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Ground calibration concept for the JWST Near-infrared Spectrograph (NIRSpec)

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1 Introduction

1.1 Purpose

This document describes a basic ground calibration concept for the Near Infrared Spectrograph (NIRSpec) on board JWST. It includes measurements to be made on component level, subsystem level and with the fully assembled and aligned instrument. The goal of this document is to provide an exhaustive list of calibration items to that might be performed on the ground and suggest requirements and priorities for each item on the list. The ground calibration time, particularly the available time in thermal vacuum (30 days, TBC) and fiscal budgets will severely limit the number and kind of calibration experiments that can be carried out in practise. This document was written in support of the "JWST NIRSpec System Requirements Document" (ESA-JWST-RQ-322), however, it can also serve as a guide to choose the final set of ground calibration items and subsequently construct a detailed calibration plan.

1.2 Scope

This document describes calibrations and their data products which will provide quantitative information about those characteristics which are directly relevant to the planning, conducting and analysis of scientific observations. It identifies the properties of NIRSpec which require calibration and the basic design of the tests which will obtain the information. A description of the facilities, equipment, time and laboratory resources needed for the calibration or a calibration plan which details steps to obtain these calibrations are not part of this document.

The experiments to obtain this calibration data will in many instances be similar or even identical to tests verifying performance requirements. Some of the ground calibration data can therefore be used to verify instrument performance and vice versa. However, the list of ground calibration tasks is neither necessary nor sufficient to verify the instrument performance. Overlaps need to be identified in a detailed calibration plan which is not part of this document.

2 Calibration goals

Ground calibration is an integral part of the overall calibration of NIRSpec. The overall goal of calibration is to *allow the determination, for each observed target, of the intensity of radiation as a function of wavelength and position along the spatial direction of the aperture and their errors.* In order to meet this goal the following information is required:

- Knowledge to operate the spectrograph
- Knowledge of wavelength scale
- Knowledge of spectrophotometric throughput and detector characteristics
- Knowledge of spatial PSF and line spread function
- Knowledge of relative astrometric positions along the aperture

Calibration data need to be obtained for all approved science modes. In addition, calibrations are needed for the operation of NIRSpec. The calibrations should be carried out under the following constraints:

- Minimise on-orbit calibration time investment (e.g., minimise science programme-specific calibrations).
- Maximise usefulness of science calibrations for general research. This will increase the value of the science data archive for other research projects than the original proposal.
- Routinely generate baseline calibration data which can be used to monitor instrument health, safety and performance.
- Minimize wear on limited lifetime components (e.g., MSA)

3 Calibration requirements

3.1 Sources of calibration requirements

Requirements in this document are derived from the overall calibration, operation and science requirements listed in the following documents:

- ST-ECF ISR-JWST-2003-01 - Calibration concept for the JWST Near-Infrared Spectrograph (NIRSpec) Harald Kuntschner, Robert Fosbury, Wolfram Freudling & Stefano Cristiani (v1.2, 18 Jun 2003)

- STScI-JWST-R-2003-0003 A - JWST Near Infrared Spectrograph (NIR-Spec) Operations Concept Michael Regan, Jeff Valenti, Wolfram Freudling, Harald Kuntschner & Robert Fosbury (v1.0, 23 Jun 2003)

3.2 Science requirements

The requirements for the accuracy of calibration data given in this document are based on top-level science requirements. These core calibration requirements are listed below. Where a requirement is given as a function of wavelength, the relevant sampling is assumed to be the size of one resolution element (FWHM) of the dispersive element. For imaging, it is the band-width of the filters. For spatial requirements, the sampling is assumed to be the pixel size at the detector level. All requirements are applicable to fully reduced and calibrated data, i.e. the end-product of a data reduction pipeline. We note that, in order to meet the following requirements, a typical, fully calibrated spectrum of a given target may need to be built up from multiple exposures. For example, in order to meet the spectrophotometric throughput one may need to dither individual exposures.

- The combination of absolute and relative wavelength calibration errors will be smaller than 1/7 (rms, goal 1/10) of the resolution element (FWHM) of a given dispersive element at all wavelengths and over at least 95% of the FOV.

- Assuming no Poisson noise in the signal, multiple observations of the same target with different MSA, IFU or fixed slit configurations will provide a repeatability for the integrated flux of better than 10% (rms) over at least 95% of the FOV. The relative flux uncertainty as a function of wavelength will be better than 10% (rms) over at least 95% of the FOV.

- The imaging quality without the MSA at the focal plane assembly will be diffraction limited for $3\,\mu$m and longer wavelengths (Strehl ratio > 0.8).

  The width (FWHM) of the *spatial* PSF at detector level will be known and mappable with a low order polynomial to better than 5% (rms) over at least 95% of the FOV and at all wavelengths.

  The first moment (i.e. FWHM) of the line-spread function will known and mappable with a low order polynomial over at least 95% of the FOV to better than 5% (rms) at all wavelengths.

- The astrometric position of a science target a will be known and mappable over at least 95% of the FOV to better than 20 mas (rms) for MOS & fixed slit and 15 mas (rms) for the IFU.

Ground calibration data will need to be supplemented or superceded by in-orbit calibration data to meet these science requirements. The in-orbit calibration concept is not part of this document.

3.3 Operational requirements

Operational calibration data are data necessary to operate the NIRSpec. Their availability at the start of the mission is essential because they are the prerequisite for obtaining science data and in-orbit calibration data. While it may be possible to obtain some of these calibrations in orbit as well, the ground calibration goal should be to minimize risk, i.e., provide as many calibrations as possible and allow an efficient start of in-orbit operations.

Operations which depend on calibration data include the fully autonomous target acquisition, and the configuration of the MSA. For more details see the "JWST Near Infrared Spectrograph (NIRSpec) Operations Concept Document". Calibration data needed for both of these operations are:

- The optical distortions from the AFP to the FPA need to be known and mappable over the full FOV to an accuracy better than 5 mas (rms) at any time.
- The distortions from the Sky to the FPA need to be known and mappable over the full FOV to an accuracy better than 5 mas (rms) at any time.
- If there are any movable parts in the un-dispersed imaging beam, the shift of an image on the sky due to positioning error of these parts must be known to better than 5 mas (rms).
- List of non operable MSA shutters with distinction of failed "open" or "closed".
- On board pixel-to-pixel variation in the flatfields of acquisition images must be known to better than 2% (rms).[1]

[1] This item is currently being discussed since storing a flat-field map on board puts stringent requirements on the on board memory.

4 Responsibilities

Ground calibration is an integrated part of the instrument construction. The prime contractor for NIRSpec will be responsible for carrying out the calibration tests and delivering the calibration data. ESA will provide scientific oversight, expertise and support during planning and execution of the ground calibration. The scientific analysis of the calibration data rests with the NIRSpec instrument science team. Ground calibration for NASA provided components, primarily the MSA and detectors, will be carried out before delivery to the NIRSpec contractors. However, responsibility for delivery of the final calibration data will still be with the NIRSpec contractor. Calibration of selected subsets will be repeated after integration in ISIM. The responsibility for these are TBD.

5 Ground calibration specifications

Ground calibration data will be collected at different stages of integration of the instrument and with different priorities. Calibration data which can only be collected before the instrument is assembled are usually of high priority because they cannot be obtained in orbit. For this reason, both the integration level and the priority for each calibration experiment are coded using the following scheme.

5.1 Integration levels

- Level 0 – At component level
- Level 1 – At sub-system level
- Level 2 – Full NIRSpec without MSA
- Level 3 – Full NIRSpec with MSA

5.2 Priorities

- Priority 1 - Must be carried out. Without these data, the goals of the mission cannot be achieved. There are two reasons for the importance of these data.

  (a) Calibrations which are impossible to obtain in orbit and are needed for general in orbit operation of the telescope and/or are needed for data-reduction.

(b) Calibrations which are needed for initial operation of the instrument in the early-phase of commissioning. Ground calibrations need to deliver reasonable accuracy while the reference files will be replaced by more accurate in orbit calibrations as soon as they become available.

- Priority 2 - Should be carried out. Without these data, mission goals might be compromised.

  These are calibrations which can be carried out on the ground much more efficiently or more accurately than in orbit.

- Priority 3 - Should be carried out. Without these data, achieving mission goals will be less efficient or more risky.

  Most calibrations in this category will serve as a first guess to allow for efficient setup of instrument modes in orbit.

5.3 Temperature range

JWST and therefore also NIRSpec will be passively cooled in orbit. The only part with active temperature control are the HgCdTe detectors. Their nominal temperature will be chosen to optimise detector performance and will be around 37 K (TBC). The detectors will be kept at their nominal temperature to better than ± 0.1 K (TBC). The temperature of the other NIRSpec parts in the ISIM can vary as much as ± 2 K (TBC) depending on observing conditions.

Temperature sensitive calibration data will need to be obtained at a range of temperatures, e.g., at the expected nominal temperatures and two bracketing values. For selected, critical calibration items a finer temperature sampling may be necessary (TBC). We note, that because of the active temperature control of the detectors and the complex combination of materials in the instrument and ISIM, there will be temperature gradients throughout the instrument. The gradients and their effects on the calibration concept are difficult to predict at the moment. Furthermore, it will be very difficult to reproduce realistic temperature gradients in the ground testing.

6 Deliverables

The construction phase of NIRSpec will be accompanied and/or preceded by the coding of a software model of the whole instrument. By modeling relevant physical properties, this model will allow to interpolate measured calibration data to parameter space not covered by the measurements. Wherever possible, calibration results will be expressed as parameters or reference data as used in this model, an exposure time calculator and a data-reduction pipeline.

Deliverables of all calibration measurements are the data themselves, error estimates for each data point, engineering data collected during the exposure, and documentation of the experimental setup. Where appropriate, the ground calibration should also deliver an analytic function that describes the large scale behavior of the data.

All error estimates include internal errors which specify the accuracy of measurements. Where applicable, they also include external errors which measure the temporal stability of calibration items. Such external errors are typically derived from repeated measurements in separate calibration campaigns.

Engineering data include the NIRSpec instrument sensor readings and measurements of parameters from the experimental setups. Time resolved readings will be recorded for critical items, such as readings of temperature sensors.

7 Ground calibration requirements

This section details the calibration data which should be considered for ground-based testing. It is not expected that all calibration items can be carried out during the ground calibration campaign. For each item, priorities, integration levels, accuracy and temperature ranges are specified.

Accuracies refer to the whole data sets. Sampling requirements are not listed but have to be derived from the necessary accuracy and variation of a value. For example, distortion has to be known to better than 5 mas for any position in the FOV (see section 7.8.1). The necessary spatial sampling to achieve this depends on the actual distortion.

7.1 Individual components

Calibration data for selected, individual components need to be obtained in thermal vacuum. Data which are not expected to depend on temperature can be obtained in ambient conditions. Many of the following calibrations will be carried out by the manufactures of the components and will be used to select the flight hardware.

7.1.1 Filters

Calibration: Measure transmission, wedge, surface flatness and figure, surface roughness, scratches or defects. The transmission curves need to be determined in 1.0 Å steps over the range where the filter transmission is greater than 1% and in 10.0 Å steps outside this region. The full wavelength range for the transmission calibration is 0.3 to 10 μm. The detailed steps and wavelength ranges are TBC.
Category: Priority 1a; Level 0
Deliverables: Transmission curves, documentation of the quality of the filters (wedge, surface roughness etc.)
Accuracy: $\pm 0.1\%$ of peak (rms, TBC).
Temperatures: Ambient and at mean ISIM temperature (TBC)

7.1.2 Mirrors

Calibration: Measure reflectivity as function of wavelength (0.3 to 10 μm.)
Category: Priority 1a; Level 0
Deliverables: Reflectivity as function of wavelengths
Accuracy: 0.02% of measurement (rms, TBC)
Temperatures: Ambient and at mean ISIM temperature (TBC)

7.1.3 Gratings/Prism

Calibration: Measure a) imaging and zeroth, first and second order resolution characteristics b) efficiency, c) 2-dim scattered light in and perpendicular to dispersion direction and, d) the dispersive element introduced polarisation. These tests are likely to be performed as part of the flight grating/prism selection.
Category: Priority 1a; Level 0
Deliverables: Resolution, efficiency curves, amount of scattered light and ghosts, polarisation
Accuracy: TBD
Temperatures: Ambient and at mean ISIM temperature (TBC)

7.1.4 Other optical elements in the beam

Calibration: Measurement of the transmission of any other optical elements in the beam such as detector window (0 - 10 μm).
Category: Priority 1a; Level 0
Deliverables: Transmission curves
Accuracy: Transmission to better than ± 0.0002 (TBC).

Temperatures: Ambient and at mean ISIM temperature (TBC)

7.1.5 Spatial uniformity of detector

Calibration: Measure the spatial uniformity of the detector pixels and fill factor. Image surface flatness. SCA Row-column orthogonality. Column, row straightness. These tests are likely to be performed as part of the flight detector selection.
Category: Priority 1a, Level 0
Deliverables: Physical sizes of detector and fill factor etc.
Accuracy: 1% (TBC)
Temperatures: Ambient

7.1.6 Physical sizes of apertures: MSA and fixed slits

Calibration: Measurements of the location of each aperture within the AFP. Measurements of the locations of identifiable features (such as corners, occulting bars, discontinuities in width etc.) for each slit or aperture. These measurements allow dimensions and areas to be inferred.
Category: Priority 1a; Level 0
Deliverables: Measurement of sizes in physical units
Accuracy: 1% (TBC)
Temperatures: Ambient

7.1.7 Integral field unit

Calibration: Measure the reflectance/transmission of the optical elements in the IFU path. There will be separate throughput measurement for the whole unit, so the reflectance/transmission measurement should provide detailed reflectance, transmission and scattered light numbers for all the IFU elements.
Category: Priority 1b; Level 0
Deliverables: Transmission, reflection and scattered light curves (as appropriate).
Accuracy: Transmission and reflectance to better than 0.001 (TBC)
Temperatures: Ambient and at mean ISIM temperature (TBC)

7.2 Micro shutter array (MSA)

7.2.1 Defective shutter map

Calibration: Provide list of all defective shutters. A shutter is defective if it fails to open in more than 10% (TBC) of all attempts. This test should be performed with a restrictive number of cycles in order not to wear out the MSA.
Category: Priority 1b; Level 1
Deliverables: Defective shutter map with distinction between open or closed failed.
Accuracy: 99% (TBC)
Temperatures: Ambient

7.2.2 Contrast

Calibration: Measure the contrast between closed and an open shutters. This test will include the overall light tightness of the MSA, particularly the borders between shutters.
Category: Priority 1a; Level 1
Deliverables: Contrast ratio between open and closed shutters. Distribution for full MSA.
Accuracy: <0.01% of signal with open shutters (TBC)
Temperatures: At nominal temperature of MSA

7.2.3 MSA polarisation

Calibration: Measure instrumental polarisation in each wavelength band
Category: Priority 1a; Level 1
Deliverables: Provide measure of MSA induced polarisation
Accuracy: TBD
Temperatures: Ambient

7.2.4 Wavefront

Calibration: Measure wavefront errors introduced by MSA
Category: Priority 1a; Level 1
Deliverables: Wavefront errors as function of position
Accuracy: 10nm (TBC)
Temperatures: At nominal temperature of MSA

7.3 Detector

Performance of the detector will depend on temperature. Calibration data for the full range of expected temperatures will be needed both to select the best temperature setting and to apply correction to science data based on the actual measured temperature during the observations. Since the temperature of the detector will be actively controlled, the range of temperatures needed will be limited to $\pm 1K$ (TBC).

The required accuracy of the flat-field and fringing calibrations depends on the quality of the flight devices and also on the observing strategies implemented when in space. Therefore, the requirements have to be carefully reviewed when more information becomes available.

Some of the detector tests can and should be carried out at several integration levels. For example, the dark current should be checked at subsystem level and then again in the fully assembled instrument.

7.3.1 Physical arrangement of FPA

Calibration: Measurement of SCA to SCA gap, SCA to SCA alignment.
Category: Priority 1a, Level 1
Deliverables: Metrology (TBD)
Accuracy: TBD μm, TBD rad
Temperatures: Nominal detector temperature and possibly bracketing values

7.3.2 Monochromatic detector response (flat-field)

Calibration: Measure relative pixel-to-pixel response as function of wavelength. This full set of information can probably not be obtained in orbit and is needed to produce flat-fielded spectroscopic data of high quality. The wavelength range must cover the nominal wavelength range of the NIRSpec (0.6–5.0 μm) in wavelength steps TBD, but not as fine as for the fringing measurement. The usefulness of this calibration depends on the size of the raw pixel-to-pixel variations of the detectors and the expected stability of a flat-field taken prior to launch. It is expected that the resulting flat-field data-cube will be monitored in orbit and up-dated as necessary.
Category: Priority 1a; Level 1
Deliverables: Relative response as function of pixel and wavelength
Accuracy: 2% of average response at any wavelength (TBC)
Temperatures: Nominal detector temperature and possibly bracketing values

Comments: This calibration possibly needs to be carried out with the right f/ratio of the incoming beam. Not clear if it should be better carried out at Level 3.

7.3.3 Fringing pattern

Calibration: Measurement of fringing as function of wavelength.
Category: Priority 2, Level 1
Deliverables: Fringing correction maps
Accuracy: <2% of illumination (TBC)
Temperatures: Nominal detector temperature and possibly bracketing values
Comments: This calibration needs to be carried out with the right f/ratio of the incoming beam.

7.3.4 Intra-pixel sensitivity

Calibration: Measure pixel response as function of position within the pixel. Needed for accurate photometric and wavelength calibration. Detailed measurements are TBC.
Category: Priority 1a, Level 1
Deliverables: Response as function of intra pixel position
Accuracy: 5% (TBC) of centre of pixel value
Comment: Due to the large pixels in NIRSpec (i.e. undersampling) the intra pixel response will be important for TA and may be important for the spectral sampling.

7.3.5 Image persistence

Calibration: Measurement of image persistence.
Category: Priority 1b, Level 1
Deliverables: Image persistence as function of flux, time and subsequent readouts.
Accuracy: 0.005% (TBC) of stimulating flux (requirement goal is 0.01%)
Temperatures: Nominal detector temperature and possibly bracketing values
Comments: This measurement is needed at the subsystem level in order to plan and control the calibrations at full NIRSpec level - perhaps need active software treatment of image persistence in ground calibrations.

7.3.6 Dark

Calibration: Determine dark current in the longest foreseen exposure time at the beginning of mission (e.g., 1 000 s) with standard up-the-ramp sampling. This long dark will include shorter exposure times since there is only one readout mode and gain setting. However, one needs to built up the signal (i.e. 20 000 s TBC) for the shorter exposure times so this task will be time consuming.
Category: Priority 1b; Level 1, 3
Deliverables: Dark current frames for all foreseen exposure times, with standard up-the-ramp sampling. The individual calibration frames should be saved and made available to the calibration team. The unit of dark current is $e^{-} s^{-1}$pixel^{-1}.
Accuracy: <5% (TBC) of dark current
Temperatures: Nominal detector temperature and possibly bracketing values

7.3.7 Bias

Calibration: Measure detector output without stimulus. The use of reference pixels may greatly reduce the need for extensive ground calibrations. However, possible bias drifts as a function of time and temperature should be documented. Also needed as input for data-reduction pipeline construction. Possibly sub-array modes need to be treated separately.
Category: Priority 1b; Level 1, 3
Deliverables: Bias frames. Documentation how to remove the bias from images.
Accuracy: 1 ADU (TBC)
Temperatures: Nominal detector temperature and possibly bracketing values

7.3.8 Total noise

Calibration: Measurement of total noise per pixel. Total noise includes read noise, shot noise from dark current, shot noise from amplifier glow, 1/f variations, electronics and cable noise, clocks and bias stability, etc. This measurement should be taken for the longest forseen exposure time at the beginning of mission (e.g., 1 000 s) and a subset of shorter exposure times (TBC). The unit for the total noise is e^{-}.
Category: Priority 2a; Level 1, 3
Deliverables: Total noise frames for a given set of exposure times
Accuracy: 5% (TBC) of total noise

Temperatures: Nominal detector temperature and possibly bracketing values
Comments: A break up of the individual noise components may be useful and the possibility should be considered in a detailed calibration plan.

7.3.9 Gain

Calibration: Measurement of conversion gain
Category: Priority 1b; Level 1, 3
Deliverables: Gain value
Accuracy: 2% (TBC) of value
Temperatures: Nominal detector temperature and possibly bracketing values

7.3.10 Full well

Calibration: Measurement of full well
Category: Priority 2; Level 1, 3
Deliverables: Full well value
Accuracy: 5% (TBC)
Temperatures: Nominal detector temperature and possibly bracketing values

7.3.11 Linearity

Calibration: Measure DN output as function of stimulus up to 99% of full well for each pixel on the array.
Category: Priority 1b; Level 1, 3
Deliverables: Response curve as function of stimulus for each pixel.
Accuracy: 0.1% of stimulus or 1 DN, whatever is larger (TBC)
Temperatures: Nominal detector temperature and possibly bracketing values

7.3.12 Detective quantum efficiency

Calibration: Measure the detective quantum efficiency in absolute terms over the wavelength range of 0.3 to 10 μm (TBC). The wavelength range outside the nominal operation range of NIRSpec is needed to control the background and potential contamination. The nominal operating wavelength range (0.6 to 5 μm) must be sampled in steps of 0.003 μm or smaller[2]. Wave-

[2] Need to sample the DQE gradient requirement 7.2.1.9 of <3% / 0.01 μm.

length sampling outside nominal range is TBC. We also need some repeat tests to check for aging effects.
Category: Priority 1a; Level 1, 3
Deliverables: Detective Quantum Efficiency curve as function of wavelength and temperature.
Accuracy: <2% of peak signal (TBC)
Temperatures: Nominal detector temperature and possibly bracketing values

7.3.13 Bad pixel map

Calibration: Identify non operable pixels. Non operable pixels are dead pixels (pixel with $QE < 10\%$), anomalous reset pixels, photo emissive defects (TBC). This information is needed for the first TA sequences.
Category: Priority 1b, Level 1, 3
Deliverables: List of non-operable pixels
Accuracy: >99% of non-operable pixels identified (TBC)
Temperatures: Nominal detector temperature and possibly bracketing values

7.3.14 Cross talk

Calibration: Measurement of (a) charge diffusion and (b) electronic cross-talk from naturally occurring cosmic rays in dark exposures.
Category: Priority 1b; Level 3
Deliverables: Calibration of cross-talk TBC
Accuracy: TBD
Temperatures: not temperature sensitive since this is second order effect

7.4 Optical performance and alignment

7.4.1 Scattered light and stray light

Calibration: Measure amount of scattered light in the system for all operating modes (including point sources, and internal calibration lamps).
Category: Priority 2; Level 3
Deliverables: values for back scattering on MSA support structure, MSA and filter back scattering, stray light due to PSF wings, strength and position of any ghosts.
Accuracy: 10% (TBC)
Temperatures: nominal ISIM temperature

7.4.2 Filter offsets

Calibration: Measure the spatial offsets resulting due to different filters.
Category: Priority 2; Level 3
Deliverables: filter offsets relative to the transparent filter wheel position
Accuracy: better than 5mas (TBC)
Temperatures: nominal ISIM temperature

7.4.3 Focus calibration

Calibration: Determine the best focus and the resulting 2-dim PSF shapes in central field of view. Also calibrate the systematic variations of PSF with deviations form the optimal focus point.
Category: Priority 3; Level 3
Deliverables: Focus position, in and out of focus PSFs
Accuracy: TBD
Temperatures: nominal ISIM temperature
Comments: The systematic variations of the PSF can be used in orbit to allow for efficient focus procedures. Particularly helpful at beginning of mission.

7.4.4 Focus variation over FOV

Calibration: Determine the variation of the PSF over the FOV at best focus
Category: Priority 2; Level 3
Deliverables: Focus positions for at least 4 points other than the center of the FOV
Accuracy: TBD
Temperatures: nominal ISIM temperature

7.4.5 PSF at field center delivered to MSA

Calibration: Measure the accurate PSF shape at field centre at aperture focal plane. For this calibration it is probably necessary to remove the MSA unit and replace it with a detector.
Category: Priority 1a; Level 2
Deliverables: Flux as function of position
Accuracy: 2% (TBC) of peak value
Temperatures: nominal ISIM temperature
Comment: Spatial sampling to be derived from accuracy requirement

7.4.6 PSF at field center delivered to Detector without MSA

Calibration: Measure the accurate PSF shape at field centre at detector level - MSA not implemented to allow for pure optics calibration.
Category: Priority 1a; Level 2
Deliverables: Flux as function of position
Accuracy: 2% (TBC) of peak value
Temperatures: nominal ISIM temperature
Comment: Spatial sampling to be derived from accuracy requirement

7.4.7 PSF field dependence (imaging mode)

Calibration: Determine the 2-dim PSF as function of FOV at optimal focus position.
Category: Priority 3; Level 3
Deliverables: 2-dim PSF as function of FOV
Accuracy: $<$5% of peak value (TBC)
Temperatures: nominal ISIM temperature

7.4.8 PSF field dependence (spectroscopic mode)

Calibration: Determine the 2-dim PSF as function of FOV and wavelength at optimal focus position.
Category: Priority 3; Level 3
Deliverables: 2-dim PSF of incoming point source and unresolved emission lines as function of FOV and wavelength for all dispersive elements
Accuracy: $<$5% of peak value (TBC)
Temperatures: nominal ISIM temperature

7.4.9 Imaging mirror on grating wheel

Calibration: Demonstrate the in orbit position calibration procedure for the imaging mirror on the grating wheel (if not in a fixed position). This calibration includes the use of some TBD fixed slits in the AFP. The procedure will happen on board and reference fields supporting this calibration need to be produced.
Category: Priority 1; Level 3
Deliverables: reference files enabling on board calibration of imaging mirror position, these must include a measure of the reproducibility of the grating wheel.
Accuracy: $<$5 mas positional accuracy (TBC)
Temperatures: nominal ISIM temperature

7.5 Wavelength calibration

Temperature dependence may be a critical calibration item for the wavelength scale. Therefore, the temperature sampling needs to be adjusted to the actual variations.

7.5.1 Dispersion relation - external source

Calibration: Measure the detector position – wavelength relation for all spectral modes with OTE simulator. The OTE-simulator must deliver a high resolution sampling of the full wavelength range (ideally, 50 to 100 semi-uniformly distributed, well separated emission lines for each band) in order to verify the spectral model. The dispersion needs to be determined over the whole FOV.
Category: Priority 1a; Level 3
Deliverables: Detector position as function of wavelength
Accuracy: <1/20 of FWHM (TBC)
Temperatures: Range of nominal operating temperatures
Comments: This data will be needed to serve as input for the instrument model, to calibrate the internal calibration channel, to develop the data-reduction pipeline and guide commissioning data-reduction.

7.5.2 Dispersion relation - internal channel

Calibration: Measure the detector position – wavelength relation for all spectral modes with internal calibration channel.
Category: Priority 2; Level 3
Deliverables: Position as function of wavelength
Accuracy: <1/20 of FWHM (TBC)
Temperatures: Range of nominal operating temperatures
Comments: This data will be needed to develop the data-reduction pipeline and guide commissioning data-reduction.

7.5.3 Wavelength zero points

Calibration: Measure the change of wavelength zero points as function of temperature, instrument configurations, operating sequences.
Category: Priority 2; Level 3
Deliverables: Zero point drifts as function of temperature and instrument configurations, operating sequences.
Accuracy: <1/50 of FWHM (TBC)
Temperatures: Range of nominal operating temperatures

7.6 Instrument throughput - imaging mode

Temperature sensitivity of instrumental throughput is mainly due to the detector which is tested separately. Therefore, throughput for imaging mode needs to be obtained only at the nominal instrument temperature.

7.6.1 Filter large scale flat fields

Calibration: Determine the flat field for each filter including the long pass filters which may be used for TA. Need to use OTE simulator with continuum lamp.
Category: Priority 1a; Level 2
Deliverables: Detector flat fields for each filter without MSA
Accuracy: <2% (TBC)
Temperatures: Nominal ISIM temperature
Comments: These flat fields will be used for the instrument model and on board to allow for TA. Note the integration level 2 which has the MSA removed.

7.6.2 Imaging flat fields

Calibration: Measure the flat field of the whole NIRSpec in imaging mode
Category: Priority 1b; Level 3
Deliverables: Flat field including MSA
Accuracy: 2% (TBC)
Temperatures: Nominal ISIM temperature

7.6.3 Absolute instrument efficiency

Calibration: Measure the overall throughput of the instrument with a source of known output. Measurement in all instrument modes.
Category: Priority 2; Level 3
Deliverables: Efficiency as function of wavelength
Accuracy: <5% (TBC)
Temperatures: Nominal ISIM temperature

7.7 Spectral instrument throughput

Temperature sensitivity of instrumental throughput is mainly due to the detector which is tested separately. Therefore, throughput for spectroscopic modes need to be obtained only at the nominal instrument temperature.

7.7.1 Response variations within MSA element

Calibration: Measure instrument throughput for point source at a grid of positions within a single MSA element. This measurement is to be repeated for a total of 10 (TBC) positions on the MSA.
Category: Priority 1a, Level 1
Deliverables: Map of throughput variations for selected shutters
Accuracy: 5% (TBC)
Temperatures: Nominal ISIM temperature

7.7.2 Relative spectroscopic throughput

Calibration: Obtain 0th, first and second order spectra of a flux calibrated continuum source for different positions within the FOV.
Category: Priority 1a, Level 3
Deliverables: Throughput as function of wavelength
Accuracy: $<$5% (TBC)
Temperatures: Nominal ISIM temperature

7.7.3 Absolute instrument efficiency

Calibration: Absolute throughput at centre of each band
Category: Priority 1a, Level 3
Deliverables: Absolute throughput at centre of each band
Accuracy: 5% (TBC)
Temperatures: Nominal ISIM temperature

7.8 Location of spectra and distortion

The location of spectra and distoration might depend on temperature. The need to carry out these test at a range of temperatures TBC.

7.8.1 Distortion OTE-FPA

Calibration: Measure the distortion from the OTE to the FPA. This calibration together with the MSA – FPA distortion map will be used to obtain the OTE – MSA distortion. The calibration involves the OTE simulator configured with a grid mask ("pin-holes") a fully opened MSA and the mirror selected in the grating wheel. To achieve the required accuracy the grid mask probably needs to be dithered on a sub-shutter level.
Category: Priority 1b; Level 3
Deliverables: Distortion map OTE – MSA

Accuracy: <5 mas (TBC)
Temperatures: Nominal temperature and possibly bracketing values

7.8.2 Distortion MSA-FPA

Calibration: Measure the distortions in the spectrographic stage. The instrument will be configured in imaging mode with the continuum lamp on. The MSA is configured in a TBC pattern which allows to measure the distortions between MSA – FPA. A distortion law (TBC) will be fit to the measurements. This model includes the orientation of the detector relative to the MSA. It is expected that several MSA configurations and high S/N levels (i.e.>100) are needed to achieve the required accuracy.
Category: Priority 1b; Level 3
Deliverables: Distortion map MSA – FPA
Accuracy: <5 mas (TBC)
Temperatures: Nominal temperature and possibly bracketing values

7.8.3 Location of spectra on detector, trace

Calibration: For each spectral configuration the spatial location of spectra on the detectors needs to be calibrated. Knowledge of moderately accurate position of the trace is relevant for the extraction of the spectra, even though the exact shape of the trace can be measured from science data. This test can be performed with the internal calibration channel (continuum lamp). The MSA will be configured with columns of open shutters separated by a few closed ones. The MSA configuration is such to avoid overlap of spectra on the detectors.
Category: Priority 2; Level 3
Deliverables: Spectral trace for all instrument configurations. Format TBC.
Accuracy: 20 mas (TBC)
Temperatures: Nominal temperature and possibly bracketing values

7.8.4 Shape and position of MSA slits on detectors

Calibration: Projection of MSA slits onto focal pane
Category: Priority 3, Level 3
Deliverables: Projected shape and position of shutters
Accuracy: 5 mas (TBC)
Temperatures: Nominal temperature and possibly bracketing values

7.8.5 Shape and position of the fixed slits

Calibration: The relative position of the fixed slits with respect to the MSA. This calibration is needed to allow for accurate TA for the fixed slits.
Category: Priority 2a, b; Level 3
Deliverables: Relative map of MSA plane
Accuracy: <3 mas (TBC)
Temperatures: Nominal temperature and possibly bracketing values

7.9 Target Acquisition

TA is not expected to be temperature sensitive (TBC).

7.9.1 Position Bias

Calibration: Determine position measured by TA algorithm as function of true position.
Category: Priority 1b; Level 3
Deliverables: Position bias as function of true position
Accuracy: <5 mas (TBC)
Temperatures: nominal temperature

7.9.2 TA slits

Calibration: Shape and position of TA slits relative to MSA
Category: Priority 1b; Level 3
Deliverables: Images of TA slits which include reference shutters of MSA
Accuracy: <5 mas (TBC)
Temperatures: nominal temperature
Comments: The special TA slits may not need to be implemented if the imaging mirror is fixed.

7.9.3 Movable Mirror Measurement

Calibration: Calibrate movable mirror positioning algorithm
Category: Priority 3; Level 3
Deliverables: Parameters of algorithm used to determine mirror position
Accuracy: Uncertainty of sky position due to mirror calibration less than 5mas (TBC)
Comments: This calibration does not need to be performed if the mirror is fixed.

7.10 Calibration of internal calibration Channel

Depending on the chosen design for the calibration lamp, calibration might be temperature sensitive. The effects of internal lamp heating need to be carefully evaluated.

7.10.1 Illumination uniformity of lamps

Calibration: Measure the illumination uniformity of line and continuum lamps.
Category: Priority 3; Level 3
Deliverables: Illumination frames
Accuracy: <5% of mean for large scale variations of both lamps; <1% of mean for small scale variations of continuum lamp (TBC)
Temperatures: Nominal temperature and possibly bracketing values

7.10.2 Applicability of internal lamps

Calibration: Compare the results from the OTE-simulator calibration lamps with the internal calibration channel and validate the ICC.
Category: Priority 1b; Level 3
Deliverables: TBD
Accuracy: TBD
Temperatures: Nominal temperature and possibly bracketing values

7.10.3 S/N vs exposure time

Calibration: Measure the S/N vs exposure time for both lamps in each of the operation modes. Including tests for lamp heating. Identify all ICC operation modes which could harm the detector or impact the observations following the calibration frames (e.g., image persistence).
Category: Priority 3; Level 3
Deliverables: Optimal set-up for calibration in all operating modes. Identification of calibration modes which could impact on the following exposures.
Accuracy: 5% (TBC) of exposure time setting.
Temperatures: Nominal temperature and possibly bracketing values

7.10.4 Line source, lines

Calibration: Measure the wavelength of all line features over the nominal wavelength range (0.6 to 5 μm). This test needs to be repeated at the resolution of all dispersive elements to handle blends. Need also high resolution

(>3000) line-identification to characterise the line-lamp. Furthermore aging tests need to be performed to characterise the stability of the lamps. A measure of the relative line-strengths as function of operating current should also be provided.
Category: Priority 1a; Level 1
Deliverables: Wavelength of all line features for each grating/prism and the relative line-strengths.
Accuracy: <1/40 FWHM for all dispersive modes (TBC)
Temperatures: Nominal temperature and possibly bracketing values

7.11 IFU Calibration

The implementation of an IFU in NIRSpec is currently an option in the "JWST NIRSpec System Requirements Document". Although it shares the same detectors as the MOS and fixed slit modes it is conceptionally sufficiently different that it warrants its own calibration items.

The goal is to be able to characterize the performance of the IFU, in particular, to know its throughput, contrast, flat field, focus, spatial and spectral PSF (both at center of field, and over the field of view), wavelength calibration, slitlet calibration

7.11.1 Throughput

Calibration: Measure the throughput of the whole instrument when used in the IFU mode. Ideally, the throughput should be known for all slitlets within the field of view, but this can be usefully split up into an absolute measurement at the center of field, combined with a relative measurement over the field of view.
Category: Priority 1b, Level 3
Deliverables: Absolute throughput of the entire instrument in IFU mode at the center of the field of view, and relative throughput of the whole instrument covering every pixel of the field of view.
Accuracy: 5% (TBC)
Temperatures: At nominal temperature of NIRSpec.

7.11.2 Contrast

Calibration: With an appropriate sized source centered on one slitlet of the IFU, measure the amount of detected scattered/stray light on all other slitlets. The source size should be chosen so as to underfill the slitlet geometrically. Ideally, the calibration should be repeated for each slitlet, although

it might be sufficient to do it for eight equispaced slitlets spanning the field of view.
Category: Priority 1a, Level 3
Deliverables: Fraction of light spilling over into other slitlets for a source centered on one slitlet of the IFU.
Accuracy: 3-5% of the measured flux in the other slitlets, up to 0.1% of the peak flux of the source (TBC)
Temperatures: At nominal temperature of NIRSpec.

7.11.3 Flat field

Calibration: Measure the relative illumination of each detector pixel when illuminated by light going through the IFU. In practice, the flat field can be decomposed into a spatial flat field and a spectral flat field, with the spatial flat field providing the variations over the field of view of the reconstructed image at a single (central wavelength), and the spectral flat field providing the variation with wavelength.
Category: Priority 1b, Level 3
Deliverables: Relative instrumental response to a spatially and spectrally flat illumination source, covering the entire field of view and the full wavelength range of operation.
Accuracy: <2% (TBC) of the average response
Temperatures: At nominal temperature of NIRSpec.

7.11.4 Focus

Calibration: Determine the best focus of the spectrograph when used with the IFU. It might be possible to modify the location of the IFU optics to achieve the optimal focus in the IFU mode. If the filter wheel is located close to the pupil plane, blocking off first the left half and then the right half of the pupil could be used to determine the distance to best focus efficiently.
Category: Priority 3, Level 3
Deliverables: Position of IFU optics for best focus, out of focus PSFs
Accuracy: TBD
Temperatures: 35-39K, in steps of 0.5 K (the dependence of focus on instrument temperature can be used as an independent means of calibrating the instrument temperature in orbit (esp. during the initial cooldown period)

7.11.5 Spatial PSF

Calibration: Reconstructed images of point sources at various locations spanning the field of view of the IFU should be obtained to characterize the

spatial PSF variations over the FoV. These observations are also useful to determine the trace of point-like sources located at various field points
Category: Priority 1b, Level 3
Deliverables: Reconstructed images (i.e. PSFs) of objects located at a number of positions (25) spanning the entire IFU field of view.
Accuracy: The source position should be known to about 5%, PSF to at least 1% of its peak (TBC)
Temperatures: At nominal temperature of NIRSpec.

7.11.6 Spectral PSF

Calibration: The spectral PSF provides the line spread function for all field points within the IFU field of view. Accurate knowledge of the line spread function is important for on-IFU background subtraction, which will be an often-used mode of the IFU. It is especially important if the background is dominated by narrow emission lines. The uniformity of the line spread function directly determines the accuracy of on-IFU sky subtraction. If feasible, observations should be made while micro-stepping the diffraction grating by a fraction of a pixel, so that the line spread function may be measured with much better than Nyquist sampling over the entire wavelength range.
Category: Priority 1a, Level 3
Deliverables: Images of arc lamps spanning the entire wavelength range, and covering the entire IFU field of view, with the gratings micro-stepped in steps of 0.2 pixels to get good sampling of the line spread function. In addition, if an array of pin-holes can be illuminated by the arc lamps, these data could be used to completely characterize the optical performance of the spectrograph.
Accuracy: 1% (TBC) of line peak intensity
Temperatures: At nominal temperature of NIRSpec.

7.11.7 Wavelength calibration

Calibration: Produce a wavelength map describing the central wavelength of each detector pixel for the nominal positions of all gratings. These are based on smooth polynomial fits of observations of arc lines with known wavelengths. Accurate vacuum wavelengths need to be used, and blends discarded appropriately.
Category: Priority 1a, Level 3
Deliverables: Wavelength maps describing the cental wavelength of each detector pixel for the nominal positions of all gratings.
Accuracy: <0.1 pixel (TBC)

Temperatures: At nominal temperature of NIRSpec. In addition, the drift of wavelength zero point with temperature will need to be investigated and tabulated.

7.11.8 Slitlet positions

Calibration: A measurement of the center-to-center distance between slitlets of the image slicer, measured in detector pixel units. This information is crucial to being able to reconstruct images from the dispersed spectra. Although by design, each IFU slitlet is designed to occupy an integer number of pixels, in-accuracies in optics fabrication lead to some error in the overall magnification provided by the spectrometer optics. The data from individual slitlets are stacked one above the other to create the reconstructed data cube. An accurate measurement of the center-to-center spacing between slitlets is required in order to perform this reconstruction. The calibration is carried out by aligning a long slit that spans the entire IFU field of view such that it is exactly orthogonal to the slitlets of the image slicer. The slit is illuminated by a continuum source, and the resulting spectra are fitted with 1-D Gaussians to determine the exact center-to-center spacing between slitlets, as measured on the detector.
Category: Priority 1a, Level 1
Deliverables: Center-to-center spacings of the individual slitlets of the IFU, as a function of wavelength, for all the nominal grating settings. (The magnification of the spectrograph optics will have a weak wavelength depedence, hence there is a need to calibrate the slitlet positions over the entire operating wavelength range.)
Accuracy: <0.1 detector pixel (TBC)
Temperatures: At nominal temperature of NIRSpec.

Table 1: Acronym description

Acronym	Description
AFP	Aperture Focal Plane
DRM	Design Reference Mission
FF	Flat Field
FGS	Fine Guidance Sensor
FOV	Field of View
FPA	Focal Plane Array
IFU	Integral Field Unit
ISIM	Integrated Science Instrument Module
JWST	James Webb Space Telescope
MSA	Micro-Shutter Array
NIRCam	Near-Infrared Camera
NIRSpec	Near-Infrared Spectrograph
POM	Pick-off Mirror
PSF	Point Spread Function
QE	Quantum Efficiency
SCA	Sensor Chip Array
SI	Science Instrument
TA	Target Acquisition