estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
Tel. (31) 71 5656565
Fax (31) 71 5656040
www.esa.int

NIRSpec Performance Report
NPR-2011-003

Authors: T. Böker

Date of Issue: 2.11.2011
Revision: 1

End-to-end Throughput of the NIRSpec Instrument as derived from Cycle 1 data

Abstract:

This report describes the data, method, and results for estimates of the end-to-end throughput of the NIRSpec instrument, obtained during the first on-ground calibration campaign in February 2011. This preliminary analysis suggests that NIRSpec likely meets all performance requirements related to instrument throughput. Nevertheless, some areas of uncertainty remain which are related to the calibration of the OGSE used for the Cycle 1 measurements; these are discussed as well.

1 INTRODUCTION

The NIRSpec instrument underwent its first cryogenic test campaign (hereafter Cycle 1) in February 2011. The content and timeline of the test campaign are detailed in Ferruit et al. 2011 (NTN-2011-001), while the design and capabilities of the Optical Ground Support Equipment (OGSE) used during the campaign are described in Birkmann et al. 2011 (NTN-2011-002).

The data acquired during the campaign allow an early assessment of some key aspects of the NIRSpec performance, and will provide the basis for evaluating whether NIRSpec meets its performance requirements detailed in the Functional Requirements Document (JWST-RQMT-002060). This note specifically addresses the requirements related to instrument throughput, in particular NFSR-42, NFSR-43, and NFSR-44. For convenience, these are reproduced in Appendix A. While formal verification of these requirements must await completion of a second NIRSpec cryogenic test campaign, this report provides an early "sanity check" of the NIRSpec throughput.

2 CALIBRATED REFERENCE SPECTRA

The reference lamp acting as the flux "standard" during Cycle 1 was the Calibration Light Source (CLS) used to illuminate NIRSpec throughout the on-ground calibration campaign. The continuum lamps FF1, FF2, FF3, and FFB were used for the throughput measurements. Their output spectra were measured by the CLS vendor (Mullard Space Science Laboratory, MSSL), and supplied together with the hardware. The NIRSpec Instrument Performance Simulator (IPS) software is used to smooth the measured output spectra, and to correct them for the reflectivity of the OGSE folding mirror that steers the CLS beam onto the NIRSpec coupling optics. The resulting spectra[1] of the CLS beam entering NIRSpec are reproduced in Figure 1.

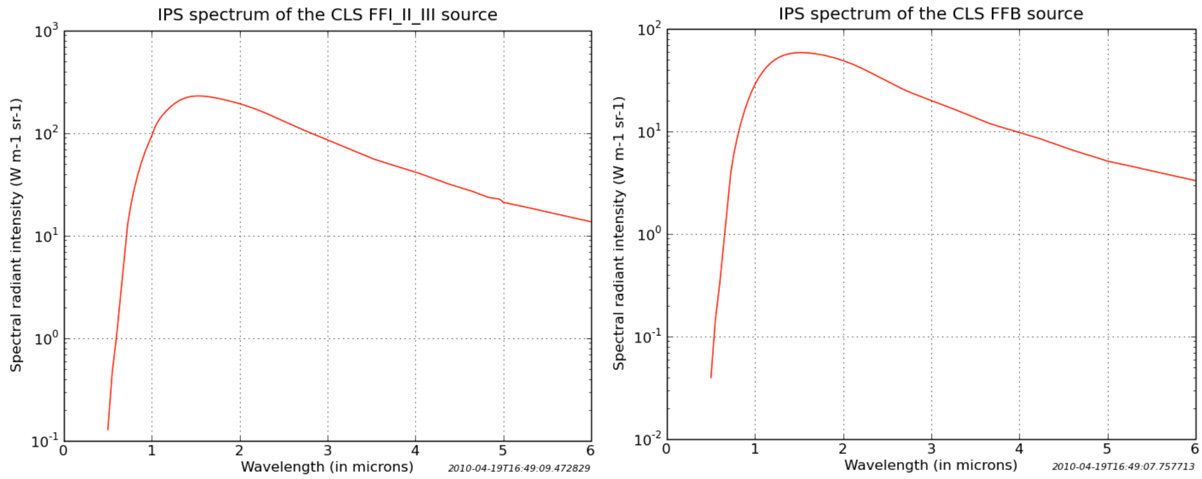

Figure 1: Output spectra for CLS lamps FF1-3 (left) and FFB (right), as measured by MSSL.

These spectra specify the spectral intensity I_{CLS} (in units of [W m^{-1} sr^{-1}]) emanating from the CLS. The expected number of photons falling onto a NIRSpec pixel covering a spectral "bin" of width $\Delta\lambda$ can be calculated as

$$n_{ph} = (I_{CLS} * A_{eff} * \Omega * \Delta\lambda) / h\nu \qquad [ph/s/pix]$$

Here, the solid angle Ω covered by the NIRSpec entrance aperture is $1/d^2$ [sr] where d=3.198m is the distance between the CLS exit aperture and the NIRSpec entrance aperture. The factor A_{eff} is the effective area of a NIRSpec resolution element in the NIRSpec entrance plane (i.e. the OTE focal plane), taking into account the magnification of the NIRSpec optics as defined by the focal ratios at the respective image planes (OTE, MSA, and FPA), the physical width of the slit aperture in the MSA plane (W_{slit}), and the physical size of a detector pixel (W_{pix}):

$$A_{eff} = W_{slit} * W_{pix} * f\#_{OTE}/f\#_{FPA} * f\#_{OTE}/f\#_{MSA}$$

With W_{pix} = 18µm, W_{slit} = 81µm (appropriate for the S200 slits), and the as-built focal ratios for the FORE, COLL and CAM optics, this becomes A_{eff} = 8.833E-09 m^2.

[1] as specified in files *OGSE05_CLS_FFI_II_III.src* and *OGSE05_CLS_FFB.src*

The desired width of the spectral bin $\Delta\lambda$ depends on the dispersive element used. To allow direct comparison with the calibration data described in Section 3, the CLS spectra were re-binned to a regular wavelength grid with a sampling of 0.005 μm (0.02 μm in the case of the FFB lamp). For this, the IDL routine *LINTERP* contained in the Astronomy User's Library was used.

Finally, the CLS calibration at MSSL was performed with the default positions of the various attenuation wheels. For FF1-3, the NIRSpec-level calibration measurements were done with identical wheel settings. In the case of FFB, however, it was necessary to reduce the CLS output in order to avoid saturation. For this reason, the position of attenuation wheel 3 was changed from position 3 (15.748% throughput) to position 1 (6.25% throughput). The reference spectrum of the FFB lamp therefore was scaled down by a factor[2] 6250/15748 = 0.3969.

3 CALIBRATION DATA

The data set used to compute a first estimate of the instrument throughput was selected from the COMBO1 test sequence executed on February 23, 2011. The numerical identifiers (NIDs) of the exposures used for each NIRSpec disperser are summarized in Appendix B.

The calibration data were run through the NIRSpec pre-processing pipeline (Birkmann et al. 2001, NTN-2011-004) to compute dark-subtracted and linearity-corrected count rate maps. From these, one-dimensional (i.e. collapsed along the spatial direction) spectra for the S200_A1 slit were extracted via the Python routine *p_getSpectrumSlit*. The output spectra are wavelength-calibrated, based on a model of the instrument dispersion[3].

To enable a direct comparison of the NIRSpec spectra to the CLS reference spectra, the former must be rebinned - over their respective wavelength bands - to the same wavelength sampling as the CLS reference spectra (0.005 μm for FF1-3, and 0.02 μm in the case of FFB).

In this step, it is important to assure that the total flux is preserved. This is because NIRSpec spectra at this stage can have a variable bin width, i.e. they are in units of [counts/pixel/bin], in contrast to the CLS reference spectra. The routine *FREBIN.pro* from the IDL Astronomy User's Library allows one to resample while conserving the total flux in the spectrum. After resampling, multiplication with the chosen bin width $\Delta\lambda$ and the detector gain yields electron rates that can be directly compared to the CLS photon rates. For the detector gain, the average values 1.453 e^-/ADU (for SCA 491) and 1.339 e^-/ADU (for SCA492) were used.

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[2] Analysis of the aperture wheel attenuation factors measured during Cycle 1 (B. Dorner, priv. comm.) shows that the correct factor is closer to 0.41. Using this value would lower the derived throughput in Fig. 2 by about 3%.

[3] Specifically, the instrument model *NIRS_FM1_optimized_02* was used.

A custom written IDL routine called *calc_throughput.pro* was used to perform the above steps and to compute, for each disperser, the instrument throughput as the ratio between the measured electron rates and the input photon rate. Note that at the moment, the routine does not accept any input parameters, and must be edited according to the combination of data set and lamp spectrum used for the computation.

4 RESULTS

The resulting throughput curves for the six NIRSpec gratings and the PRISM, are presented in Figs. 2 and 3 (black curves). They are compared to the expected throughput (red curves) as derived from sub-system and component-level data as described in the NIRSpec Performance Analysis Report (NIRS-CRAL-RP-002). For convenience, the formal throughput requirement for each NIRSpec mode as specified in the FRD (see Appendix A) is plotted as well (horizontal black lines).

As can be seen, the calculated NIRSpec throughput significantly exceeds the expectations in all modes. This seems somewhat surprising, and warrants a critical discussion of the reliability of the CLS calibration.

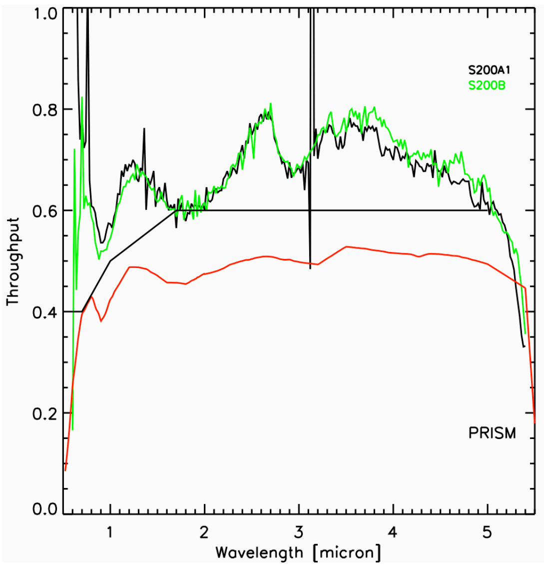

Figure 2: End-to-end instrument throughput for the NIRSpec PRISM, estimated using the calibrated lamp spectra for the CLS lamp FFB as reference. Spectra for two NIRSpec slits are plotted. The lower red curve indicates the expected throughput based on component-level measurements. The horizontal black line marks the requirement NSFR-042 listed in Appendix A.

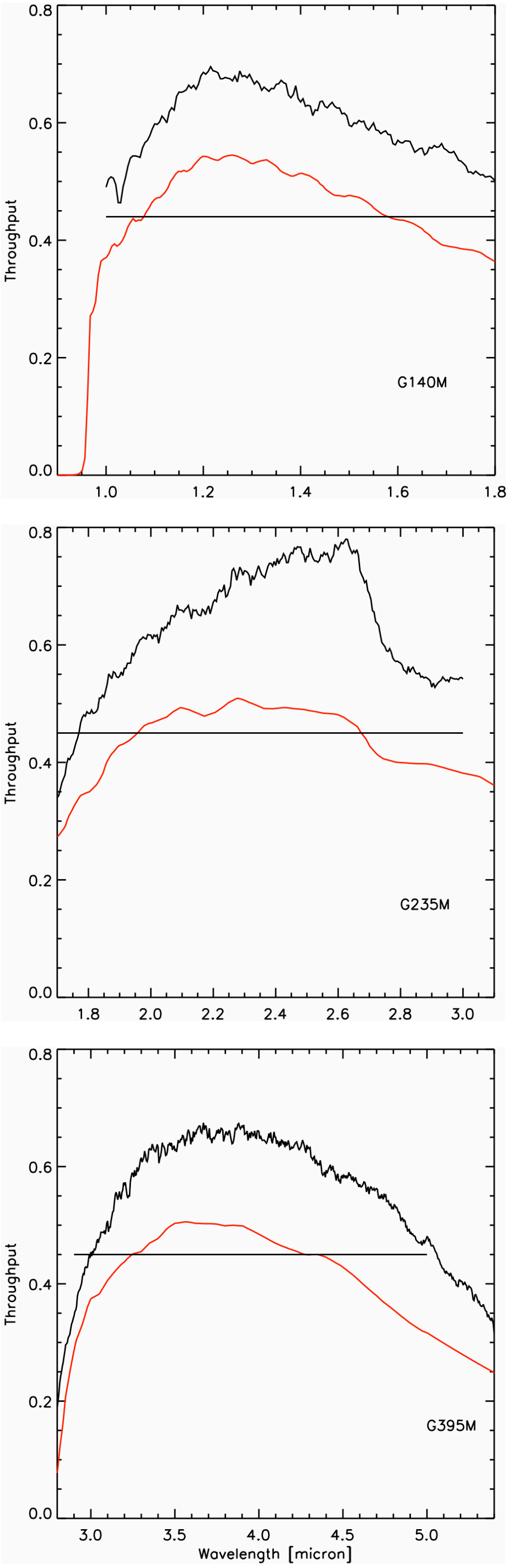

Figure 3: End-to-end instrument throughput for the six NIRSpec gratings (black curves), estimated using the calibrated lamp spectra for CLS lamps FF1, FF2, and FF3 as reference. For comparison, the expected throughput based on component-level measurements is also shown (red curves). The black horizontal lines denote the requirements listed in Appendix A.

5 DISCUSSION AND SUMMARY

Given the significant difference between the measured and modelled throughput curves, it seems prudent to further investigate the reliability of the CLS calibration. One potential source of error is the use of a "transfer function" when calibrating the CLS output spectra. Because of the intrinsic faintness of the sources, measuring directly the CLS output spectrum was only possible for the brightest setting, i.e. setting all aperture wheels in the lightbox to open. As described in the CLS test plan (NIRS-MSSL-TR-1021, issue B) this mode was measured both with the CLS proper, and with a smaller (and hence brighter) "laboratory sphere".

All other "standard" lightbox modes used during the NIRSpec test campaign were only calibrated via the laboratory sphere, and their CLS output spectra were calculated using a "transfer function" derived from the ratio of the two spectra (i.e. via the CLS and via the laboratory sphere) for the brightest lightbox mode.

The Cycle 1 test procedure *PHM-PS-XCAL-D*[4] used the brightest possible non-saturated aperture wheel settings in the lightbox, and can be used to assess the reliability of the transfer function. The wheel settings used during this measurement are identical to those used for the direct CLS measurements at MSSL, except for wheel #4 which was used in position 5 during the NIRSpec test, and in position 7 at MSSL. In order to compensate for this difference, a correction factor of 0.623 should be applied, as listed in Table 5-2 of the MSSL test report. The *PHM-PS-XCAL-D* spectra can be used to provide a more direct test of the NIRSpec throughput, albeit only for the high-resolution gratings (all other NIRSpec modes are saturated at these light levels).

Figure 4 shows the results derived as described, but using the file *sourceCLS_NAKED.src* as the CLS reference spectrum (after applying the correction factor of 0.623). For all three gratings, the calculated throughput is significantly lower than derived from the "standard" CLS reference spectra, and much better matches the expectations based on component-level measurements. This points to possible problems with the transfer function used to compute the output spectra for the FF1-3 sources.

In summary, this preliminary analysis indicates that the NIRSpec throughput is no worse than expected from sub-system and component-level data, and will likely meet or exceed the requirements. During Cycle 2, a more extensive test procedure to calibrate all CLS modes is planned. This should help to further reduce the uncertainties in the NIRSpec throughput.

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[4] By mistake, the procedure name was not correctly updated, it should have been *PREP-CLS-XCAL-D*. All exposures produced by running *PHM-PS-XCAL-D* are actually named *PREP-CLS-XCAL-D-nn*.

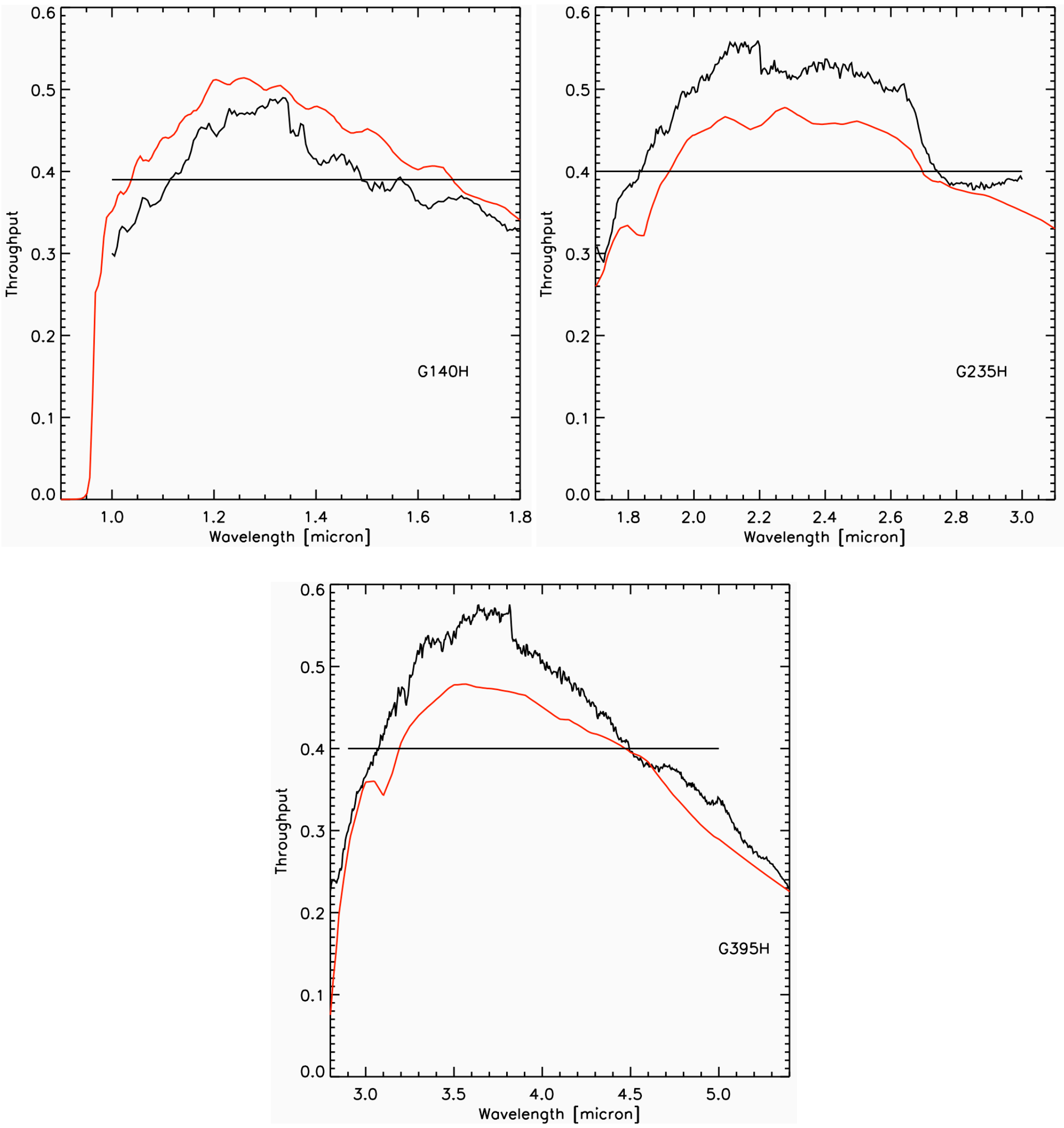

Figure 4: End-to-end instrument throughput for the three high-resolution NIRSpec gratings (black curves), estimated using data from the *PREP-CLS-XCAL-D* test procedure, and the calibrated lamp spectrum *sourceCLS_NAKED.src* as reference. For comparison, the expected throughput based on component-level measurements is also shown (red curves).

APPENDIX A   THROUGHPUT REQUIREMENTS

The relevant section of the NIRSpec Functional Requirements Document (FRD) reads as follows:

3.4.2 Throughput

Note: Throughput at wavelength λ is defined as the product of the reflectivity and/or transmission of all optical elements along the NIRSpec optical train, multiplied with the peak efficiency of the relevant grating and its blaze function at wavelength λ. The optical train comprises all NIRSpec mirrors, (starting at the pick-off mirror [POM] and ending at the last camera optics mirror just in front of the FPA) and the optical filter(s), but does not include diffraction light losses at the slit(s) or the quantum efficiency of the detector.

NSFR-42
In R=100 mode, the optical throughput at BOL of the NIRSpec optics, including the R=100 dispersing element and any required order blocking filter shall be, for any position in the FOV:

≥ 40 % for the spectral range between 0.6μm and 0.7μm
≥ 50 % at 1.0μm
≥ 60 % for the spectral range between 1.7μm and 5.0μm

Linear interpolation shall apply for wavelengths between 0.7μm and 1.0μm and for wavelengths between 1.0μm and 1.7μm.

NSFR-43
In R=1000 mode, the average optical throughput at BOL of the NIRSpec optics including the relevant R=1000 dispersive element and the relevant order blocking filters, shall be for any position in the FOV:

≥ 44 % for Band I (between 1.0μm and 1.8μm)
≥ 45 % for Band II (between 1.7μm and 3.0μm)
≥ 45 % for Band III (between 2.9μm and 5.0μm)

NSFR-44
In R=3000 mode, the average optical throughput at BOL of the NIRSpec optics including the relevant R=3000 dispersive element and the relevant order blocking filters, shall be for any position in the FOV:

≥ 39 % for Band I (between 1.0μm and 1.8 μm)
≥ 40 % for Band II (between 1.7μm and 3.0 μm)
≥ 40 % for Band III (between 2.9μm and 5.0 μm)

APPENDIX B CALIBRATION DATA

The following Table summarizes which exposures were used to analyze the NIRSpec throughput in the various dispersers:

NID	Disperser	Filter	CLS lamp	comment
"standard" calibration (COMBO1-01)				
5653	G140H	F100LP	FF1	
5662	G235H	F170LP	FF2	
5663	G395H	F290LP	FF3	
5664	G395H	F290LP	CLOSE	background exp.
5677	G140M	F100LP	FF1	
5678	G235M	F170LP	FF2	
5686	G395M	F290LP	FF3	
5687	G395M	F290LP	CLOSE	background exp.
5701	PRISM	CLEAR	FFB	
5702	PRISM	CLEAR	CLOSE	background exp.
PREP-CLS-XCAL-D (with manual setting of aperture wheels)				
5385	G140H	F100LP	PSB	
5391	G235H	F170LP	PSB	
5394	G395H	F290LP	PSB	