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

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NIRSpec wavelength calibration accuracy

Author(s):	Stephan Birkmann, Catarina Alves de Oliveira	Date:	October 11, 2013
Reviewed by:		Date:	
Approved by:		Date:	

Document change log

Issue	Date	Pages	Description of change
Draft	May 24, 2013	all	Initial version
1	October 11, 2013	9	Added information on spot checks performed (answer to RID-68)
		4,23,24	Updated abstract, section 5.2, and section 6 to reflect that the necessary data for prism wavelength calibration has been obtained in FM2 cycle 2 testing (answer to RID-68)

Contents

List of Tables

List of Figures

1 ABSTRACT

This report summarizes the wavelength calibration of the NIRSpec instrument. Based on data acquired during on ground instrument level testing and our current understanding of the error budgets, NIRSpec will very likely meet its wavelength calibration accuracy requirements for all dispersers, although additional data is needed for the verification of the prism. The acquisition of this data was part of the FM2 cycle 2 cryogenic testing.

2 INTRODUCTION AND SCOPE

This document serves to demonstrate that NIRSpec will likely meet its requirements on in orbit and on ground wavelength calibration accuracy. The governing requirement document is AD01, the NIRSpec Functional Requirements Document (FRD). It contains the following requirement and explanatory note that address the wavelength calibration:

NSFR-15 *After calibration, the wavelength scale of NIRSpec spectra shall be determined with an accuracy of better than 1/8 of a spectral resolution element.*

Note: *Spectral resolution is defined as* $R = \Delta\lambda/\lambda$ *where* λ *is the wavelength of observation and* $\Delta\lambda$ *is the FWHM wavelength of the slit function at the FPA, i.e. the convolution of an uniformly illuminated MSA shutter or fixed slit with the PSF of the spectrograph.*

The corresponding requirement in AD02, the NIRSpec System Requirements Document (SRD) reads as follows:

R 175: *The absolute errors in the in orbit spectral calibration shall be smaller than 1/8 (rms) of a spectral resolution element (FWHM) for a given grating/prism. Assuming 1 spectral resolution element corresponds to 2 detector pixels, the spectral calibration shall be performed to an accuracy better than 1/4 pixel (rms). This requirement applies to all standard observing modes R=100 (MSA and fixed slit), R=1000 (MSA and fixed slit) and R=3000 (fixed slit and IFU) and for any source position within the NIRSpec FOV.*

Since both requirements above are applicable after in orbit calibration, the final verification can only be done once in orbit. However, we will present the associated error budgets derived from the on ground calibration and show that the in orbit requirements can very likely be met.
In the SRD, there is also a requirement on the on ground spectral calibration accuracy:

R 180: *The absolute errors in the spectral calibration shall be smaller than 1/8 (rms) of a spectral resolution element (FWHM) for a given grating/prism. Assuming 1 spectral resolution element corresponds to 2 detector pixels, the spectral calibration shall be performed to an accuracy better than 1/4 pixel (rms). This requirement applies to all standard observing modes R=100 (MOS and SLIT), R=1000 (MOS and SLIT) and R=3000 (SLIT and IFM) and for any source position within the NIRSpec FOV.*

Section 3 of this document describes the used data and how it was (pre-)processed. In section 4 we show the results of the NIRSpec wavelength calibration effort based on data taken during on ground instrument level testing. In section 5 we present the on ground and in orbit wavelength calibration error budgets. The conclusion is given in section 6.
For a comprehensive overview of NIRSpec itself, please consult the Operations Concept Document (OCD, RD01).

2.1 Applicable and reference Documents

Reference	Identifier	Title, issue & date
AD01	JWST-RQMT-002060	Near-Infrared Spectrograph Functional Requirements Document, Revision C, 10 March 2008
AD02	ESA-JWST-RQ-322	Near-Infrared Spectrograph System Requirements Document, Issue 6, Revision 1, 27 March 2013

Table 1: The list of applicable documents.

Reference	Identifier	Title, issue & date
RD01	ESA-JWST-TN-0297	NIRSpec Operations Concept Document, Issue 7, 23 August 2012
RD02	NTN-2011-002 ESA-JWST-TN-18255	Description of the NIRSpec OGSE, Version 1, 26 October 2011
RD03	NTN-2011-004 ESA-JWST-TN-18257	Description of the NIRSpec pre-processing pipeline, Version 1.1, 03 May 2012
RD04	NIRS-MPI-TN-0012	NIRSpec IPS Pipeline software description
RD05	NPR-2013-008 ESA-JWST-RP-19657	Calibration of the GWA position sensors - Part II
RD06	N/A (ADS link)	The Spectrum of Th-Ar Hollow Cathode Lamps in the 691-5804 nm region: Establishing Wavelength Standards for the Calibration of Infrared Spectrographs; Kerber, F., Nave, G., & Sansonetti, C. J. 2008, ApJS, 178, 374
RD07	N/A (ADS link)	Precision in Condensed Phase Vibrational Spectroscopy; D. G. Cameron, J. K. Kauppinen, D. J. Moffatt and H. H. Mantsch, Applied Spectroscopy, Vol. 36, Issue 3, pp. 245-250 (1982)
RD08	NIRS-CRAL-TN-0001	Review of the in-orbit wavelength calibration of the NIRSpec instrument, Issue 2, 18 October 2005

Table 2: The list of reference documents.

3 DATA AND PROCESSING

3.1 Data used

All data presented and analyzed in this report were taken during the FM2 cycle 1 performance verification and calibration campaign (PVC) that took place from December 2012 to February 2013 at IABG, Ottobrunn, Germany. For details on the test setup and the on ground calibration sources mentioned in the following sections, please refer to RD02.
During the campaign, a number of different MSA configurations were used to take data with all dispersive elements in NIRSpec with the appropriate internal and external calibration sources. In total, 44 data sets with 51 exposures each were obtained, where the only difference is the pattern/location of opened shutters in the MSA. Each individual exposure has its unique identifier (NID). Table 3 lists

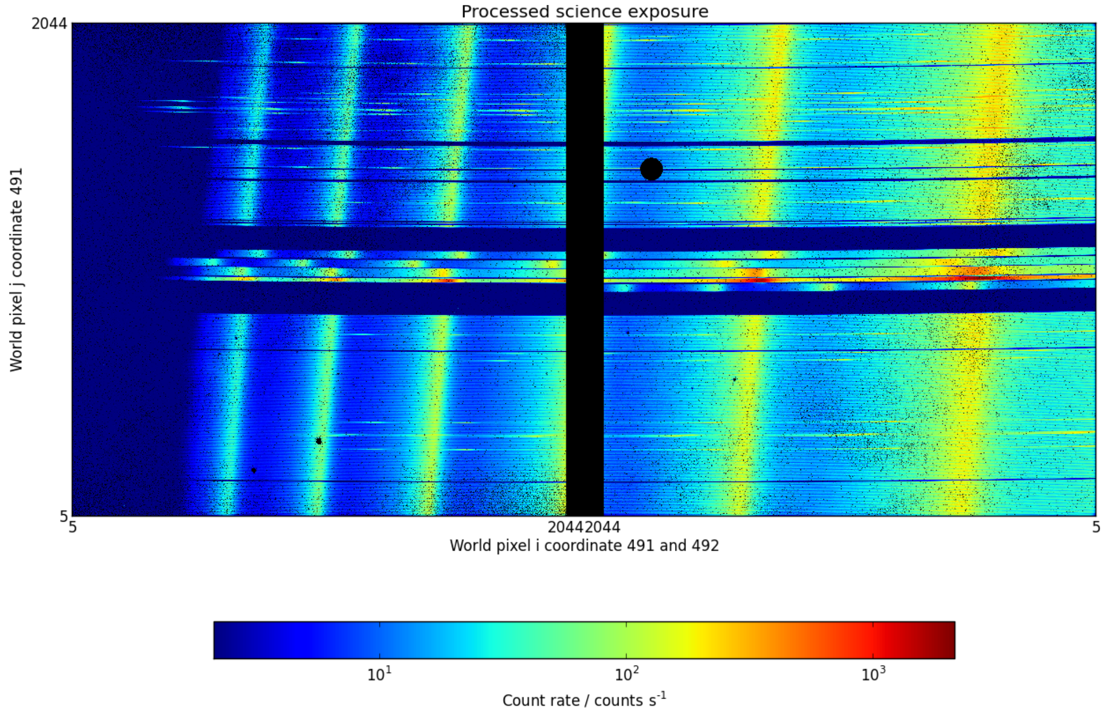

Figure 1: Count rate image showing spectra of the CAA/LINE1 lamp taken with the G140H grating. SCA491 is on the left, SCA492 on the right, wavelength increases from left to right.

the number of the data set, its observation ID, date/time, and the range of NIDs for each block of measurements.
The MOS-COMBO test sequence has 40 long slits sparsely covering the full field of view of NIRSpec. For the data presented in this report, only the exposures that use the internal and external wavelength calibrators were used. These are the exposures with the CAA/LINE1-3, CAA/REF (all internal), and CLS/Argon (external) sources. The internal continuum lamps CAA/FLAT1-3 were used to flat field the wavelength calibration related CAA data. Information on the (pre-)processing steps is provided in the next section.

3.2 Data processing

All data have been pre-processed by the NIRSpec pre-processing pipeline. This pipeline uses the raw data cubes (up-the-ramp sampling) and computes the count rate images and associated data products (uncertainty maps, data quality maps, etc.) from them. See RD03 for details on the pre-processing.
Examples of three pre-processed count rate images are shown in Figs. 1 to 3. In those images, pixels values that are not considered usable (e.g. open pixels) are shown in black.
The count rate images were then used as the input for the NIRSpec extraction software in order to extract wavelength calibrated and rectified spectra. Exposures taken with the CAA/LINE1-3 and CAA/REF sources were flat-fielded using the corresponding CAA/FLAT1-3 count rate images. This approach is not optimal for the CAA/REF lamp for the Band II and III gratings, because CAA/REF is observed in second and third order there, while the flat field lamp is observed in first order. However, the impact of this shortcoming seems to be limited. Exposures taken with the CAA/LINE4 source were

#	OBS_ID	Start date and time	NID range
1	PREP-COMBO-MOS	2013-01-11 01:02:08	7911 - 7961
2	MOS-COMBO-01	2013-01-18 22:21:45	9567 - 9617
3	MOS-COMBO-02	2013-01-19 02:08:28	9618 - 9668
4	MOS-COMBO-03	2013-01-19 08:11:35	9674 - 9724
5	MOS-COMBO-04	2013-01-19 12:18:14	9725 - 9775
6	MOS-COMBO-05	2013-01-20 04:23:39	9894 - 9944
7	MOS-COMBO-06	2013-01-20 08:39:54	9945 - 9995
8	MOS-COMBO-07	2013-01-20 16:31:33	10029 - 10079
9	MOS-COMBO-08	2013-01-21 21:11:08	10193 - 10243
10	MOS-COMBO-09	2013-01-22 01:14:23	10244 - 10294
11	MOS-COMBO-10	2013-01-22 05:17:56	10295 - 10345
12	MOS-COMBO-11	2013-01-22 09:21:20	10346 - 10396
13	MOS-COMBO-12	2013-01-22 16:55:51	10409 - 10459
14	MOS-COMBO-13	2013-01-22 21:02:45	10460 - 10510
15	MOS-COMBO-14	2013-01-23 01:36:25	10511 - 10561
16	MOS-COMBO-15	2013-01-23 19:45:42	10566 - 10616
17	MOS-COMBO-16	2013-01-23 23:48:51	10617 - 10667
18	MOS-COMBO-17	2013-01-24 03:51:31	10668 - 10718
19	MOS-COMBO-18	2013-01-24 11:12:58	10732 - 10782
20	MOS-COMBO-19	2013-01-24 15:22:47	10783 - 10833
21	MOS-COMBO-20	2013-01-24 19:30:58	10834 - 10884
22	MOS-COMBO-21	2013-01-24 23:38:17	10885 - 10935
23	MOS-COMBO-22	2013-01-25 03:53:17	10936 - 10986
24	MOS-COMBO-23	2013-01-25 08:00:02	10987 - 11037
25	MOS-COMBO-24	2013-01-25 12:06:05	11038 - 11088
26	MOS-COMBO-25	2013-01-25 16:17:01	11089 - 11139
27	MOS-COMBO-26	2013-01-25 23:38:17	11153 - 11203
28	MOS-COMBO-27	2013-01-26 03:44:32	11204 - 11254
29	MOS-COMBO-28	2013-01-26 07:56:37	11255 - 11305
30	MOS-COMBO-29	2013-01-26 12:00:21	11306 - 11356
31	MOS-COMBO-30	2013-01-26 16:35:46	11357 - 11407
32	MOS-COMBO-31	2013-01-26 20:47:21	11408 - 11458
33	MOS-COMBO-32	2013-01-27 00:55:26	11459 - 11509
34	MOS-COMBO-33	2013-01-27 05:00:21	11510 - 11560
35	MOS-COMBO-34	2013-01-27 12:17:43	11574 - 11624
36	MOS-COMBO-35	2013-01-27 16:29:08	11625 - 11675
37	MOS-COMBO-36	2013-01-27 20:36:47	11676 - 11726
38	MOS-COMBO-37	2013-01-28 00:44:37	11727 - 11777
39	MOS-COMBO-38	2013-01-28 05:13:57	11778 - 11828
40	MOS-COMBO-39	2013-01-28 09:24:52	11829 - 11879
41	MOS-COMBO-40	2013-01-28 14:37:40	11880 - 11930
42	MOS-COMBO-41	2013-01-28 18:43:53	11931 - 11981
43	MOS-COMBO-03	2013-01-29 02:05:43	11995 - 12045
44	MOS-COMBO-04	2013-01-29 06:14:32	12046 - 12096

Table 3: Observation IDs, start date and time (UTC), and NID ranges of the data used for the wavelength calibration of the gratings.

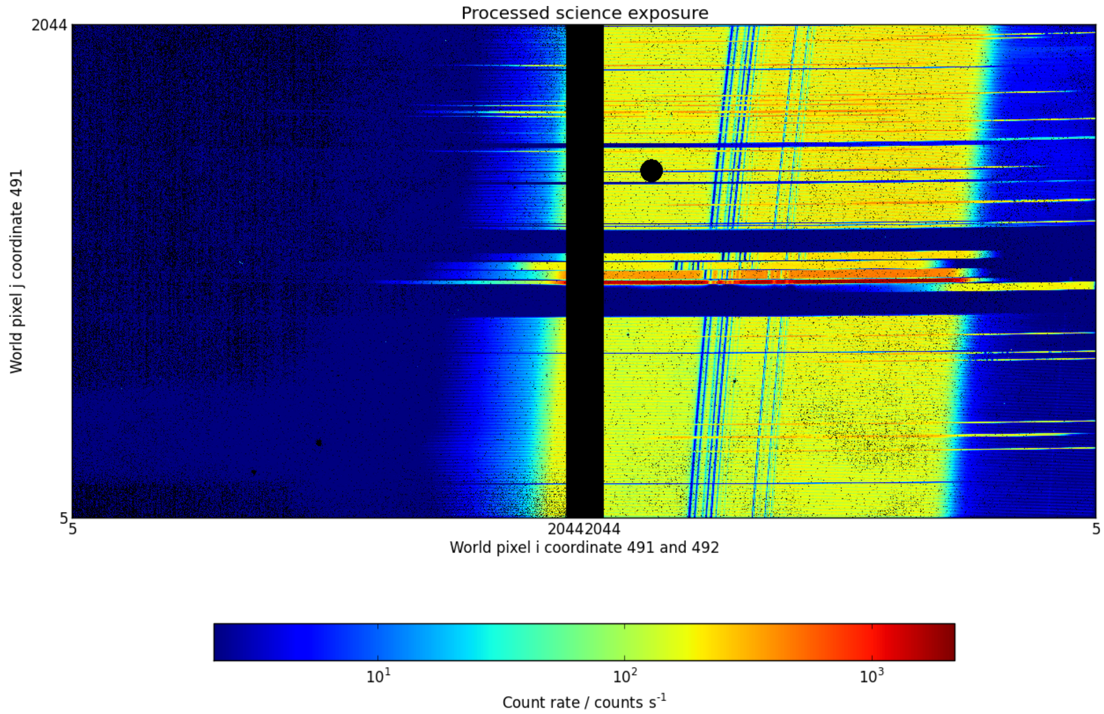

Figure 2: Count rate image showing spectra of the CAA/REF lamp taken with the G140H grating.

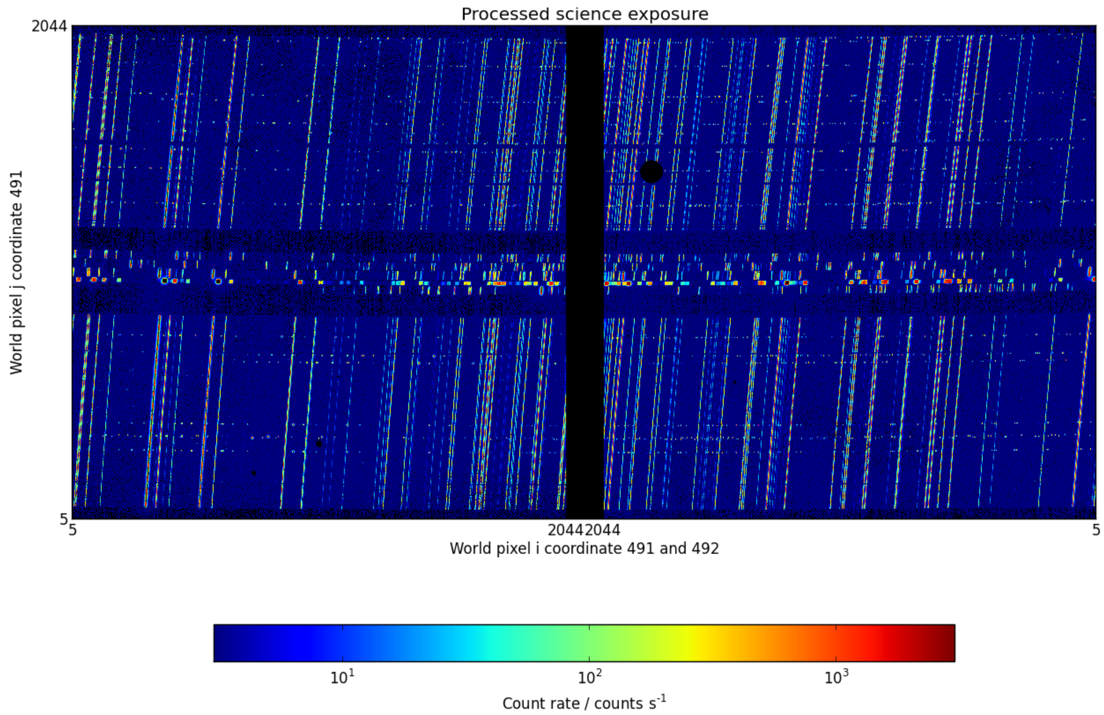

Figure 3: Count rate image showing spectra of the CLS/Argon emission line lamp taken with the G140H grating.

flat-fielded using the CAA/FLAT5 lamp. For the exposures with the CLS/Argon emission line source, no flat field correction was applied.
Examples of rectified spectra of the S200A1 slit for the three count rate images shown in Figs. 1 to 3 are shown in Fig. 4.
The extraction pipeline also takes into account the measured tilt for the NIRSpec grating wheel for the wavelength scale. However, the underlying instrument model used was adjusted using data acquired early in the test campaign, and there is some room for improving the model. This is part of normal work to be done in the years leading to launch and commissioning. For this report, the wavelength scale on the extracted spectra was refined using the Argon emission line source (see section 4.1.2 below for details).
The pipeline also provides a final spectrum (taking the average or median along the spatial direction) with uniform wavelength steps. These spectra were used to generate the plots and results presented in this report.
Unless otherwise noted, the results shown are from the extracted S200A1 slit. In addition, the following spot checks were carried out:

1. For one dataset, the wavelength calibration accuracy of the remaining 200 mas wide fixed slits (S200A2, S200B) was checked for all gratings. Results were in line with the ones reported for S200A1.

2. For one dataset, the wavelength calibration accuracy of a few selected micro-shutters was checked for the medium resolution gratings.

3. For the IFU, the consistency of the wavelength calibration with respect to the one obtained for the fixed slits was checked for G140H.

The results of the spot checks indicate that the reachable wavelength calibration accuracy is comparable to that reported for the fixed slit S200A1.

4 RESULTS OF THE GROUND CALIBRATION CAMPAIGN

4.1 Wavelength calibration with the Argon emission line lamp

We have chosen the CLS/Argon emission line lamp as the primary source for on ground wavelength calibration of the NIRSpec instrument. The Argon spectrum has the advantage that it delivers i) a large number of unresolved lines[1] in the wavelength range of interest for NIRSpec, and ii) that the wavelength of these lines has been very accurately determined by Kerber et al. (RD06) using measurements performed at the National Institute of Standards and Technology (NIST).
Extracted spectra of the CLS/Argon lamp acquired with NIRSpec's high resolution gratings are shown in Fig. 5. The F070LP filter was used for the band I gratings, and the F140X filter was used for the band II and III gratings. Therefore, multiple orders are present for many lines and there is sufficient coverage over the whole wavelength range of interest.
For the prism, the Argon source cannot be used directly, because i) the lines are too blended/confused due to the low resolution of the prism and ii) because it only covers wavelengths up to $\sim$2.8 μm (no higher orders as for the gratings). Therefore, the wavelength calibration of the prism is based on the CAA/LINE1-4 sources and is discussed in section 4.3 below.

[1] typical Ar linewidths $\Delta\lambda$ are such that $\lambda/\Delta\lambda > 100000$, significantly higher than the resolving power of NIRSpec

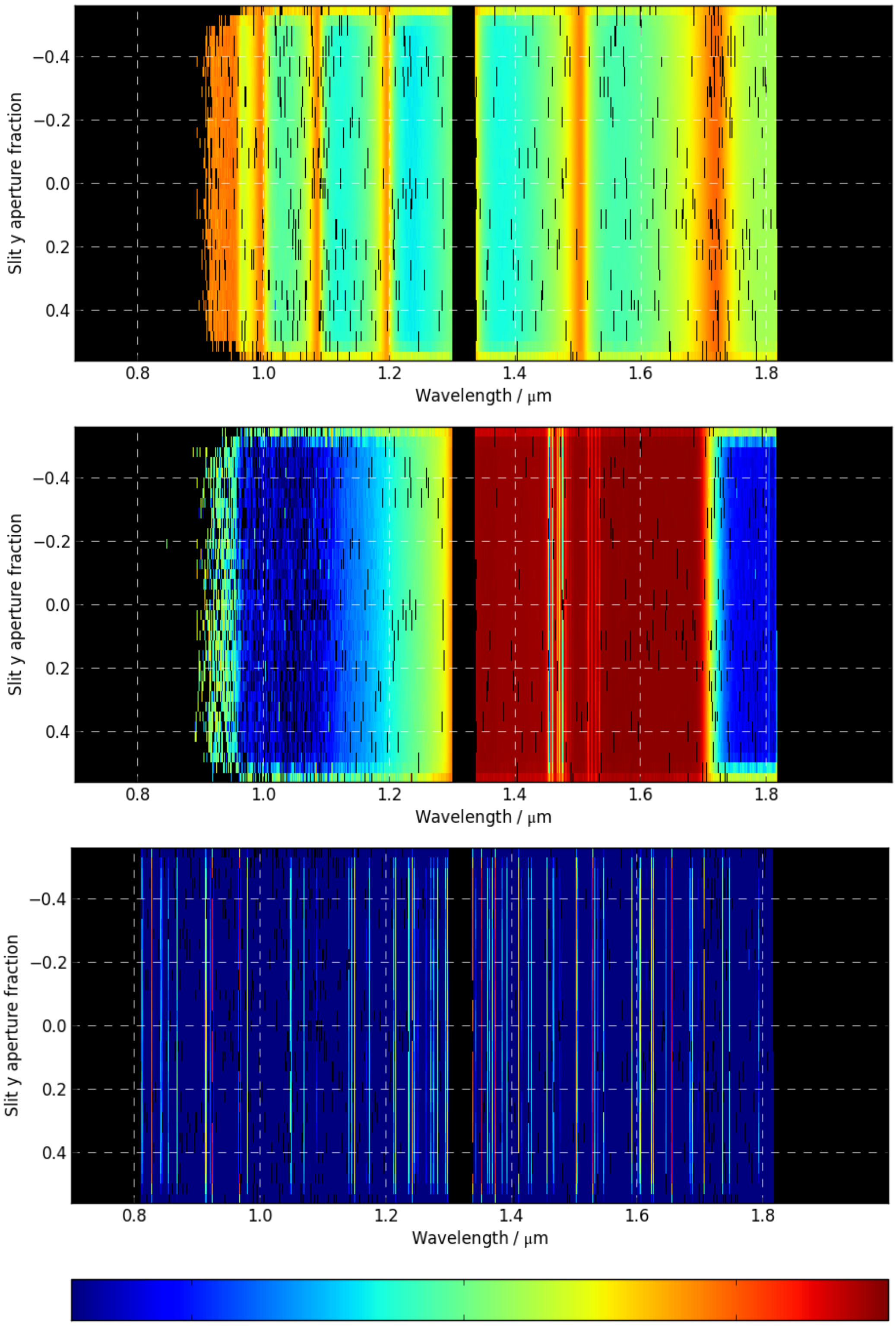

Figure 4: Rectified spectra of the S200A1 slit for CAA/LINE1 (top), CAA/REF (middle), and CLS/Argon (bottom), all three taken with the G140H grating. The color scale is logarithmic from low (blue) to high (red) counts.

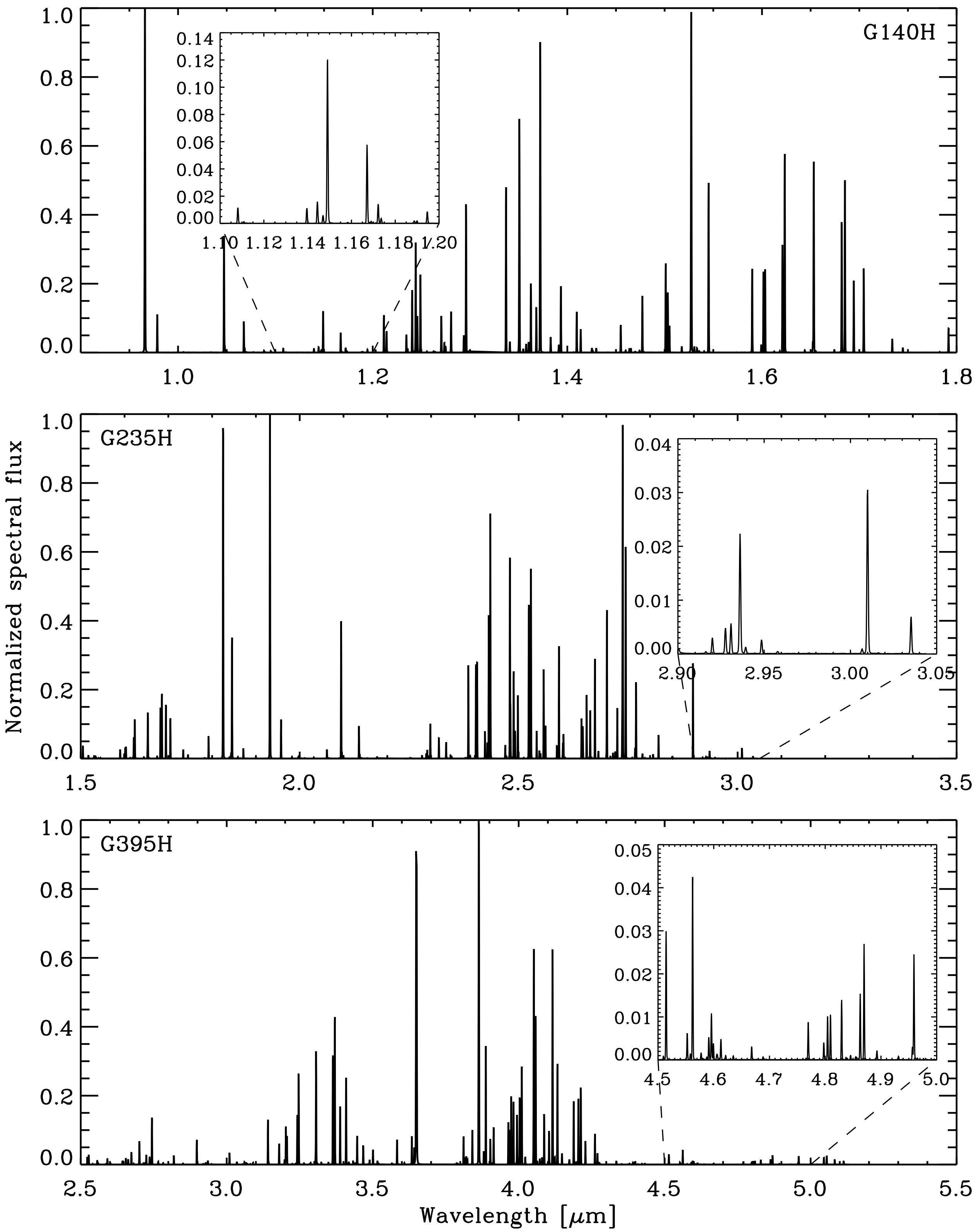

Figure 5: Extracted and normalized spectra of the CLS/Argon lamp with the G140H, G235H, and G395H gratings (top to bottom). The inlays give an idea of the dynamic range and line density.

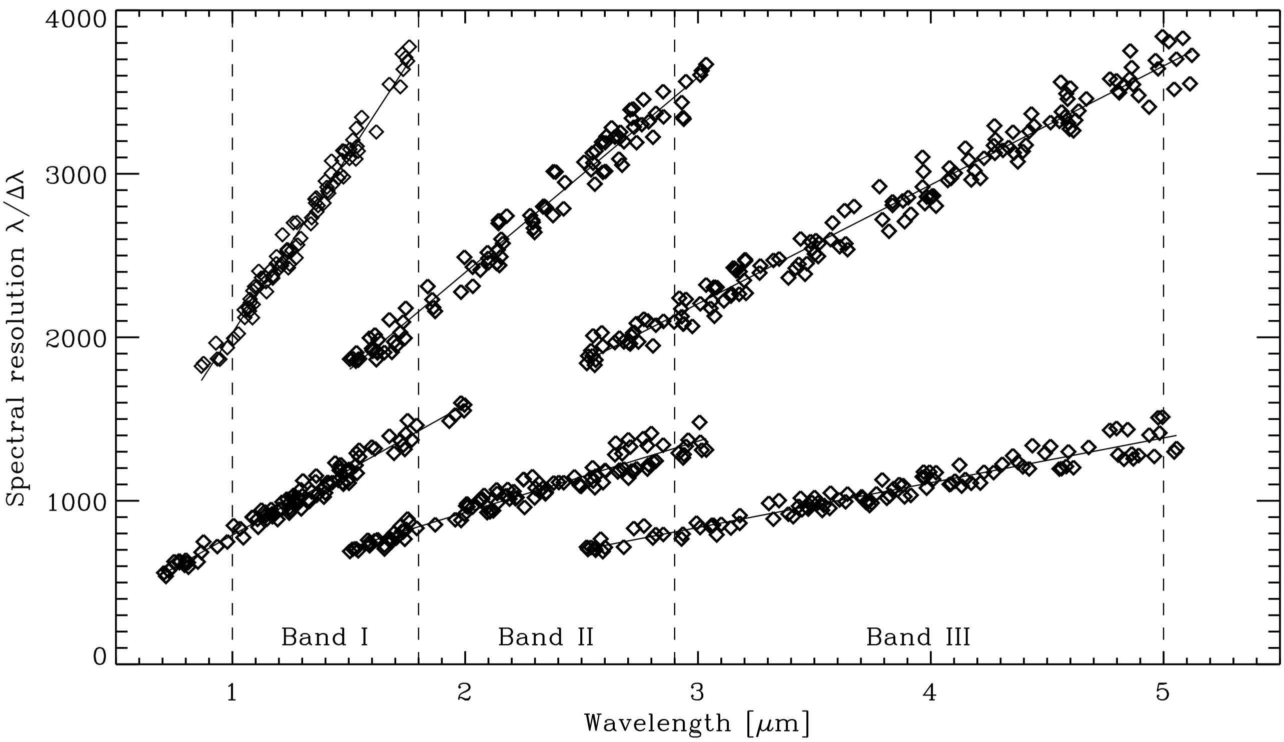

Figure 6: The spectral resolution $\lambda/\Delta\lambda$ of NIRSpec for the three high (upper series) and medium (lower series) resolution gratings. The vertical dashed lines denote the boundaries of the three science bands.

4.1.1 Verifying the spectral resolution

In order to verify the requirements on spectral resolution, the extracted CLS/Argon data was used. For each identified line in the spectrum, the position (wavelength), amplitude, and full width at half maximum (FWHM) was fitted with a Gaussian function. From these data, the spectral resolution $R = \lambda/\Delta\lambda$ can be computed. We show the results in Fig. 6, using only data with reliable positions and measured FWHMs, i.e. blended/confused lines were removed.
The measured and required spectral resolutions for each of the six gratings in NIRSpec is shown in Table 4. In all cases, the requirement is met, taking into account the measurement uncertainties. Therefore, for the rest of this document, we will adopt the nominal resolution element $\Delta\lambda$ as

$$\Delta\lambda = \frac{\lambda_{\rm mid}}{R_{\rm nom}}, \tag{1}$$

where $\lambda_{\rm mid}$ is the wavelength at the middle of the science band for the three NIRSpec bands (i.e. 1.40, 2.35, and 3.95 μm for bands I, II, and III), and $R_{\rm nom}$ is the nominal resolution of the NIRSpec gratings (i.e. 1000 and 2700 for the mid and high resolution gratings, respectively).

4.1.2 Wavelength calibration

In order to perform the wavelength calibration (dispersion relation) of NIRSpec with the CLS/Argon data, we measured the positions of the Argon lines in the extracted spectrum and compare those

grating name	Spectral resolution $\lambda/\Delta\lambda$ requirement	measured
G140H	2700 ± 270 @ 1.40 μm	2900 ± 90
G235H	2700 ± 270 @ 2.35 μm	2810 ± 90
G395H	2700 ± 270 @ 3.95 μm	2900 ± 70
G140M	1000 ± 100 @ 1.40 μm	1110 ± 40
G235M	1000 ± 100 @ 2.35 μm	1080 ± 60
G395M	1000 ± 100 @ 3.95 μm	1100 ± 60

Table 4: The required (as per R 28 and R 29 in AD02) and measured spectral resolutions for the six NIRSpec gratings.

Grating Name	Wavelength calibration accuracy [$\times 10^{-5}$ μm]	[resolution elements]
G140H	0.91	0.0175
G235H	1.31	0.0150
G395H	2.32	0.0158
G140M	1.83	0.0131
G235M	2.88	0.0122
G395M	4.14	0.0105

Table 5: The mean wavelength calibration accuracy for the six NIRSpec gratings derived from the available set of CLS/Argon spectra.

positions with the ones provided in the NIST catalog from RD03. Typically, the NIRSpec extraction pipeline in its current state (with preliminary tuning of the instrument model) already yields a wavelength calibration to better than one pixel, i.e. 0.5 resolution elements. The small deviations were then corrected for by a low order (quadratic terms) polynomial. The typical outcome of this exercise is shown in Fig. 7. The derived (small) corrections to the wavelength scale were applied to all data taken with the same grating, i.e. the spectra of the CAA/LINE and REF sources (see sections 4.2 and 4.3 below) were put on the same wavelength scale.

The root-mean-square (RMS) residuals after the low order correction of the measured minus true wavelengths of the Argon lines is taken as the accuracy of the wavelength calibration. The RMS value was derived for all 44 data sets of the PREP-COMBO-MOS and MOS-COMBO series for the six gratings. The results are shown in Table 5. For all six gratings the wavelength calibration accuracy for the S200A1 slit is better than 0.020 resolution elements. Similar results are obtained for the other fixed slits and the IFU, for which spot checks on a few exposures have been carried out.

For multi object spectroscopy (MOS) with NIRSpec, the wavelength calibration for each micro shutter must be established. Since it would take too long to directly calibrate each shutter, we will calibrate 40 long slits over the NIRSpec field of view (FOV). The calibration for these shutters will then be used to calibrate the shutters in between by interpolation using the instrument model. In order to assess the additional uncertainty that arises from this interpolation, we applied the derived calibration of the S200A1 slit directly to the S200A2 slit and determined the residuals. After subtracting a constant offset, which corresponds to the zero point calibration (see below), we get RMS residuals of less than 0.025 resolution elements for all dispersers. Since the separation in the spectral direction between the

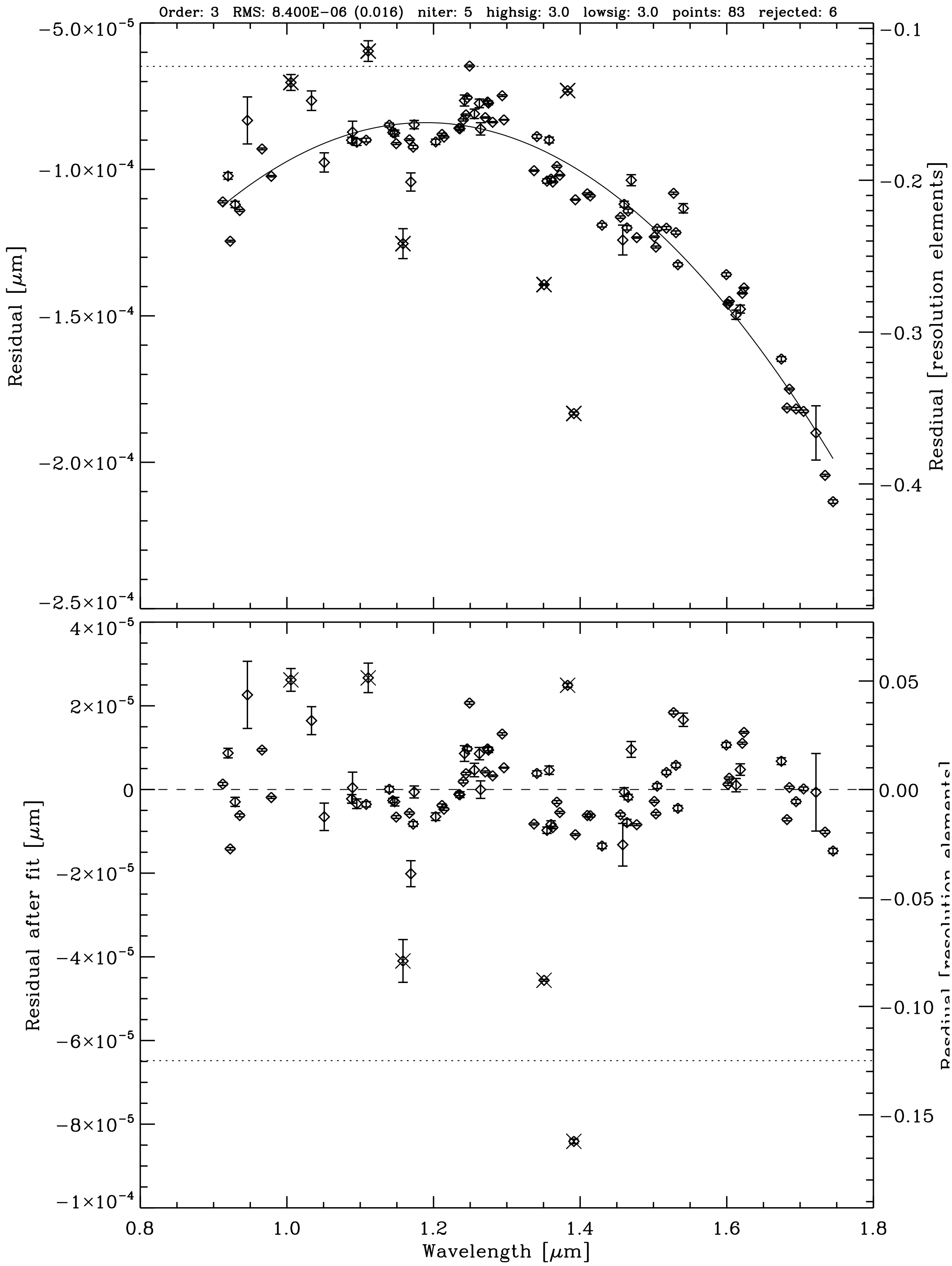

Figure 7: The residuals (measured minus NIST data) of the Argon line positions after extraction with the NIRSpec pipeline (top panel) and after correcting with a low order polynomial (bottom panel). Argon lines not used in the fit (outliers) are crossed out.

line index	CAA/REF Measured Center of Gravity [μm]				
	G140H	G235H		G395H	
	1^{st} order	1^{st} order	2^{nd} order	2^{nd} order	3^{rd} order
1	**1.457998(2)**	-	**1.458000(2)**	1.458018(3)	**1.458008(1)**
2	**1.478840(2)**	-	**1.478829(2)**	1.478869(16)	**1.478851(2)**
3	**1.486609(4)**	-	**1.486698(3)**	1.486622(9)	**1.486620(4)**
4	1.510999(9)	-	1.510964(6)	1.511010(14)	1.511001(12)
5	1.540918(8)	-	-	-	-
6	1.545622(8)	1.545630(30)	-	1.545613(11)	1.545631(13)
	G140M	G235M		G395M	
	1^{st} order	1^{st} order	2^{nd} order	2^{nd} order	3^{rd} order
1	**1.45799(1)**	-	**1.45802(1)**	-	**1.45802(2)**
2	1.47887(5)	-	**1.47886(1)**	1.47905(28)	**1.47888(4)**
3	1.48666(9)	-	**1.48661(1)**	1.48664(7)	**1.48662(2)**
4	-	-	-	-	1.51112(45)
5	**1.54087(4)**	-	-	-	-
6	**1.54559(3)**	1.54576(36)	-	1.54579(26)	1.54563(4)

Table 6: The mean centre of gravity for the six selected lines of the CAA/REF source for all six gratings. The number in brackets denote the measured standard deviation. The numbers in bold denote the three best measured lines for each of the gratings.

two S200A slits is comparable to the separation of the configured long slits in the MSA for the MOS-COMBO test sequence, this value is considered a conservative estimate of the wavelength calibration uncertainty due to the interpolation over the MOS FOV.

4.2 The CAA/REF lamp

The CAA/REF source uses an Erbium doped filter and a band pass filter to generate a set of narrow absorption lines in the 1.45 to 1.55 μm region. Due to the band pass filter, the CAA/REF source can also be used in order 2 and 3 without order overlap. Extracted spectra with the three high resolution NIRSpec gratings are shown in Fig. 8.
The absorption lines are resolved with the high resolution gratings and partly so with the medium resolution gratings. Six lines were selected for the NIRSpec wavelength zero point calibration. They are marked in Fig. 9 with numbers one to six. The positions of these lines was computed using the centre of gravity (CoG) method by Cameron et al. (RD07, see Appendix A for details on the computation) for the 44 measurements available. The mean and standard deviation of the measured CoGs are presented in Table 6.
For the high resolution gratings, the three best measured and thus most stable lines are the ones with indices 1 to 3 when observed in first, second, and third order with the Band I, II, and III gratings, respectively. For the medium resolution gratings, the three best measured lines are those with the indices 1, 5, and 6 for Band I, while they are 1 to 3 for Bands II and III.
For the high resolution gratings, these three lines are stable to better than 0.010 resolution elements over the covered period of approximately 18 days. For the medium resolution gratings, they are stable to better than 0.029 resolution elements. By averaging the three best lines, the accuracy for the

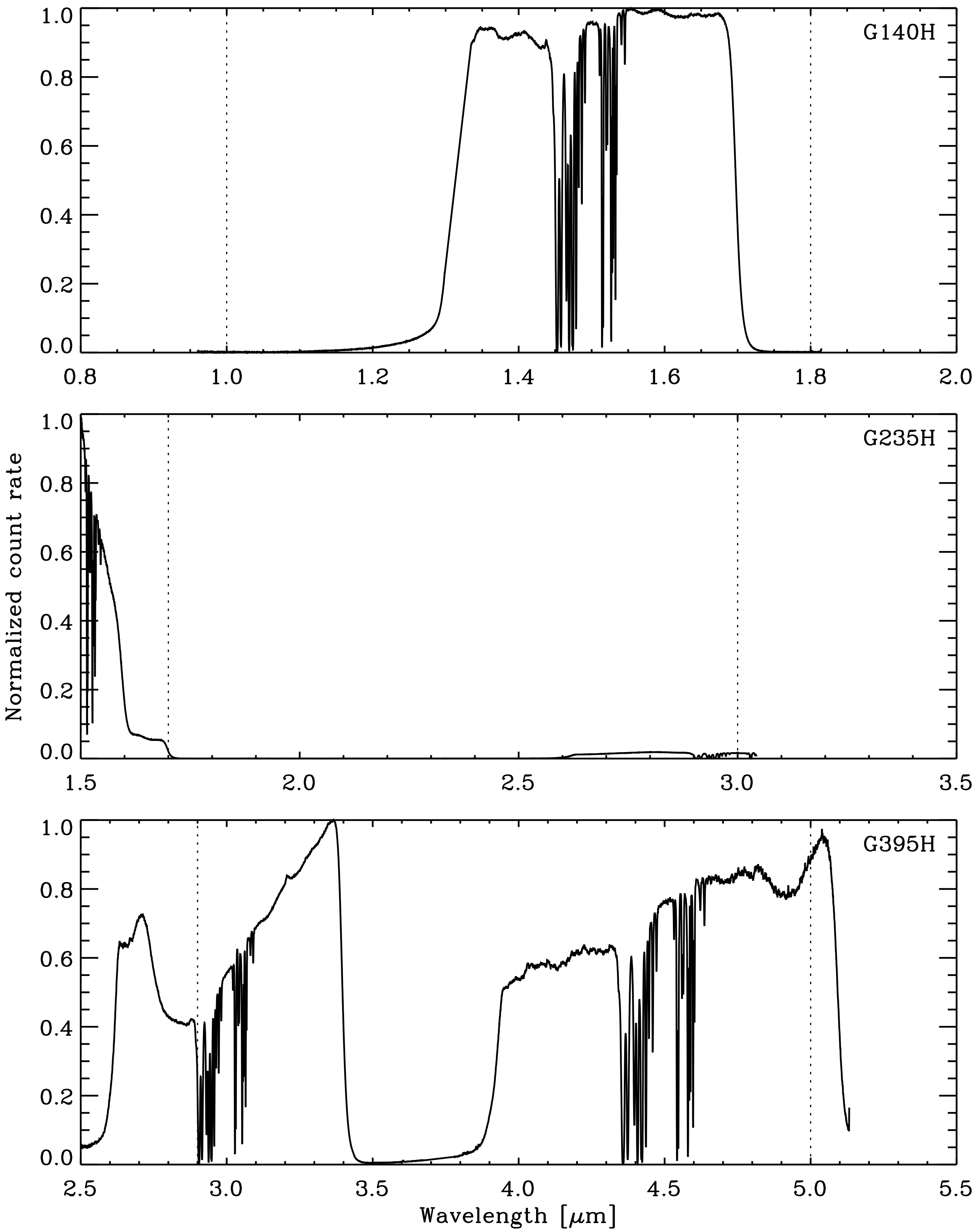

Figure 8: Extracted and normalized spectra of the CAA/REF source taken with the high resolution gratings. The vertical dotted lines denote the boundaries of the nominal science bands.

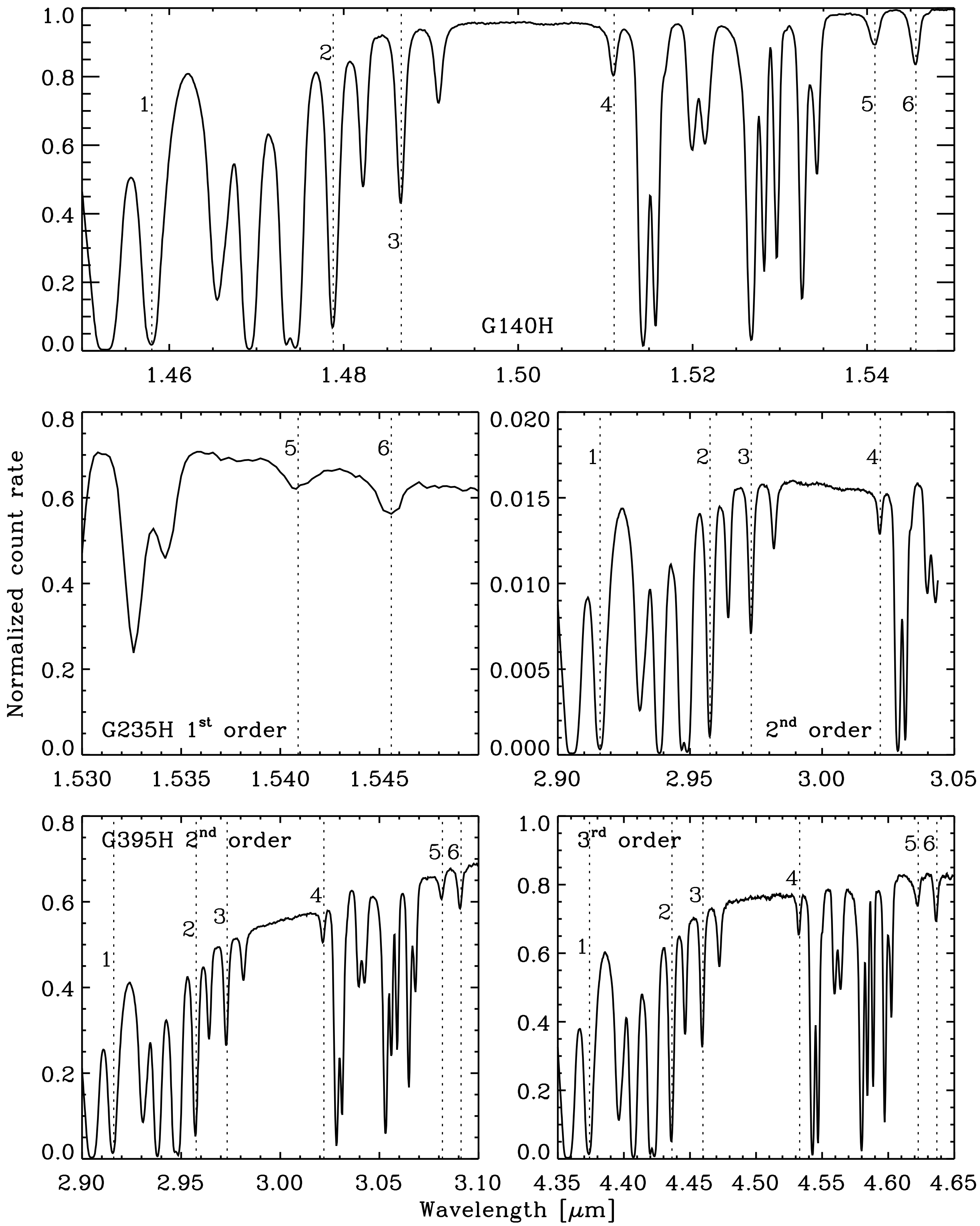

Figure 9: Closeup view of the regions with the six selected absorption lines (same data as in Fig. 8).

line index	CAA/LINE1-3 Measured Center of Gravity [μm]		
	G140H LINE1	G235H LINE2	G395H LINE3
0	0.993418(18)	1.595748(70)	2.659259(748)
1	1.083419(11)	1.752650(16)	2.923148(15)
2	1.194060(7)	1.948182(14)	3.250669(21)
3	-	-	-
4	1.500905(8)	2.513930(18)	4.172508(18)
5	1.715847(11)	2.927798(25)	4.825220(67)
	G140M LINE1	G235M LINE2	G395M LINE3
0	0.99345(6)	1.59573(6)	2.65952(63)
1	1.08343(7)	1.75261(3)	2.92314(2)
2	1.19410(7)	1.94831(5)	3.25064(2)
3	1.33066(6)	2.19627(4)	3.65886(2)
4	1.50086(1)	2.51420(3)	4.17249(2)
5	1.71586(1)	2.92783(3)	4.82524(6)

Table 7: The mean centre of gravity for the lines of the CAA/LINE1-3 sources for all six gratings. The number in brackets denotes the measured standard deviation. Line index 3 for the high resolution gratings is missing, because it falls into the detector gap for the S200A1 slit.

wavelength zero-point calibration using the CAA/REF source is 0.006 resolution elements for the high and 0.017 resolution elements for the medium resolution gratings, respectively.
The reason for the better accuracy for the high resolution gratings is most likely their superior resolution, as the CoG method tends to work better on resolved features. Because both high and medium resolution gratings use the same CAA/REF lamp, it is safe to assume that the intrinsic stability of the lines is at least as good as measured with the high resolution grating in all cases.
The measured CoG of the lines in different orders/gratings agree with each other within the uncertainties that are due to the absolute wavelength calibration using the Argon lines described above.

4.3 The CAA/LINE lamps

The CAA/LINE1-3 lamps provide 5-6 broad spectral features for each of the gratings distributed over the science bands. The extracted spectra for the three line lamps are shown in Fig. 10. Like for the CAA/REF source, the position of the individual peaks of the CAA/LINE1-3 sources was calculated using the CoG method. This was done for all 44 available measurements and the mean CoG of the lines and the standard deviation (stability) is reported in Table 7. No systematic trends or time dependence are visible in the data taken over roughly 18 days.
Considering only the 5 lines inside the nominal science bands (line indices 1 to 5), the CoG of the lines is typically stable to better than 0.02 resolution elements, and stable to better than 0.05 resolution elements in the worst case.
Like for the CAA/REF source, the CoGs of the CAA/LINE1-3 sources measured with the high and medium resolution gratings agree with each other within the uncertainties.
For the prism, the CAA/LINE4 source provides 10 spectral features in the 1 to 5 micron range for wavelength calibration. The extracted and flat fielded spectrum is shown in Fig. 11. Because the

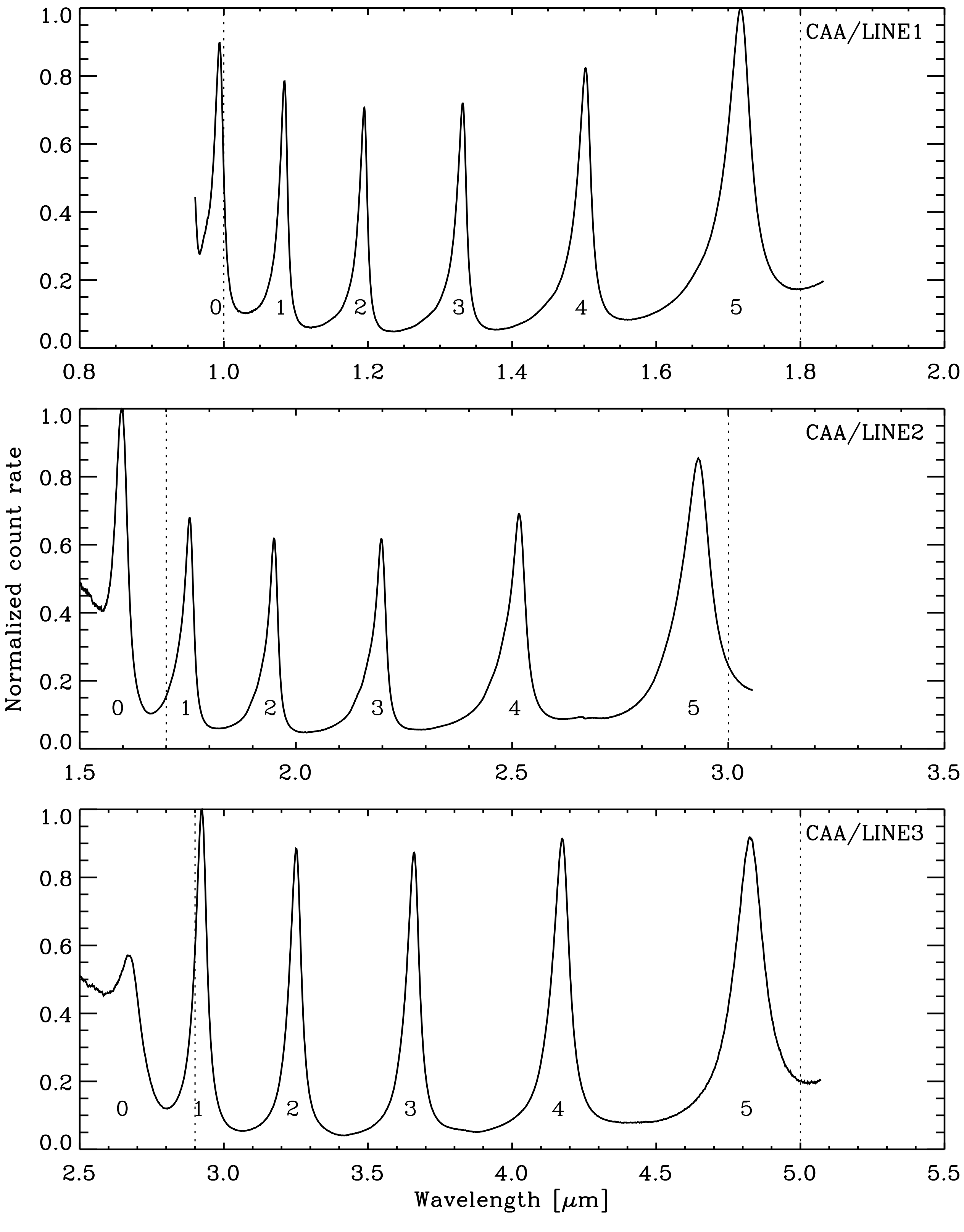

Figure 10: Extracted and normalized spectra of the CAA/LINE1 to LINE3 sources (top to bottom) taken with the appropriate medium resolution gratings (G140M, G235M, G395M, top to bottom). The vertical dotted lines denote the boundaries of the nominal science bands.

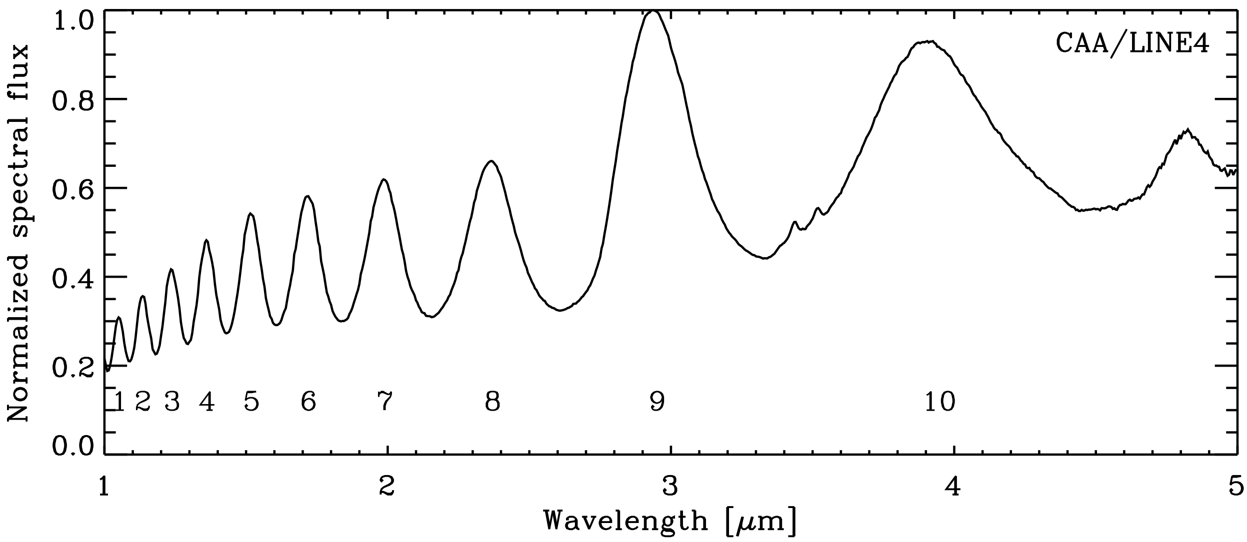

Figure 11: Extracted and normalized spectrum of the CAA/LINE4 source taken with the prism.

resolution of the prism is too low to get a reliable wavelength calibration using the Argon emission line spectra (lines very blended/confused), it is foreseen to calibrate the CAA/LINE4 lamp against the CAA/LINE1-3 sources with the prism. However, the appropriate data was not taken during FM2 cycle 1 testing an thus needs to be acquired during cycle 2. This is considered in the planning of the next calibration campaign.

4.3.1 Field of view dependence

As for the primary wavelength calibration using the Argon lines, the solution for the CAA/LINE sources will have to be interpolated over the FOV accessible for MOS observations, as not every single shutter can be calibrated on its own. If the CoGs of the CAA/LINE sources show a field dependence, then an additional uncertainty due to this dependence must be considered for the in orbit wavelength calibration. Only the medium resolution gratings are considered, because these are the ones foreseen for MOS observations.

We extracted the spectra of 128 micro shutters distributed over the FOV (from the PREP-COMBO-MOS test sequence) to get an estimate on the variation of the measured CoGs. A typical CoG map for one line is shown in Fig. 12. There seems to be only a very moderate FOV dependence, and the final wavelength calibration will interpolate over the full FOV using the 40 (in dispersion direction) times $\sim$300 (in cross-dispersion direction) micro shutters for which data were acquired in the MOS-COMBO series.

We use the observed standard variation of the CoGs across the FOV as the uncertainty due to the interpolation. The results are summarized in Table 8. The uncertainty of less than 0.065 resolution elements in all cases is regarded as a conservative number, as it was derived without interpolating the measured CoGs.

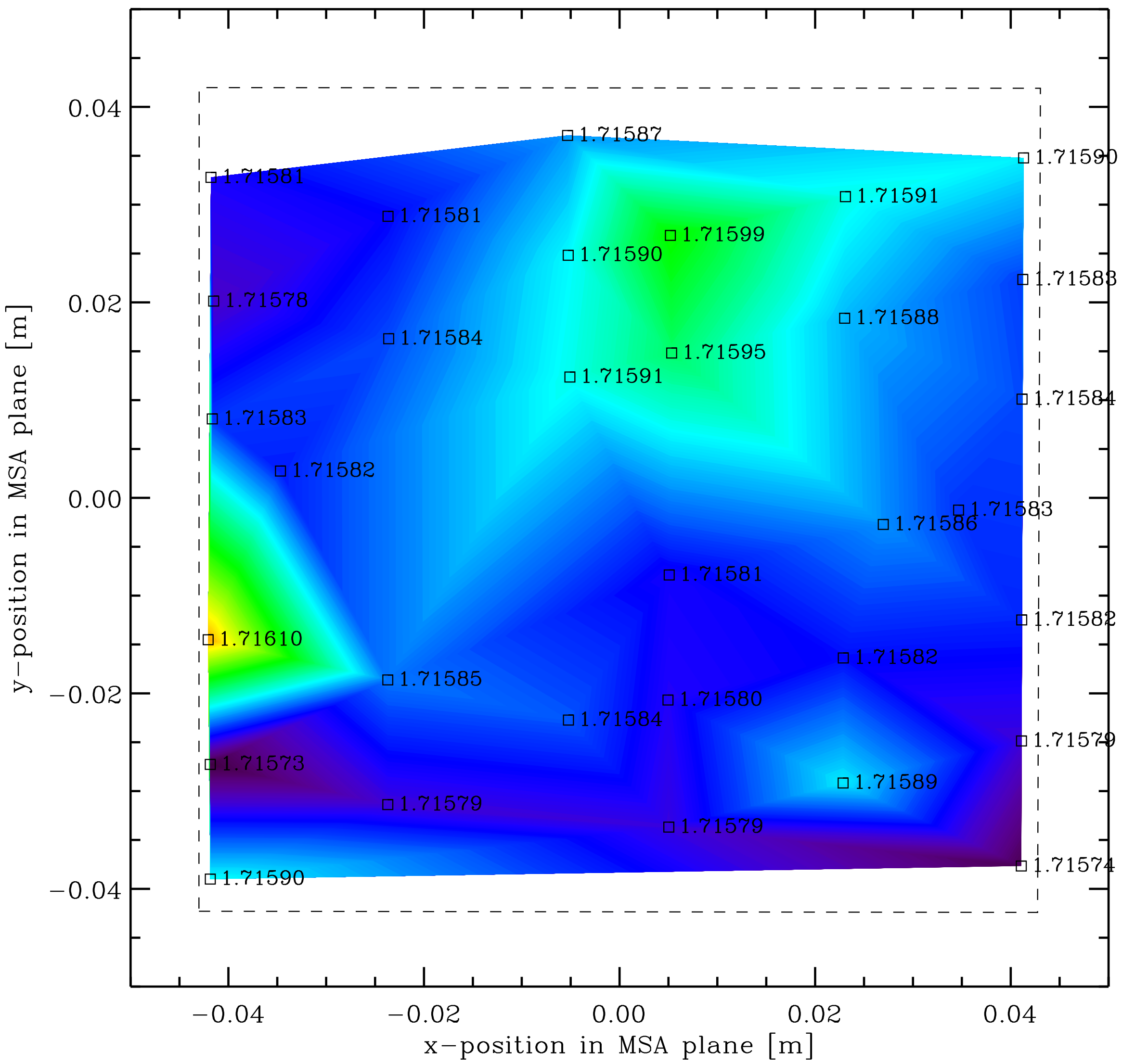

Figure 12: The measured CoG for CAA/LINE1 line index 5 over the (sparsely covered) FOV of NIRSpec. The dashed box gives the full FOV.

disperser name	CAA/LINE1-3 mean STDDEV over FOV [$\times 10^{-5}$ μm]	resolution elements
G140M	8.8	0.063
G235M	13.7	0.059
G395M	23.6	0.060

Table 8: The mean standard deviation of the COG of the five lines per CAA/LINE1-3 source over the NIRSpec FOV.

5 THE WAVELENGTH CALIBRATION ERROR BUDGETS

5.1 On ground calibration

For the gratings, the on ground wavelength calibration is based on the spectra taken of the CLS/Argon source and no transfer to the internal calibration sources in the CAA is necessary. As pointed out above, this direct approach is not viable for the prism. Therefore, the prism is foreseen to be calibrated using the CAA/LINE1-4 sources, and the plan is to acquire the necessary data during the second calibration campaign in summer 2013.

5.1.1 Fixed SLITS and IFU

For the fixed slits and IFU wavelength calibration, the accuracies reported in Table 5 apply, as no interpolation is necessary. Furthermore, we have to consider the zero point wavelength calibration accuracy due to the tilt induced by grating wheel movements. The latter can be achieved by i) using the CAA/REF source or ii) using the GWA tilt sensor. As shown above, the first approach yields an accuracy of better than 0.017 resolution elements, while the latter achieves better than 0.030 resolution elements (corresponding to 0.06 pixels, see RD04) for all dispersers. We adopt the second value for the budgets in order to be conservative.
The requirement is met with margin, the error budget is shown in Table 9 below.

Requirement/Measurement/Budget	resolution elements (1σ, RMS)
Wavelength calibration accuracy	0.0361
Dispersion relation calibration accuracy*	0.0200
Zero point calibration accuracy*	0.0300
Margin	0.1196
Requirement	0.1250

*includes stability over ~18 days

Table 9: The on ground wavelength calibration accuracy for the fixed slits and IFU for the six gratings.

5.1.2 MOS mode

For the MOS mode, only a subset of all possible micro shutters can be directly calibrated. For the remaining shutters, the derived wavelength calibration must be interpolated.
The requirement is met with margin, the error budget is shown in Table 10 below.

Requirement/Measurement/Budget	resolution elements (1σ, RMS)
Wavelength calibration accuracy	0.0440
Dispersion relation calibration accuracy*	0.0321
Calibration accuracy for fixed slits*	0.0200
Accuracy of the interpolation between slits	0.0250
Zero point calibration accuracy*	0.0300
Margin	0.1170
Requirement	0.1250

*includes stability over ~18 days

Table 10: The on ground wavelength calibration accuracy for the MOS mode for the six gratings.

5.2 In orbit calibration

The current in orbit wavelength calibration approach is based on using the internal calibration sources (see RD08). As internal calibration sources, the CAA features the REF and LINE1 to LINE4 lamps. Furthermore, the wavelength zero point calibration can be achieved using the tilt sensor of the grating wheel, as it is the case for the on ground calibration.
In the following, we list the error budgets for the in orbit wavelength calibration of the NIRSpec gratings, based on the results of the on ground testing. The existing data are not sufficient to derive the final results for the prism. However, due to the large margins in the grating budgets and the fact that the resolution elements for the prism is typically much larger than those for the gratings, we are confident that the wavelength calibration accuracy requirements can be met for the prism as well.This data was obtained during FM2 cycle 2 testing this summer.

5.2.1 Fixed SLITS and IFU

For the fixed slits and the IFU, the on ground calibration of the dispersion solution has to be transferred to the CAA/LINE sources, and thus their accuracy and stability enter the wavelength calibration budget. We have used the observed worst case value of 0.05 resolution elements for the CAA/LINE1-3 accuracy and stability.
The requirement is met with margin, the error budget for the gratings is shown in Table 11 below.

Requirement/Measurement/Budget	resolution elements (1σ, RMS)
Wavelength calibration accuracy	0.0617
Dispersion relation calibration accuracy	0.0539
On ground calibration accuracy*	0.0200
CAA/LINE1-3 calibration accuracy/stability*	0.0500
Zero point calibration accuracy*	0.0300
Margin	0.1087
Requirement	0.1250

*includes stability over ~18 days

Table 11: The in orbit wavelength calibration accuracy for the fixed slits and IFU for the six gratings.

5.2.2 MOS mode

For the MOS mode, we also have to consider the additional uncertainty in wavelength calibration due to the interpolation of the wavelength calibration and the CoG variations of the CAA/LINE sources over the FOV.
The requirement is met with margin, the error budget for the grating is shown in Table 12 below.

Requirement/Measurement/Budget	resolution elements (1σ, RMS)
Wavelength calibration accuracy	0.0931
Dispersion relation calibration accuracy	0.0881
On ground calibration accuracy*	0.0200
CAA/LINE1-3 calibration accuracy/stability*	0.0500
Accuracy of the interpolation between slits	0.0697
On ground calibration accuracy	0.0250
FOV dependence of CAA/LINE1-3 sources	0.0650
Zero point calibration accuracy*	0.0300
Margin	0.0834
Requirement	0.1250

*includes stability over ~18 days

Table 12: The in orbit wavelength calibration accuracy for the MOS mode for the six gratings.

6 CONCLUSION

In this report we have shown that the in orbit requirements on the wavelength calibration accuracy will likely be met. The requirements for on ground are shown to be met for the six gratings, and will very likely be met for the prism as well. For the latter, additional data was acquired during the FM2 cycle 2 test campaign. The data is of good quality and the wavelength calibration of the prism will continue as part of normal work after instrument delivery. Table 13 below summarizes the findings.

Requirement ID	Topic	Status
NSFR-15	In orbit wavelength calibration accuracy	LIKELY COMPLIANCE
SRD R 175	In orbit wavelength calibration accuracy	LIKELY COMPLIANCE
SRD R 180	On ground wavelength calibration accuracy	COMPLIANCE*

*LIKELY COMPLIANCE for the prism

Table 13: The status of the requirements covered by this report.

A CENTRE OF GRAVITY CALCULATION

The centre of gravity calculation is based on the method described by Cameron et al. (RD07). The CoG of a function $E(\lambda)$, in the region where $E(\lambda) \geq E_t$, is given by:

$$\mathrm{CoG} = \frac{\int_{\lambda_j}^{\lambda_k} \lambda \left[E(\lambda) - E_f\right] \, \mathrm{d}\lambda}{\int_{\lambda_j}^{\lambda_k} \left[E(\lambda) - E_f\right] \, \mathrm{d}\lambda}, \tag{2}$$

where E_t and E_f (the threshold and floor values respectively) are fractions f_T and f_F of the maximum value and λ_j and λ_k are the wavelengths on opposite sides of the peak maximum value at which $E(\lambda) = E_t$. If the peak is symmetric, the CoG will be the wavelength of the absorption/emission peak maximum. If the peak is asymmetric, as is the case for the CAA sources, the CoG will differ from the peak maximum by an amount dependent on the selection of f_T and f_F as well as the degree of asymmetry of the selected band. For a discrete set of spectral values E_i at wavelengths λ_i and bin widths w_i, the CoG can be calculated using

$$\mathrm{CoG} = 0.5 \left[\frac{\sum_{i=j}^{k} \lambda_i w_i (E_i - E_k)}{\sum_{i=j}^{k} w_i (E_i - E_k)} + \frac{\sum_{i=j}^{k-1} \lambda_i w_i (E_i - E_j)}{\sum_{i=j}^{k-1} w_i (E_i - E_j)} \right], \tag{3}$$

where E_k is the value of $E(\lambda)$ closest to E_t, and E_j is the value closest to E_t on the other side of the peak maximum, such that $E_j \geq E_k$. The double summation is required because the separate summations are biased in opposite directions.