Status of the NIRSpec Instrument

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ABSTRACT

The Near Infrared Spectrograph (NIRSpec) is one of the four science instruments aboard the James Webb Space Telescope (JWST) scheduled for launch in 2014. NIRSpec is sensitive in the wavelength range from ~ 0.6 to $5.0\,\mu$m and will be capable of obtaining spectra of more than a 100 objects simultaneously, as well as fixed slit high contrast spectroscopy of individual sources. It also features an integral field unit for 3D spectroscopy. The key scientific objectives of the instrument include studies of star formation and chemical abundances of young distant galaxies and tracing the creation of the chemical elements back in time. In this paper, we present the status of the NIRSpec instrument as it is currently being prepared for its extensive ground calibration campaign later in 2010.

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

1. INTRODUCTION

The Near Infrared Spectrograph (NIRSpec) is one of the four science instruments of the James Webb Space Telescope (JWST). JWST features a deployable and passively cooled ($T \leq 50\,$K) primary mirror with $\sim 6.5\,$m diameter and is scheduled for launch in 2014. A comprehensive description of the observatory and its main science goals is given by Ref. 1 and its current status is presented in this volume in Refs. 2 and 3.

NIRSpec is a near-infrared multi-object spectrograph capable of simultaneously obtaining more than 100 spectra in a $3.6 \times 3.4\,$arcmin field of view (FOV) and is developed by the European Space Agency (ESA) with EADS Astrium Germany GmbH as the prime contractor. Six gratings with resolving powers of $R = \lambda/\Delta\lambda \sim 1000$ and $R \sim 2700$ will cover the wavelength range from $1.0 - 5.0\,\mu$m in three bands, while one prism will span the full range of $\sim 0.6 - 5.0\,\mu$m and yield a wavelength dependent resolution of $30 \leq R \leq 300$. In addition to the multiobject capability, NIRSpec will feature a selectable integral field unit (IFU) with $3 \times 3\,$arcsec FOV and five fixed slits for detailed high contrast studies of single objects.

Fig. 1 shows the layout of the instrument. In total, NIRSpec features three three-mirror anastigmats (TMAs) – the fore optics, collimator and camera –, a filter and a grating wheel assembly (FWA and GWA), a refocus mechanism assembly (RMA), a calibration assembly (CAA), the microshutter assembly (MSA), and the IFU. Light is detected by the focal plane assembly (FPA) that is a mosaic of two 2k × 2k HAWAII-2RG detector arrays. With the exception of the filters in the FWA and the prism in the GWA, the entire optics is all-reflective. A more detailed description of NIRSpec and its optical train is given in Refs. 4 and 5.

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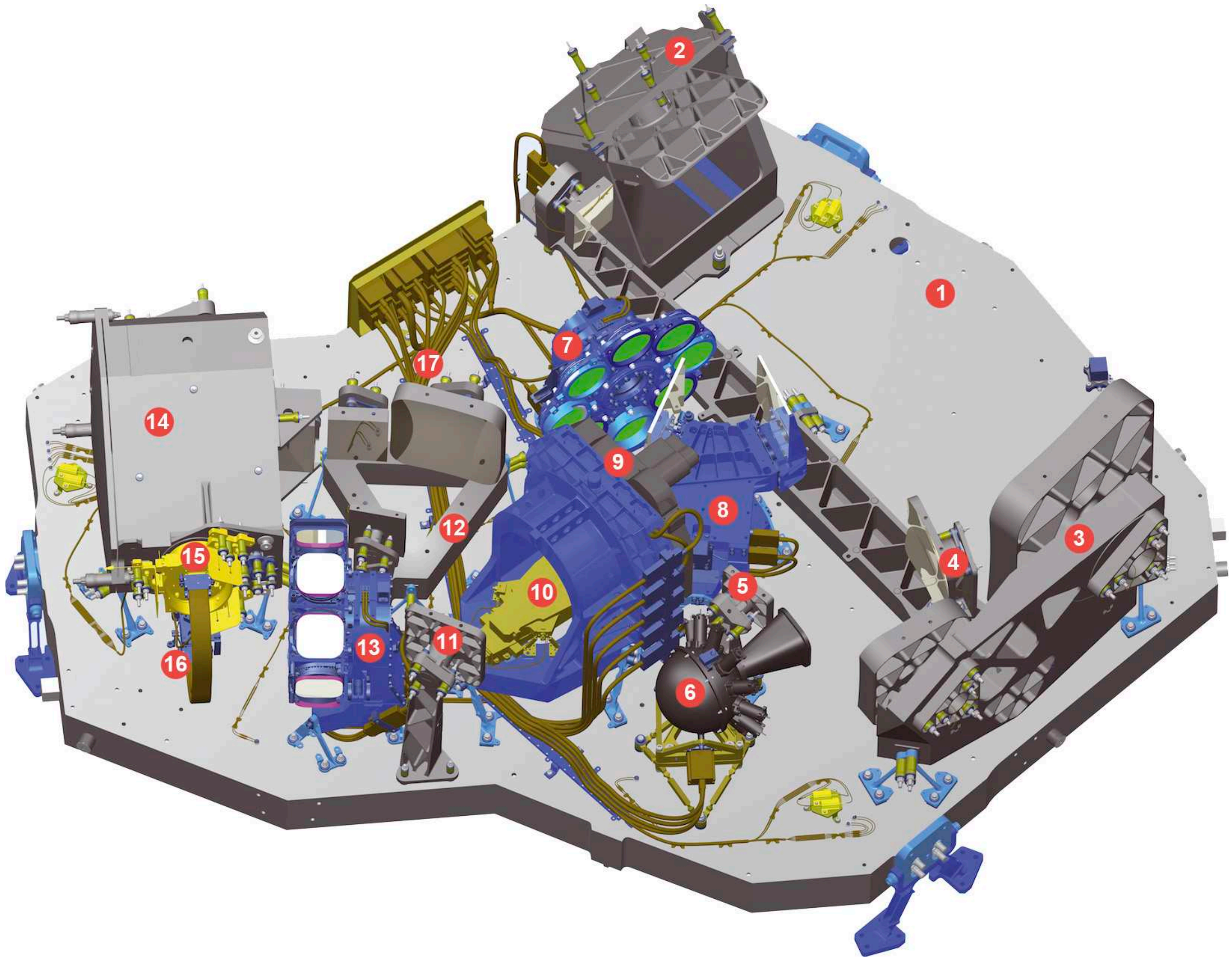

Figure 1. A 3D model of the NIRSpec instrument with the main components labeled: optical bench base plate (1), coupling optics (2), fore optics TMA (3), calibration mirror 1 and 2 (4 and 5), calibration assembly (6), filter wheel assembly (7), refocus mechanism assembly (8), micro shutter assembly (9), integral field unit (10), fold mirror (11), collimator TMA (12), grating wheel assembly (13), camera TMA (14), focal plane assembly (15), SIDECAR ASIC (16), optical assembly internal harness (17).

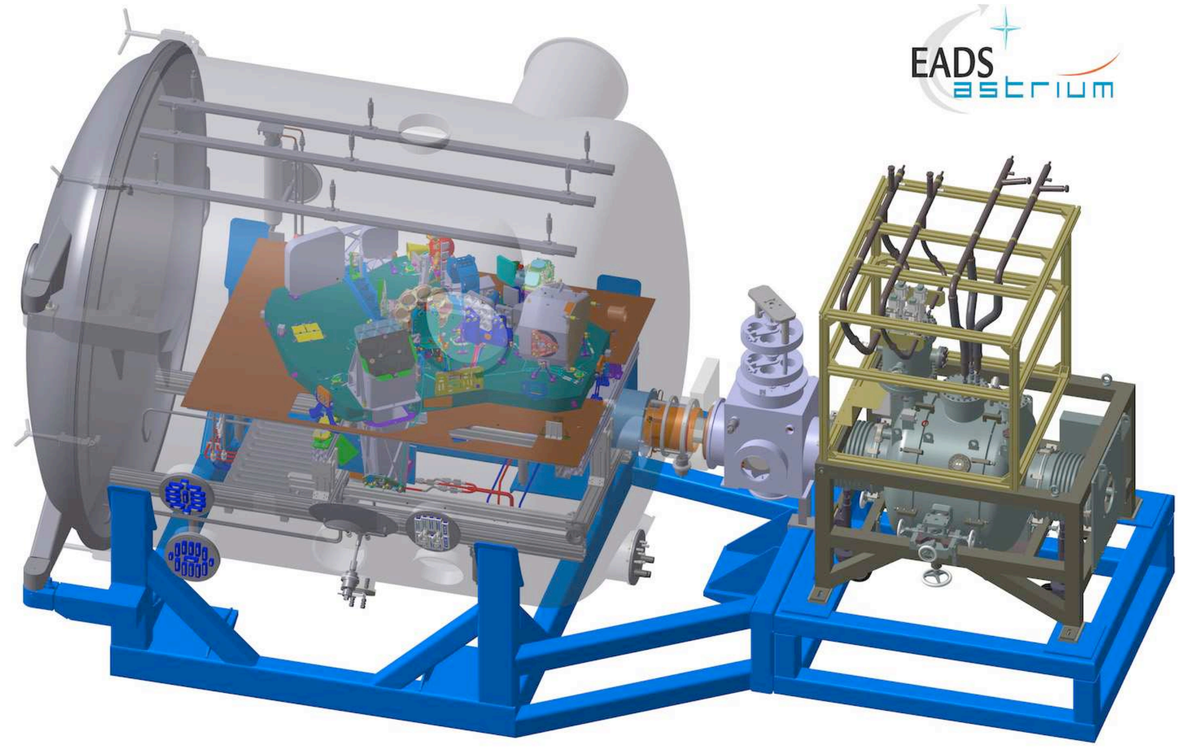

Figure 2. Sketch of the thermal vacuum test setup. NIRSpec is located in the cryo chamber on the left, the calibration light source (CLS) is located on the right. The middle part is the cross piece that is used as a view port to align NIRSpec and the CLS to each other.

2. HARDWARE STATUS

The engineering test unit (ETU) of NIRSpec has been tested three times under cryogenic operating conditions and was successfully delivered to NASA in early 2010. The optical train of the ETU terminates at the MSA plane, where the ETU FPA is located. Furthermore, instead of a fully functioning filter wheel, a structural model with a clear CaF_2 substrate was used. The main purpose of the ETU and its test campaign was to verify the structural and optical integrity of the NIRSpec design, as well as to check the cryo chamber and test the entire suite of on ground support equipment (OGSE).[6] Fig. 2 shows a sketch of the NIRSpec test chamber and parts of the OGSE. Some issues with the test setup – mostly related to thermal background and light leaks inside the test chamber – could be identified and were solved. The results of the tests are also compared against and correlated with the output from the NIRSpec instrument performance simulator.[8] A more detailed description of the NIRSpec ETU and its test campaign is given in Ref. 7.

With the ETU delivered, the focus has now shifted to the NIRSpec flight model (FM). The FM is currently being integrated at Astrium in Munich, and with all but three sub-systems delivered, integration is proceeding rapidly towards the extensive verification and calibration campaign, foreseen to begin later in 2010. In the following we will briefly report on the status of the individual sub-systems and the optical assembly.

2.1 The Optical Assembly

The NIRSpec optical assembly largely relies on Silicon Carbide (SiC) components, as the optical bench base plate, the three TMAs, coupling optics and calibration path are all made of SiC.[9] All SiC parts were manufactured and tested by Boostec, France. The polishing and coating of the mirrors was carried out by Sagem.[10] All SiC components have been delivered to Astrium and the instrument is fully assembled and aligned up to the MSA plane. The performance of the optical train is discussed in Sec. 3.

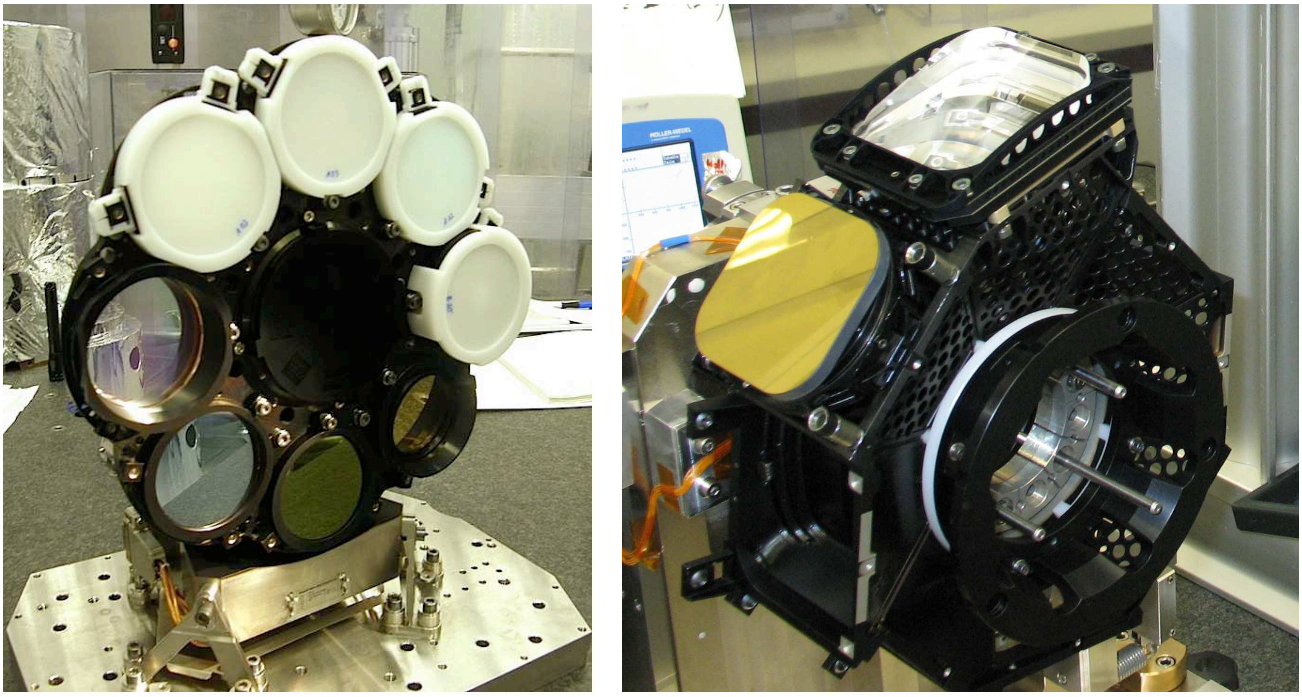

Figure 3. The NIRSpec FWA on the left and the wheel disk of the GWA on the right.

2.2 The Filter Wheel and Grating Wheel Assembly

The FWA is located in the pupil plane of the fore optics and carries seven transmission filters and one mirror. The latter is used to close NIRSpec's optical path towards the telescope and allows light from the internal calibration source to reach the detectors. The GWA also has eight positions in total and carries the six gratings, the prism, and a flat mirror to allow undispersed observations for target acquisition. Four of the eight FWA filters are long pass filters to block the higher dispersion orders of the gratings. Fig. 3 shows images of the flight FWA and GWA. Both mechanisms and their optical components are build by Carl Zeiss Optronics, Germany.[11, 12]

While the FWA has been delivered and integrated onto the NIRSpec optical bench, the GWA is still undergoing final performance testing. After initial difficulties in manufacturing high quality gratings, these units now turn out to be excellent, with peak efficiencies above 90 %. One remaining challenge is the relatively high wavefront error (WFE) of the gratings and target acquisition mirror when mounted onto the wheel disk. This is partly due to the high preloads needed to keep the gratings in place during launch. At the moment a modified mounting strategy is under evaluation and test that should improve the WFE and might be incorporated in the flight spare unit. The GWA FM is scheduled for delivery in late Summer.

2.3 The Refocus Mechanism Assembly

The RMA gives the possibility to focus NIRSpec to the telescope image plane, the exact position of which is not known prior to launch due to the fact that the individual primary mirror segments have to be aligned and phased. Furthermore, it can be used to deliberately defocus NIRSpec for enabling multi-instrument wavefront sensing and phase retrieval for JWST.[13] Phase retrieval results obtained from focus sweep data taken during the NIRSpec ETU test campaign are presented at this conference.[14]

The RMA is based on a pentaprism design with two mirrors on a common linear translation stage with 6 mm travel range.[15] It was designed an built by Galileo Avionica, Italy, and it has already been integrated into the NIRSpec FM. Images of the flight unit are shown in Fig. 4 and a more detailed description of the RMA and its optical components is given in Ref. 16.

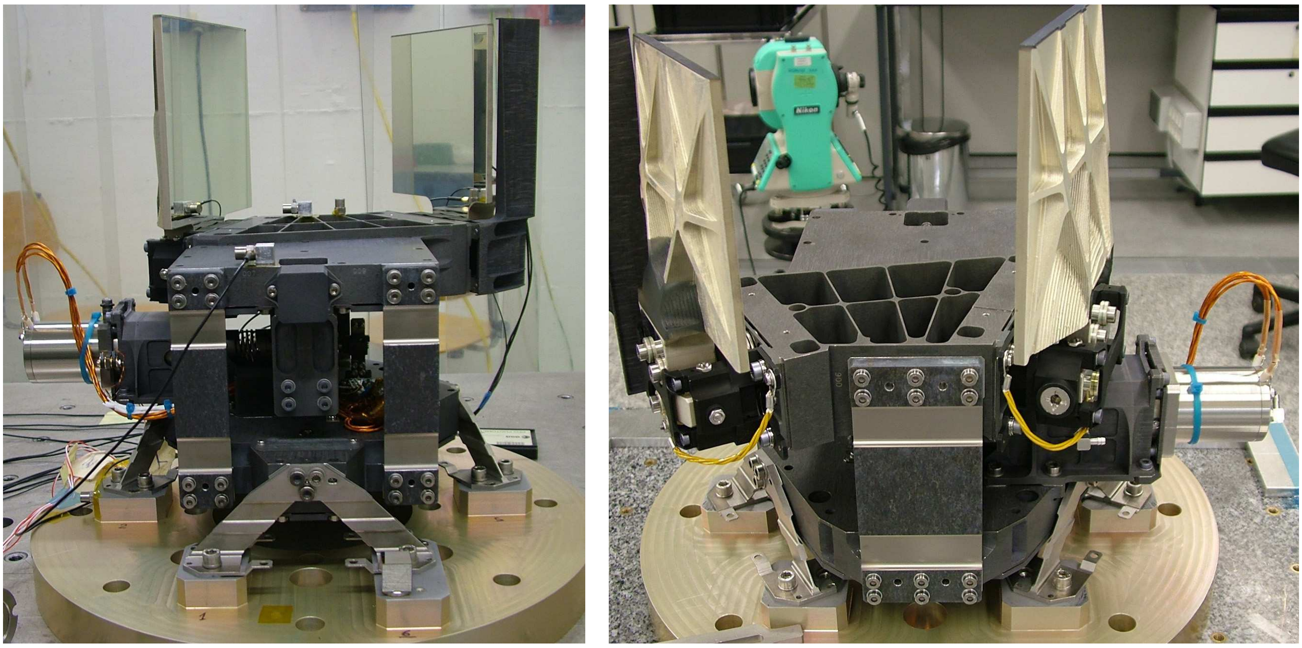

Figure 4. The NIRSpec RMA flight model.

2.4 The Calibration Assembly

The CAA is the internal calibration source of NIRSpec. It was built by the Mullard Space Science Laboratory (MSSL), UK, and consists of a gold coated integrating sphere with eleven individual light sources, so-called telescopes. Each telescope holds an assembly of lenses and filters and two (redundant) light bulbs, providing flat field and wavelength calibrators for the different spectrographic modes of NIRSpec. Light exiting the integrating sphere is constrained by a snout and then directed towards the MSA by two dedicated mirrors, the closed (mirror) position in the FWA and parts of the fore optics optical train, including the RMA mirrors. Fig. 5 shows images of the CAA.

The intensity of all the CAA modes has been verified to be in the suitable range for NIRSpec, but due to the low flux, a full absolute calibration was not possible even with state of the art systems. Therefore, the CAA will be calibrated using NIRSpec itself by comparison to the external on-ground support equipment (see Sec. 2.8).

2.5 The Integral Field Unit

The NIRSpec IFU will allow to perform 3D spectroscopy of a 3×3 arcsec FOV by means of dissecting the square entrance aperture into 30 parallel sub-slits and forming a single virtual slit for the spectrograph. It is built by Surrey Satellite Technology Ltd., UK. A detailed description of the IFU is given in Refs. 17 and 18. The IFU flight model has been delivered to Astrium and is ready for integration into the mounting bracket that also holds the MSA. An image of the flight model is shown in Fig. 6. The performance of this unit is presented in detail at this conference.[19]

2.6 The Microshutter Assembly

The MSA will give NIRSpec its multiobject capability. It consists of four quadrants producing a final array of 730×342 individually addressable shutters.[20] The MSA is developed and built by the NASA Goddard Space Flight Center, USA, with the technology being based on micro-electrical mechanical structures (MEMS). The shutters are opened by sweeping a magnet across the surface, and then kept open electrostatically. Individual shutters can be addressed and released, which is synchronized with the return sweep of the magnet.

The flight model of the MSA has been assembled and is currently undergoing final performance testing. Fig. 7 shows the magnet translation stage and the four quadrants mounted onto the system board. During the test

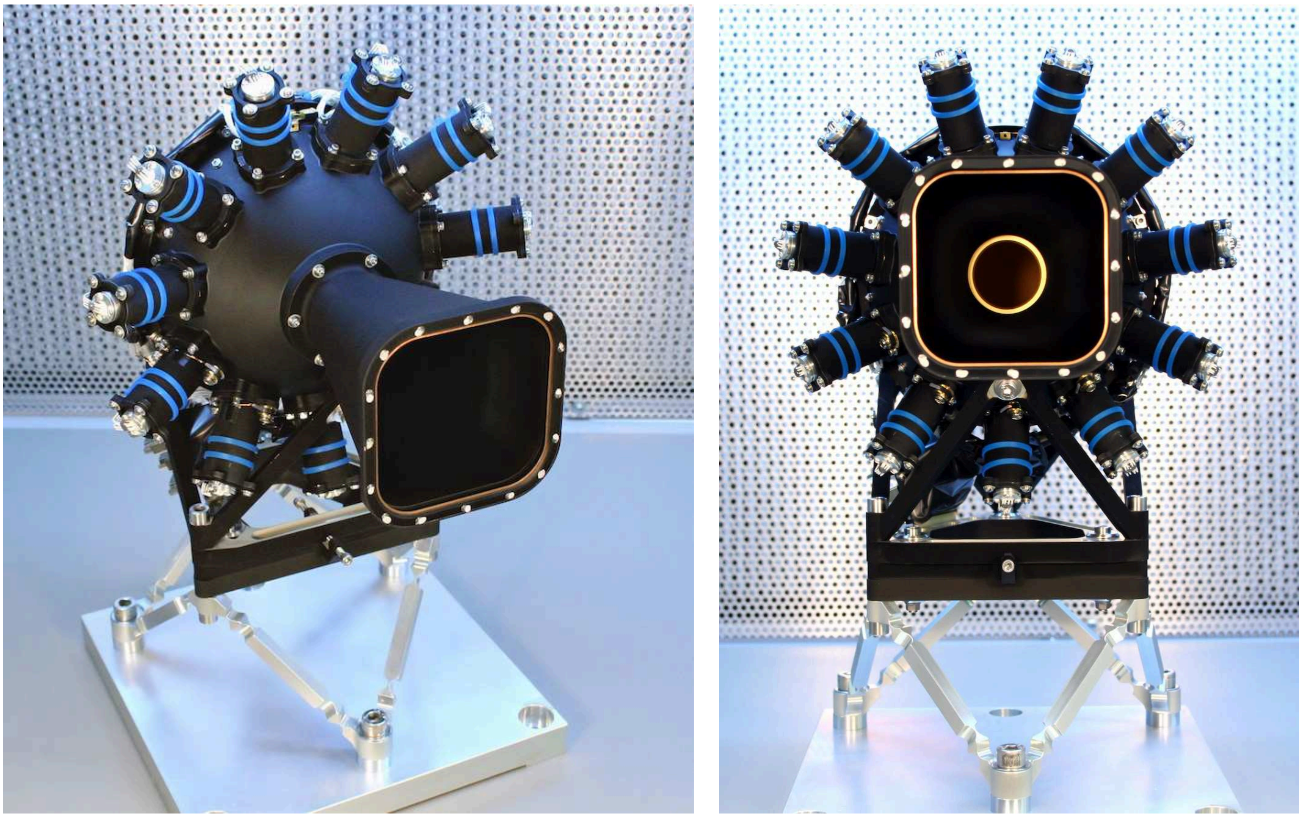

Figure 5. Images of the CAA flight model.

Figure 6. Image of the IFU flight model.

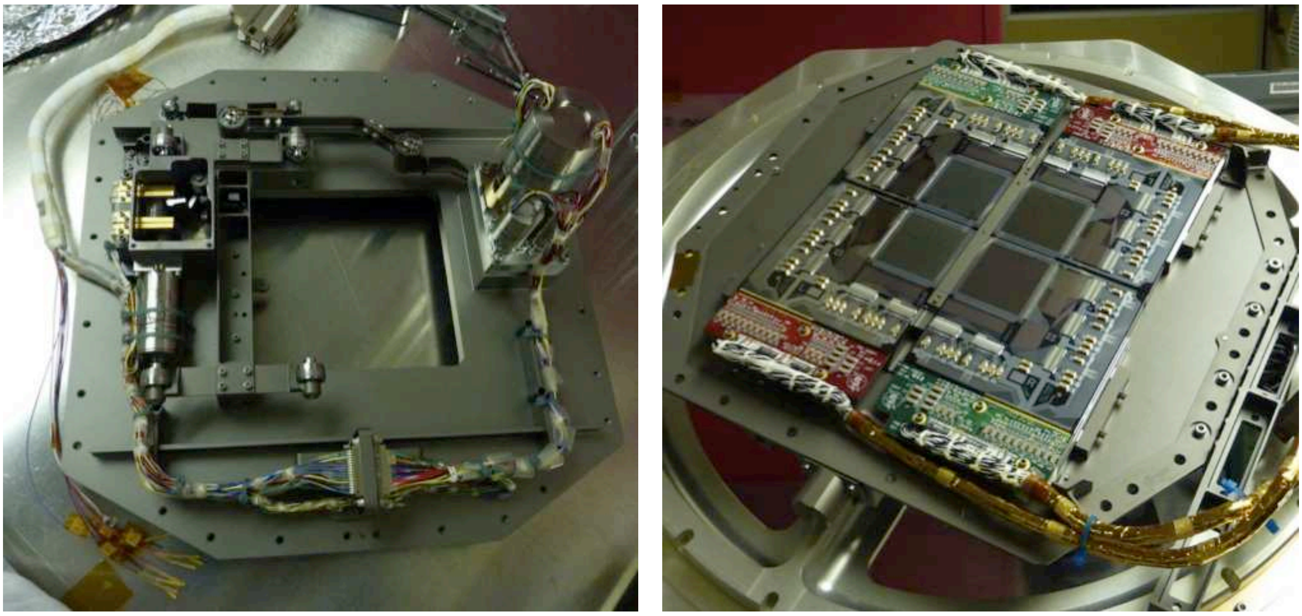

Figure 7. The magnet translation stage (left) and the four microshutter quadrants (right) of the MSA.

and verification program one flight quadrant had to be replaced by a spare due to too low contrast. First test results indicate that the MSA will meet its requirement in failed shutters (stuck closed/open). Delivery of the flight unit is scheduled for June 2010.

2.7 The Focal Plane Assembly

The NIRSpec FPA consists of a mosaic of two HAWAII-2RG HgCdTe sensor chip assemblies (SCAs) with 2048×2048 pixels each.[21] The HgCdTe detectors are manufactured by Teledyne, USA, and are identical to the ones used in the Fine Guidance Sensor / Tunable Filter Imager (FGS/TFI)[22] and the long wavelength channel of the NIRCam[23] instrument. They are sensitive to wavelengths up to $5\,\mu$m and are read out using a dedicated Teledyne SIDECAR ASIC (System for Image Digitization, Enhancement, Control And Retrieval Application Specific Integrated Circuit) operating at temperatures below 40 K.

As in the case of the MSA, NASA GSFC is delivering the NIRSpec detector system to ESA and is also responsible for its characterization. Tests on the flight FPA were recently finished and delivery is scheduled for June 2010. The detectors show state of the art performance in general, and we present some key parameters and their requirements in Table 1. Monochromatic flat fields of the SCAs are shown in Fig. 8. It must be noted that all values given here are based on preliminary data analysis[24] and thus subject to change once data evaluation is finalized.

Requirement	Specified	Measured	Unit
Total noise per pixel	< 6	5.97 - 6.75	e^- rms
Mean dark current per pixel	< 0.01	0.0074	e^-/s/pixel
Pixel operability for science observations	> 89 (EOL)	96.65	%
Detective quantum efficiency	≥ 0.7 ($\lambda < 1.0\,\mu$m)	0.58 - 0.75	
	≥ 0.8 ($\lambda \geq 1.0\,\mu$m)	0.71 - 0.84	

Table 1. Key parameters of the NIRSpec flight FPA measured at $T_{\mathrm{FPA}} = 38.5\,$K based on preliminary data analysis.

In most of its spectroscopic modes NIRSpec will be detector-noise limited for faint sources. Therefore, both DQE and total noise have a direct impact on NIRSpec's sensitivity. A considerable fraction of the measured total noise is due to $1/f$-noise originating in the ASICs and there are efforts to reduce this noise term by operating the ASICs differently, i.e. with a revised readout scheme[25] that could be incorporated in the future.

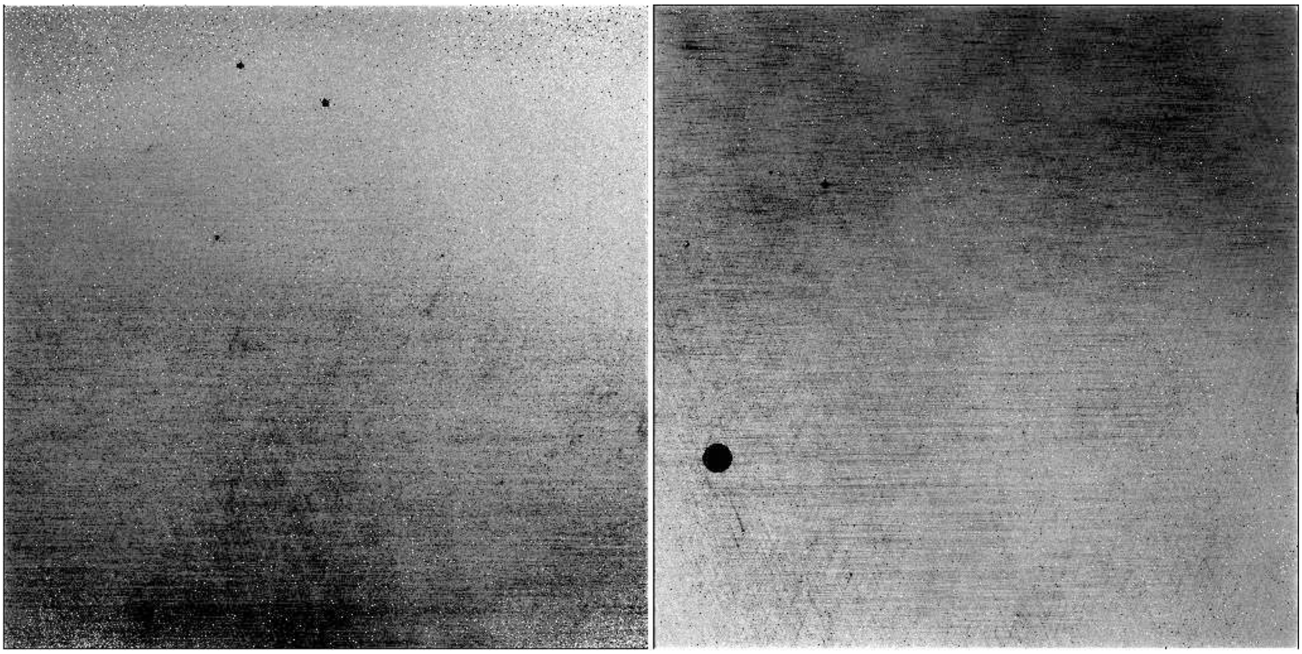

Figure 8. Flat field image of the NIRSpec flight FPA at a wavelength of $\lambda = 2.6\,\mu$m. Full grey scale corresponds to ±20 % of the mean response.

2.8 On Ground Calibration Sources

There is a vast amount of on ground support equipment needed to align and operate NIRSpec before and during its verification and calibration campaign. This also includes hardware and software needed to analyze science data taken during the tests.[26] Here we focus on the two on ground calibration sources that will be used to establish the spectro-radiometric calibration of NIRSpec: the calibration light source (CLS) and the radiometric calibration spectral source (RCSS). A comprehensive overview of the full OGSE is given in Ref. 27.

The CLS consists of a gold coated integrating sphere with 60 cm diameter and a light box carrying four filter and aperture wheels and the light source from Helioworks, a tungsten filament inside a hermetically sealed package with a Sapphire window. The integrating sphere and the light box are cooled to temperatures of $\sim 80\,$K in order to suppress thermal background radiation in the wavelength regime of NIRSpec.

The filters and apertures in the light box are used to provide suitable illumination levels for all modes of the NIRSpec instrument, including flat fields and spectral references using Fabry-Perot filters and rare earth standards. An Argon emission line lamp will be used to achieve an accurate wavelength calibration. The CLS was built by MSSL and radiometrically calibrated by the National Physics Laboratory, UK. The CAA, NIRSpec's internal calibration source, will be calibrated during the ground campaign using the CLS as a secondary standard.

The RCSS consists of a small integrating sphere with several continuum light sources and a pinhole. This pinhole is imaged by a telescope of an Offner design that mimics the JWST telescope's $f/20$-beam and pupil, and supplies a point source to the instrument. Despite the extremely low ouptut flux levels of the device, a subset of its operating modes could be radiometrically calibrated by the Physikalisch Technische Bundesanstalt, Germany, in the wavelength range from $0.7 \leq \lambda \leq 1.65\,\mu$m.[28] The main use of the RCSS will be to measure the slit and diffraction losses of NIRSpec for its spectroscopic modes.[29]

3. INSTRUMENT PERFORMANCE AND GROUND CALIBRATION

Currently, the NIRSpec FM is fully integrated and aligned up to the collimator TMA. Fig. 9 shows an image of the optical bench taken during alignment. The wavefront error of the optical train up to the MSA has been measured and found to be $\leq 57\,$nm rms over the entire MSA image plane, with an excellent average WFE of $\sim 39\,$nm rms. In early 2010, the WFE at the FPA image plane has been measured with an almost complete

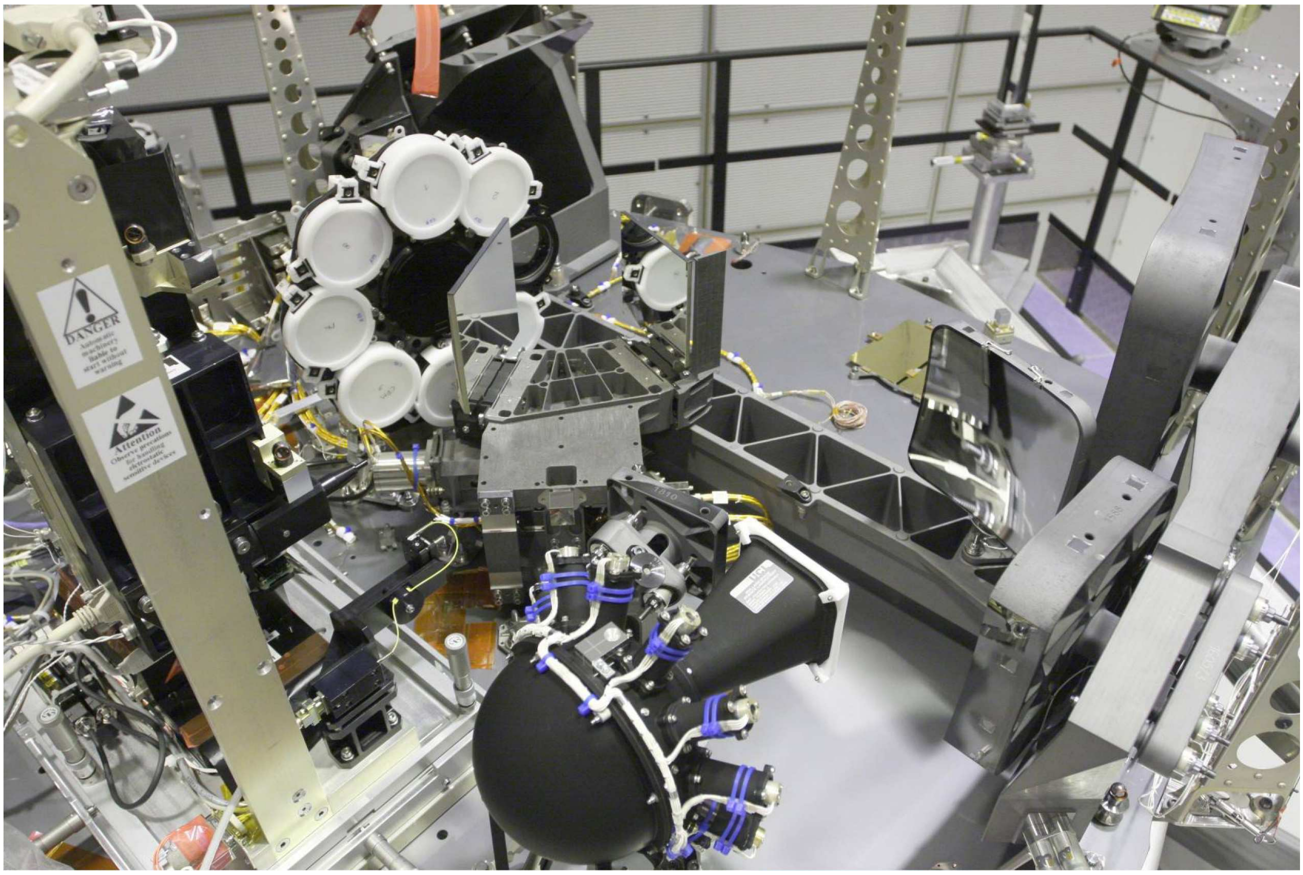

Figure 9. The NIRSpec FM optical bench. The structure on the left is ground support equipment used align the fore optics.

optical train to $\sim 90\,\mathrm{nm}$ rms on average, again an excellent value. That setup used a non-flight RMA, and lacked the flight FWA and GWA. Once fully integrated and aligned, the NIRSpec FM is expected to meet its wavefront error requirements.

By now, there are throughput measurements for all optical sub-components available. This allows the throughput of the entire optical train to be estimated using the as-built values. Fig. 10 shows the throughput of the instrument in $R \sim 100$ mode and for one of the gratings. For the full optical train throughput a $15\,\%$ system margin is included to account for measurement uncertainties at component level. Slit and diffraction losses and detector DQE are not considered. The estimated throughput is in line with the requirements.

After its completion, NIRSpec will undergo a comprehensive suite of tests to verify its function and performance. The thermal-vacuum campaign is foreseen to take place towards the end of 2010, and preparation for these tests is ongoing. Apart from an update in expected instrument sensitivity and performance, the ground calibration campaign is also crucial to create the data products that are needed for the implementation of the NIRSpec science pipeline.[27]

4. SUMMARY

With all but three sub-systems already delivered, the flight model of the NIRSpec instrument is nearing completion. The measured wavefront error of the optical train up to the MSA is excellent, and the throughput of the entire instrument is estimated to meet specifications. Preparation for the extensive ground calibration campaign is ongoing.

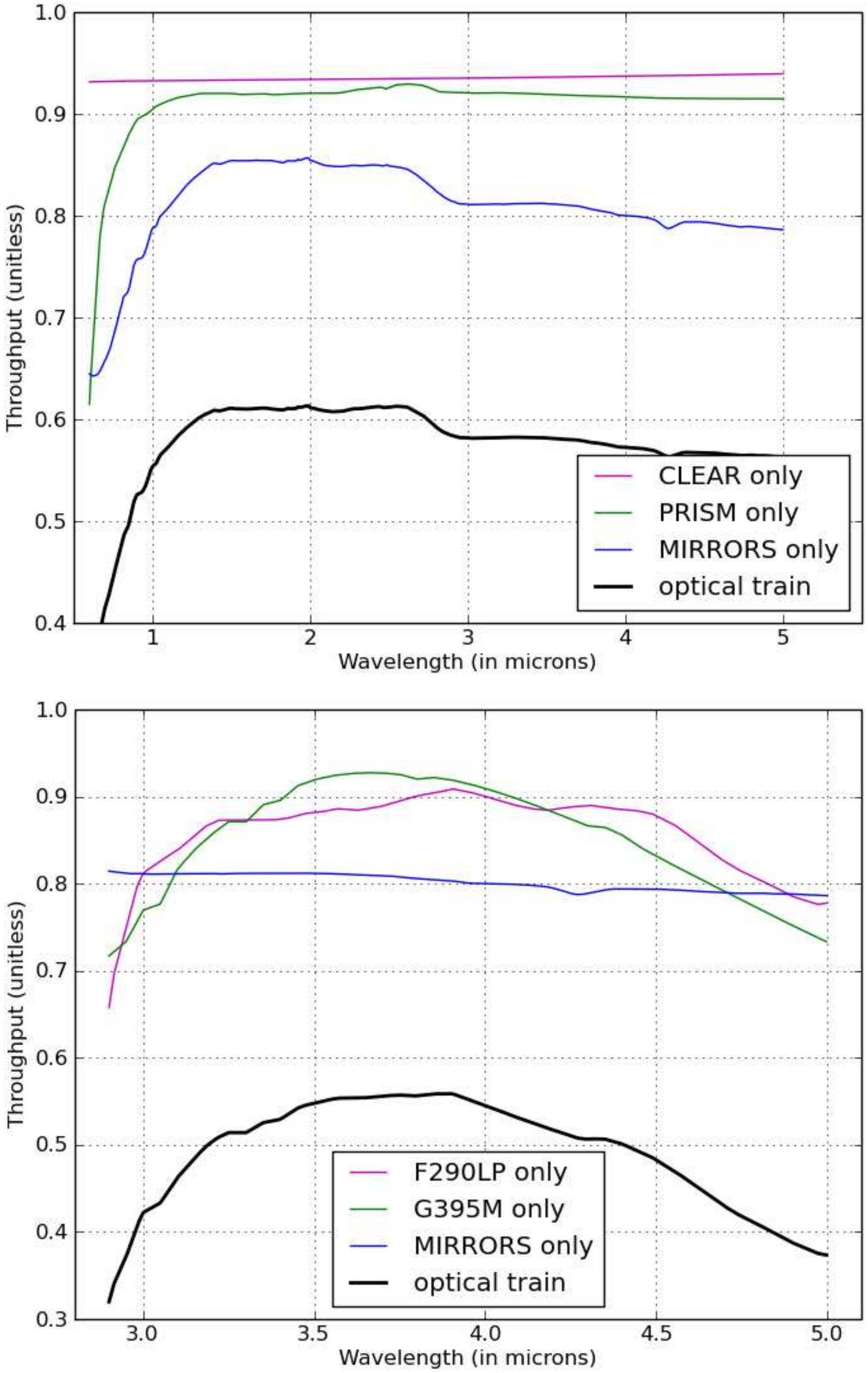

Figure 10. Predicted throughput (black lines) with the prism (top) and the $R \sim 1000$ band-III grating (bottom) as dispersing elements. In both graphs the throughput of the used filter, the dispersing element, and the mirrors is also shown separately in magenta, green, and blue, respectively.

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] Gardner, J. P., "Science with the James Webb Space Telescope," *Proc. SPIE* **7731-5** (2010).

[3] Clampin, M. C., "Overview of the James Webb Space Telescope Observatory," *Proc. SPIE* **7731-6** (2010).

[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., "Opto-mechanical 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., de Marchi, G., Jakobsen, P., Sirianni, M., Ferruit, P., Gnata, X., Mosner, P., Ehrenwinkler, R., and Beck, T., "The NIRSpec Demonstration Model Test Campaign," *Bulletin of the American Astronomical Society* **41**, 396–+ (Jan. 2010).

[7] Dorner, B., Ferruit, P., Gnata, X., Birkmann, S. M., Böker, T., de Marchi, G., Sirianni, M., Hupfer, W. J., Köhler, J., Kolm, M.-G., Ehrenwinkler, R., Piquéras, L., Legros, E., Legay, P.-J., Pécontal-Rousset, A., Jarno, A., and Pons, A., "Confronting the NIRSpec instrument performance simulator outputs with results of the NIRSpec demonstration model calibration campaign," *Proc. SPIE* **7738-40** (2010).

[8] Piquéras, L., Legros, E., Pons, A., Legay, P.-J., Ferruit, P., Dorner, B., Pécontal-Rousset, A., Gnata, X., and Mosner, P., "The JWST/NIRSpec instrument performance simulator software," *Proc. SPIE* **7738-41** (2010).

[9] Honnen, K., Kommer, A., Messerschmidt, B., and Wiehe, T., "NIRSpec OA development process of SiC components," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7018** (July 2008).

[10] Rodolfo, J., "Polishing, coating, and integration of SiC mirrors for space telescopes," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7018** (July 2008).

[11] Weidlich, K., Sedlacek, M., Fischer, M., Trunz, M., Ellenrieder, M., Lemke, D., Krause, O., Hofferbert, R., Grözinger, U., Königsreiter, G., and Neugebauer, C., "The grating and filter wheels for the JWST NIRSpec instrument," *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **6273** (July 2006).

[12] Ellenrieder, M. M., Weidlich, K., Nelles, B., Ploss, B., Bruynooghe, S., Köhler, J., and Te Plate, M., "The optical components of the NIRSpec wheel mechanisms," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7018** (July 2008).

[13] Smith, J. S., Aronstein, D. L., Dean, B. H., and Acton, D. S., "Phase retrieval on broadband and under-sampled images for the JWST testbed telescope," *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **7436** (Aug. 2009).

[14] Smith, J. S., Aronstein, D. L., Davila, P. S., Dean, B. H., Gnata, X., Melf, M., Pittet, J.-F., te Plate, M. B. J., and Dorner, B., "Optical wavefront characterization using phase retrieval for the NIRSpec demonstration model for the James Webb Space Telescope," *Proc. SPIE* **7731-131** (2010).

[15] Taccola, M., Bagnasco, G., Barho, R., Caprini, G. C., Di Giampietro, M., Gaillard, L., Mondello, G., Salvignol, J., Te Plate, M., and Tonetti, N., "The cryogenic refocusing mechanism of NIRSpec opto-mechanical design, analysis, and testing," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7018** (July 2008).

[16] Novi, A., Taccola, M., Koehler, J., and Di Giampietro, M., "The optical manufacturing of the refocusing mechanism of NIRSpec," *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **7018** (July 2008).

[17] Lobb, D., Robertson, D., Closs, M., and Barnes, A., "Design and manufacture of the integrated field unit for the NIRSpec spectrometer on JWST," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7100** (Sept. 2008).

[18] Closs, M. F., Ferruit, P., Lobb, D. R., Preuss, W. R., Rolt, S., and Talbot, R. G., "The Integral Field Unit on the James Webb Space Telescope's Near-Infrared Spectrograph," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7010** (Aug. 2008).

[19] Purll, D. J., Lobb, D. R., Barnes, A. R., Talbot, R. G., Rolt, S., Closs, M. F., and Robertson, D. J., "Flight model performance of the integral field unit for the James Webb Space Telescope's near-infrared spectrograph," *Proc. SPIE* **7739-40** (2010).

[20] Kutyrev, A. S., Collins, N., Chambers, J., Moseley, S. H., and Rapchun, D., "Microshutter arrays: high contrast programmable field masks for JWST NIRSpec," *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7010** (Aug. 2008).

[21] Rauscher, B. J., Böker, T., Cabelli, C., De Marchi, G., Ferruit, P., Garnett, J., Hill, R. J., Loose, M., Regan, M. W., Waczynski, A., Wen, Y., Wong, S., Zandian, M., Alexander, D., Brambora, C. K., Derro, R., Dunn, C., Ellis, T., Garrison, M. B., Howe, B., Jakobsen, P., Johnson, T. E., Jurado, M., Lee, G., Manthripragada, S. S., Marsh, J. M., Marshall, C., Martineau, R. J., Mott, B., Nieznanski, J., Roher, W. D., Shakoorzadeh, K. B., Smith, M. T., Strada, P., Wallis, P., Xia-Serafino, W., and York, J., "Detectors for the James Webb Space Telescope near infrared spectrograph (NIRSpec)," *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **6265** (July 2006).

[22] Doyon, R., Hutchings, J. B., Rowlands, N., Beaulieu, M., Lafrenière, D., Abraham, R., Chayer, P., Ferrarese, L., Fullerton, A. W., Jayawardhana, R., Johnstone, D., Martel, A. R., Meyer, M., Pipher, J. L., Sawicki, M., Sivaramakrishnan, A., Volk, K., and Saad, K., "The JWST tunable filter imager (TFI)," *Proc. SPIE* **7731-14** (2010).

[23] Greene, T. P., Rieke, M. J., Beichman, C. A., Horner, S. D., Jaffe, D. T., and Kelly, D. M., "NIRCam: development and testing of the JWST near-infrared camera," *Proc. SPIE* **7731-11** (2010).

[24] Rauscher, B. J., "NIRSpec Detectors." Talk at ELIXIR school at Astrium, Ottobrunn; 02 June (2010).

[25] Moseley, S. H., Arendt, R. G., Fixsen, D. J., Lindler, D. J., Loose, M., and Rauscher, B. J., "Optimization of noise performance of low-background detector arrays," *Proc. SPIE* **7742-96** (2010).

[26] Gerssen, J., Janssen, K., Meeus, G., Hupfer, W., Gnata, X., Ferruit, P., Roth, M., Mosner, P., de Marchi, G., and Becker, T., "IQLAC: a data analysis system for the nirspec on-ground test campaign," *Space Telescopes and Instrumentation 2008: Optical, Infrared, and Millimeter* **7010**(1), 70103H, SPIE (2008).

[27] Bagnasco, G., Ferruit, P., Boeker, T., Closs, M., Dorner, B., Gnata, X., Koehler, J., Kolm, M., Kuechel, C., Langenbach, H., Melf, M., Pittet, J., Te Plate, M., and Wetteman, T., "The on-ground calibration of the Near Infrared Spectrograph (NIRSpec) instrument on-board the James Webb Space Telescope (JWST)," *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **7010** (Aug. 2008).

[28] Taubert, R. D., Monte, C., Baltruschat, C., Schirmacher, A., Gutschwager, B., Hartmann, J., Hollandt, J., Kochems, D., Küchel, C., and te Plate, M., "The spectral photon flux of the radiometric calibration spectral source for the NIRSpec instrument of the James Webb Space Telescope," *Metrologia* **46**, 207–+ (Aug. 2009).

[29] te Plate, M., Alvarez, J. L., Frugier, P., and Marenaci, P., "Physical optics model for simulating the optical performance of the NIRSpec," *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **6692** (Oct. 2007).