Research Article

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The European optical contribution to the James Webb Space Telescope

https://doi.org/10.1515/aot-2018-0041
Received August 15, 2018; accepted September 7, 2018; previously published online October 1, 2018

Abstract: The James Webb Space Telescope (JWST) is frequently referred to as the follow-on mission to the Hubble Space Telescope (HST). The ‘Webb’ will be the biggest space telescope ever built and is expected to enable astounding new science. The observatory comprises a 6.5-m-diameter telescope with a segmented primary mirror and four high-performance optical science instruments. The JWST has mostly been optimized to work in the near- (0.6–5.0 μm) and mid-infrared (5.0–29 μm) wavelength regions. The project is a strong international partnership led by the National Aeronautics and Space Administration (NASA) with contributions from the European Space Agency (ESA) and the Canadian Space Agency (CSA). The observatory is currently scheduled for launch in early 2021 from Kourou, French Guyana, by an ESA-provided Ariane 5 rocket. This paper will focus on the European optical contribution to the mission, which mainly consists of two highly advanced optical science instruments: The multi-object near-infrared spectrograph (NIRSpec) and the mid-infrared instrument (MIRI). The opto-mechanical design considerations and the realization of both instruments will be described, and we will conclude with a short JWST project status report and future outlook.

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Keywords: European Space Agency (ESA); James Webb Space Telescope; MIRI; NIRSpec.

1 Introduction

1.1 Introduction to the JWST mission

The James Webb Space Telescope (JWST) observatory is a revolutionary new infrared space telescope that will primarily focus on the following four science themes: (1) the identification of first light, (2) understanding the assembly of galaxies, (3) the formation of stars and planetary systems, and (4) the evolution of planetary systems and the conditions of life. Figure 1 shows the JWST observatory.

The observatory consists of two main parts: (1) The Optical Telescope and Integrated Science (OTIS) comprised of the 6.5-m-diameter Optical Telescope Element (OTE) and the Integrated Science Instrument Module (ISIM) with four instruments sharing the OTE focal plane, (2) The Space Craft Element (SCE) consisting of the spacecraft bus and the tennis court-sized sunshield.

In its full flight configuration, the complete observatory is too large to fit in the fairing of the Ariane 5 launch vehicle and, therefore, needs to be folded up. Once in space, the observatory will go through a series of deployments that will last approximately 2 weeks. After the in-flight commissioning period, lasting roughly 6 months, the observatory will be ready for science.

1.2 JWST: a true international partnership

The JWST is a true international partnership led by the National Aeronautics and Space Administration (NASA) with contributions from the European Space Agency (ESA) and the Canadian Space Agency (CSA). Inspired by the success of the Hubble Space Telescope, the three agencies have collaborated since 1996 on the design and

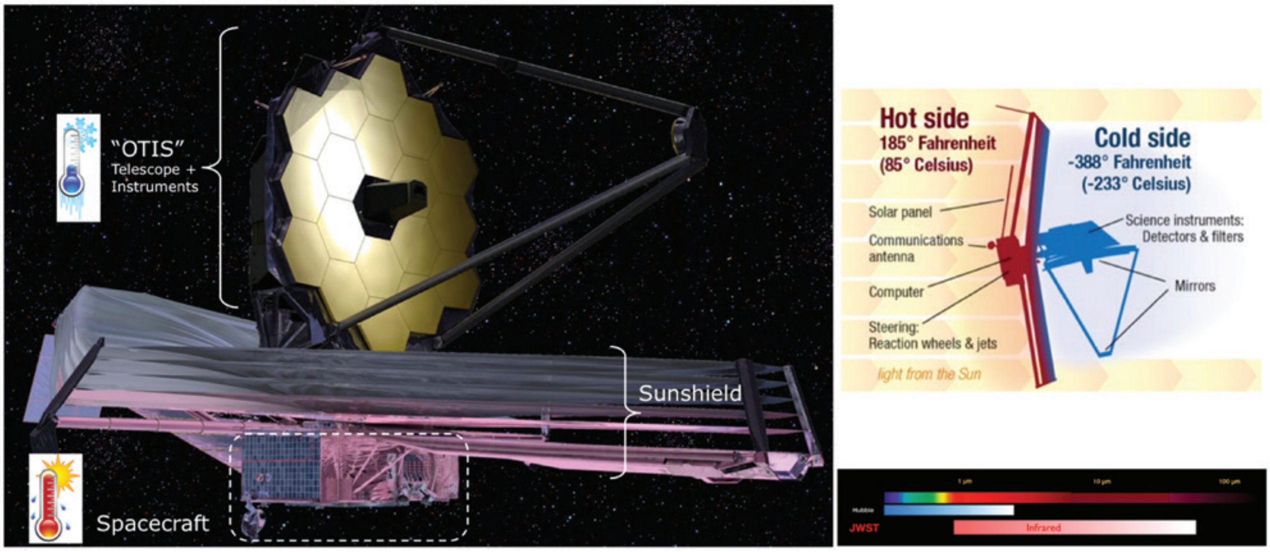


Figure 1: The JWST observatory and thermal environment.

construction of a worthy successor [1]. Europe's participation to the JWST consists of four major contributions: (1) the provision of a fully tested and verified near-infrared spectrograph (NIRSpec); (2) the provision of a fully tested and verified optical bench assembly of the mid-infrared instrument (MIRI) through special funding from a number of ESA member states, united in the MIRI European Consortium; (3) the provision of the Ariane 5 launcher; and (4) the provision of 15 ESA staff members to support the JWST operations at the Space Telescope Science Institute (STScI) in Baltimore, Maryland, USA. The main elements of the JWST mission and their respective European contributions are shown below in Figure 2.

In return for these contributions, ESA has gained full partnership in the JWST mission, and scientists from the ESA member states will obtain at least 15% of the JWST observing time.

2 The near-infraRed spectrograph (NIRSpec)

2.1 Introduction to NIRSpec

The NIRSpec is one of the four scientific instruments on board the JWST. The NIRSpec was provided to the NASA by the ESA. The Airbus Defence and Space GmbH (formerly Astrium GmbH) in Ottobrunn, Germany, is the prime contractor that designed, built, and tested

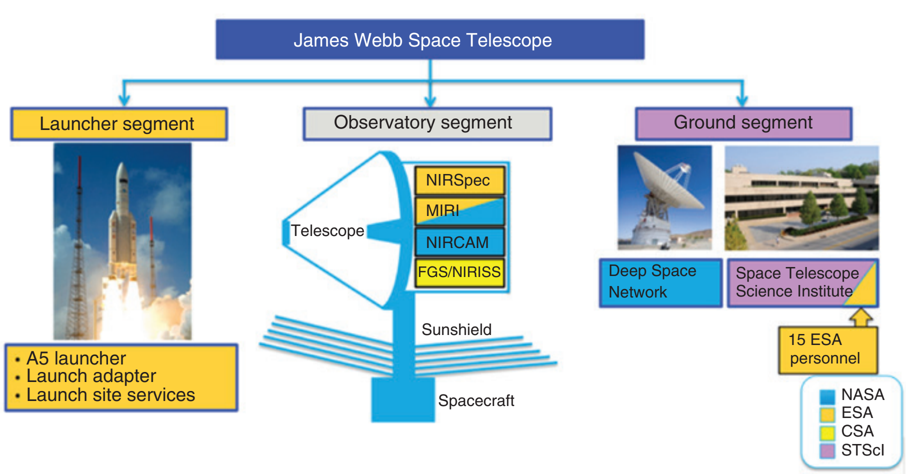


Figure 2: The JWST main elements with the contributions of the ESA and Europe highlighted in orange.

the instrument. The micro shutter assembly (MSA) and Focal Plane Assembly (FPA) were provided by the NASA Goddard Space Flight Center (GSFC).

The NIRSpec (see Figure 3) is a multi-object spectrograph capable of simultaneously observing up to 100 astronomical objects, such as stars or galaxies, and to measure their near-infrared spectra with low (R ~ 100), medium (R ~ 1000), and high (R ~ 2700) spectral resolutions. The observations are performed in an approximately 3′ × 3′ field of view (FoV) over a wavelength range from 0.6 to 5.3 μm.

The primary observational mode is the multi-object spectroscopy (MOS). In this mode, the NIRSpec uses the MSA to select scientific objects. The MSA is a programmable micro-electro-mechanical system (MEMS) that was developed in house at the NASA GSFC. It has about 250 000 individually selectable and programmable apertures (each about 80 μm × 180 μm in size) that are mounted in four so-called quadrants. Besides the MOS mode, the NIRSpec also features a set of fixed slits and a square 1.6″ × 1.6″ aperture for high-contrast spectroscopy of individual sources (e.g. exoplanets). In addition, there is an integral field unit (IFU) with a 3″ × 3″ FoV for three-dimensional (3D) spectroscopy of extended objects.

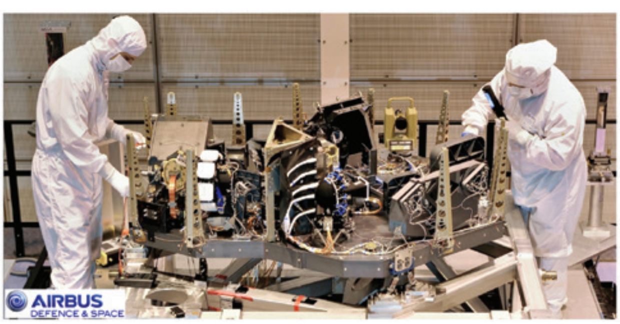


Figure 3: The NIRSpec flight model instrument with the soft cover removed.

2.2 The micro shutter assembly (MSA)

The MSA, positioned in a plane conjugated to the telescope focal plane, is shown in Figure 4. It has about 250 000 individually selectable and programmable apertures, each of which can be closed or opened individually. The micro shutters are mounted in four so-called quadrants, each carrying a 365 × 171 array of shutters (dispersion Xcross-dispersion). For small objects, a single shutter will be used, whereas larger objects may require multiple shutters to be opened to obtain an appropriately filled spectrometer entrance slit. By programming the MSA to only open those shutters that coincide with the preselected objects of interest, light from these objects is then isolated and allowed to enter the spectrographic stage of the instrument.

The width of the open area of each shutter in the dispersion direction is ~80 μm, equaling ~200 milli-arcsec or 2 pixels on the detector. The length of the open area in the spatial direction is ~180 μm, equaling ~450 milli-arcsec or 4½ pixels on the detector. The MSA arrays have a physical pitch of 100 μm in the dispersion direction and 200 μm in the spatial direction. The ratio of the open-area dimensions to the pitch dimensions leads to a (geometrical) slit loss of approximately 30%.

2.3 NIRSpec opto-mechanical architecture

In order to enable very long duration near-infrared observations with cumulative exposure times that can reach 100 000 s, the instrument operates around –233°C (~40 K) and utilizes an all-reflective, highly a-thermal opto-mechanical design concept. The mirror mounts and the optical bench base plate were all manufactured out of the novel Silicon Carbide ceramic material BOOSTEC SiC100®. This material guarantees very high stiffness and excellent

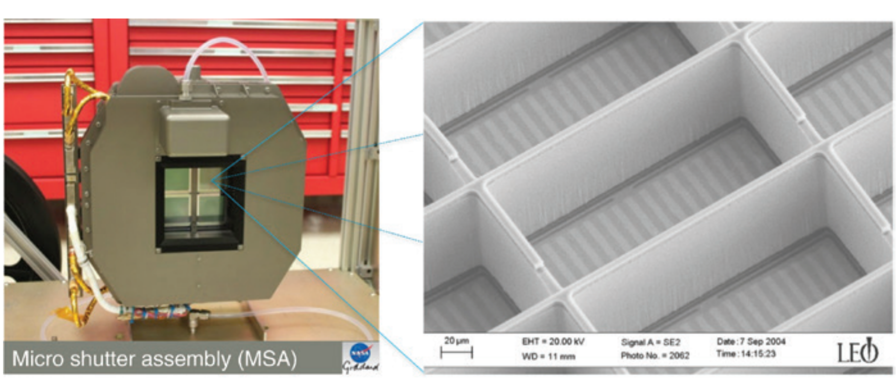


Figure 4: The MSA with a close-up of a few shutters shown at the right.

thermal characteristics. More details regarding the design of the NIRSpec can be found in Refs. [2] and [3].

The opto-mechanical architecture of the instrument is shown in Figure 5. It primarily consists of a very stiff silicon carbide (SiC) baseplate to which the optical and opto-mechanical components are attached. The flat coupling mirrors pick-off the NIRSpec FoV fraction from the OTE focal plane and redirect this light to the NIRSpec instrument.

The remainder of the optical path is mainly defined by three three-mirror anastigmatic assemblies (TMAs): (i) the fore optics TMA (FOR), which provides a telecentric intermediate focal plane at the location of the MSA and an accessible pupil location at which the filter wheel assembly (FWA) is positioned, (ii) the collimator TMA (COL), which collimates the light onto the disperser-carrying grating wheel assembly (GWA), and (iii) the camera TMA (CAM), which images the spectra onto the two 2k × 2k mercury cadmium telluride (MCT) detectors.

2.4 NIRSpec optical performance

The image quality of the NIRSpec optics is excellent as shown in Figure 6. The diagrams below shows spots at wavelengths of 0.6, 1.0, and 5.0 μm, respectively. The box size is 50 × 50 μm for the spots on the MSA plane (left) and 10 × 10 μm for the spots on the FPA (right). The MSA shutter size is ~80 × 180 μm (open aperture), and the detector pixel size on the FPA is 18 × 18 μm.

The complete optical system (i.e. the JWST optical telescope element and NIRSpec) generates diffraction-limited images (Strehl ≥0.80) at wavelengths longward of 2.4 μm at the MSA and longward of 3.0 μm at

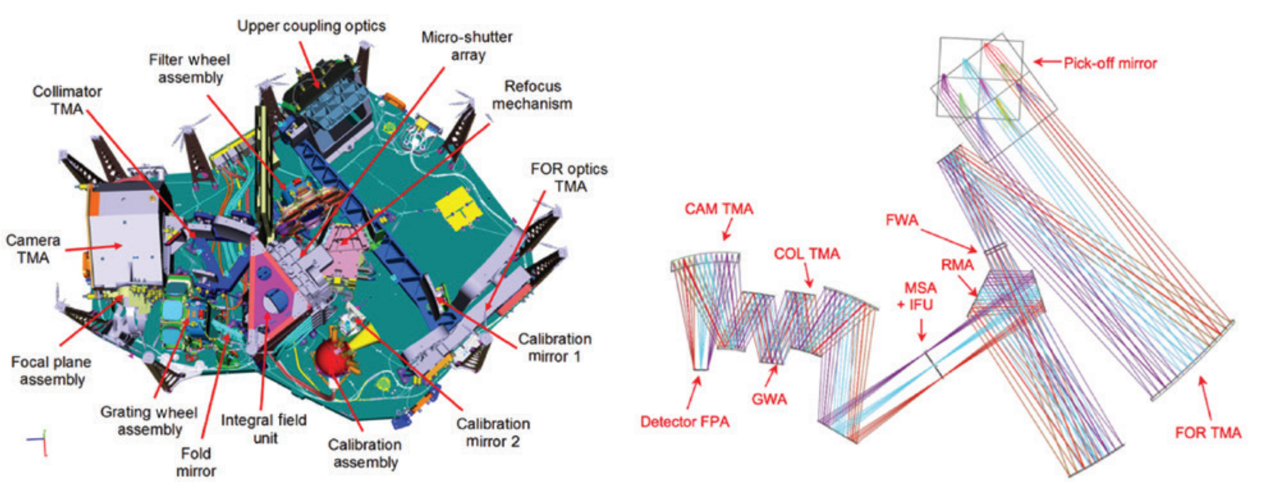


Figure 5: The NIRSpec mechanical design (left) and optical design (right).

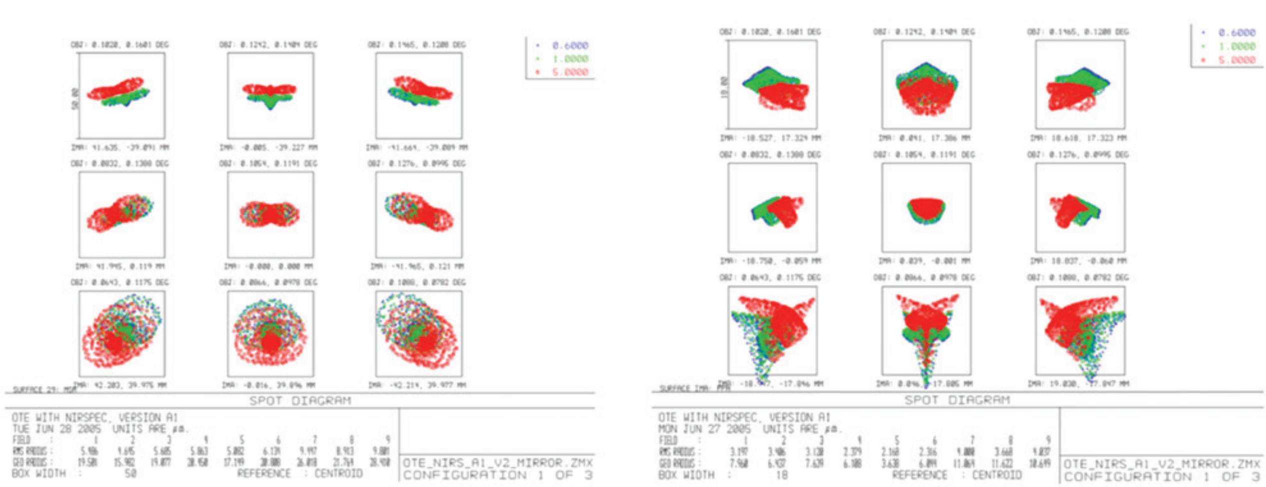


Figure 6: Spot diagrams over the full 3′ × 3′ NIRSpec FoV at the planes of the MSA (left) and FPA (right).

the FPA. Further important hardware components are the refocusing mechanism assembly (RMA), the FWA, and an on-board calibration assembly (CAA). The latter assembly provides several spectral line and flat-field illumination sources for in-orbit instrument calibrations.

The NIRSpec will be operated in three different spectral modes with resolutions of R ~ 100, R ~ 1000, and R ~ 2700. The R ~ 100 mode covers the full spectral range with a single CaF_2 prism, positioned on the GWA, as the dispersing element, while in the other two modes, the wavelength range is split into three wavelength bands, with a grating available for each of them. The NIRSpec's spectroscopic capabilities are summarized in Figure 7.

2.5 Fixed slit for high-contrast spectroscopy

In addition to the multi-object spectroscopy, the NIRSpec will also be able to carry out single-object, high-contrast spectroscopy using a set of five fixed slits. These slits are located between the four MSA quadrants and occupy a separate section of the NIRSpec FoV. The largest aperture has a square opening of 1.6″ × 1.6″ and will be used to obtain spectra of transiting exoplanets. The other slits are more traditional in size and have apertures of 200 milli-arcsec and 400 milli-arcsec, respectively. The fixed-slit spectra can be taken independently to, and simultaneously with, the spectra taken with the MSA or the IFU as they are imaged on different areas of the detector.

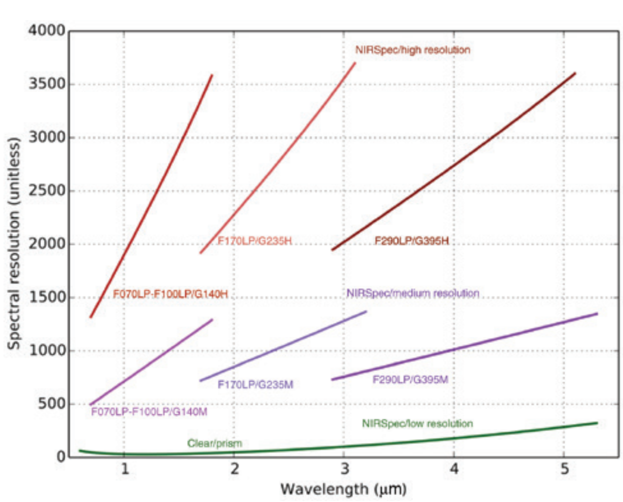


Figure 7: The NIRSpec's multiple spectroscopic modes and their spectral resolutions as a function of wavelength.

2.6 Integral field unit (IFU)

For astronomical targets up to 3″ × 3″ wide, spectra of 900 spatial elements of 100 × 100 milli-arcsec can be obtained by means of an IFU, mounted just behind the MSA. The NIRSpec's all-aluminum IFU uses the image-slicing technique to cut the image of the object into 30 slices, each of them giving rise to 30 spectra on the detectors.

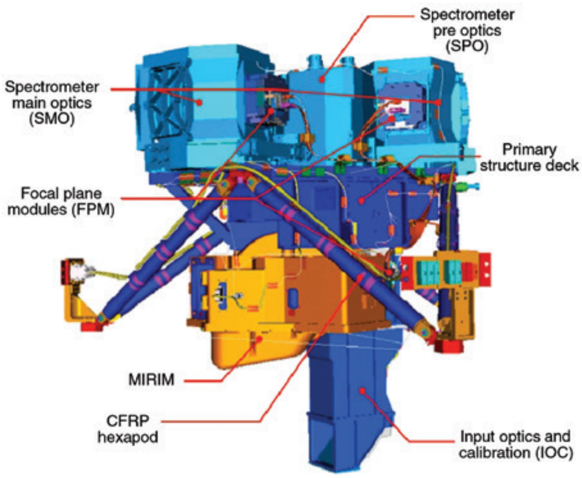
2.7 Focal plane array (FPA)

The NIRSpec FPA consists of two Hawaii-2RG Sensor Chip Assemblies (SCAs). Each chip is a 2D array of 2048 × 2048 pixels, 18-μm pitch, hybridized onto a dedicated read-out-integrated circuit. Two application-specific integrated circuits (ASICs) control the detector chips and digitize their extremely low analog signals. The detector chips have pixels of 18 × 18 μm, and the plate scale is about 100 milli-arcsec/px.

3 The mid-infrared instrument (MIRI)

3.1 MIRI overview

The MIRI provides imaging, coronagraphy, low-resolution spectroscopy (LRS), and medium resolution integral field spectroscopy over the 4.9- to 28.8-μm wavelength range [4]. The MIRI (shown in Figure 8) is a very versatile and complex instrument that was developed as a 50/50 partnership between Europe and the US. In Europe, the main partners are the ESA and a consortium of nationally funded European industries and institutions known as the MIRI European Consortium (MIRI EC). In the US, the main partners are the NASA GSFC and the NASA Jet Propulsion Laboratory (JPL). The European partners were responsible for providing the MIRI optical system, whereas NASA was in charge of providing the MIRI detector system as well as the closed-loop MIRI cryogenic cooling system. MIRI is the only mid-infrared instrument on the JWST observatory, and the complete instrument must be cooled down to a temperature of <7 K, which is significantly lower than those of the other near-infrared instruments that operate at a temperature of around 40 K. In order to provide this cooling capability, MIRI employs a specially developed closed loop Joule-Thomson cooler, pre-cooled by a three-stage pulse tube cryo-cooler. The



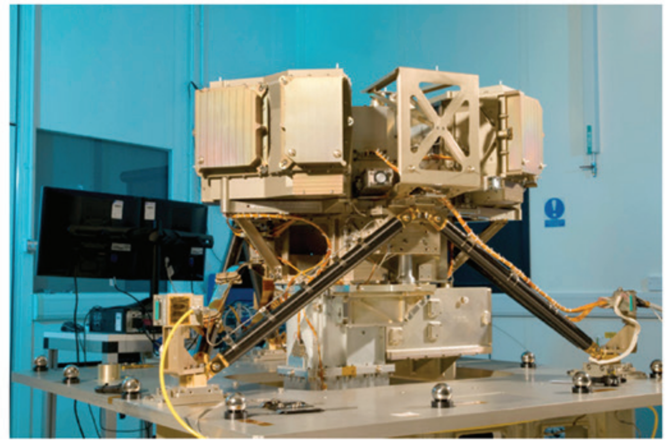


Figure 8: The MIRI Optical Bench key sub assemblies (left) and image of the MIRI flight model (right).

MIRI cooler system was developed by NASA JPL with Northrop Grumman Aerospace Systems (NGAS) as the prime contractor.

The ambitious JWST science goals require a mid-infrared instrument that can provide: (1) imaging through broad- and narrow-band filters in the 5- to 28-µm wavelength range, (2) an LRS in the 5- to 10-µm wavelength range, (3) medium-resolution spectroscopy (MRS) with R ~ 3000 spectral resolution, and (4) a high dynamic range coronagraphy. The MIRI design provides all these complex functions in one single instrument. A schematic representation of the MIRI is shown in Figure 9.

A pick-off mirror (POM), positioned 450 mm in front of the JWST focal plane, directs the MIRI fraction of the telescope's FoV toward the MIRI deck, which is the center stiff structure that holds the imager and spectrometer optics modules as well as the input optics and calibration subsystem (IOC). The POM is part of the IOC. A second fold mirror then directs the FoVs of the imager and of the coronagraphs into the imager subsystem (MIRIM). The MIRIM is located at the lower side of the instrument deck. Not the complete MIRI FoV (~1.9′ × 1.9′ in size) is reflected by the second fold mirror, as a small fraction of ~8″ × 8″ bypasses this mirror. This small field

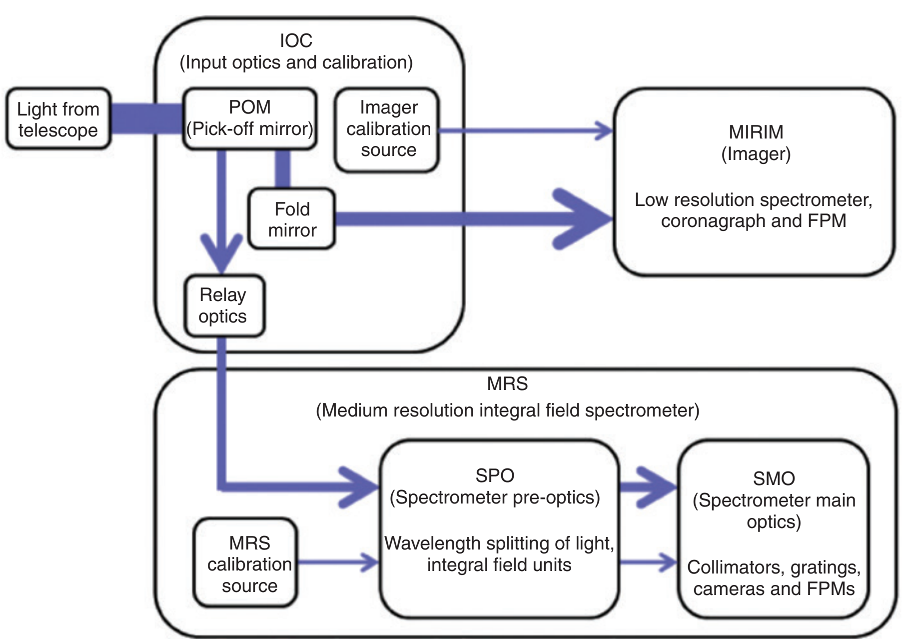


Figure 9: The MIRI schematic, showing the different instrument modules.

is relayed toward the medium-resolution spectrometer system. This system is located on the upper side of the instrument deck. Almost the complete MIRI optical system (structure and mirrors) is made out of aluminum. As such, the MIRI is a highly a-thermal and iso-thermal opto-mechanical structure. Thermal isolation of MIRI from the 40 K mounting was achieved via a CFRB hexapod and careful thermal design of radiative shielding and harnesses.

The imager and each of the two spectrometer modules is equipped with a focal plane module (FPM). In total, there are three FPMs: one for the imager and two for the spectrometer. In the next sections, the various MIRI operational modes are described in more detail.

3.2 MIRI imaging mode

In the imaging mode, the MIRI has a plate scale of ~0.11″/px, in which Nyquist samples the point spread function (PSF) at a wavelength of ~5.6 µm. The FoV of the MIRIM is approximately 1.2′ × 1.8′. The imager allows MIRI to operate in (1) imaging mode (2) LRS mode, and (3) coronagraphic mode. At the entrance of the imager, and positioned precisely at the OTE focal plane, a special mask is positioned that holds three different four quadrant phase masks (4-QPM) and a traditional occulting disk for coronagraphy. The mask also holds a fixed slit that will be used for LRS mode. After passing through the field stop/mask, the beam enters the imager optical system where the diverging beam from the OTE focus is collimated by mirror M1 that has an ellipsoidal figure. The MIRIM optical system is shown in Figure 10. Mirror M1 also produces an accessible pupil image of the JWST primary mirror. At this position, a cold stop is positioned along with a FWA. The FW holds imaging filters, coronagraphic masks, and a double prism that is used for the LRS mode.

The remaining mirrors M3, M4, and M5 comprise a TMA that forms the MIRIM camera. The TMA systems have a large FoV and an excellent image quality and low optical distortion. The TMA images the field (and spectra in the case of the LRS) onto the 1024 × 1024-pixel Si:As detector at an f-ratio of ~f/7 that results in the 0.11″/px plate scale. The imaging quality and optical distortion of the MIRIM system are excellent as can be seen in the spot diagrams and distortion grid presented in Figure 11. All spots are diffraction limited (Airy spot size shown for 5.6 µm as a circle in each of the nine spots), and Strehl is >98% for even the shortest MIRI wavelengths. The distortion over the complete MIRIM FoV is less than 1%, which is well within the 5% requirement.

3.3 MIRI low-resolution spectroscopy (LRS) mode

In the LRS, the MIRI uses a special dual prism that is mounted as one of the optical elements in the filter wheel (FW) to disperse the light. The first prism is made out of germanium (Ge), and the second prism, which cancels the beam deviation of the first prism, is made out of zinc sulfide (ZnS). The mounted double prism as well and the optical raytrace through this prism in the LRS mode are shown in Figure 12. The prism was optimized to work at the cryogenic temperatures (~7 K) and will generate a 5- to 10-µm spectrum with a spectral resolution of R ~ 100.

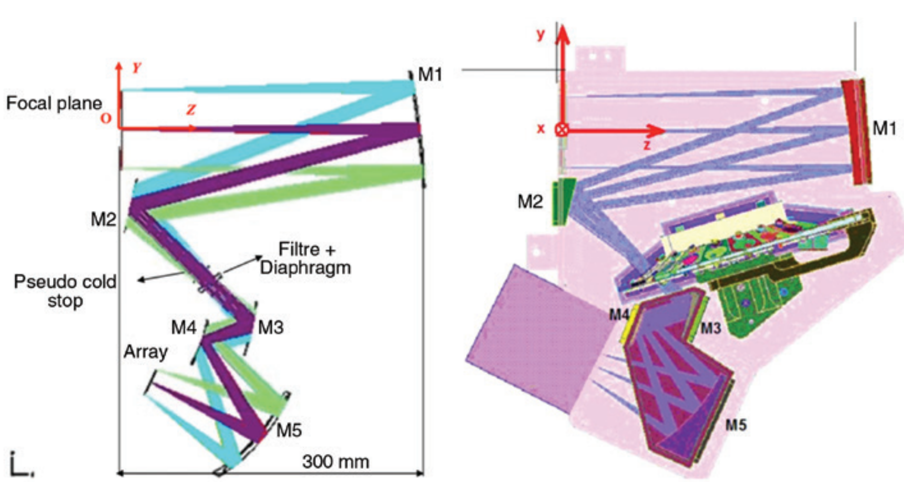


Figure 10: The MIRIM optical lay out. Imaging mode (left); mechanical design (right).

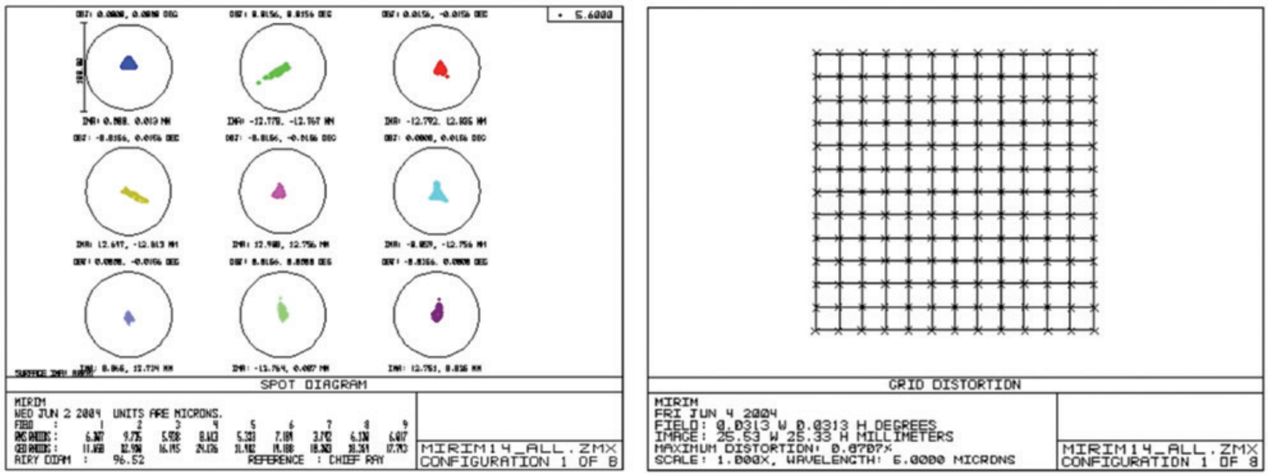


Figure 11: The MIRIM imager spot diagrams (left) and distortion grid over full FoV (right).

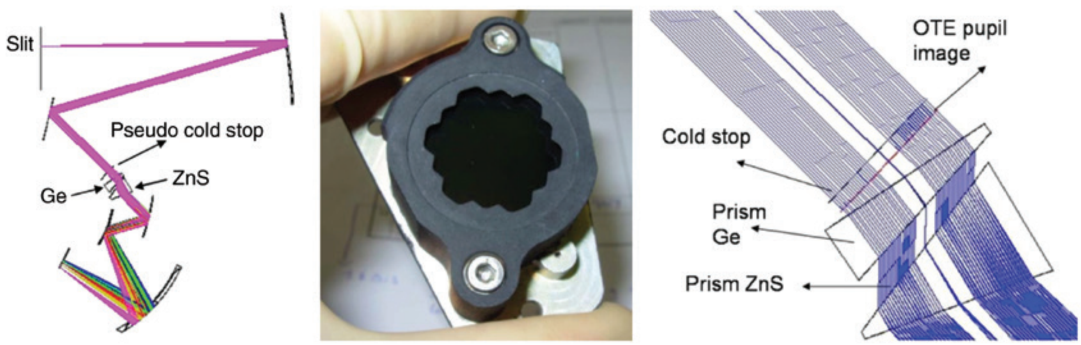


Figure 12: The MIRI LRS raytrace in imager (left), mounted double prism (center), and raytrace through the double prism (right).

3.4 MIRI coronagraphy mode

In the coronagraphic mode, the MIRI will employ special masks to perform high-contrast imaging in various wavelength bands from 10 to 23 μm. In total, there are four coronagraphic masks available: one traditional Lyot-type coronagraph and three four-quadrant phase masks (4-QPM), which work at wavelengths of 23, 15.5, 11.4, and 10.65 μm, respectively. The 4-QPMs each has a corresponding narrow bandpass filter and coronagraphic diaphragm in the FW. The 4-QPMs are implemented in the special mask that is located at the JWST telescope focal plane, at the entrance of the MIRIM. Inner working angles (IWA), defined as the 50% transmission radius, vary from 0.3″ to 0.5″ for the 4-QPMs to ~2.2″ for the Lyot mask. On-axis rejection ratios of ~300 are being achieved for the 4-QPMs, and ~800 is being achieved for the Lyot mask.

3.5 MIRI medium-resolution spectroscopy (MRS) mode

In the MRS mode, the MIRI will acquire spectral information between 4.9 and 28.8 μm over a small FoV of ~8″ × 8″. The MRS is being performed by making use of four IFUs. Each of these IFUs covers a different part of the MIRI wavelength range. There is spectral overlap between the four MRS channels. The following describes the MRS optical light path from the sky to the spectrometer detectors.

The IOC optical system relays and transforms the f/20 beam from the JWST focal plane to an f/39 beam at the entrance of the spectrometer pre-optics (SPO). The SPO has a dual task as it splits the light both spectrally and spatially. It does this using a set of nine dichroic beam splitters (three of which are used at the time), fold mirrors, order blocking optical filters, and some toroidal relay mirrors. The dichroic elements are mounted onto two mechanical wheels. These dichroic and grating assemblies (DGAs) have a dual functionality as they, in addition to the dichroic beam splitters, also hold the diffraction gratings. This is achieved by mounting two turrets to each mechanism: the dichroics are mounted on the bottom side turret, and the gratings are mounted on the top side turret. The rotating mechanisms, of which there are two, reside in the center, mounted to the MIRI deck. The full 5- to 28-μm spectrum requires that three exposures (A, B, and C) are made, one at each of the three positions of the two DGAs. An MRS functional diagram and the spectral bands that are reflected by the dichroics are shown in Figure 13.

After the initial spectral band selection was performed by the dichroics and filters, the optical beams that are heading toward the four IFUs are reshaped by anamorphic pre-optics (APO) units. These APOs are small, reflective optical systems that provide anamorphic magnification (i.e. different magnification ratios in the two lateral directions) of the beam so that in the across slice (dispersion) direction, one slice width is equal to the FWHM of the Airy pattern at the shortest operating wavelength for the IFU. The APOs also provide pupil images located at the entrance aperture of each IFU and re-image the input focal plane onto the IFU's image slicer mirrors. Each APO consists of four toroidal mirrors and an output fold mirror.

After the light was transmitted through the APOs, the beams enter the IFU optics. The IFUs (see Figure 14) are optical systems that transform a square input FoV into

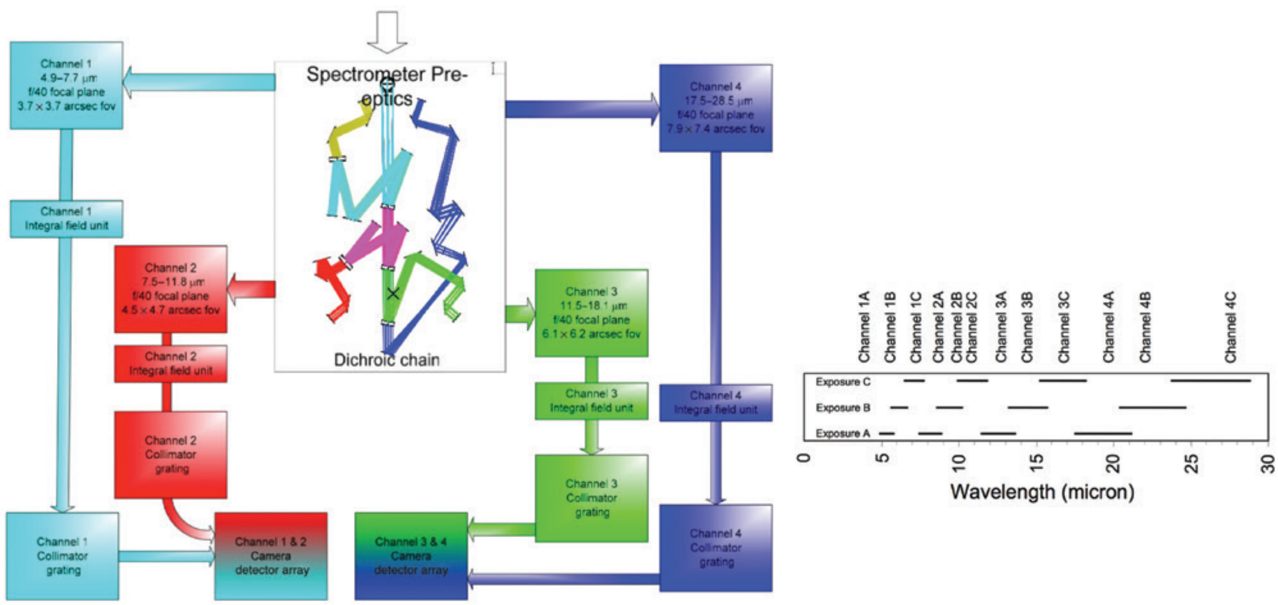


Figure 13: The MRS functional diagram (left) and the reflections and transmission for the MRS spectral bands (right).

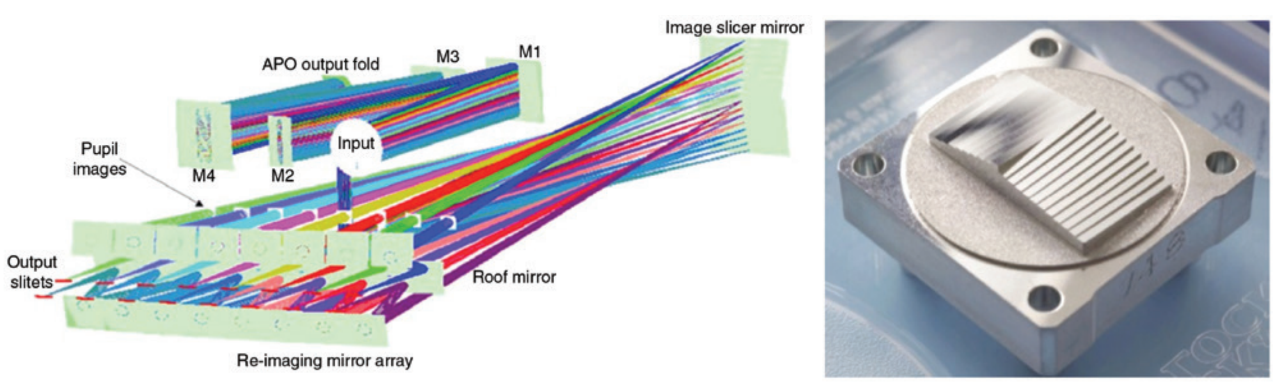


Figure 14: The IFU optics with APO 3D raytrace (left) and image of slicer mirror (right).

a number of narrow spatial ‘slices’ at the IFU output. Together, these slices form the entrance slit for each of the four MRS channels. The IFU spectrometers simplify the observations of point sources and, unlike traditional long slit spectrographs, do not suffer from light losses due to vignetting and diffraction effects. These losses can become very significant, especially at longer wavelengths. The IFU slicer width was optimized such that two slices sample the FWHM of the PSF at the lowest wavelength of that spectrometer channel. Each IFU employs two aperture masks to reduce potential straylight: one at the plane where the internal IFU pupils are formed and one at the exit slit plane.

The spectrometer main optics (SMO), then allow the light from the four IFU exit slits to enter the SMO boxes and directs it to each of the four spectrometer channels. As shown in Figure 15, the SMO has four channels but only two detectors. In the SMO, two spectrometer channel ‘arms’ are combined to form spectra in separate areas on one detector. The short-wave (SW) arm operates from 5 to 12 µm and combines channels 1 and 2 (left side image) and the long wavelength (LW) arm operates from 12 to 28 µm and combines channels 3 and 4 (right side image).

All gratings are ruled directly in the aluminum substrate and coated with gold to have the highest possible reflectance in the mid-infrared. The gratings are all used in first order and close to the top of their blaze function. Unwanted zeroth-order light is absorbed by a light dumps that are located above each of the gratings.

3.6 MIRI detector system

The imager and short- and long-wavelength spectrometer modules each have a focal plane module (FPM) provided by JPL. The MIRI FPMs (shown in Figure 16) comprise two

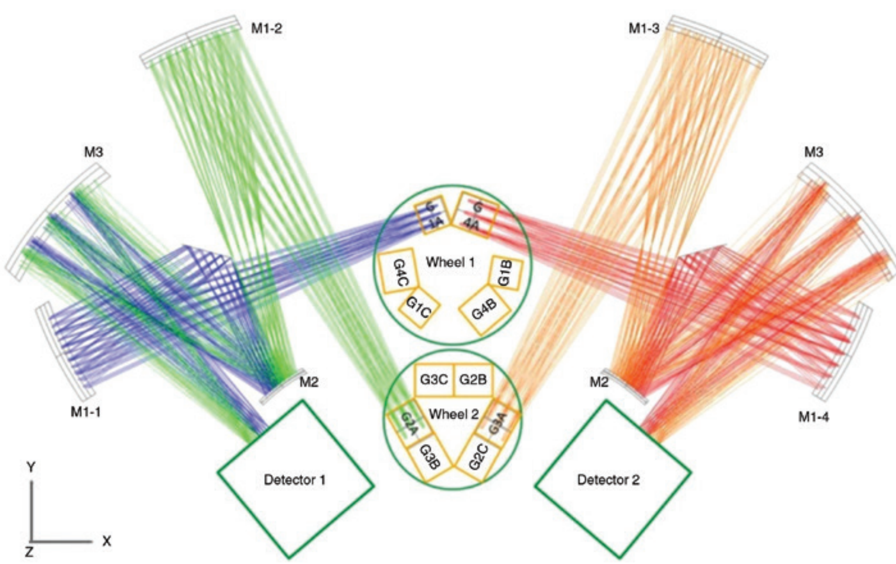


Figure 15: Top view of the SMO optics, showing the four channels/arms (dispersion perpendicular to plane of drawing).

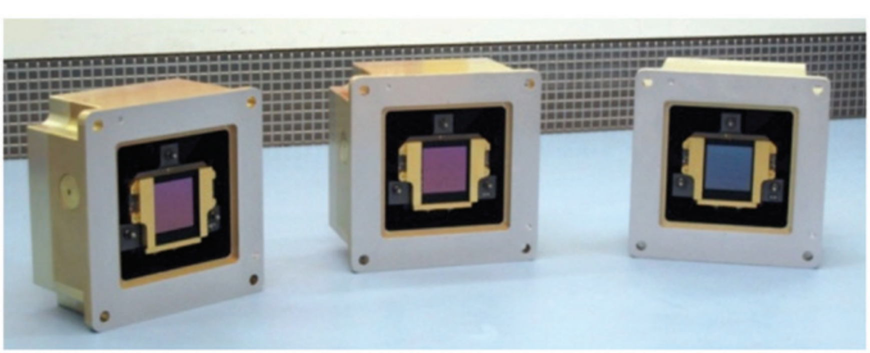


Figure 16: The three MIRI detector modules.

major portions: (1) the detector assembly and (2) the detector housing. The detector assemblies each include one 1024 × 1024 px arsenic-doped silicon (Si:As) sensor chip assembly (SCA). The detector pixels are 25 × 25 μm in size. The analog detector signal is relayed to the warm focal plane electronics (FPE) box, which resides in the ISIM Electronics Compartment (IEC). The FPE amplifies and digitizes the analog signals from the FPE and transmits the science and housekeeping data to the ISIM Command and Data Handling unit (ICDH).

4 Integrated Science Instrument Module (ISIM)

After all four instruments were delivered to the NASA GSFC, they were subjected to incoming inspections, optical metrology, and various functional test campaigns. The instruments were then integrated to the ISIM (see Figure 17). The ISIM mechanical structure is mostly made out of carbon fiber-reinforced plastic (CFRP) material, and it houses all the four science instruments of the JWST. The ISIM resides at the backside of the OTE's primary mirror, where it is attached to the OTE's back structure frame (BSF).

In total, three cryogenic test campaigns were performed at the NASA GSFC. The final one, designated CV3, confirmed that all the JWST scientific instrumentation was working properly [5, 6].

After CV3, the ISIM was integrated to the flight OTE, which was constructed and functionally tested at the GSFC in parallel to the ISIM activities. The new system of the ISIM and OTE is now called OTIS (Optical Telescope and Integrated Science). After the integration of the OTIS was completed in the summer of 2016, it was subjected to an extensive 'pre-environmental', warm functional test campaign. These tests took place at ambient temperature and checked all the electrical connections, settings, and functionalities of the various subsystems. A post-environmental repeat of these warm functional tests was also performed after OTIS had gone through the environmental test campaign (i.e. vibration and acoustic testing).

After all the test activities were finished at the NASA GSFC, the OTIS was packed in its special transportation container, known as the Space Telescope Transporter for Air Road and Sea (STTARS) and flown to Houston in Texas where further testing followed at NASA's Johnson Space Center (JSC). At the JSC, over a period of 3 months, the OTIS underwent its final cryogenic testing. This testing took place inside Thermal Chamber A (see Figure 18), the largest high-vacuum, cryogenic, optical test chamber in the world. The testing, mostly focusing on OTE performance, alignment, and the verification of potential straylight paths, was very successful and demonstrated that the OTE and ISIM were both in an excellent shape.

On February 2018, the JWST was transported to Northrop Grumman Aerospace Systems (NGAS) in Redondo Beach, California, for final assembly and testing with the spacecraft bus and sunshield, prior to launch in early 2021 from the Europe's spaceport in Kourou, French Guiana. At NGAS, the OTIS will be combined with the SCE (i.e. sunshield and space craft bus). This integration activity will complete the JWST observatory. The final environmental testing and functional testing will be performed to confirm that the complete observatory can withstand the Ariane 5 launch loads and that all systems are still working properly.

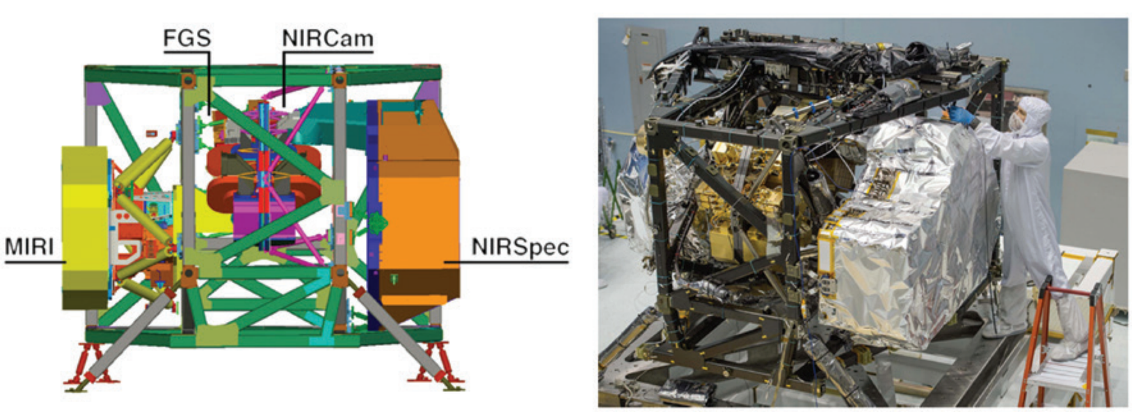


Figure 17: The ISIM of the JWST.

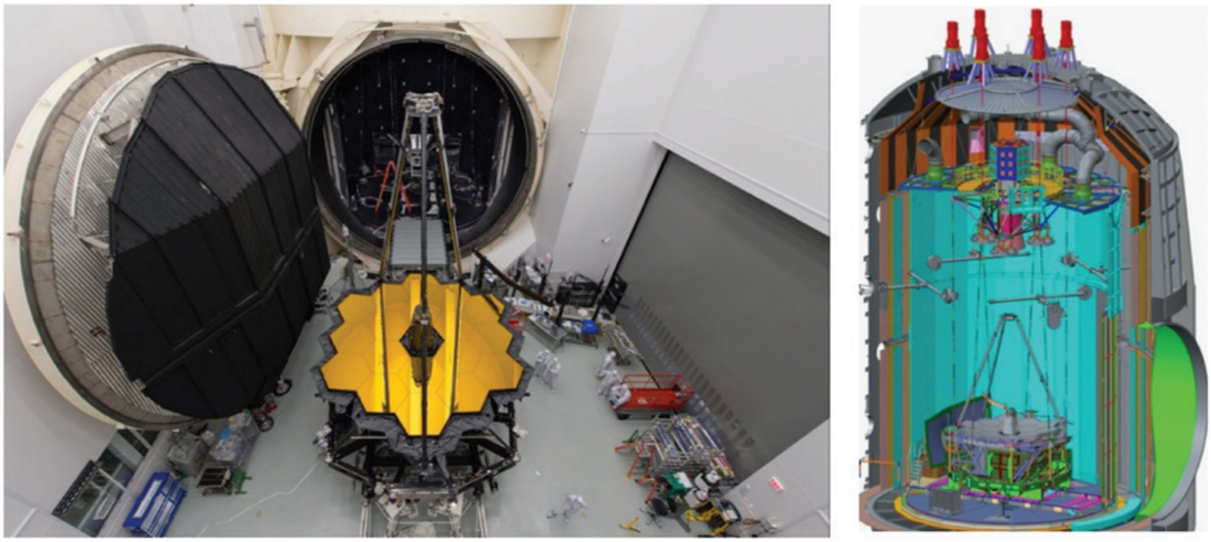


Figure 18: The OTIS ready for final cryogenic testing at the NASA JSC with cross section test chamber (right).

It shall also be mentioned that, in parallel with this testing, teams of astronomers located across the US, Canada, and Europe have started to write proposals for scientific observations that will take place with the JWST once the observatory has reached its final orbit and is ready for science.

5 Conclusion

The JWST has been a long-time international partnership between NASA, ESA, and CSA. The European optical contribution to the mission in the form of the two scientific instruments, the NIRSpec and MIRI was described in detail. The NIRSpec and MIRI instruments will play a pivotal role in the upcoming JWST science. After delivery to NASA, the instruments were integrated to the ISIM that later became part of the OTIS system. During all ambient and cold test campaigns, the NIRSpec and MIRI continue to perform excellently. The two instrument teams are convinced that this will continue during future testing at observatory level as well as in space after launch in early 2021.

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