The Near Infrared Spectrograph (NIRSpec) on-ground calibration campaign

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ABSTRACT

The Near Infrared Spectrograph (NIRSpec) is one of four science instruments aboard the James Webb Space Telescope (JWST) scheduled for launch in 2018. NIRSpec is sensitive in the wavelength range from ∼0.6 to 5.0 micron and will be capable of obtaining spectra from more than a 100 objects simultaneously by means of a programmable micro shutter array. It will also provide an integral field unit for 3D spectroscopy and fixed slits for high contrast spectroscopy of individual sources and planet transit observations. We present results obtained during the first cryogenic instrument testing in early 2011, demonstrating the excellent optical performance of the instrument. We also describe the planning of NIRSpecs forthcoming second calibration campaign scheduled for 2013.

Keywords: James Webb Space Telescope, JWST, Near Infrared Spectrograph, NIRSpec, on-ground calibration

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 ($T \leq 50\,\mathrm{K}$) primary mirror with $\sim 6.5\,\mathrm{m}$ diameter. A comprehensive description of the observatory and its main science goals is given by Gardner et al.[1] and at this conference.[2]

NIRSpec is a near-infrared multi-object spectrograph developed by the European Space Agency (ESA) with Astrium Germany GmbH as the prime contractor with many sub-contractors across Europe. In section 2 we briefly describe the instruments main characteristics. Some of the highlights of the first cryogenic performance testing that was concluded in March 2011 are shown in section 3 . In section 4 we give an overview of the planning of the second performance verification and calibration (PVC) campaign scheduled for early 2013.

2. THE NIRSPEC INSTRUMENT

NIRSpec features three three-mirror anastigmats (TMAs), namely the fore optics (FOR), the collimator (COL) and the camera (CAM). Furthermore, it holds a filter and a grating wheel assembly (FWA and GWA), a refocus mechanism assembly (RMA), a calibration assembly (CAA), the micro shutter assembly (MSA), and the integral field unit (IFU). Light is detected by the focal plane assembly (FPA), a mosaic of two 2k × 2k HAWAII-2RG detector arrays with a $\sim 5.3\,\mu\mathrm{m}$ cut-off. Both the FPA and the MSA are provided by NASA. With the exception of the filters in the FWA, a double pass prism in the GWA, and the two RMA mirrors, the entire optics is reflective and made out of Silicon Carbide, as is the optical bench.

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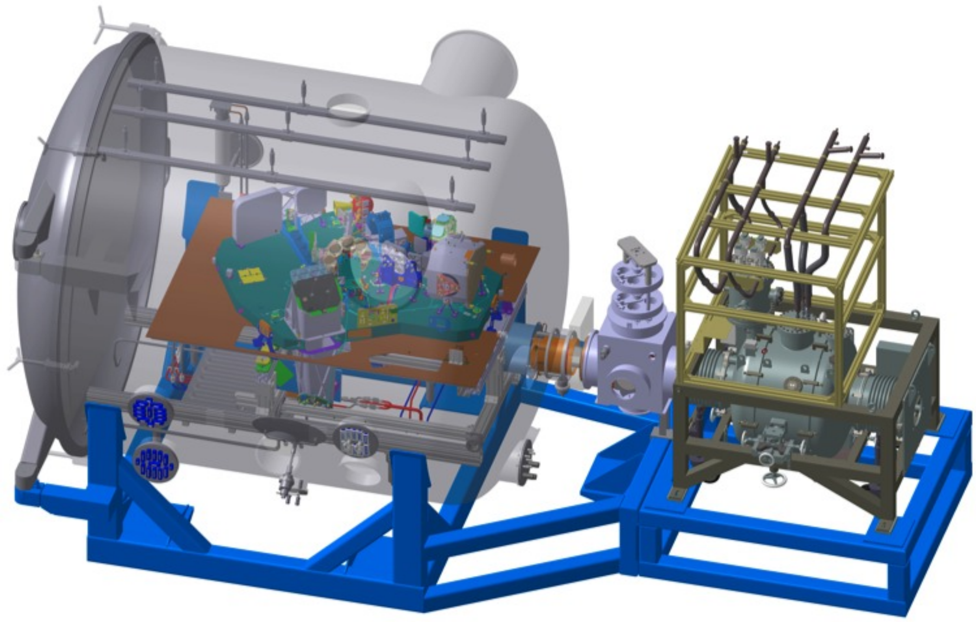

Figure 1. Sketch of the thermal vacuum test setup. NIRSpec is located in the cryo chamber on the left, the calibration light source (CLS) is located on the right. The middle part is the cross piece that is used as a view port to align NIRSpec and the CLS with respect to each other.

NIRSpec offers seven dispersers. A CaF_2 prism covers the entire wavelength range (0.6 to $5\,\mu$m) in a single exposure with varying spectral resolution ($30 \lesssim R \lesssim 300$). Six gratings offer medium ($R \sim 1000$) and high ($R \sim 2700$) resolution spectroscopy in four bands covering 0.7 to $5\,\mu$m. A mirror is available for imaging and target acquisition.

The micro shutter assembly offers a total of 730×342 individually addressable shutters over a field of view (FOV) of more than $3 \times 3\,\mathrm{arcmin}^2$, giving NIRSpec its multi-object capabilities. For individual object studies, NIRSpec 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 fixed slits for high contrast spectroscopy (e.g. for exo-planet transit observations), with their spectra falling onto dedicated detector areas.

A more detailed description of NIRSpec and its optical train is given by Bagnasco et al.[3] and te Plate et al.[4] The current status of the NIRSpec instrument is presented at this conference by Ferruit et al.[5]

3. THE NIRSPEC ON-GROUND CALIBRATION CAMPAIGN

In this section we describe the NIRSpec test chamber and on-ground support equipment, as well as present results from the first verification and calibration campaign performed from January to March 2011. During this campaign the MSA was not fully operational and thus only results obtained with the fixed slits or the IFU are presented.

3.1 Test chamber and optical ground support equipment

The NIRSpec cryogenic test facility consists of three parts (see Fig. 1):

1. The main chamber where the NIRSpec instrument is mounted
2. The calibration light source (CLS)
3. The cross-piece connecting the two and providing some alignment capabilities

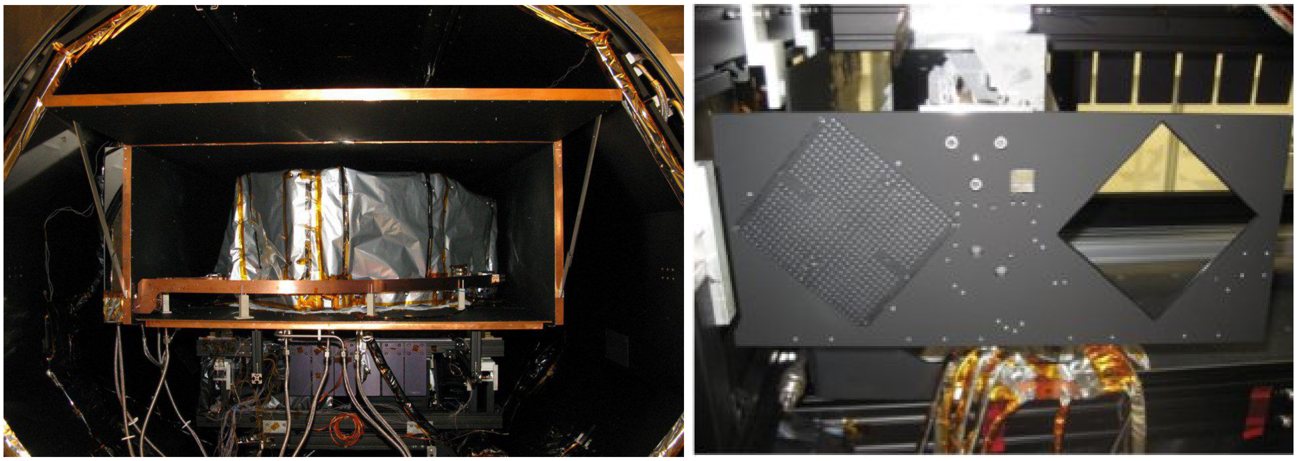

Figure 2. Left: the NIRSpec FM (with cover) installed inside the Helium shroud of the cryo chamber. Right: the CMO with its pinhole mask (PHM) to the left and field stop mask (FSM) to the right. The size of each mask is approximately $14 \times 14\,\mathrm{cm}^2$.

The main chamber holds the NIRSpec instrument, a cryo-mechanism (CMO), and a folding mirror. NIRSpec is enclosed in an inner shroud cooled by gaseous Helium to temperatures around 40 K, simulating the thermal environment the instrument will see in space (see Fig. 2, left). Only the lower part of the coupling optics is protruding out of this shroud so that it can be illuminated by the CLS. The chamber also has an outer shroud cooled to $\leq 100\,\mathrm{K}$ by means of liquid Nitrogen. This outer shroud encloses the inner shroud, the CMO, and the fold mirror. It extends through the cross-piece and up to the exit port of the CLS, so that no part of NIRSpec directly sees any surface with $T > 90\,\mathrm{K}$.

The cross-piece has a pair of 45° mirrors that can be lowered into the beam in order to align the CLS with NIRSpec via two side windows. When these mirrors are retracted, cold shutters are put in place.

The CLS is housed in its own vacuum vessel and can be isolated from the main chamber by means of a vacuum valve that goes through a retractable part of the outer shroud at the cross piece. It consists of a gold-coated integrating sphere of 60 cm diameter and a light box mounted on top. The light box carries four filter- and aperture-wheels and holds the primary light source, a tungsten filament inside a hermetically sealed package with a Sapphire window. The integrating sphere and the light box are cooled to a temperature $\leq 90\,\mathrm{K}$ in order to suppress thermal background radiation in the wavelength regime of NIRSpec. The output of the sphere holds a mask that mimics the JWST pupil. Light coming from the sphere is going through the cross-piece and is then re-directed to the NIRSpec pick-off mirror by a fold mirror in the cryo chamber.

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 (for both imaging and spectroscopy) and spectral references using Fabry-Perot filters and a rare earth standard (Erbium absorption lines). An Argon emission line lamp is directly mounted on the sphere and its light coupled in via a small hole and a short-pass filter. This source is used as the primary wavelength standard for NIRSpec during the on-ground calibration,[6] because the wavelengths of the Argon emission lines are very accurately known.[7] Furthermore, the CLS features a fiber coupled $2.8\,\mu\mathrm{m}$ laser to measure the slit function (line spread function for uniform illumination) at this wavelength and to cross check the wavelength calibration.

The CMO holds two masks that are located in the focal plane in front of NIRSpec and that are illuminated by the CLS. The field stop mask (FSM) is used to provide a flat illumination to NIRSpec, whereas the pinhole mask (PHM) provides a grid of point sources for distortion and focus measurements in imaging mode (see Fig. 2, right).

Independent from the CLS, the radiometric calibration spectral source (RCSS) is also located on the CMO. It consists of a small integrating sphere with six redundant continuum light sources and a pinhole at the sphere exit. This pinhole is imaged by a telescope of an Offner design that mimics the JWST telescope's f/20-beam and

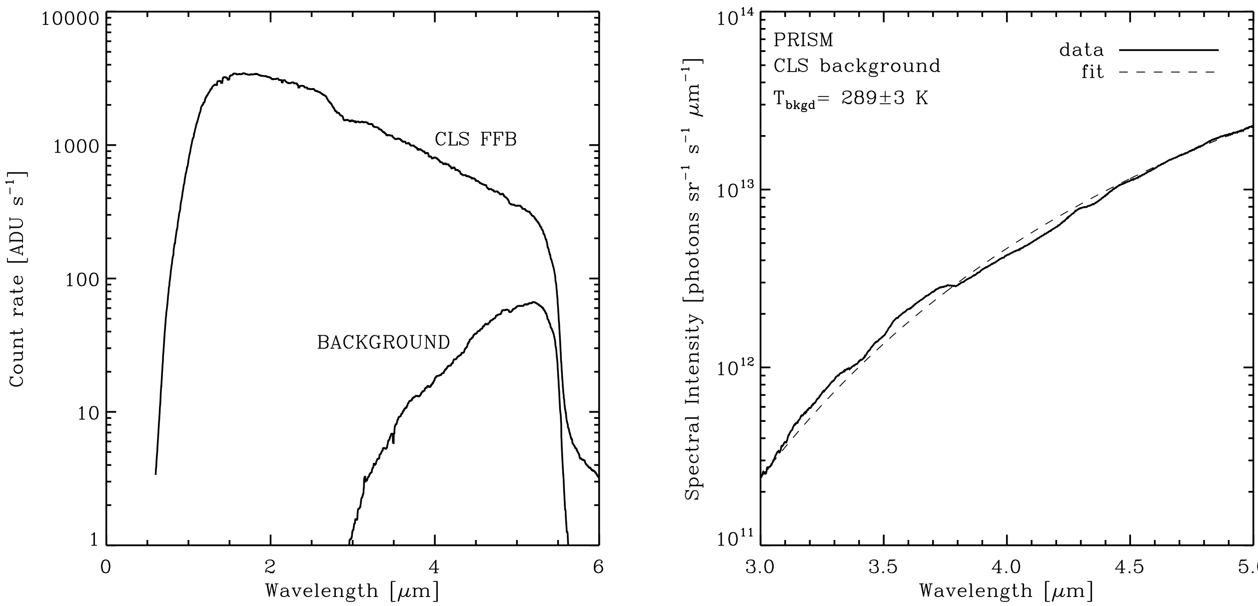

Figure 3. Left: Extracted spectra of the CLS FFB light source and the thermal background obtained with the NIRSpec prism in data units per second. By comparison with the known CLS FFB input spectrum, the observed background spectrum can be calibrated and brought to physical units. Right: The measured background spectrum (solid line) is well approximated with a grey body of about room temperature and a wavelength independent emissivity of $\epsilon \ll 1$ (dashed line).

pupil, and supplies a point source to the instrument. The patrol range of the RCSS is limited to an area close to the fixed slits in NIRSpec. Its main use is to measure the slit and diffraction losses of NIRSpec's spectroscopic modes.

3.2 Results

At the beginning of the calibration campaign we verified that the thermal background from the cold test chamber seen by the instrument is sufficiently low. We obtained a spectrum of the CLS with its light source switched off and compared it to the calibrated input spectrum of the CLS when turned on (see Fig. 3 left). This comparison allowed us to calibrate the measured background spectrum and model it with a grey body of approximately room temperature (see Fig. 3 right), indicating that the observed thermal background originates from the warm chamber walls and probably makes it through small (venting) holes in the Nitrogen cooled shroud and into the integrating sphere of the CLS. The background was only contributing significantly to the signal at wavelengths $\lambda \gtrsim 3\,\mu$m. Because it was stable in time, it was removed by subtracting dedicated off exposures when necessary.

A general finding of the first calibration campaign was that NIRSpec behaved as designed in almost all aspects and thus the image quality was very good. This is illustrated in Fig. 4 showing spectra of the Argon emission line source in the CLS obtained with the fixed slits and the integral field unit. Features are sharp, the traces of the spectra and the observed slit tilt are as expected from the NIRSpec as-built optical model.

Exposures like the one shown in Fig. 4 can also be used to verify the spectral resolution of NIRSpec, as most of the observed Argon lines are unresolved, i.e. their intrinsic line widths $\Delta\lambda$ (in terms of full width at half maximum - FWHM) is such that $\lambda/\Delta\lambda > 100000$, significantly higher than the resolving power of NIRSpec. The measured spectral resolution for the six NIRSpec gratings is presented in Fig. 5. They have been obtained using the NIRSpec instrument model and data extraction pipeline to perform the wavelength calibration and get the dispersion solution. As is expected for gratings, the spectral resolution increases linearly with wavelength in all cases. The data is consistent with the target average resolution (over the science bands) of 1000 for the medium resolution and 2700 for the high resolution gratings, respectively.

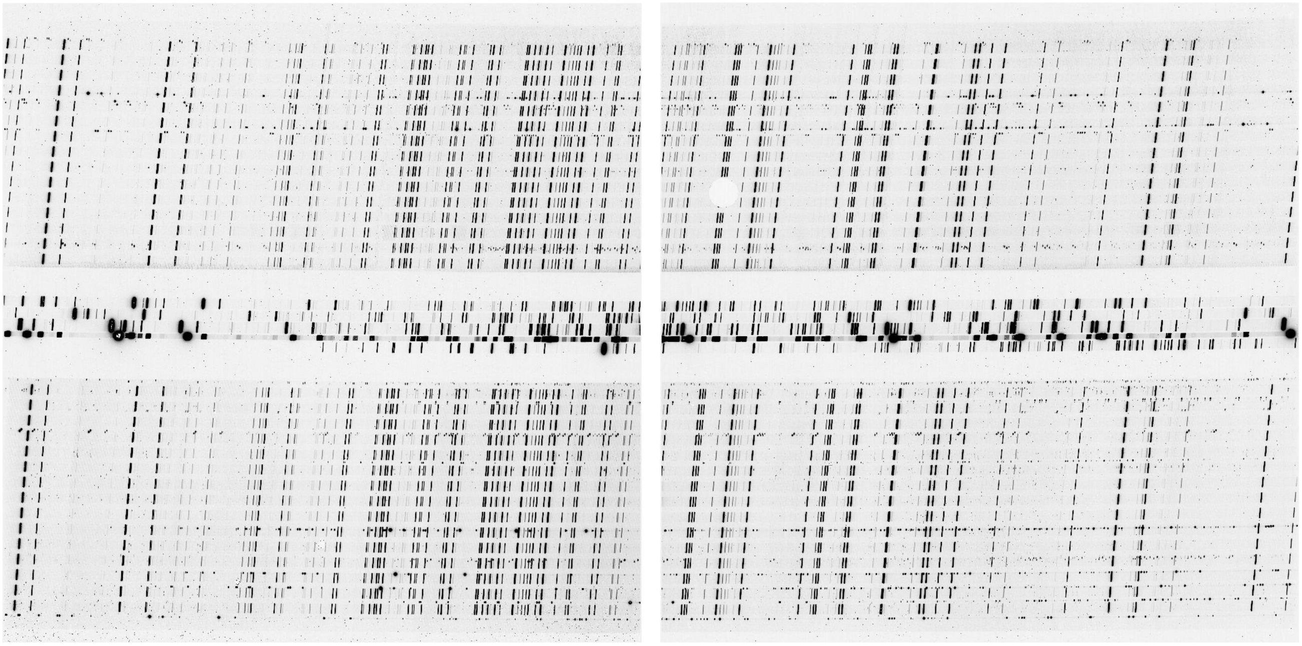

Figure 4. Spectra of the Argon emission line source obtained with NIRSpec's band I high resolution grating (1.0 - 1.8 μm), covering both detectors. Darker color denotes higher count rates, wavelength increases from left to right, and the spatial direction extends vertically. The five spectra in the middle are from the fixed slits, the spectra at the top and bottom (15 each) originate from the IFU. Spectra with small height in these regions are due to permanently failed open shutters in the MSA.

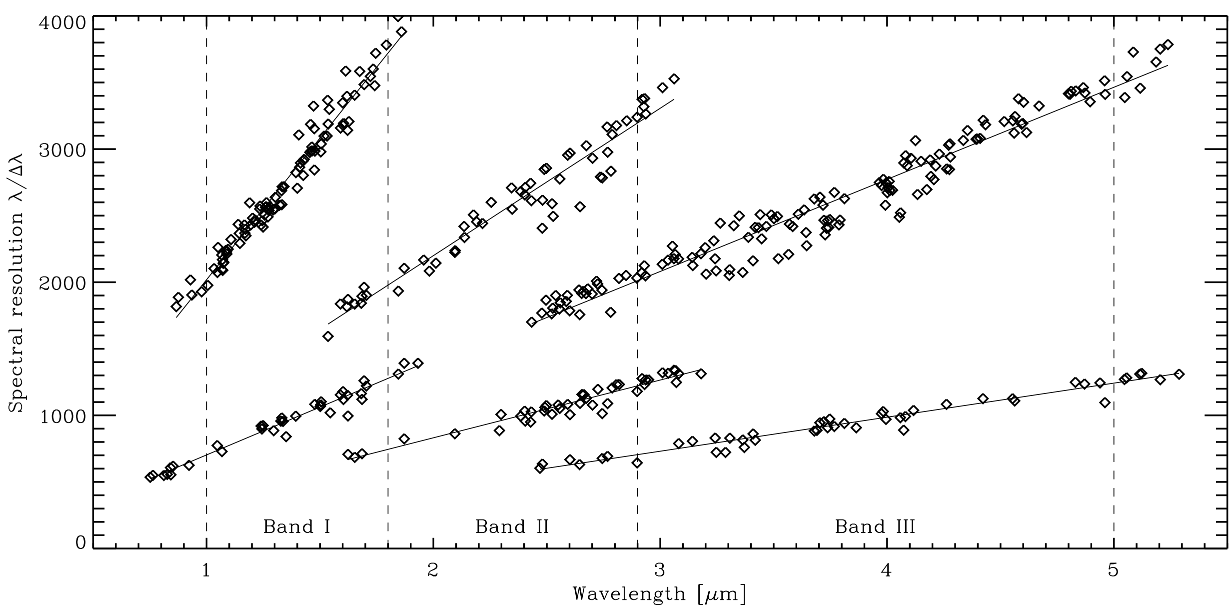

Figure 5. Spectral resolution of NIRSpec obtained by measuring the line widths of Argon lines from one of the 200 mas wide fixed slits. The vertical dashed lines indicate the boundaries of the three NIRSpec spectral ranges, Band I to III. The solid lines are linear fits to the measured data points for each of the six gratings.

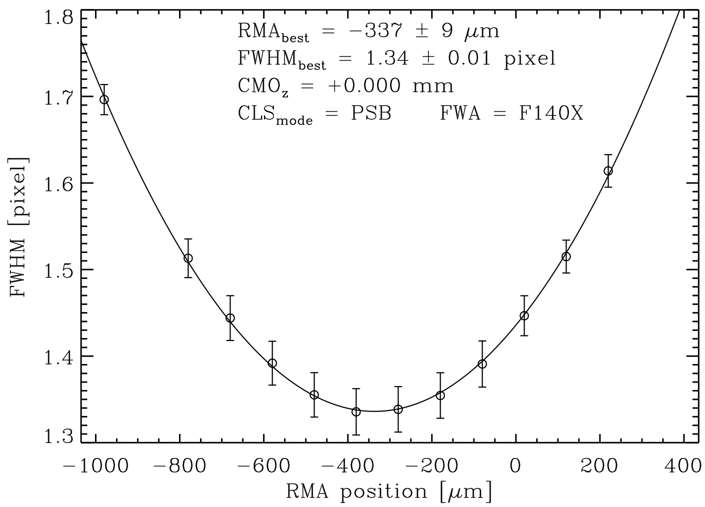

Figure 6. Plot of the measured FWHM of pinhole images observed through the NIRSpec fixed slits as a function of RMA position. The data is well approximated by a parabolic function yielding the best focus position for the CMO alignment during the first calibration campaign.

NIRSpec must be able to compensate for small shifts of the focal plane of the JWST telescope that might occur during the JWST mission. For this reason the instrument features the RMA as part of its fore optics. This unit defines the exact position where the focal surface of the JWST telescope is re-imaged onto NIRSpec's aperture plane, e.g. the fixed slits and the MSA. In Fig 6 we present the data of an RMA focus sweep, measuring the size of the pinhole images in the CMO PHM as a function of the position of the RMA, demonstrating that the instrument can be put into focus. Similar data was obtained for all seven filters of NIRSpec. The determined best focus positions are found to be the same within the measurement uncertainties, i.e. the filters are confocal as required.

More findings and results from this test campaign and on the NIRSpec HgCdTe HAWAII-2RG detectors in general are presented at this conference by De Marchi et al.,[8] Giardino et al.,[9] and Sirianni et al.[10]

4. PLANNING THE NIRSPEC CALIBRATION CAMPAIGN

NIRSpec is currently being integrated at Astrium in Ottobrunn, Germany. Once completed, it will undergo a thermal cycle from room temperature down to survival temperature ($T_{bench} = 20\,\mathrm{K}$). Then vibration and acoustic tests will take place to verify workmanship and in order to prove the structural integrity of the instrument. Finally, NIRSpec will see another cryo cycle during which the second verification and calibration campaign will take place.

While the main purpose of the first cryo exposure is to load the interfaces with their maximum stresses, it also allows us to perform an early check of NIRSpec and the test facility. A limited set of exposures will be taken in order to verify a sufficiently low thermal background in the chamber, like it was demonstrated during the first cryo performance test (see section 3.2). Furthermore, there have been a few modifications to the NIRSpec hardware and we will verify that these small changes turned out as intended. The total duration of the first cryo cycle is estimated to be about one month, governed by the time that is needed to cool down and warm up the instrument without exceeding temperature gradients that are considered safe.

The simplified test flow of the second calibration campaign is shown in Fig 7. This cycle will last about two months, with the actual performance verification and calibration (PVC) phase and its preparation taking roughly 30 days.

In general, all tests that are conducted during the PVC and preparation phases follow test procedures. Part of the test procedures is a list of the exposures to be taken with the instrument configuration fully specified, e.g.

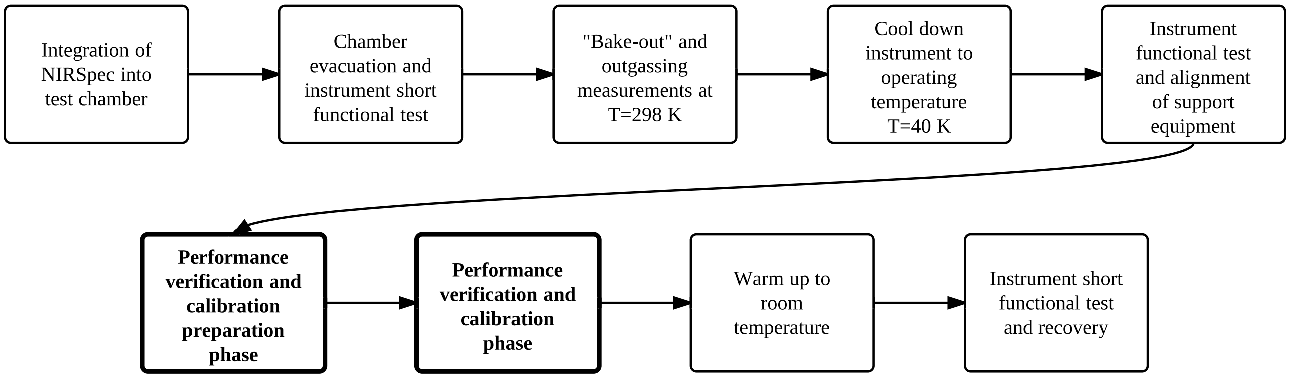

Figure 7. Flow chart showing the order of activities for the second NIRSpec performance verification and calibration campaign under cryogenic conditions.

giving the filter and disperser to be used, the integration time and illumination source, and so on. These test blocks are executed sequentially and can or in some cases must be updated during the campaign, as some tests will yield results that impact sequences that are still to be executed. One example is the determination of the best focus position of the RMA, that will then need to be incorporated into the following test sequences.

The main purpose of the tests run during the PVC preparation phase is to determine all parameters that are needed for the PVC phase but not fully known before the start of the calibration campaign. Examples for such parameters are the exposure times under different illumination conditions (external flat field illumination, point sources, internal calibration sources, etc.), the position of spectra for the different dispersers, and the best focus for the instrument as mentioned above. Another important part of the preparation phase is the determination of the coordinate transformations that are needed to move external illumination source like the RCSS to a given position in the NIRSpec FOV, e.g. the center of a fixed slit or a specific shutter in the MSA.

In the PVC phase we will run numerous test sequences that aim at i) verifying all applicable performance requirements, ii) obtaining the necessary exposures to create the needed (detector) reference files, iii) obtaining data that is suited to test in-orbit scripts and simulate exposures of scientific targets (e.g. multi object spectroscopy and planetary transits), and iv) measuring distortion, throughput, and other instrument properties that are required to update and refine the NIRSpec instrument model. The latter is needed as input for the NIRSpec performance simulator (IPS)[11] and also to extract and (wavelength) calibrate the spectra obtained with NIRSpec.[12]

The preparation and/or update of test sequences by the NIRSpec science operations team (SOT) at ESA has been kicked off. Each test sequence has an owner who is responsible to maintain the procedure up to date and organize internal reviews with other members of the SOT. It is foreseen that other stakeholders like the instrument science team and scientists/engineers at the Space Telescope Science Institute (STScI) in Baltimore and at Astrium in Ottobrunn will also have the opportunity to review the test procedures and provide comments on the planned tests well before the calibration campaign is executed.

In parallel, the planning of the execution of the PVC and its preparation phase has been started, defining the order in which individual test sequences will be run. Obviously, this planning takes into account the prerequisites and dependencies between the test sequences, e.g. it only makes sense to measure the spatial point spread function after the instrument has been put into best focus. Other constraints like the availability of key personnel for certain tasks are also considered. Furthermore, the planning takes into account lessons learned from the first calibration campaign. To give one example, back then dark exposures were taken throughout the campaign in order to trend the detector noise. However, this resulted in many darks being affected by persistence from previous exposures under illuminated conditions, rendering them unusable for creating a master dark. Therefore, during the upcoming NIRSpec PVC we will acquire darks en block in a dedicated test sequence in addition to the exposures used for detector trending. Naturally, the planning will evolve while the test sequences are being updated.

Finally, the acceptance and delivery of the NIRSpec instrument is foreseen shortly after the end of the second cryogenic test campaign. Here, Astrium will deliver the instrument to ESA and after acceptance the instrument will be shipped to NASA Goddard Space Flight Center for the integration of NIRSpec into the integrated science instrument module system (ISIM).[13] Getting the necessary documentation for this process ready in time will be challenging. It will require a coordinated and joint effort in preparing documents during the course of the calibration campaign, and this has to be considered in the planning as well.

5. SUMMARY

The NIRSpec instrument showed excellent performance during its first verification and calibration campaign in early 2011. Currently, NIRSpec is being integrated at Astrium Ottobrunn and prepared for environmental testing. Once that is completed, NIRSpec is expected to be ready for its second performance verification and calibration campaign in 2013. The planning of this campaign has started and takes into account the results and lessons learned from the first cryogenic testing.

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