Optical alignment of James Webb Space Telescope breaks new ground

Joseph Howard and Raymond Ohl

NASA’s next flagship telescope will be aligned prior to launch, but its large size requires it to be folded into the rocket and realigned on orbit.

The US National Space and Aeronautics Administration’s (NASA’s) next major space observatory, the James Webb Space Telescope (JWST) (see Figure 1), will explore new frontiers in astronomy and astrophysics. This new telescope, the scientific successor to the aging Hubble Space Telescope, is so large that it must be folded up into the rocket fairing for launch, then unfolded and aligned on orbit. Proper optical alignment is key to enabling groundbreaking science. The fixed components will be lined up before launch and the movable ones on orbit. The movable components include the telescope’s primary and secondary mirrors, as well as the focus mechanisms of science instruments such as cameras. The fixed components include the telescope’s back-end optics and the science instruments’ internal optical train. The JWST’s ground test and verification program is designed to assure final proper optical alignment, and performance can be achieved on orbit during commissioning.

The JWST’s optical design is a three-mirror anastigmat with four optical surfaces of interest: the segmented primary, secondary, tertiary, and fine-steering mirrors. The primary mirror is composed of 18 hexagonal segments mounted to a backplane structure that serves as the observatory’s backbone. Each primary mirror segment spans approximately 1.3m from flat to flat, giving the observatory a full aperture of about 6.6m. Both the primary and secondary mirrors are deployed after launch, requiring on-orbit alignment of the observatory. The secondary mirror is on a hexapod allowing full control in rigid-body motion. Each of the primary mirror segments is also mounted on a hexapod with an additional actuator for adjusting the curvature radius to match the other segments. The resultant primary mirror control has two components: a global alignment motion where the primary moves in common or monolithic rigid-body motion, and a non-common figure control where the primary control can bend into low spatial frequency modes. The two primary and secondary mirror controls provide three fundamental compensators to align the JWST.

The remaining telescope optics include fixed tertiary and flat fine-steering mirrors that provides a small amount of tip/tilt motion for image stabilization. Each is mounted on a structure called the aft optics subsystem (AOS), which in turn is fixed to the primary mirror backplane. The telescope’s light enters the AOS through a baffle near the internal image that is formed between the secondary and tertiary mirrors. Another baffle is at the telescope’s exit pupil near the fine-steering mirror. During on-orbit commissioning, the moveable primary and secondary mirrors are aligned to the fixed AOS and science instruments.

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Figure 2. The Integrated Science Instrument Module’s flight, composite, optical bench metering structure just prior to cryogenic alignment verification in a vacuum chamber at NASA’s Goddard Space Flight Center (GSFC). A canister housing a photogrammetry camera is just above and to the left of the worker’s head.

Also mounted on the backplane is the Integrated Science Instrument Module (ISIM), at the heart of which is a structure (see Figure 2) that holds the mission’s four science instruments: the near-IR camera (NIRCam), near-IR spectrometer (NIRSpec) (see Figure 3), the mid-IR camera (MIRI), and the fine-guidance sensor/tunable filter instrument (FGS/TFI). With the exception of MIRI, each optical system has a focus mechanism. The NIRCam can also align its pupil. During integration, the science instruments and ISIM are each aligned using photogrammetry and other methods to position their object surfaces to a common telescope focal surface. Their entrance pupils are aligned to a common telescope exit pupil near the fine-steering mirror.\textsuperscript{3,4} These fixed settings will be verified under flight-like conditions using a telescope simulator at NASA’s Goddard Space Flight Center.

The ISIM is then integrated into the primary mirror backplane so the common pupil and focal surface are properly aligned to the pupil and focal surface presented by the telescope’s AOS. This fixed alignment will also be verified under flight-like conditions at an observatory level test located at NASA’s Johnson Space Center. During this test, the primary and secondary mirror alignments will also be verified in order to ensure that they have enough movement-capture range to achieve final alignment on orbit. After this test, the primary and secondary mirrors will be stowed for launch to allow for observatory integration into the spacecraft bus.

The on-orbit commissioning alignment process is enabled using wavefront sensing and control methods (WFSC) via phase retrieval on through-focus point spread function (PSF) image data taken by the science instruments. The alignment process includes coarse adjustments on the primary mirror segments.

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to correct tip-tilt and piston alignment errors, followed by fine adjustments to phase the mirror to serve as a monolithic surface with the desired figure. The secondary mirror and instrument focus mechanisms are also controlled, giving approximately 140 degrees of freedom to align the JWST. After initial line-up, PSF data is taken across the observatory field to ensure proper global alignment of the telescope for all instruments. This WFSC process is verified experimentally using an optical test-bed telescope, an approximate 1/6 scale of the JWST (see Figure 4), as well as extensive optical modeling. Contingency cases are also being addressed, such as a Hubble-like primary mirror figure error. They have shown only marginal (and graceful) degradation of the observatory’s optical performance.

The JWST’s optical alignment approach breaks new ground for NASA in both complexity and in its verification. These methods will likely be duplicated in NASA’s future space observatories.

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References