Status of the JWST/NIRSpec instrument

Stephan M. Birkmann[a], Pierre Ferruit[b], Catarina Alves de Oliveira[c], Torsten Böker[a], Guido De Marchi[b], Giovanna Giardino[b], Marco Sirianni[a], Martin Stuhlinger[c], Peter Jensen[b], Peter Rumler[b], Massimo Falcolini[b], Maurice B. J. te Plate[d], Giovanni Cresci[e], Bernhard Dorner[f], Ralf Ehrenwinkler[g], Xavier Gnata[g], Thomas Wettemann[g],

[a]European Space Agency - STScI, 3700 San Martin Dr, Baltimore, MD 21218, USA;
[b]European Space Agency - ESTEC, Keplerlaan 1, 2200AG Noordwijk, Netherlands;
[c]European Space Agency - ESAC, P.O. Box 78, 28691 Villanueva de la Cañada, Madrid, Spain;
[d]European Space Agency - GSFC, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA;
[e]INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy;
[f]Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany;
[g]Airbus Defence and Space, 81663 Munich, Germany;

ABSTRACT

The Near-Infrared Spectrograph (NIRSpec) is one of the four instruments on the James Webb Space Telescope (JWST), scheduled for launch in 2018. NIRSpec has been designed and built by the European Space Agency (ESA) with Airbus Defense and Space Germany as prime contractor. The instrument covers the wavelength range from 0.6 to 5.3 micron and will be able to obtain spectra of more than 100 astronomical objects simultaneously by means of a configurable array of micro-shutters. It also features an integral field unit and a suite of slits for high contrast spectroscopy of individual objects. The extensive ground calibration campaign of NIRSpec was completed in Summer 2013, after which it was delivered to NASA for integration into the Integrated Science Instrument Module (ISIM). We highlight the major results from the instrument level calibration campaign which demonstrated full compliance with all opto-mechanical performance requirements. In addition, we present the current status of the instrument, describe the ongoing preparations for the Integrated Science Instrument Module (ISIM) test campaign to begin in June 2014, and briefly discuss plans for the pending exchange of the detector and micro-shutter assemblies following the first ISIM test cycle.

Keywords: James Webb Space Telescope, JWST, Near Infrared Spectrograph, NIRSpec

1. INTRODUCTION

The Near Infrared Spectrograph (NIRSpec) is one of the four main science instruments (SIs) aboard the James Webb Space Telescope (JWST), which is designed to enable observational breakthroughs in many areas of near- and mid-infrared (NIR and MIR) astronomy. With its large ($D \sim 6.5\,\mathrm{m}$) and cold ($T \sim 50\,\mathrm{K}$) primary mirror, JWST will significantly surpass the sensitivity and wavelength range of the Hubble Space Telescope (HST) as well as 8m-class ground-based telescopes. JWST is scheduled for launch in October 2018 from ESA's spaceport in Kourou, French Guyana onboard an Ariane 5 rocket. A comprehensive description of the observatory and its main science goals is given by Gardner et al.[1] and its current status is summarized at this conference.[2]

NIRSpec has been designed as the main JWST instrument for NIR spectroscopy, and will be the first multi-object spectrograph in space. It was developed by the European Space Agency (ESA) with Airbus Defence and Space Germany (formerly Astrium Germany GmbH) as the prime contractor and many sub-contractors from various ESA member states. In section 2 we briefly describe the instrument and its main features. In section 3 we show a few results from the cryogenic performance test campaigns conducted at instrument level. The delivery to NASA and the current status of the instrument are described in sections 4 and 5, respectively.

Further information: `http://cosmos.esa.int/web/jwst`
Send correspondence to S.M.B: e-mail: stephan.birkmann@esa.int; telephone +1 410-338-2609

Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, edited by Jacobus M. Oschmann, Jr., Mark Clampin, Giovanni G. Fazio, Howard A. MacEwen, Proc. of SPIE Vol. 9143, 914308 · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2054642

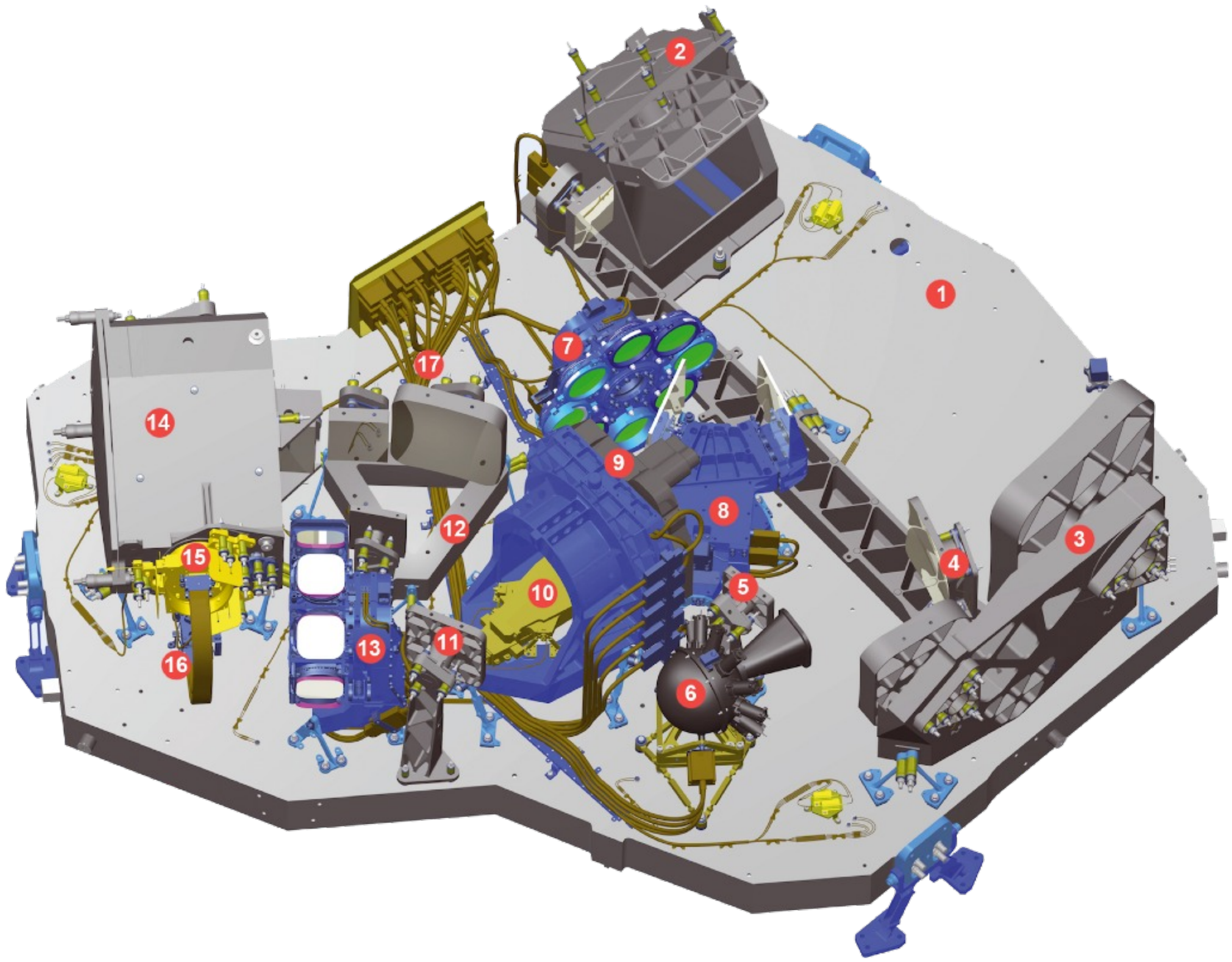

Figure 1. CAD drawing of NIRSpec identifying its main components: 1. optical bench, 2. coupling optics (pick-off mirror below bench), 3. fore optics TMA, 4. calibration mirror 1, 5. calibration mirror 2, 6. calibration assembly (CAA), 7. filter wheel assembly (FWA), 8. refocus mechanism assembly (RMA), 9. micro shutter assembly (MSA), 10. integral field unit (IFU), 11. fold mirror, 12. collimator TMA, 13. grating wheel assembly (GWA), 14. camera TMA (inside camera housing), 15. focal plane assembly (FPA), 16. SIDECAR ASIC, 17. optical assembly internal harness.

2. DESIGN OF THE NIRSPEC INSTRUMENT

A CAD drawing of NIRSpec identifying the main components is shown in Figure 1. NIRSpec features three three-mirror anastigmats (TMAs), namely the fore optics (FOR), the collimator (COL) and the camera (CAM). Furthermore, it holds a filter wheel assembly (FWA) and a grating wheel assembly (GWA), as well as a refocus mechanism assembly (RMA) for focussing the instrument. The calibration assembly (CAA) provides sources for internal calibration. The micro shutter assembly (MSA) and the integral field unit (IFU) are located in an intermediate imaging plane that is conjugate with the focal plane, where light is detected by the focal plane assembly (FPA). The FPA is a mosaic of two $2\text{k} \times 2\text{k}$ HAWAII-2RG detector arrays with a $\sim 5.3\,\mu$m cut-off that are read out by a pair of SIDECAR ASICs.[3] Both the MSA and the FPA are provided by NASA. NIRSpec and its detector system are passively cooled to an operating temperature of around 40 K.

The NIRSpec optical bench is made out of Silicon Carbide, as are most folding mirrors and the three TMAs. The mirrors are coated with protected silver. With the exception of the filters in the FWA and a prism in the GWA, the NIRSpec optical train is an all-reflective design. A more complete description of NIRSpec's optical train and its design are given by Bagnasco et al.[4] and te Plate et al.,[5] and up-to-date information on the instrument is always available on the ESA/JWST webpage: `http://cosmos.esa.int/web/jwst`.

FWA element	GWA element	Spectral coverage [μm]
CLEAR	PRISM	0.6 - 5.3
F070LP	G140M/H	0.7 - 1.2
F100LP	G140M/H	1.0 - 1.8
F170LP	G235M/H	1.7 - 3.1
F290LP	G395M/H	2.9 - 5.2
F110W	MIRROR	1.0 - 1.3
F140X	MIRROR	0.8 - 2.0

Table 1. Standard filter and disperser combinations for NIRSpec. GWA elements starting with a 'G' are gratings, where the 'M' or 'H' at the end denote the medium or high resolution grating, respectively.

The FWA has eight positions, occupied by seven filters and a closed aperture. The latter is used to block external illumination for dark exposures and internal calibrations, as it also provides a mirror to complete the internal calibration path that is fed by the CAA. The seven transmission filters are comprised of two target acquisition filters, four long-pass filters for use with the gratings, and a clear CaF_2 filter for prism observations.

The NIRSpec GWA offers a mirror for target acquisition and confirmation imaging, as well as seven dispersers for spectroscopy. One of these is a double pass prism made of CaF_2 that covers the entire wavelength range (0.6 to $\sim$5.3 μm) in a single exposure with varying spectral resolution ($30 \lesssim R \lesssim 300$). The other six dispersers are reflection gratings that offer medium ($R \sim 1000$) and high ($R \sim 2700$) resolution spectroscopy in four bands between 0.7 and 5.2 μm. The most commonly used filter/disperser combinations and their respective wavelength ranges are summarized in Table 1.

The micro-shutter assembly (MSA) provides NIRSpec with its multi-object capabilities. It contains 730×342 individually addressable shutters covering a field of view (FOV) of more than $3 \times 3\,\mathrm{arcmin}^2$. For observations of individual astronomical objects, NIRSpec also features an IFU with a $3 \times 3\,\mathrm{arcsec}^2$ FOV. The IFU spectra fall on the same detector area as the MSA spectra, therefore the IFU aperture is blocked when performing multi-object observations, and all shutters have to be closed when using the IFU. Finally, there are five permanently open fixed slits for high contrast spectroscopy (e.g. for exo-planet transit observations[6]), with their spectra falling onto dedicated detector areas that can be read out with a high cadence using sub-arrays.

3. RESULTS FROM INSTRUMENT-LEVEL TESTING

In 2013, NIRSpec underwent two test cycles in cryogenic vacuum (cryovac) conditions that included a full performance characterization and instrument calibration, in order to verify all instrument-level requirements. Between the two cryovac cycles, the instrument was exposed to sine vibration and acoustic testing to demonstrate robustness against the launch conditions. This test sequence was chosen to i) thermally stress all bolted joints prior to environmental testing and ii) be able to check for any potential alignment or performance changes following the environmental test. NIRSpec completed this test sequence successfully, i.e. with full performance and without any anomalies.

We found that all instrument performances reported from previous tests[7–9] are still valid. Furthermore, the calibration campaigns conducted in 2013 were the first ones where the MSA was fully operational. An example exposure illuminated by an Argon emission line lamp (part of the NIRSpec optical ground support equipment) is shown in Figure 2. In that exposure, the MSA was configured to open a set of dashed mini slits that sparsely cover the entire field of view of the instrument.

One key result we would like to highlight is the outstanding throughput of NIRSpec's optical train. For all spectrographic modes, the measured throughput is significantly higher than the requirements. Even the throughput values derived using a worst case analysis meet the requirements with margin (see Table 2 for the total throughput in each of the spectrographic configuations).

4. SHIPMENT AND ARRIVAL AT GSFC

Following the last cryovac test, the evaluation of the test data, and a successful pre-shipment and acceptance review, NIRSpec was delivered to NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD, in September

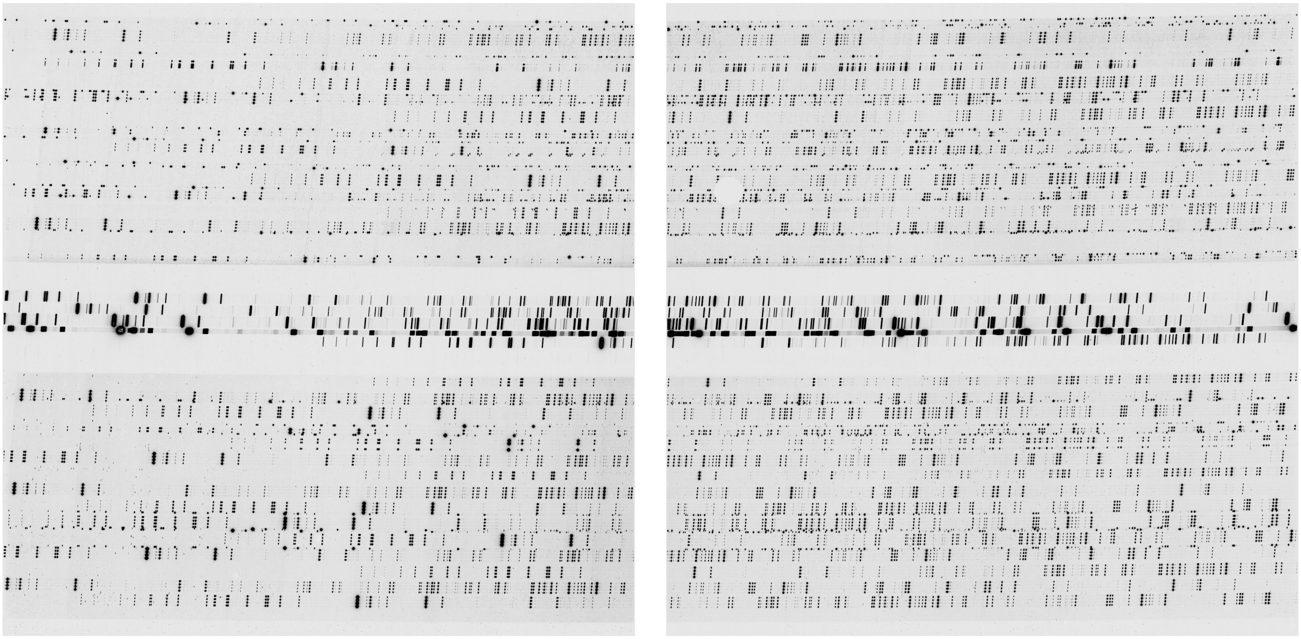

Figure 2. Exposure of an Argon emission lamp sources taken with NIRSpec G140H grating and the MSA configured to open a number of dashed mini slits. The spectra along the center of both detectors are from the five fixed slits.

Grating	Average throughput	Requirement
G140M	0.61	0.44
G235M	0.58	0.45
G395M	0.55	0.45
G140H	0.57	0.39
G235H	0.54	0.40
G395H	0.51	0.40

Table 2. The worst case average throughput for the six spectrographic modes using gratings compared to the requirements.

2013. A picture of the instrument prior to delivery is shown in Figure 3. After the incoming inspection and functional testing, NIRSpec was moved to the SSDIF* clean room facility at GSFC for integration into the integrated science instrument module (ISIM).

5. CURRENT STATUS OF THE NIRSPEC INSTRUMENT

NIRSpec was the last instrument to be mounted on the ISIM structure, and it was successfully integrated in March 2014. Figure 4 (left) shows NIRSpec mounted on the Horizontal Integration Tool (HIT) that is used to maneuver the four JWST instruments into position. The successful completion of the JWST instrument suite (see Figure 4, right) and their mechanical and electrical integration into ISIM presents a major milestone for the JWST project which is described in more detail elsewhere in these proceedings.[10]

After a successful verification of all electrical connections, the fully assembled ISIM was placed in the Space Environment Simulator (SES) cryogenic chamber at GSFC in preparation for the second ISIM cryovac (CV2) test which is scheduled to begin mid-June 2014 and will last until the end of September 2014.

The NIRSpec Optical Assembly (OA) is not yet in its final flight configuration. Both the FPA and the MSA will be exchanged with improved versions following the completion of the ISIM CV2 test campaign. After completion of these hardware changes (and a number of changes for some of the other SIs), the re-assembled ISIM structure will be subjected to vibration and acoustic testing. Exchange of these sub-assemblies and vibration and acoustic testing is foreseen for winter 2014/15. Afterwards, it will be fully verified during a third cryo vacuum

*see http://www.jwst.nasa.gov/webcam.html for a live feed of the SSDIF facility

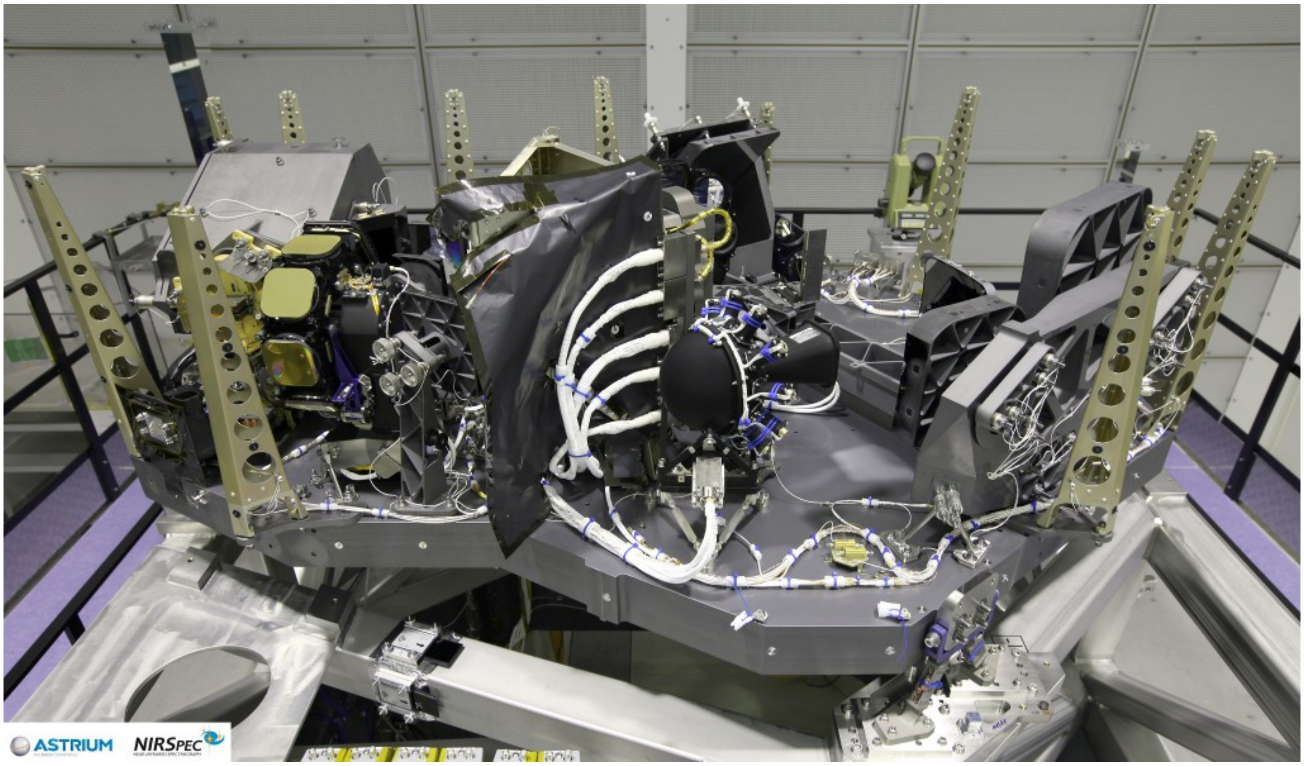

Figure 3. Image of the NIRSpec instrument with its cover removed, taken prior to the delivery to NASA in September 2013.

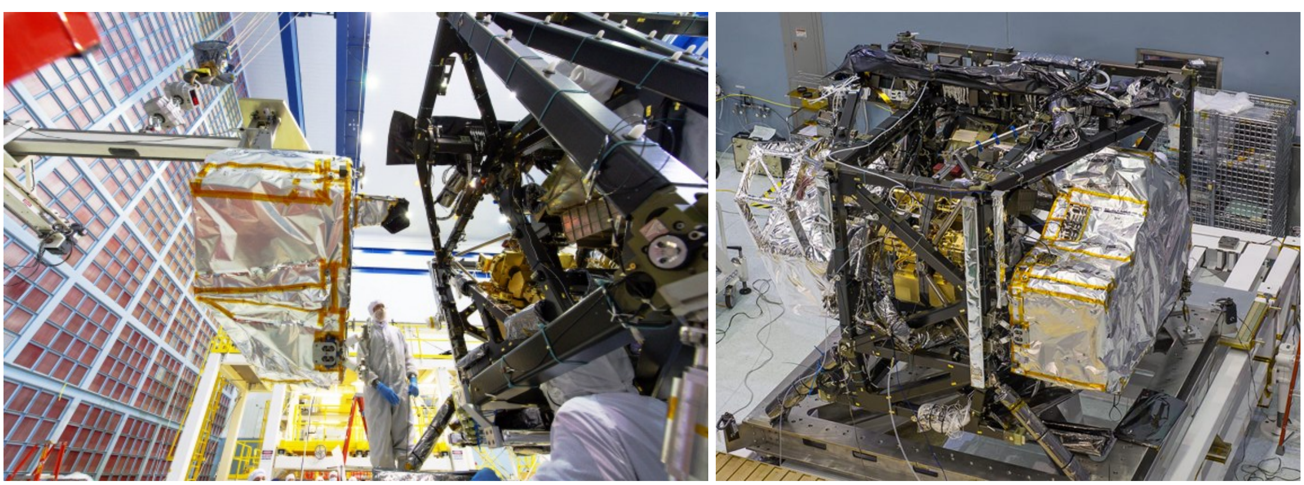

Figure 4. Left: NIRSpec on the Horizontal Integration Tool during installation to ISIM. Right: Image of the fully assembled ISIM structure, with NIRSpec visible on the right. Credit NASA.

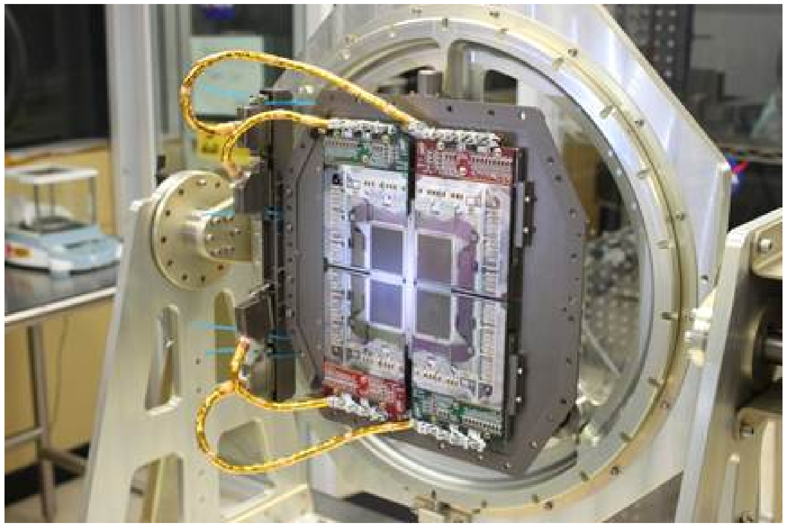

Figure 5. Image of the new MSA (without the full enclosure) to be installed in NIRSpec following the ISIM CV2 test campaign. Credit NASA.

campaign (CV3) in summer/fall 2015. More details on the ISIM level test and verification campaigns are given by Kimble et al.[11] The status of the two NIRSpec subassemblies to be exchanged is described in the following sections.

5.1 Status of the Micro-Shutter Assembly

The MSA that is currently installed on the NIRSpec OA suffers from an unexpected susceptibility to acoustic exposure that leads to an increased number of failed-closed micro shutters, i.e. shutters that cannot be opened but are permanently stuck closed. Therefore, it is foreseen to replace the current MSA with a new model. This new model contains recently fabricated micro-shutter arrays that show much improved performance (e.g. lower number of failed shutters, and higher open to closed contrast) compared to those that were originally installed in NIRSpec, as well as better robustness against the acoustic loads imposed during the JWST launch. The newly assembled MSA, shown in Figure 5, is currently undergoing environmental testing, following which it will enter the final performance characterization in cryovac conditions (second half of June 2014). Assuming successful completion of these tests, it will be integrated onto the NIRSpec OA after the completion of the ISIM CV2 test campaign.

5.2 Status of the Focal Plane Assembly

The original suite of NIR detectors for all JWST instruments is affected by a well-understood design flaw that causes significant performance degradation over time due a growing population of hot pixels.[12] This issue has been successfully fixed in a new set of JWST NIR detectors which have been shown to meet or exceed the required performance specifications, and have a small (and stable) hot pixel population.[13] For NIRSpec, the new Focal Plane Assembly (FPA) shown in Figure 6 is currently in its final performance characterization test, and will also be integrated onto the OA following the conclusion of the ISIM CV2 test.

With the new flight MSA and FPA installed, NIRSpec is projected to meet all its sensitivity requirements. Estimates of the sensitivities of all instruments onboard JWST and a comparison with current observatories can be found at `http://www.stsci.edu/jwst/science/sensitivity`.

6. SUMMARY

Following a highly successful instrument-level verification campaign that demonstrated the expected performance of all operational modes, the NIRSpec instrument is currently being tested in the second ISIM cryovac campaign at GSFC. Following completion of this test, two critical sub-assemblies (the focal plane and micro-shutter assemblies) will be replaced with improved models to ensure full science performance. NIRSpec and the entire ISIM

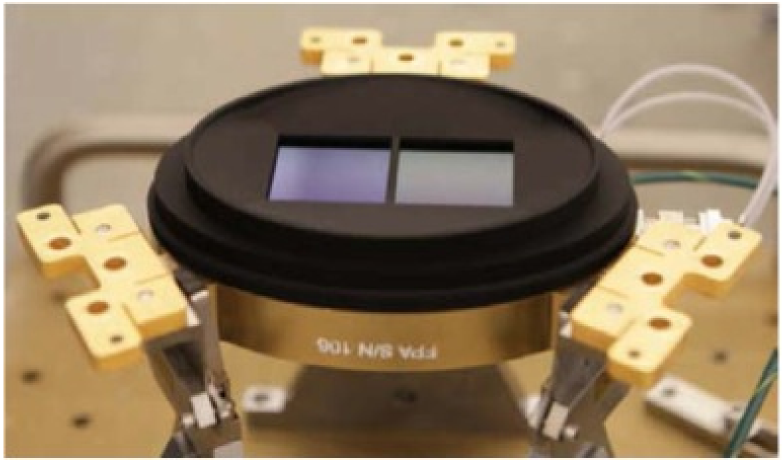

Figure 6. Image of the new FPA (S/N 106) to be installed in NIRSpec following the ISIM CV2 test campaign. Credit NASA.

will then be fully verified in a third cryovac test campaign in the second half of 2015 before being delivered to the prime contractor (Northrop Grumman) for higher-level integration and testing.

REFERENCES

[1] Gardner, J. P., Mather, J. C., Clampin, M., Doyon, R., Flanagan, K. A., Franx, M., Greenhouse, M. A., Hammel, H. B., Hutchings, J. B., Jakobsen, P., Lilly, S. J., Lunine, J. I., McCaughrean, M. J., Mountain, M., Rieke, G. H., Rieke, M. J., Sonneborn, G., Stiavelli, M., Windhorst, R., and Wright, G. S., [*The James Webb Space Telescope*], 1–29 (2009).

[2] Clampin, M., "Recent progress with the JWST Observatory s," *Proc. SPIE* **9143-1** (2014).

[3] Loose, M., Beletic, J., Blackwell, J., Garnett, J., Wong, S., Hall, D., Jacobson, S., Rieke, M., and Winters, G., "The SIDECAR ASIC: focal plane electronics on a single chip," in [*Cryogenic Optical Systems and Instruments XI*], Heaney, J. B. and Burriesci, L. G., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5904**, 293–302 (Aug. 2005).

[4] Bagnasco, G., Kolm, M., Ferruit, P., Honnen, K., Koehler, J., Lemke, R., Maschmann, M., Melf, M., Noyer, G., Rumler, P., Salvignol, J., Strada, P., and Te Plate, M., "Overview of the near-infrared spectrograph (NIRSpec) instrument on-board the James Webb Space Telescope (JWST)," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **6692** (Oct. 2007).

[5] te Plate, M., Holota, W., Posselt, W., Koehler, J., Melf, M., Bagnasco, G., and Marenaci, P., "Optomechanical design of the near infrared spectrograph NIRSpec," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5904**, 185–198 (Aug. 2005).

[6] Böker, T., Birkmann, S. M., Ferruit, P., Sirianni, M., Giardino, G., Alves de Oliveira, C., and Dorner, B., "Observing transiting exoplanets with NIRSpec onboard JWST," *Proc. SPIE* **9143-10** (2014).

[7] Birkmann, S. M., Böker, T., Ferruit, P., Giardino, G., Jakobsen, P., de Marchi, G., Sirianni, M., Te Plate, M. B. J., Savignol, J.-C., Gnata, X., Wettemann, T., Dorner, B., Cresci, G., Rosales-Ortega, F., Stuhlinger, M., Cole, R., Tandy, J., and Brockley-Blatt, C., "Wavelength calibration of the JWST near-infrared spectrograph (NIRSpec)," in [*Cryogenic Optical Systems and Instruments XIII. Edited by Heaney, James B.; Kvamme, E. Todd. Proceedings of the SPIE, Volume 8150, pp. 81500B-81500B-9 (2011).*], **8150** (Sept. 2011).

[8] Birkmann, S. M., Ferruit, P., Böker, T., De Marchi, G., Giardino, G., Sirianni, M., Stuhlinger, M., Jensen, P., te Plate, M. B. J., Rumler, P., Dorner, B., Gnata, X., and Wettemann, T., "The Near Infrared Spectrograph (NIRSpec) on-ground calibration campaign," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8442** (Sept. 2012).

[9] De Marchi, G., Birkmann, S. M., Böker, T., Ferruit, P., Giardino, G., Sirianni, M., Stuhlinger, M., te Plate, M. B. J., Salvignol, J.-C., Barho, R., Gnata, X., Lemke, R., Kosse, M., and Mosner, P., "The accuracy of the NIRSpec grating wheel position sensors," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8442** (Sept. 2012).

[10] Greenhouse, M. A., "The JWST science instrument payload: mission context and status," *Proc. SPIE* **9143-7** (2014).

[11] Kimble, R. A., Antonille, S. R., Balzano, V., Comber, B. J., Davila, P. S., Drury, M. D., Glasse, A., Glazer, S. D., Lundquist, R., Mann, S. D., McGuffey, D. B., Novo-Gradac, K. J., Penanen, K., Ramey, D. D., Sullivan, J., Van Campen, J., and Vila, M. B., "First Cryo-Vacuum Test of the JWST Integrated Science Instrument Module," in [*American Astronomical Society Meeting Abstracts*], *American Astronomical Society Meeting Abstracts* **223**, #149.36 (Jan. 2014).

[12] Rauscher, B. J., Stahle, C., Hill, R. J., Greenhouse, M., Beletic, J., Babu, S., Blake, P., Cleveland, K., Cofie, E., Eegholm, B., Engelbracht, C. W., Hall, D. N. B., Hoffman, A., Jeffers, B., Jhabvala, C., Kimble, R. A., Kohn, S., Kopp, R., Lee, D., Leidecker, H., Lindler, D., McMurray, R. E., Misselt, K., Mott, D. B., Ohl, R., Pipher, J. L., Piquette, E., Polis, D., Pontius, J., Rieke, M., Smith, R., Tennant, W. E., Wang, L., Wen, Y., Willmer, C. N. A., and Zandian, M., "Commentary: JWST near-infrared detector degradation — finding the problem, fixing the problem, and moving forward," *AIP Advances* **2**(2), 021901 (2012).

[13] Hill, J. H., J., R. M., Rauscher, B. J., Greenhouse, M. A., Wen, Y., Lindler, D. J., and Mott, D. B., "New detectors for the JWST near-IR instruments," *Proc. SPIE* **9154-13** (2014).