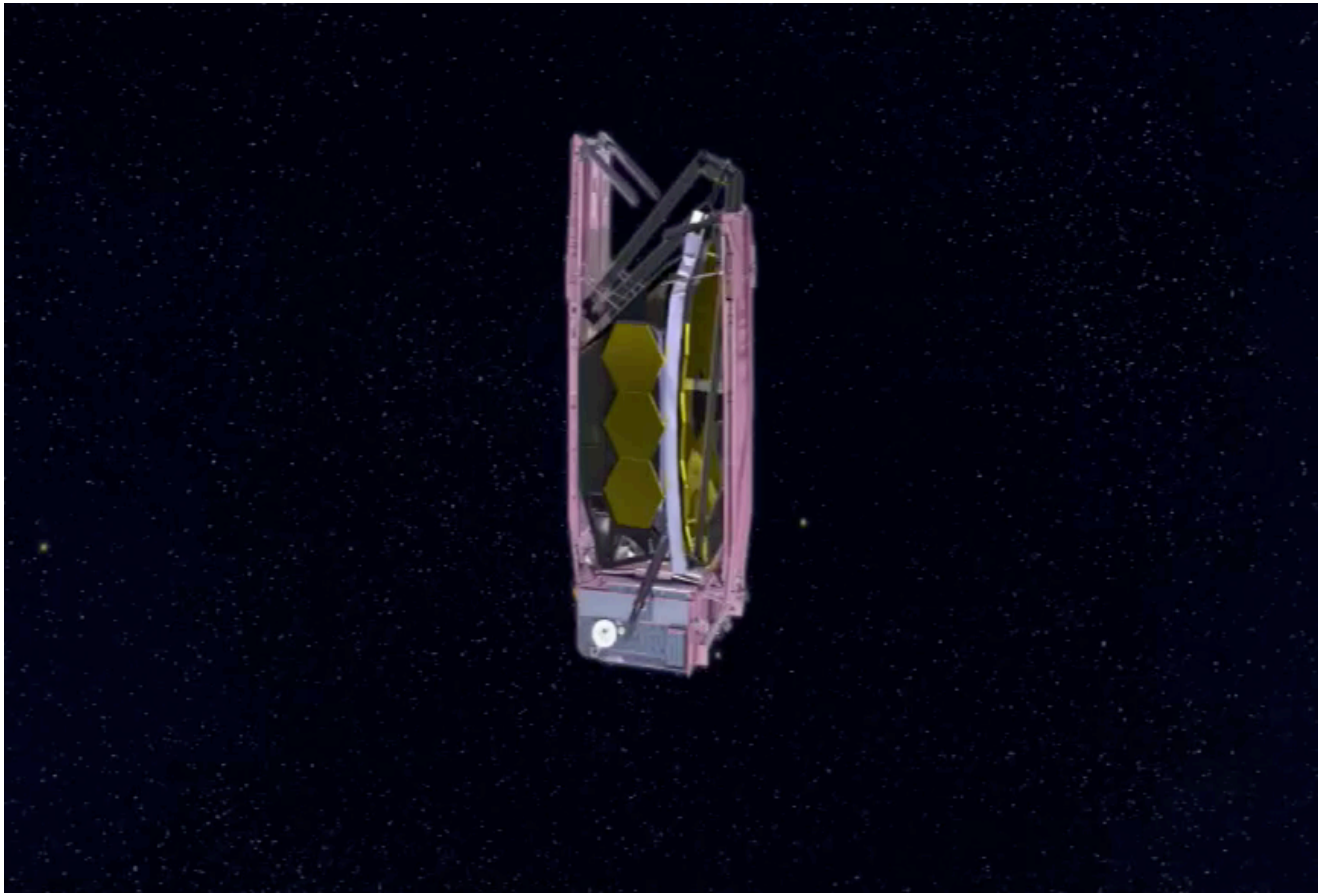


Anatomy of the Observatory

- **The James Webb Space Telescope observatory consists of:**
  - –Optical Telescope Element (OTE)
  - –Integrated Science Instrument Module (ISIM)
    - Near Infrared Camera (NIRCam)
    - Mid Infrared Camera (MIRI)
    - Near Infrared Spectrograph (NIRSpec)
    - Near Infrared Imager and Slitless Spectrograph (NIRISS)
    - Fine Guidance Sensor (FGS)
  - –Spacecraft Element (SE)
    - Spacecraft Bus
    - Sunshield

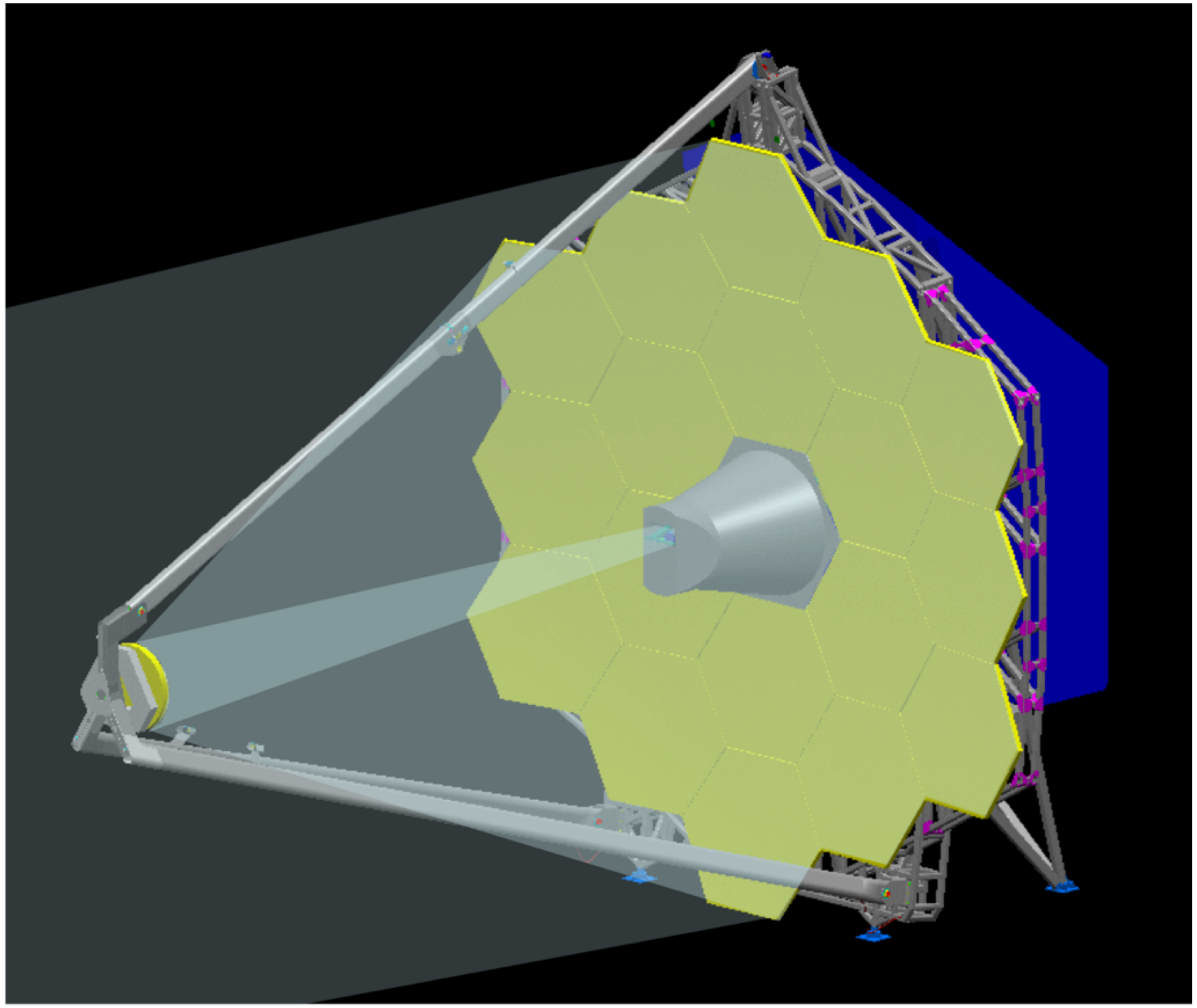


Deployment of JWST On Orbit



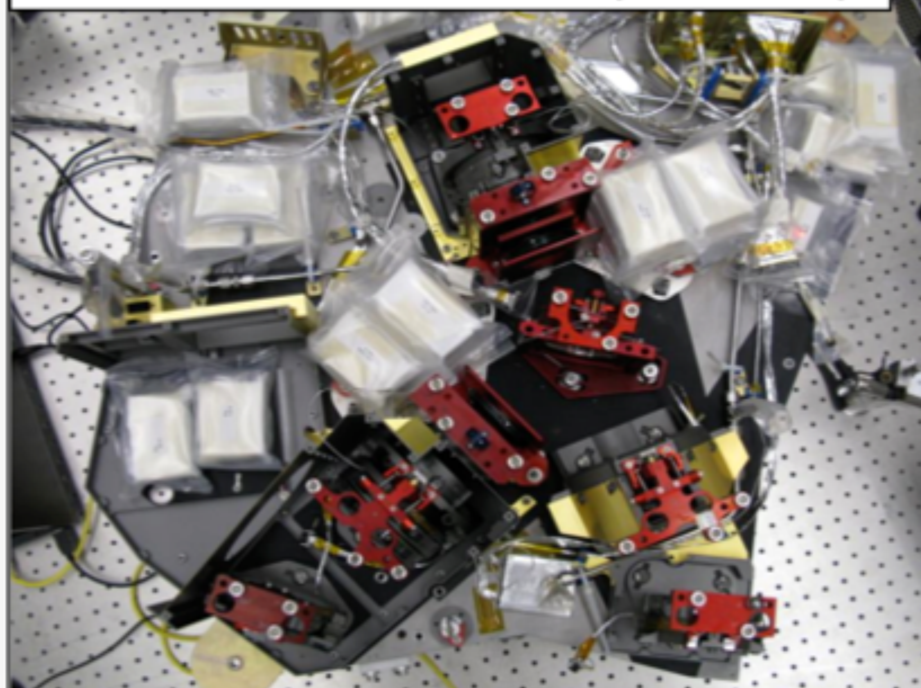
Optical Telescope Element

- The Optical Telescope Element is a three-mirror anastigmat, with a primary, secondary, and tertiary mirror.
- The primary mirror is comprised of 18 Beryllium segments.
- Each mirror segment can be moved in position, orientation, and ROC
- The telescope is designed to have diffraction-limited performance above 2μm; it operates at a temperature of ~ 40K.



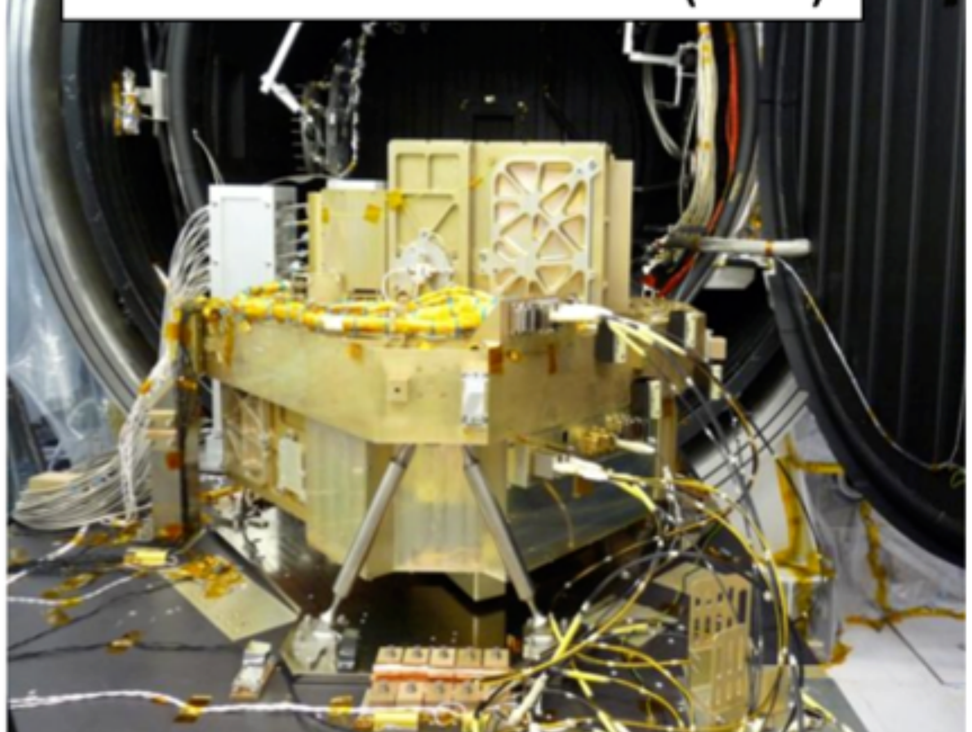
JWST Science Instruments

Near Infrared Camera (NIRCam)



Near Infrared Spectrometer (NIRSpec)

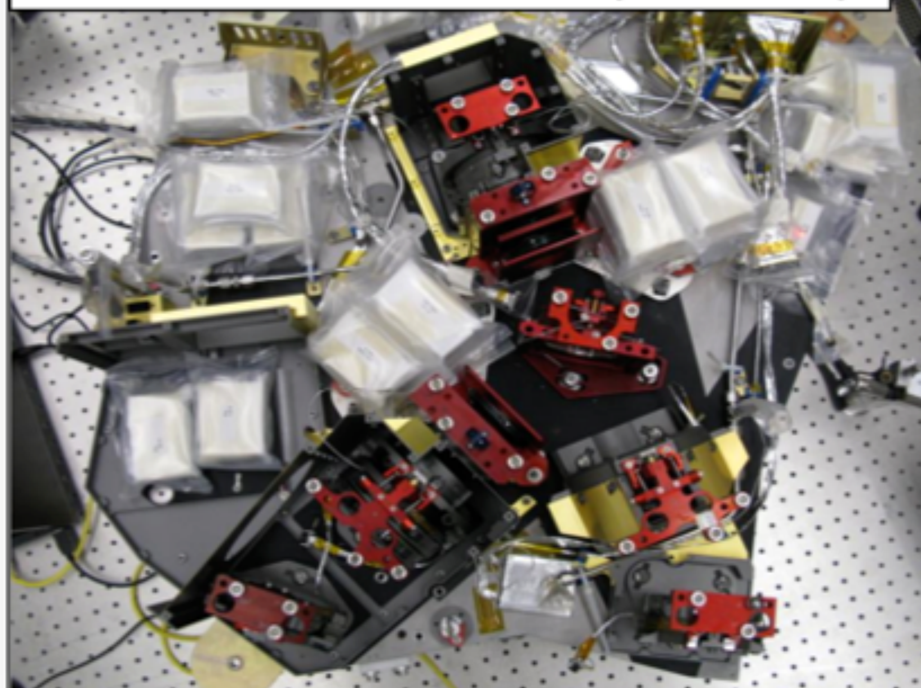
Fine Guidance Sensor (FGS)



Mid Infrared Instrument (MIRI)

JWST Science Instruments

Near Infrared Camera (NIRCam)



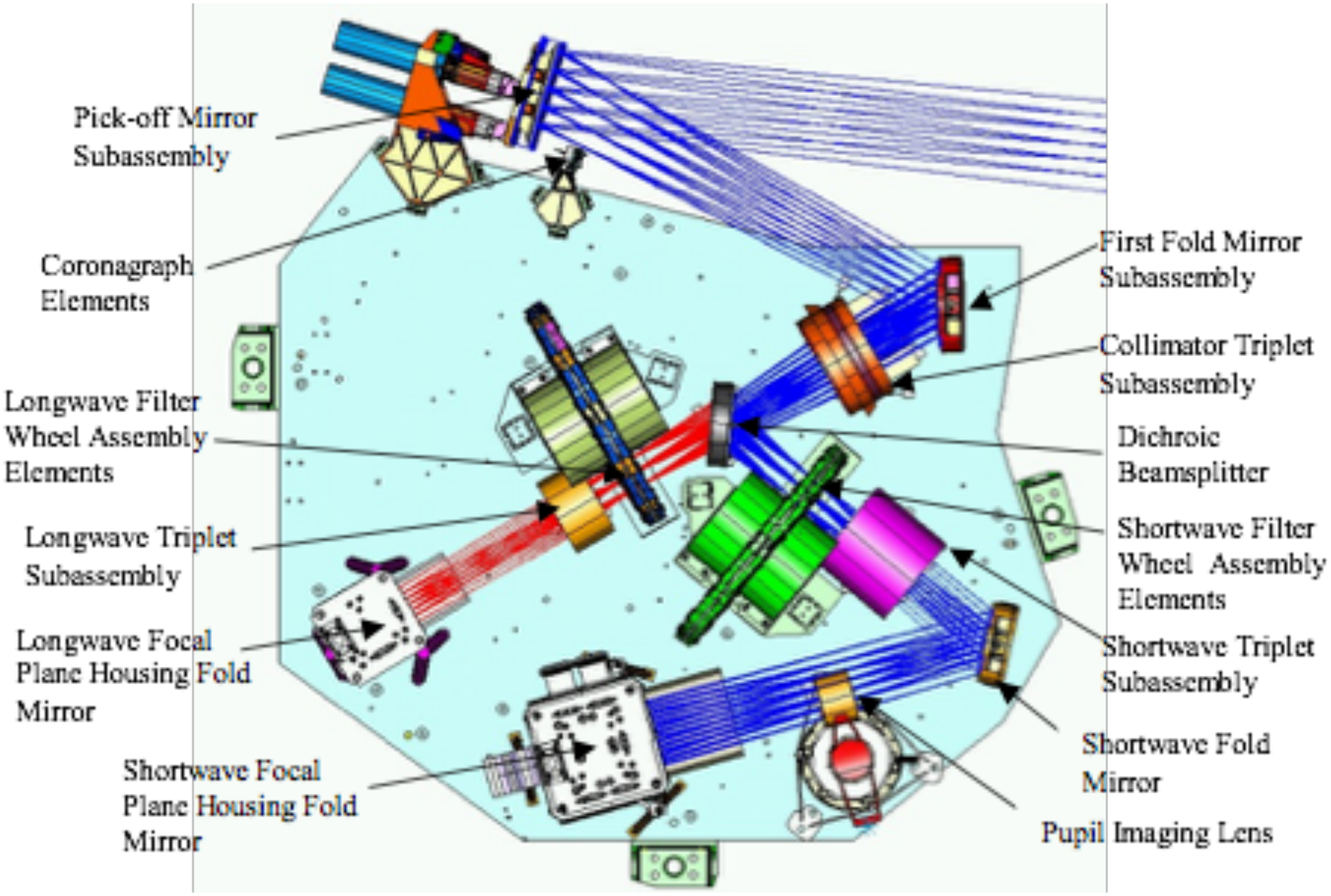
Near Infrared Spectrometer (NIRSpec)

Fine Guidance Sensor (FGS)

Mid Infrared Instrument (MIRI)

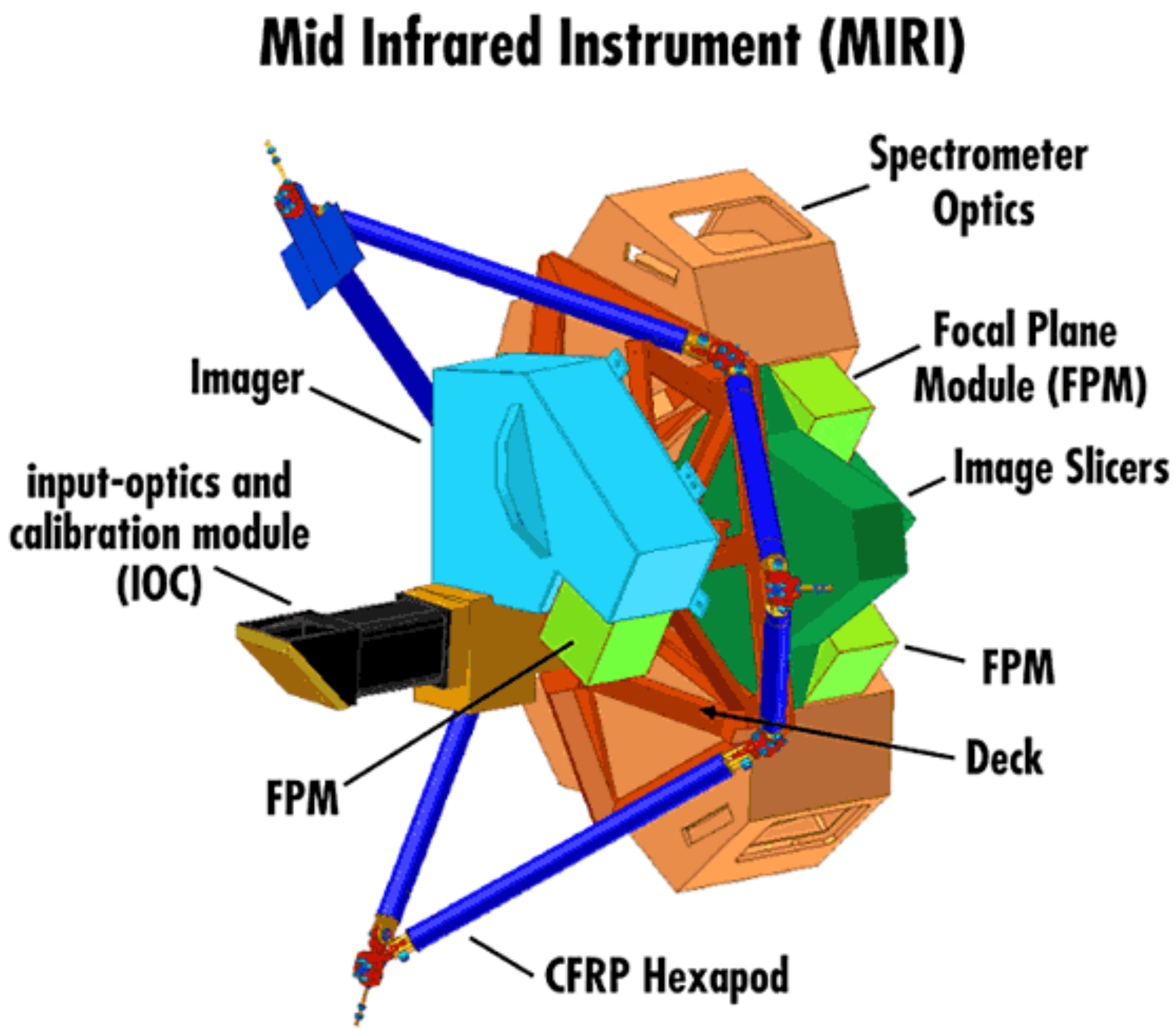
NIRCam, the Near Infrared Imager

- NIRCam is the primary imager for the JWST
- Developed by University of Arizona & Lockheed Martin ATC
- Operates at 0.6 – 5.0µm, separated into shortwave & longwave channels
- Used for imaging and coronagraphy
- HgCdTe detector, 2048 x 2048 pixel arrays (10 in all)
- Supports wavefront sensing for commissioning and maintenance
- Refractive optics



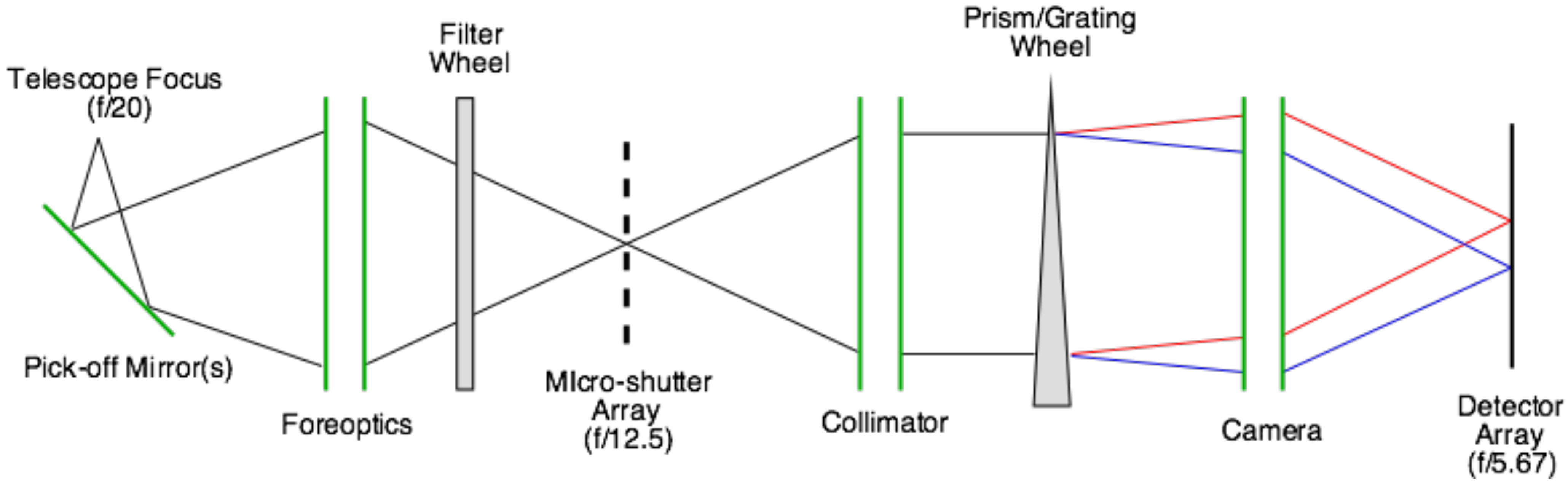
MIRI, the Mid Infrared Imager

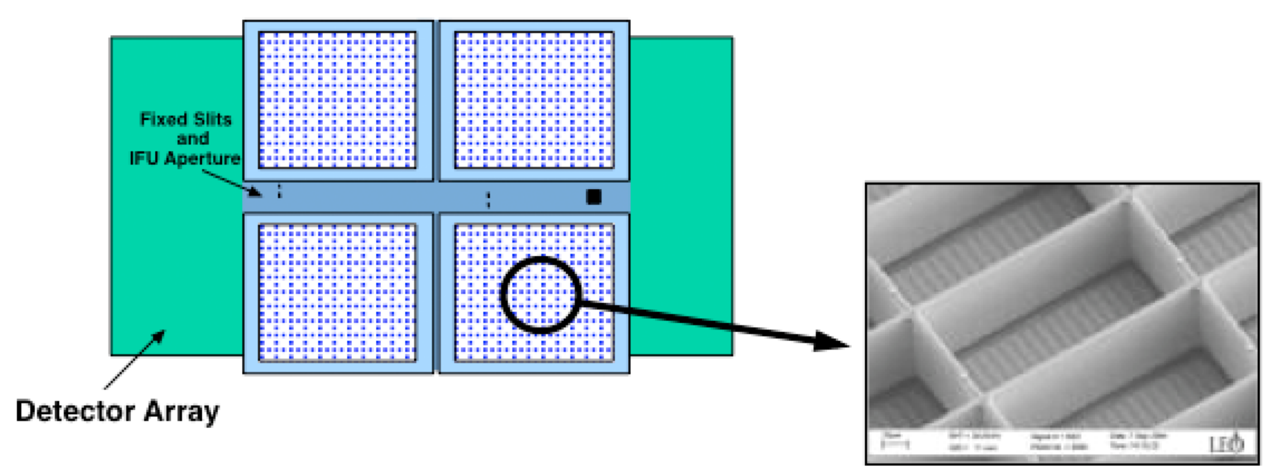
- Developed by a European Consortium and JPL
- Operates at 5 - 29 µm
- Used for mid-IR imaging, coronagraphy, and spectroscopy
- Si:As detector, 1024 x 1024 pixel array
- Uses external 7 K cryo-cooler



NIRSpec, the Near Infrared Spectrograph

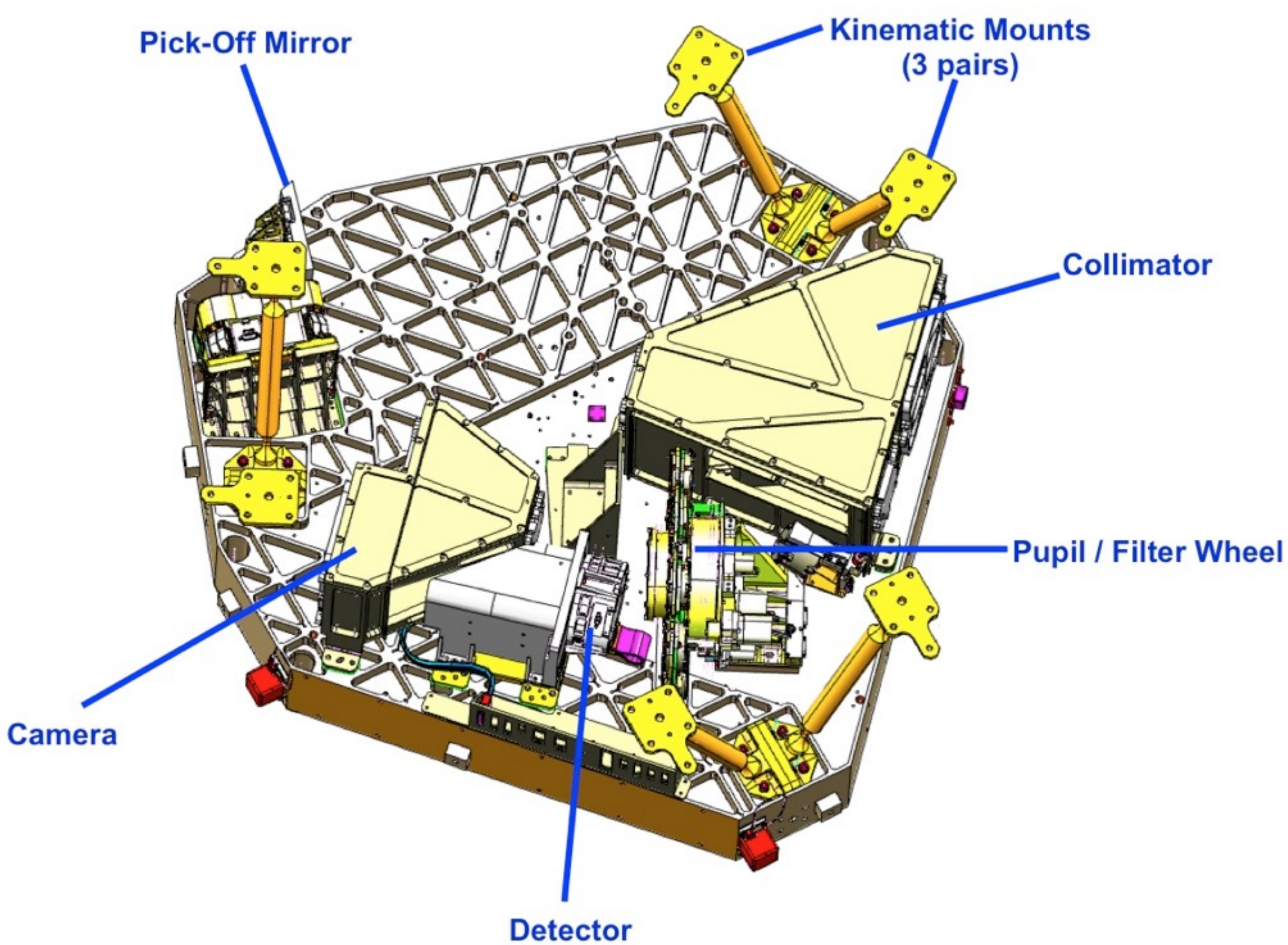
- **Developed by the European Space Technology Center (ESTEC) with Airbus Defence & Space and Goddard Space Flight Center**
- **Operates at 0.6 – 5.0 µm**
- **Spectrographs can be obtained through programmable microshutters (for spatially resolved spectra), fixed long slits, or an image slicer (IFU)**

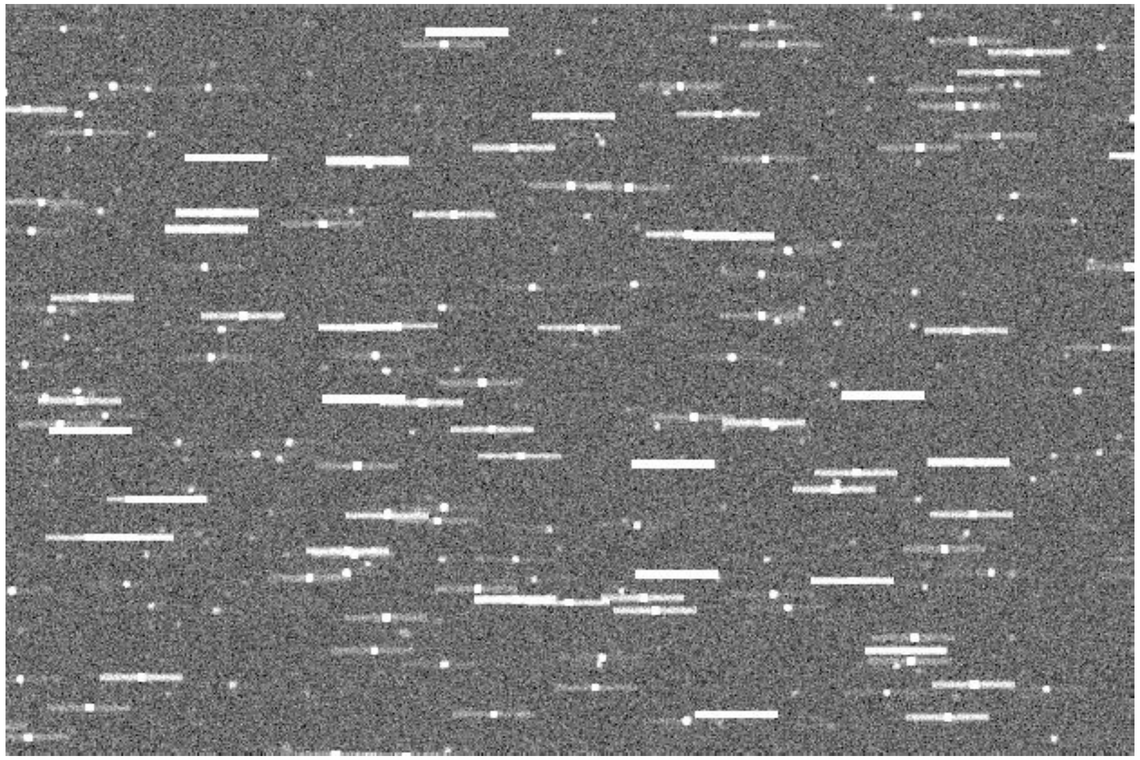




FGS/NIRISS

- **Developed by the Canadian Space Agency and COM DEV (now Honeywell Aerospace)**
- **Operates at 0.8 – 4.8 µm**
- **The Fine Guidance Sensor is used for telescope pointing. There are two separate FGS modules for redundancy.**
- **The Near Infrared Imager and Slitless Spectrograph complements NIRCam’s imagery and NIRSpec’s spectrographs. Slitless spectrographs give spectra in one direction as well as imagery.**





On-Orbit Commissioning

JWST Optical Commissioning

- **Aligning the OTE's mirror segments, secondary mirror, and tertiary mirror on orbit is done using a multi-step, image-based commissioning procedure:**

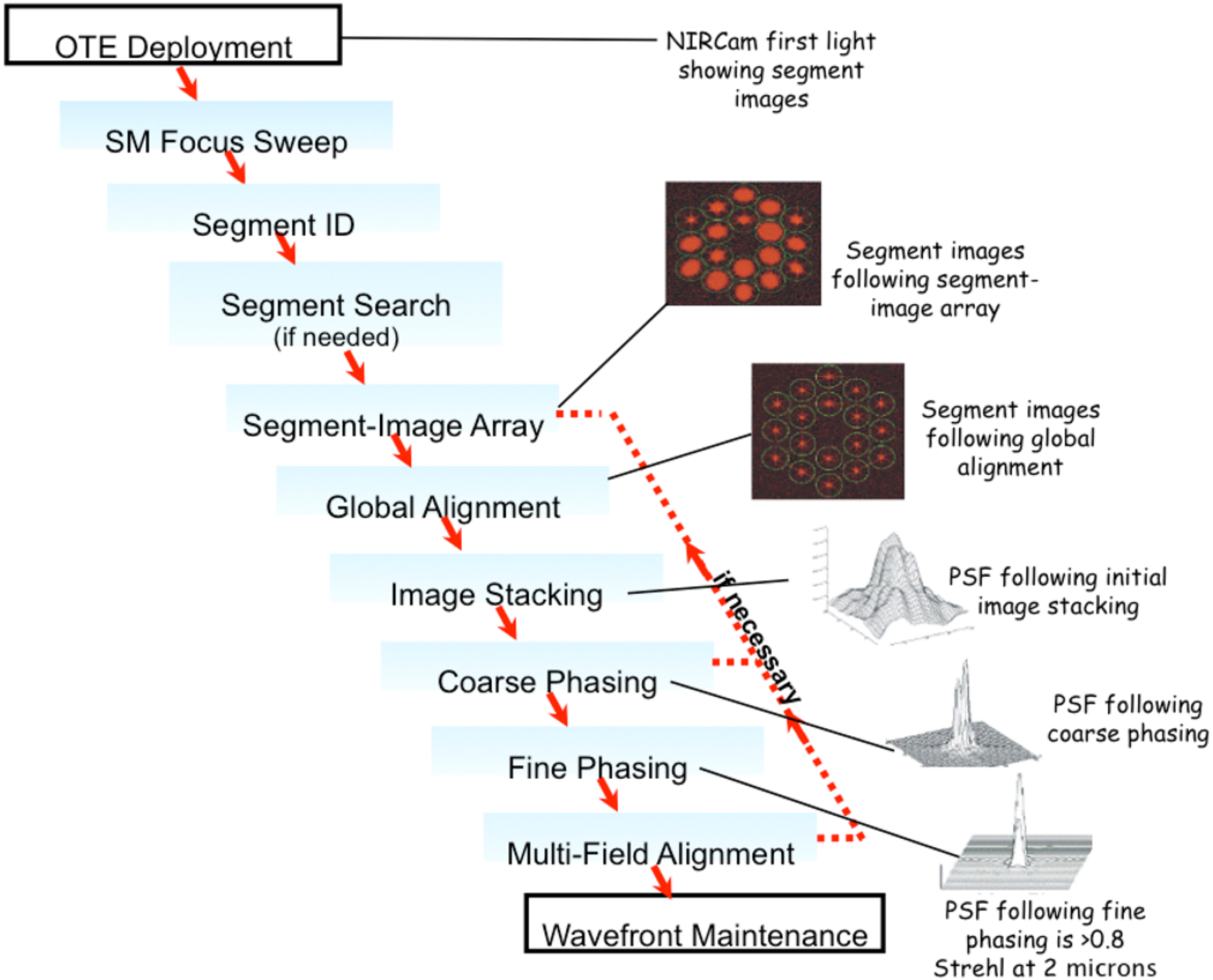


Image-Based Wavefront Sensing: From Hubble to the JWST

- **When the Hubble Space Telescope was launched in 1990, its initial images were highly aberrated.**
- **Three parallel investigations ("fossil data," image metrology, and wavefront sensing / phase retrieval) lead to the design & successful installation of the Corrective Optics Space Telescope Axial Replacement (COSTAR) in 1993.**
- **The success of some of the HARP teams' use of image-based wavefront sensing (phase retrieval), to successfully determine the HST spherical aberration, led it to become a key enabling technology for JWST:**
  - –Commissioning the observatory on orbit
  - –Evaluating the science instruments' wavefront error during ground testing

JWST Integration Steps & Test Campaigns

- **All the optics for the JWST (the OTE mirrors, the ISIM science instruments) have been built and tested as components**

- **Optical testing for the JWST consists of two test campaigns:**

  – **ISIM Level Testing**:
  The Science Instruments are placed in the **Integrated Science Instrument Module (ISIM)** & tested as a unit, using the **OTE Simulator (OSIM)** as a light source.
  This testing took place at NASA's Goddard Space Flight Center in Greenbelt, MD.
  There were 3 cryo-vacuum tests of the instruments (2013, 2014, 2015)

  – **OTIS Level Testing**:
  The ISIM and OTE are tested together (**OTE + ISIM = OTIS**), using sources in the middle of the structure as a light source (the Aft Optical System Source Plate Assembly, **ASPA**).
  These tests took place at NASA's Johnson Space Center in Houston, TX.
  There was a single cryo-vacuum test of OTIS (2017)

NASA Is Like the Post Office

"Neither snow nor rain nor heat nor gloom of night stays these [engineers] from the swift completion of their appointed [tests]."

ISIM CV1RR

The Washington Post

TUESDAY, OCTOBER 1, 2013

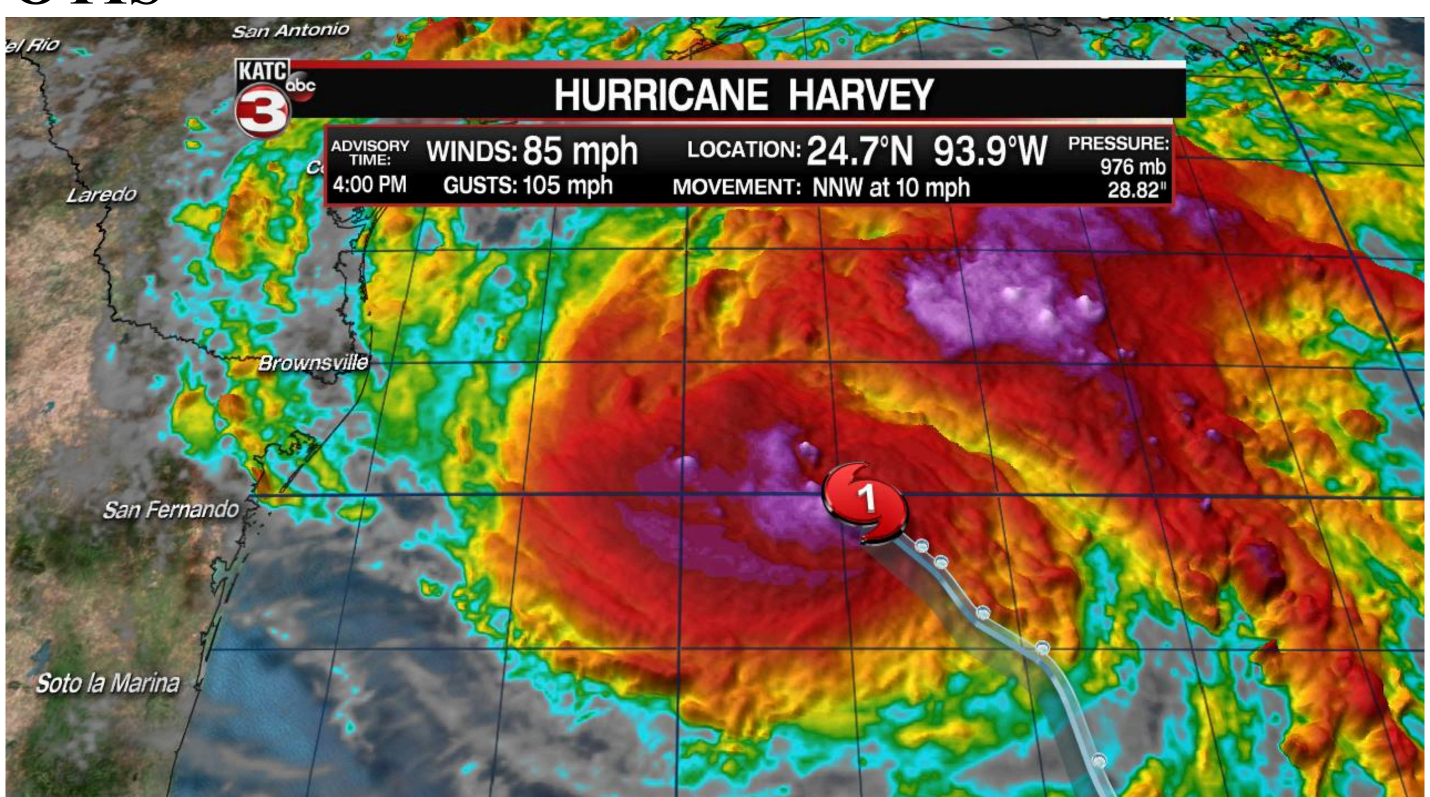
SHUTDOWN

Congress stuck in funding stalemate

2 Marine generals fired over base attack

Taliban entered NATO airfield in Afghanistan, killing 2, destroying jets

OTIS



Snowed in at NASA, Keeping Watch Over a Space Colossus

ISIM CV3

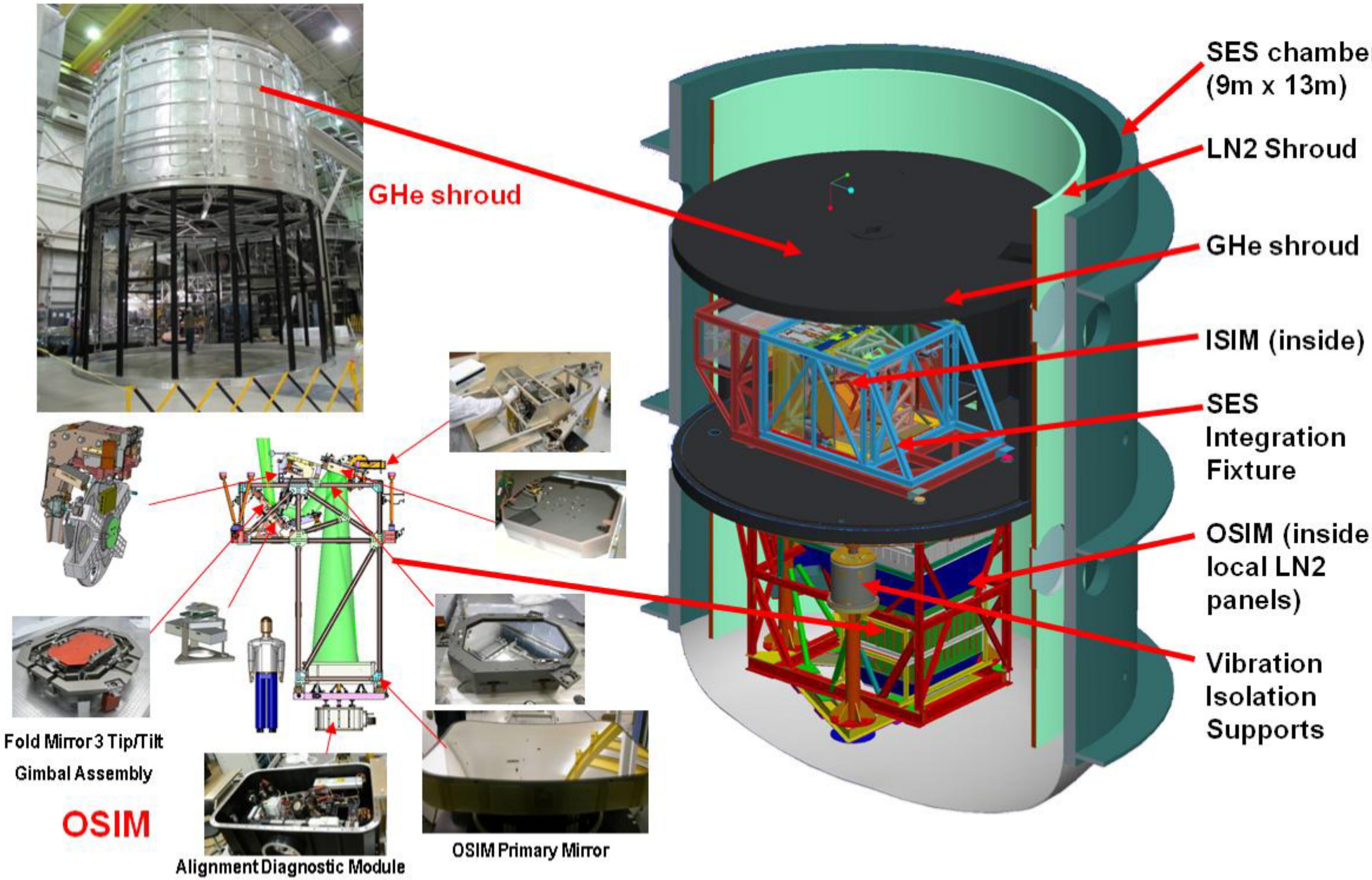
The Atlantic ROSS ANDERSEN | FEB 1, 2016 | SCIENCE

ISIM-Level Testing

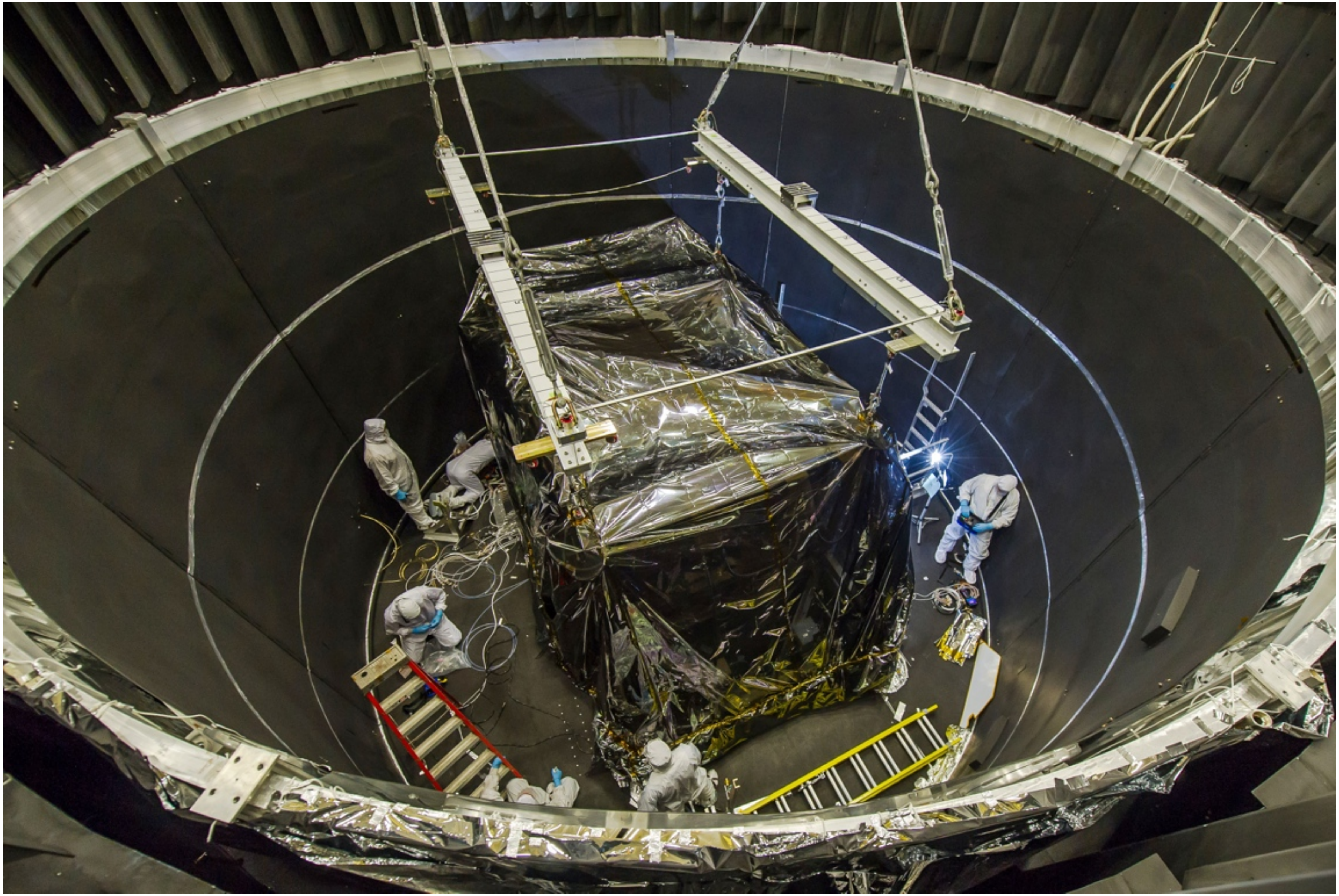
Integration into the ISIM Structure

GSFC's Space Environment Simulator Chamber

ISIM-Level Testing with OSIM



ISIM Lowered Into the Space Environment Simulator



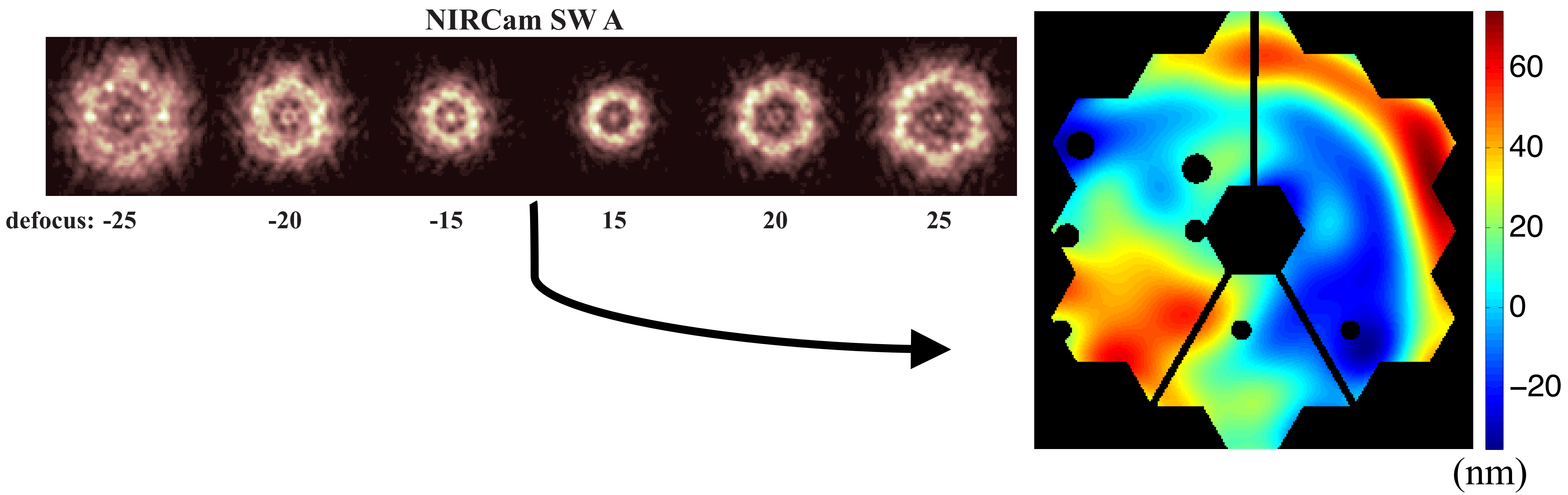
ISIM-Level Tests

- Optical tests at ISIM level are designed to test the focus, wavefront error, boresight & pupil shear for the science instruments.

- Focus and wavefront error are established using focal sweeps, taking a set of images with the focus intentionally adjusted between frames.

  Near-focus data is used to establish best focus (e.g. encircled energy)

  Far-defocused images are used to establish wavefront error using phase retrieval.



Phase Retrieval vs. Interferometry

"Phase retrieval trades optical hardware for computer software."

- **Pros:**
  - PR tests are in situ, using the same conjugate and alignment as in the optical system's actual use.
  - PR tests are single pass, without a retroreflector. This avoids retrace errors & wavefront contributions from the retroreflector.

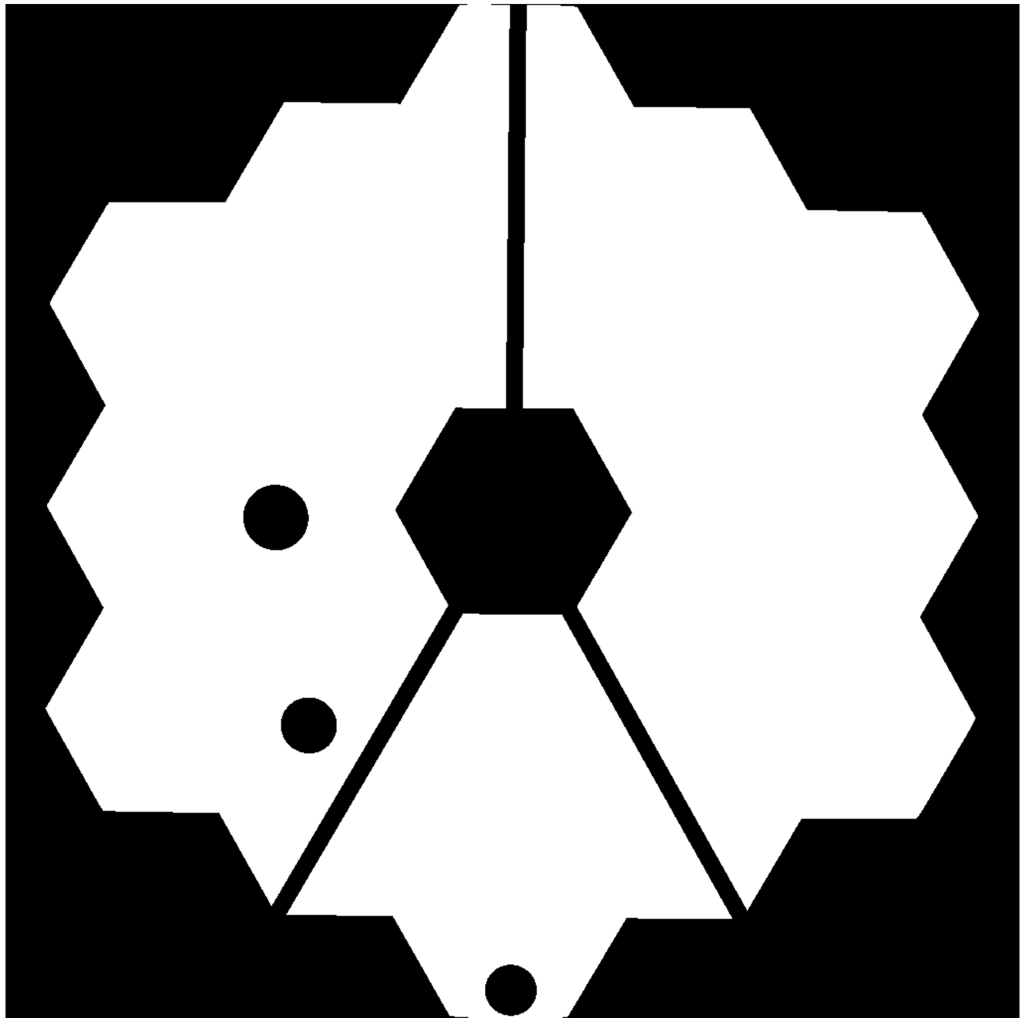
- **Cons:**
  - Computer processing is slow and benefits from high-end computers.
  - Need a way to systematically introduce *diversity*, like defocus.

- **Neutral:**
  - Fringe density / resolvability in an interferogram is equivalent to Nyquist sampling & caustic regions of focal-sweep PSFs.
  - Interferometers need well-characterized illumination and non-common-path optical components. Phase retrieval needs well-characterized illumination and a good starting model for the optical system under test.

Phase Retrieval: OGSE Calibration

- **During ISIM-level testing, the SIs were illuminated using the OTE Simulator (OSIM). OSIM was characterized over three cryogenic-vacuum tests at NASA GSFC.**

- **For successful, high-precision wavefront sensing, OSIM characterization was needed for:**
  - OSIM wavefront error across its FOV, to be removed from the results of OSIM + SI field point wavefront sensing
  - OSIM source spectrum
  - OSIM source apodization
  - OSIM exit-pupil geometry

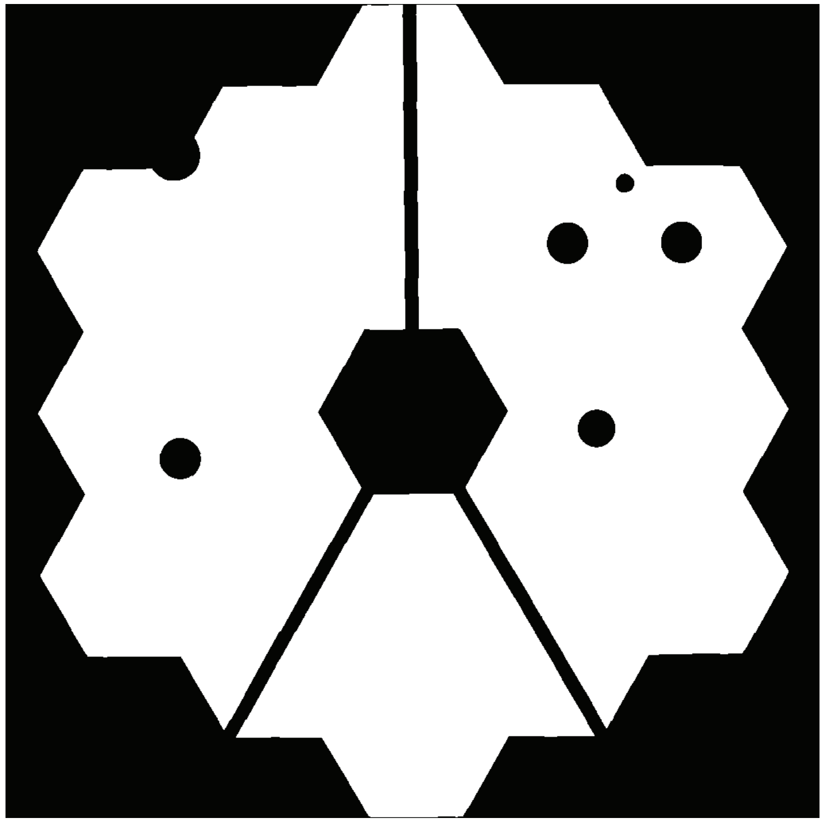


Phase Retrieval: SI Pupil Distortion

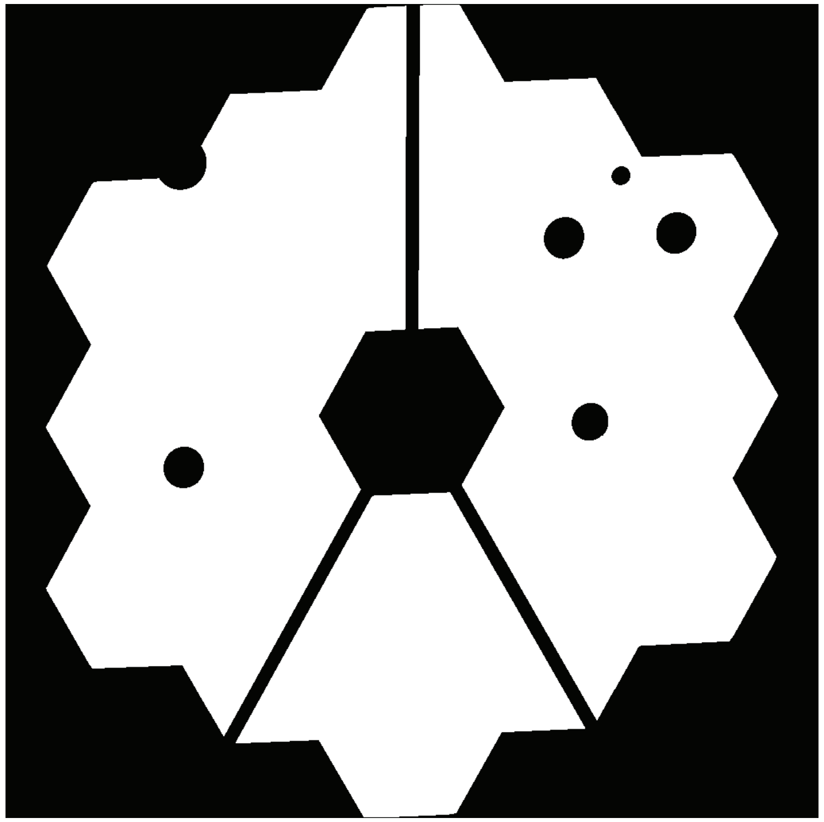
- Each SI has pupil distortion, that needs to be well characterized for exit-pupil geometry and for OSIM wavefront-error subtraction.

- Largest pupil distortion is in FGS Guiders (~5%) :

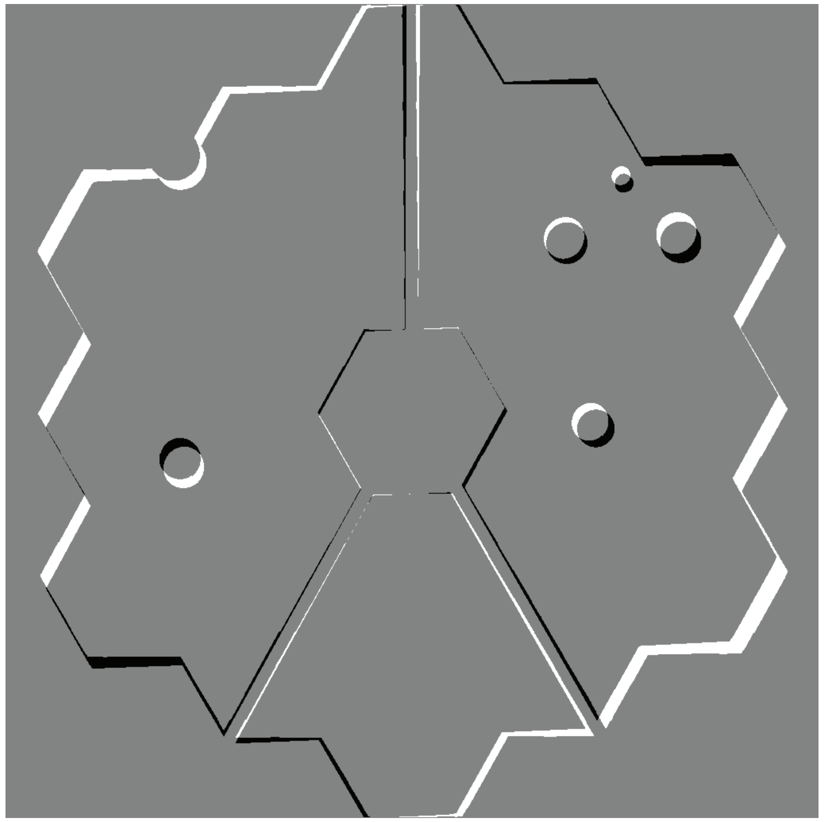
OSIM exit pupil



OSIM + Guider 1 exit pupil



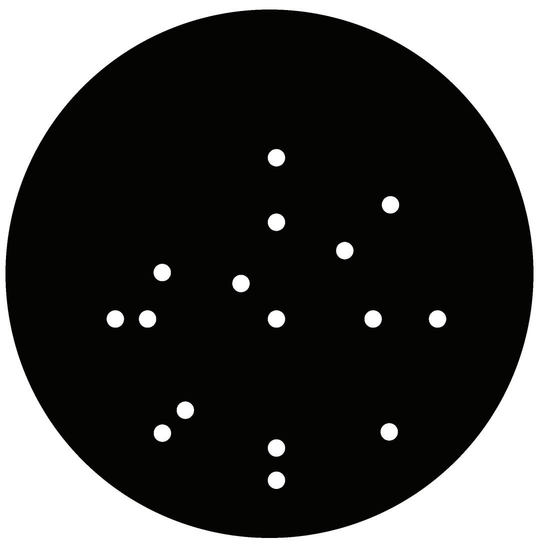
Difference



Phase Retrieval: Measuring Pupil Distortion and f/#

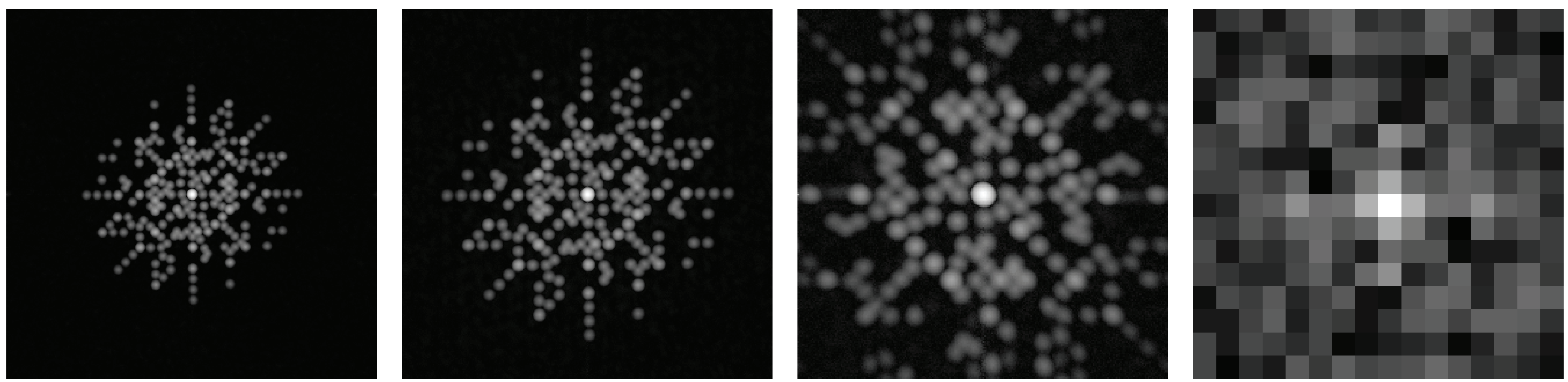
- SI pupil distortion & f/# are measured using a Pseudo-Nonredundant Mask (PNRM) in OSIM.

PNRM Mask



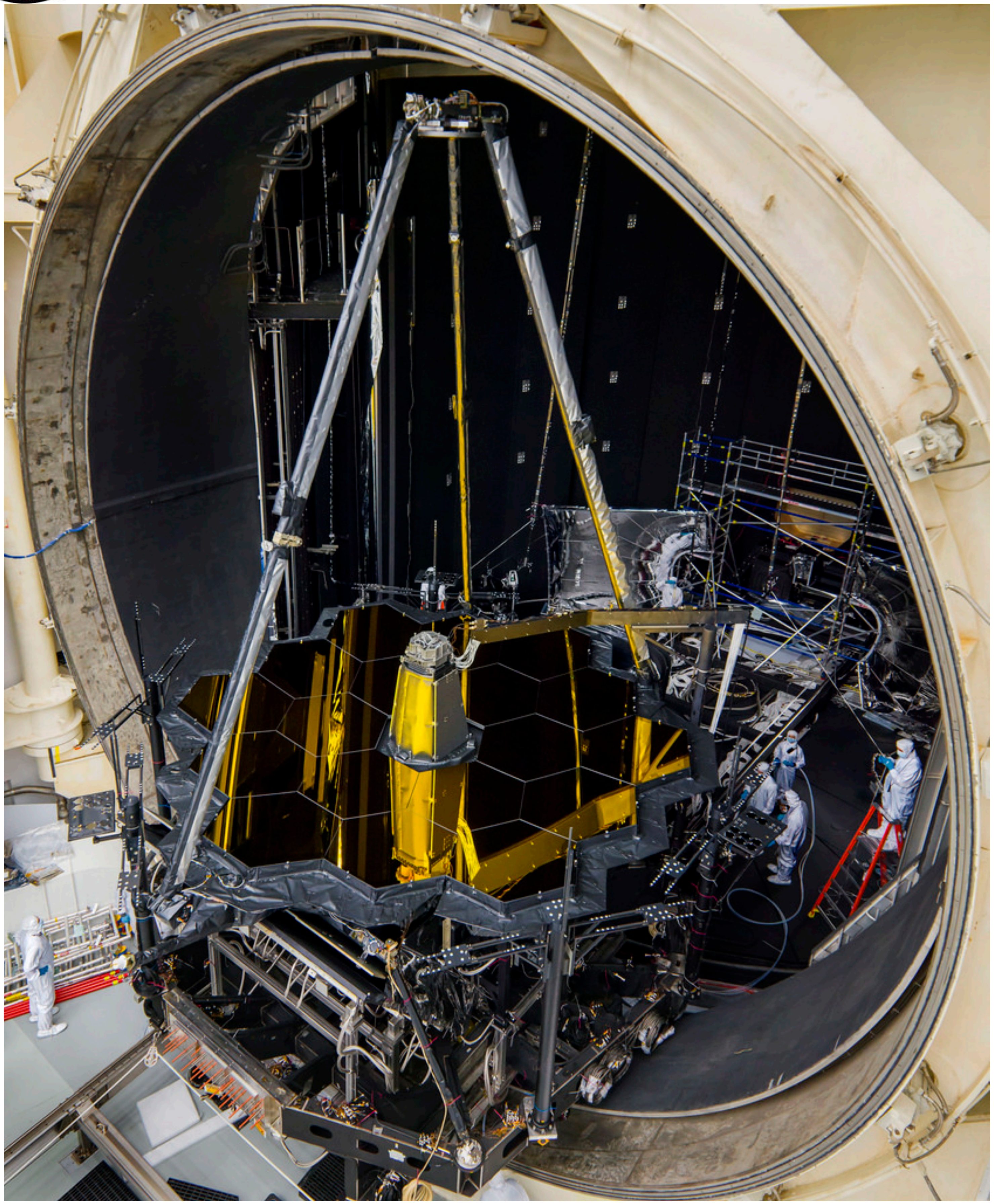
Example MTFs using the PNRM

NIRCam SW A | NIRCam LW A | Guider 1 | NIRSpec (fixed slit)

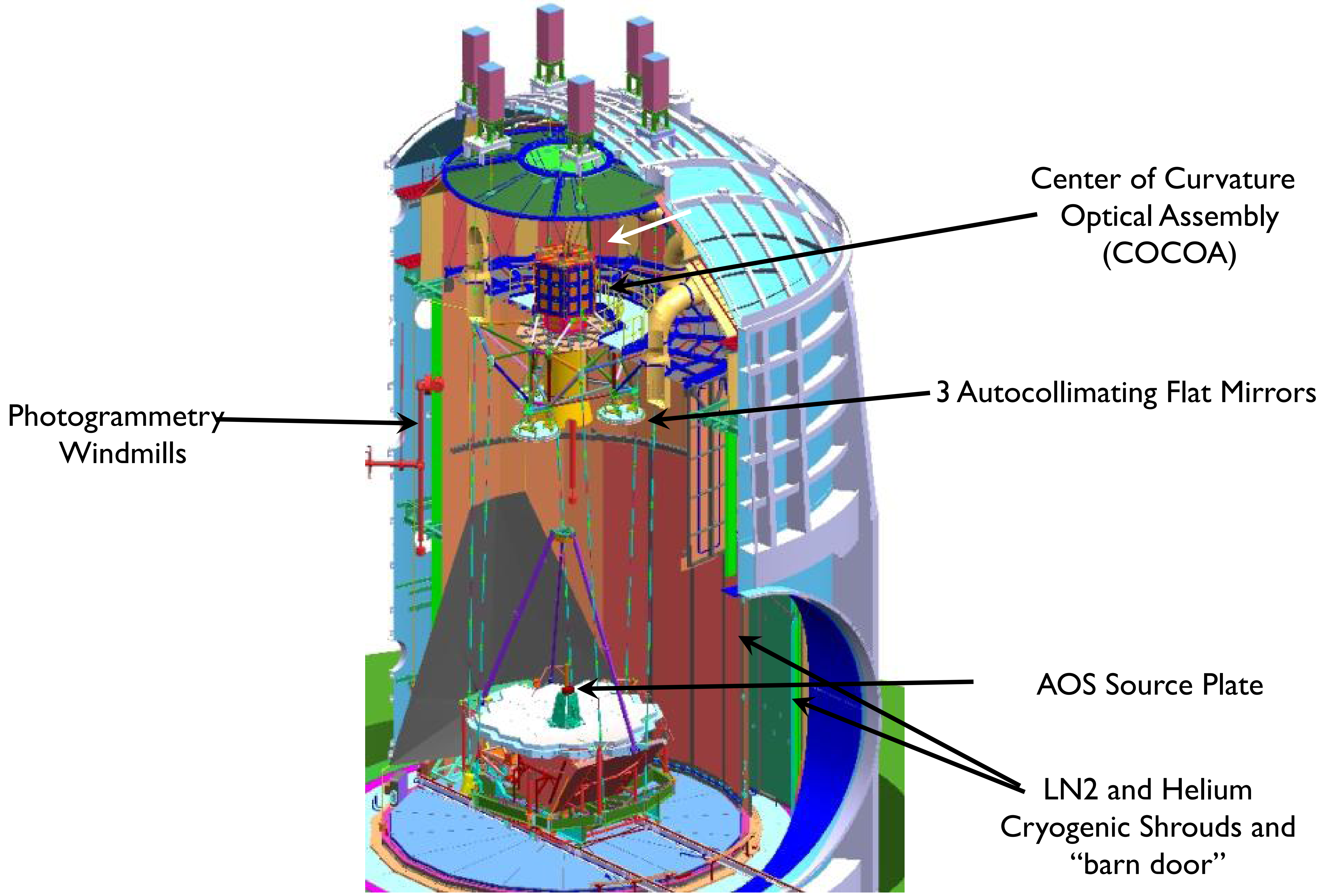


OTIS-Level Testing

Johnson Space Center Chamber A



OTIS-Level Testing



OTIS-Level Tests

- **Radius of curvature tests using the Center of Curvature Optical Assembly (COCOA)**

- **Tests using the Aft Optical System (AOS) Source Plate Assembly (ASPA):**
  - **"Pass And A Half" Test** for measuring OTE + ISIM instruments
    Use Auto-Collimating Flats (ACFs) for returning light through the system
  - **Half Pass Test** for measuring OTE Tertiary Mirror, Fine Steering Mirror, and the ISIM instruments