NIRSpec

Operations Concept Document

JWST Ops-02

James Webb Space Telescope

prepared by

original signed by
T. Böker - ESA JWST Deputy Project Scientist

25 March 2010

Date

electronically signed by
J. Tumlinson - STScI NIRSpec Instrument Scientist

25 March 2010

Date

approved by

original signed by
P. Jakobsen - ESA JWST Project Scientist

25 March 2010

Date

original signed by
P. Jensen - ESA JWST Project Manager

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</tr>
<tr>
<td>ESA Science Team</td>
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1 PURPOSE AND SCOPE

This document gives an overview of the principles and concepts for operating NIRSpec. All observational modes of the instrument are described, and the main aspects relevant for using NIRSpec are discussed. Moreover, all major hardware components and mechanisms requiring attention from an operational point-of-view are described, and estimates for their on-orbit usage are given.

1.1 Reference Documents

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Table 1-1 List of reference documents
2 OVERVIEW OF NIRSPEC

NIRSpec is the Near-Infrared Spectrograph for the James Webb Space Telescope (JWST), a large-aperture, infrared-optimized telescope to be operated in deep space at the second Lagrange point (L2). The JWST focal plane (see Figure 1.1-1) contains apertures for four science instruments and the Fine Guidance Sensor (FGS), which assures an accurate and stable telescope pointing. The NIRSpec adds a spectrographic capability at near-infrared (NIR) wavelengths to the JWST instrument suite. Designed as a multi-object spectrograph (MOS), NIRSpec will be able to observe up to 100 astronomical objects simultaneously. It has a large field of view (≈3′×3′) and is highly sensitive over its wavelength range (0.6–5μm). The purpose of NIRSpec is to provide low (R = 100), medium (R = 1000), and high-resolution (R = 2700) spectroscopic observations in support of the four main science themes of JWST:

1. The end of the dark ages: first light and re-ionization
2. The assembly of galaxies
3. The birth of stars and proto-planetary systems
4. Planetary systems and the origins of life

A complete description and discussion of the NIRSpec science goals and requirements is provided in the JWST Science Requirements Document (RD4). In what follows, we only present a short overview of the NIRSpec science applications, observing modes, and design characteristics to provide some context for the remainder of this document, which presents the NIRSpec functional elements and operational modes in more detail.

Figure 1.1-1 Layout of the JWST focal plane. The entrance fields of the four science instruments and the Fine Guidance Sensor are indicated. The arrow in the NIRSpec FOV denotes the dispersion axis.
2.1 NIRSpec Scientific Applications and Observing Modes

NIRSpec is capable of obtaining NIR spectra of a rich diversity of astronomical objects. While optimized for observations of objects that are distant, faint, compact, and numerous (science themes 1 and 2 above), NIRSpec also offers observing modes that can accommodate studies of sources that are nearby, bright, and perhaps extended. Table 2-1 summarizes the various observing modes of NIRSpec and their main scientific applications. Multi-object spectroscopy will make use of the Micro-Shutter assembly (MSA), while single-object spectroscopy will be performed using either the IFU (for extended objects) or the fixed slit aperture that best matches the object size and desired spectral resolution. To avoid the confusion that would be caused by overlapping grating orders, the full spectral range of NIRSpec is divided into three separate wavelength intervals, each requiring a separate exposure with a different order-sorting long-pass filter.

Every instrument mode listed in Table 2-1 is allowed by instrument flight software and can be used safely. However, it is possible that some modes will not be fully calibrated or fully supported operationally. See Section 4 for details on how these modes make use of the various filters and gratings in combination.

Table 2-1 NIRSpec instrument modes

<table>
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<th>Mode</th>
<th>Target type</th>
<th>Wavelength range</th>
<th>Aperture mask</th>
<th>Spectral Resolution</th>
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<td>MSA spectroscopy</td>
<td>rich fields or very extended object</td>
<td>0.6 – 5.0 ( \mu \text{m} )</td>
<td>any config. of 0.2&quot; x 0.46&quot; micro-shutters</td>
<td>R<del>100 or R</del>1000 or R~2700</td>
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<tr>
<td>Fixed Slit Spectroscopy</td>
<td>single compact object</td>
<td>0.6 – 5.0 ( \mu \text{m} )</td>
<td>0.1&quot; x 1.9&quot; or 0.2&quot; x 3.3&quot; or 0.4&quot; x 3.8&quot; FS</td>
<td>R<del>100 or R</del>1000 or R~2700</td>
</tr>
<tr>
<td>Integral-field Spectroscopy</td>
<td>moderately extended object</td>
<td>0.6 – 5.0 ( \mu \text{m} )</td>
<td>3.0&quot; x 3.0&quot; IFU</td>
<td>R<del>100 or R</del>1000 or R~2700</td>
</tr>
<tr>
<td>Target Acquisition</td>
<td>reference stars (n~10-20)</td>
<td>0.8 – 2.0 ( \mu \text{m} )</td>
<td>shutters open, except around bright targets</td>
<td>undispersed imaging (MIRROR)</td>
</tr>
<tr>
<td>Internal Calibrations</td>
<td>none</td>
<td>0.6 – 5.0 ( \mu \text{m} )</td>
<td>any config. of micro-shutters and FS/IFU</td>
<td>undispersed or R<del>100 or R</del>1000 or R~2700</td>
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2.2 **NIRSpec Design Overview**

Before describing in detail each component of the NIRSpec instrument, it is instructive to review the overall instrument design. NIRSpec is an all-reflective system with a total of 14 mirrors along with 7 interchangeable dispersive elements and 8 interchangeable filters. The three major optical sub-systems (FORE, COLL, and CAM) are implemented as three mirror anastigmats (TMAs) that will be fabricated, aligned, and verified as stand-alone units in order to simplify instrument alignment. Figure 2.2-1 is a simplified diagram of the optical path from the optical telescope element (OTE) to the NIRSpec detector. The optical train has three image planes (shown in blue) and three pupil planes (shown in red). The pupil planes are located (i) at the OTE primary mirror, which is the limiting pupil stop of the system, (ii) at the position of the optical filters, and (iii) at the position of the dispersive element (prism or grating). The three image planes of the NIRSpec optical train are located (i) at the OTE focal surface, (ii) the micro-shutter assembly (MSA), and (iii) at the focal plane assembly (FPA).

![Figure 2.2-1](image1.png)

**Figure 2.2-1:** Schematic diagram of the telescope and NIRSpec optical path.

Figure 2.2-2 shows a projected view of the NIRSpec optical path, and Figure 2.2-3 shows the mechanical implementation of NIRSpec on the optical bench assembly (OBA).

### 2.2.1 COUPLING OPTICS

The Coupling Optics consist of two flat mirrors that “pick off” the NIRSpec portion of the OTE focal plane, and redirect the diverging OTE beam (with an f/20 focal ratio) into the NIRSpec fore optics (FORE). A field mask is positioned just in front of the first coupling mirror. The field mask together with a closed optical base plate structure and an internal pupil mask acts to minimize the amount of out-of-field stray light entering the NIRSpec beam.
Figure 2.2-2 Projected view of the NIRSpec optical path. A 90 degree counter-clockwise rotation would match this projection to the optical diagram in Figure 2.2-3.

Figure 2.2-3 Mechanical implementation of NIRSpec on the optical bench assembly. Note: the acronym CIS is no longer used, it should read CAA instead.
2.2.2 FORE OPTICS, FWA, RMA, AND MSA

The FORE optics telecentrically reimage part of the curved OTE focal surface onto the flat MSA aperture plane, creating an accessible pupil image at the filter wheel assembly (FWA). The field of view (FOV) is rotated 41.5° with respect to most other instruments, to take advantage of the natural symmetry axis of the OTE (see Figure 1.1-1). At the position of the FWA, the beam is nearly collimated (minimizing longitudinal chromatic aberrations), with a nominal incidence angle (of the chief ray) of 5.3° in order to avoid ghosting. The filter wheel itself contains two broadband filters, four long-pass filters, and one clear aperture, all on CaF₂ or BK7 substrates, as well an opaque position that serves as an instrument shutter. The FWA is described in detail in Section 4.4.

The refocus mechanism assembly (RMA, described in Section 4.6) determines the exact position where the telescope focal surface is reimaged onto the MSA. The RMA compensates for any changes in OTE focal position that may occur during launch and throughout the JWST lifetime. Due to the penta-prism geometry of the RMA, adjusting the focus does not affect wave front error (WFE) and does not translate the optical beam laterally. This design minimizes the need for calibration data at different focus positions, increasing NIRSpec operational efficiency.

An important feature of the FORE optics system is that it is telecentric at the MSA plane. This means that the magnification is invariant to changes in the focus position. In other words, the image scale as well as the location of individual sources at the MSA remains constant during a focus “sweep” with the RMA. This obviously has tremendous advantages for calibrating the exact field distortion at the MSA plane.

The MSA itself is described in Section 4.2. It is a configurable aperture mask that enables NIRSpec to obtain simultaneous spectra of many targets distributed across the FOV. Observers form apertures by opening selected micro-shutters that contain targets or background regions, and by closing all remaining micro-shutters. The aperture plane also contains 5 “fixed” (permanently open) slits (“FS”) and the aperture for the integral field unit (IFU, described in Section 4.3).

Generally speaking, the image scale is defined by the optimal aperture size on the sky (0.2") and the physical size of the individual shutters used to generate it (80 μm in dispersion direction). This leads to a magnification of the FORE optics of ~0.624 and a focal ratio at the MSA of f/12.5. The exact image scale at the MSA is 2.5421 arcsec/mm in dispersion direction, and 2.5881 arcsec/mm in cross-dispersion direction.

2.2.3 COLLIMATOR OPTICS AND GWA

After passing through the one or more apertures, the f/12.5 optical beam enters the spectrograph optical system that starts with the collimator optics (COLL). The purpose of the COLL is to transform the divergent f/12.5 beam from the MSA into a highly collimated beam at the grating wheel position. The grating wheel assembly (GWA, Section 4.5) contains 7 dispersive elements for spectroscopy (a double-pass CaF₂ prism and six reflection gratings), and an imaging mirror for target acquisition, flat fielding, and optical distortion calibrations.
FORE and COLL optics together provide a good quality pupil image at the GWA, thus minimizing the size of the gratings and the requirements for grating spatial homogeneity.

2.2.4 CAMERA OPTICS AND FPA

After being dispersed or reflected by an optical element in the GWA, the NIRSpec beam enters the camera (CAM), which is the third and final TMA. The CAM focuses the collimated and dispersed beam onto the focal plane assembly (FPA). The nominal image scale at the FPA is 5.56 arcsec/mm, so an 18 μm pixel projects to 100 mas on the sky. The focal ratio at the FPA is f/5.6.

The FPA contains two butted HgCdTe sensor chip assemblies (SCAs). Each SCA is a 2048 x 2048 pixel HgCdTe detector array, hybridized to a dedicated readout integrated circuit. More details on the FPA can be found in Section 4.1.
3  NIRSPECF PERFORMANCE

3.1  Flux Units and Conversion Formulae

In order to facilitate comparison of the sensitivity values discussed in this chapter with those of other instruments, we give a short tutorial on astronomical flux units and the conversion between them. In infrared astronomy, the preferred units of wavelength and (continuum) flux are

\[ 1 \mu m = 10^4 \text{Å} = 10^{-6} \text{m}, \quad 1 \text{nJy} = 10^{-9} \text{Jy} = 10^{-39} \text{W cm}^{-2} \text{Hz}^{-1} = 10^{-32} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \]

Using \( \lambda F_\lambda = \nu F_\nu \), the conversion between \( F_\lambda \) and \( F_\nu \) in these preferred units becomes

\[ F_\nu \text{ [nJy]} = 3.34 \cdot 10^{21} \cdot \lambda^2 \text{[µm]} \cdot F_\lambda \text{ [erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}] \]

It is often useful to express the source flux in terms of a differential photon flux, which can be calculated with the following expressions:

\[ f_\lambda \text{ [photons s}^{-1} \text{cm}^{-2} \text{µm}^{-1}] = 5.04 \cdot 10^{15} \lambda \text{[µm]} \cdot F_\lambda \text{ [erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}] \]
\[ f_\nu \text{ [photons s}^{-1} \text{cm}^{-2} \text{µm}^{-1}] = 1.51 \cdot 10^{-6} \lambda^{-1} \text{[µm]} \cdot F_\nu \text{ [nJy]} \]

Finally, the brightness of an astronomical source is often expressed in terms of the “monochromatic” AB magnitude system which is defined as

\[ \text{AB [magnitudes]} = 31.43 - 2.5 \cdot \log(F_\nu \text{ [nJy]}) \]
3.2 Wavefront Error and Optical Quality

Figure 3.2-1 Illustration of the NIRSpec PSF (at a wavelength of ~ 2.5 μm) in the MSA focal plane (top left), and in the FPA plane (top right), for the case of a point source centered in a micro-shutter. The bottom panels show the PSF after sampling with the correct pixel size of the NIRSpec FPA, both without (left) and with (right) the expected pixel crosstalk (~5%). These PSFs are based on simulations of the instrument, as designed.

Figure 3.2-2 Three plots showing the encircled energy as a function of radius in arcsec for three wavelengths in the NIRSpec band, for perfect images (dashed lines) and with realistic wavefront errors included (solid lines).
3.3 **Slit Losses and the Micro-shutter “Acceptance Zone”**

The total transmission of the NIRSpec optical train is a strong function of wavelength. By far the most important effects are the slit losses, defined as the combined effects of **geometric** light loss at the MSA aperture and **diffraction** losses at the grating. The former is simply due to the fact that the slit apertures (micro-shutters, fixed slits, and also the IFU) have a fixed size, but have to accommodate a PSF that varies by almost a factor of 10 over the NIRSpec wavelength range. This is illustrated in Figure 3.3-1 which shows the expected NIRSpec PSF within the micro-shutter for a number of wavelengths spanning the 1-5 micron region. It is obvious that at longer wavelengths, a much smaller amount of incident light passes through the open shutter.

The second effect contributing to the overall light loss is due to diffraction at the MSA apertures, which widens the optical beam. Since the dispersive elements in the GWA (i.e. the gratings and the CaF prism) are limited in size, some portion of the beam “misses” the optical surface of the grating/prism, resulting in further light loss. Again, the effect is stronger at longer wavelengths.

![Figure 3.3-1 NIRSpec PSFs at a number of wavelengths within a micro-shutter aperture (ca. 200 mas x 450 mas).](image)

Clearly, both effects also depend on the source location within the shutter. This is demonstrated in Figure 3.3-2 (upper panels) which shows the total slit transmission, i.e. \((1 - \text{slit loss})\), as a function of source position within the micro-shutter for a number of wavelengths, both in the dispersion and cross-dispersion directions. Note that there is a region around the center of the micro-shutter over which the losses are relatively insensitive to source position. Because the actual source position is only known to within the target acquisition accuracy, the photometric calibration error is also a function of position within a slit: towards the edges of the shutter (or slit), the intrinsic position uncertainty causes a higher photometric error.
Figure 3.3-2 Top: total slit transmission (i.e. geometric plus diffraction loss) for a point source as a function of distance from shutter center, in dispersion (x, left) and cross-dispersion direction (y, right). Bottom: Gradient of the slit transmission as a function of offset from the shutter center in x (left) and y (right). The dashed horizontal lines denote the value for which a 12.5 mas 1σ positioning accuracy yields a 10% uncertainty in the slit transmission.

The area over which the slit losses vary by less than 10% (the required photometric calibration accuracy) over the target acquisition error is called the “acceptance zone” of a shutter. Figure 3.3-3 shows the size of the acceptance zone for the center of the three NIRSpec wavelength bands.

Figure 3.3-3 Size of the acceptance zone within an (undistorted) MSA shutter. The contours show for each of the three NIRSpec bandpasses the region in which the target needs to be placed in order that the target acquisition positioning accuracy leads to a less than 10% photometric error due to uncertainty in the slit transmission. The shape of the shutter and therefore of the acceptance zone on the sky will vary slightly across the MSA owing to optical distortions.
3.4 Spectral Resolution

NIRSpec contains two sets of dispersing elements for R = 1000 medium (M) and R = 2700 high (H) resolution spectra and a prism for low-resolution (R = 100) spectra. The delivered spectral resolution of these elements is shown in Figure 3.4-1.

Figure 3.4-1 Dispersion vs. wavelength curves for the R = 1000 M gratings (upper left), the R = 2700 H gratings (upper right) and the R = 100 CaF$_2$ prism, as computed at the center of the FOV. NOTE: The title of the upper right plot erroneously states “medium-resolution”, but the curves and legend in that plot correctly show the H gratings.
3.5 **Location, Length, and Distortion of Recorded Spectra**

In order to assess the multiplexing capabilities of NIRSpec, it is useful to illustrate the location of spectra on the FPA. Figure 3.5-1 to Figure 3.5-3 show where the spectra of the fixed slits and the virtual slit of the IFU fall on the FPA for all the dispersive elements. Although based on detailed optical simulations, these figures are indicative only, because small differences will be introduced by alignment tolerances and the actual performance of the dispersive elements. For the R1000 and R2700 modes, there are also slight differences in length and position for the three bands.

**Figure 3.5-1** Location of NIRSpec spectra obtained using the R100 CaF prism. Four of the spectra originate from micro-shutters in the corners of the MSA, the middle two spectra are from virtual shutters in the center of the field. Also indicated are the wavelengths and the slit tilt (which changes across the field due the variable beam entrance angle onto the prism). In this figure and the next two, the large square outlines mark the SCA edges.

**Figure 3.5-2** Location of the *nominal* R1000 Band I spectra for the fixed slits and the extreme upper and low ends of the IFU virtual slits (at the upper and lower left). As in **Figure 3.5-1** the wavelength and slit tilt is indicated, the latter varying only slightly across the field. The corresponding figure for bands II and III appears almost identical. Note that because NIRSpec uses long-pass filters, the red end of the spectra is *not* an actual cut-off, the intrinsic source spectrum (plus overlapping higher orders of the in-band light) will extend up to the detector cut-off wavelength around 5 micron. Therefore, only one object can be observed per MSA row.
NIRSpec is a wide-field spectrograph. As a consequence, the incidence angles of light onto the disperser (grating or prism) are relatively large (up to 16°), and are dependent on the position of the source within the field of view. This results in NIRSpec spectra being far from uniform across the field of view as they are shown to be in Figures 3.5-1 to 3.5-3. More realistic views appear in Figure 3.5-4 and Figure 3.5-5, which show that the tilt of the slit aperture image on the detector, as well as the length of NIRSpec spectra, can vary in some modes (esp. R100) by as much as 20%. In addition, the wide NIRSpec field causes optical distortion in the imaging optics (see Section 3.10), which results in curved spectra on the detector. This distortion complicates the data reduction because the spectra must be traced individually. Note, however, that all these variations in the properties of NIRSpec spectra are completely predictable (and hence can be modeled accurately) once the location of the source on the MSA shutter grid is known.

Figure 3.5-4 Variation of spectral curvature, dispersion, and slit tilt across the NIRSpec field-of-view in \( R = 1000 \), Band II mode. Numbers are indicative only, and will be revised following flight model calibration.
In the $R = 1000$ and $R = 2700$ modes, the NIRSpec science spectra are produced in the first order of the gratings. For some of these spectra, orders other than the nominal fall onto the detector, as illustrated in Figure 3.5-5. The second order simply overlaps with the red extension of the science spectrum (which is always present because of the long-pass filters). However, because of its brightness, the undispersed, "white light", zeroth order can potentially compromise the quality of some science data, as seen on the left-hand side of Figure 3.5-5.

Figure 3.5-5 Location of 0th and 2nd order spectra on the FPA for an arbitrary configuration of open MSA shutters (indicative only, will be revised following flight model calibration).

These figures illustrate why only the R100 mode can, in principle, observe more than one science object per MSA row. This is because the prism spectra are rather short and – more importantly – extend all the way to the cut-off wavelength of the SCAs. In contrast, the R1000 and R2700 grating spectra will extend much beyond the nominal long-wavelength cut-off of the respective NIRSpec band indicated in Figure 3.5-2 and 3.5-3. There are two effects here: first, the order-sorting filters in the FWA are long-pass filters, and hence the intrinsic source spectrum extends redward up to the detector cut-off at 5 $\mu$m. Secondly, the higher grating orders of in-band wavelengths will appear on the detector. For example, the second and third orders of emission at $\lambda=1.6$ $\mu$m will coincide with the nominal position of $\lambda=3.2$ $\mu$m and $\lambda=4.8$ $\mu$m. This is true also for the R2700 spectra, but because their intrinsic length almost covers the entire detector, observing more than one object per MSA row is not an option to begin with. In summary, the default usage for MOS spectroscopy with NIRSpec in the R1000 and R2700 modes will allow only one open micro-shutter per MSA row. In R2700 mode, only a portion of the field of view will deliver complete spectral coverage.
3.6 Zodiacal Light, Straylight, and Micro-shutter Contrast

The limiting sensitivity of NIRSpec will be affected by photon noise in the background, which arises from several sources. Figure 3.6-1 illustrates a few potential background sources that may affect NIRSpec sensitivity: scattered light from objects outside of the FOV, light from non-science targets leaking through the MSA, and zodiacal background light.

Particulate contamination on OTE (or NIRSpec) surfaces will scatter light from bright sources in (left panel) and out of (right panel) the NIRSpec FOV. This straylight will effectively fill the entire FOV, potentially compromising the detection of faint targets. The same mechanism can also cause thermal emission from the sunshield or other warm spacecraft parts to enter the NIRSpec optical path.

Lightshields reduce but do not eliminate light leaks around the edges of a closed micro-shutter. The contrast ratio between the open and closed micro-shutters is required to be at least 2000 with a goal of $10^5$. Bright sources in the FOV will illuminate the detector, even though they are nominally blocked by closed micro-shutters. Spectra from such “spoiler” sources can overlap spectra of science targets in the same MSA row.

At short wavelengths zodiacal light is sunlight scattered by solar system dust, while at long wavelengths it is thermal emission by the same dust. The breakpoint is approximately $3.3 \mu m$.

Figure 3.6-2 shows contributions from each component and their sum. Variations due to the Earth’s motion are relatively large in the ecliptic plane and small at the poles. We anticipate that...
very faint sources will be observed near the maximum allowed sun angle to minimize the zodiacal background and maximize S/N ratio. Zodiacal light is in the foreground of more distant astronomical sources, so it traverses the same optical path as light from the target.

![Figure 3.6-2](image1) Zodiacal light intensity in the ecliptic plane or at the ecliptic pole. Scattering and emission components are shown separately. Shaded regions indicate the range of intensities throughout the year, assuming sun angle is restricted to the range 85° and 135°. Dotted and solid lines indicate the mean intensity over the course of a year.

### 3.7 Throughput and Sensitivity

In most observing modes, NIRSpec sensitivity is limited by detector noise. The signal-to-noise ratio then depends linearly on the instrument throughput. The reflectivity of the 14 mirrors in the NIRSpec optical train, the transmission of the various filters, and the efficiency of the reflection grating (or double-pass prism) are therefore subject to very challenging requirements, and must be tightly monitored. Currently, only preliminary information exists on these parameters. Figure 3.7-1 compares NIRSpec throughput requirements (ignoring OTE and detector losses) with the expected throughput for the R=1000 and R=2700 spectrographic modes.

![Figure 3.7-1](image2) Expected throughput curves for the R=1000 and R=2700 spectrographic modes. Note that these curves exclude the OTE/ISIM optics and the detector response.
Using these throughput curves and otherwise following the recipe outlined in RD 5, one can calculate the expected NIRSpec emission-line sensitivity for integration times of $10^5$ s, as shown in Figure 3.7-2 and 3.7-3.

**Figure 3.7-2** Baseline sensitivity estimates for $R = 1000$ (left panels) and $R = 2700$ (right panels), for continuum sources in units of nJy (top panels) and line sources in units of erg s$^{-1}$ cm$^{-2}$ (bottom panels). These estimates assume S/N = 10 per resolution element and $10^5$ sec integration time. No margin is included, except for the black point at lower left, which shows the $R = 1000$ line sensitivity with 20% margin added.

**Figure 3.7-3** Baseline sensitivity curve for the CaF$_2$ prism ($R = 100$), for a continuum source in units of nJy.
3.8 Calibration Accuracy

RD 10 lists two high-level requirements for the calibration of NIRSpec:

**NSFR-14** After on-ground and in-orbit calibration, the absolute photometric accuracy of all NIRSpec science data shall be better than 10%.

**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.

However, meeting these requirements for NIRSpec (and, in fact, any multi-object spectrograph) is challenging. The main reason is that the targets all have slightly different positions within their respective slit apertures. As discussed in Section 3.3, the wide wavelength range of NIRSpec leads to pronounced variation in the slit loss even for small differences in source location. It is therefore critical for the NIRSpec photometric calibration that source positions within the micro-shutters are stable throughout the integration, and well known. This is the reason why the target acquisition accuracy is driving the photometric calibration error budget for NIRSpec. On the other hand, target positioning accuracy can, to some extent, be traded against photometric calibration accuracy, depending on the needs of a specific science program.

The specific measurements, both on-ground and in-orbit, that will be used to characterize fully the NIRSpec slit losses and dispersion solution, are described in RD 7.

3.9 Bright Object Limits and Spoilers

NIRSpec’s bright limits are imposed by the desire to avoid saturating the full-well depth of the detector pixels (~60000 electrons) or reaching the ASIC analog-to-digital conversion limit of 16 bits (65536). Saturated detector pixels do not provide a reliable measure of flux and may show charge persistence effects that will affect subsequent observations. For this reason users will want to avoid saturating the detectors, though doing so creates no immediate safety issue. These bright limits are calculated here following the logic and notation of the 2004 technical memo “Observing Eclipsing Exoplanets with NIRSpec” by P. Jakobsen.

To calculate bright limits we need to know the minimum time between readouts for a given pixel. In general, the time required to read out a subarray is given by:

\[ t_{\text{frame}} = 10 \times (\Delta_i + 12) \times (\Delta_j + 1) \, \mu s \]

Here, \(\Delta_i\) refers to the subarray dimension in the dispersion direction, and \(\Delta_j\) to the dimension in the cross-dispersion direction. The minimum subarray size is 128 by 8, with a readout time of \(t_{\text{frame}} = 0.0258\) s. See section 4.1.7 for a complete discussion of readout times and the constraints on valid subarray sizes.

Bright limits are given for each grating and a combination of (sub)array sizes in Table 3.1. These values were estimated by assuming a two-pixel resolution element, a full well of 60000 e\(^{-}\), and that \(1/4\) of the flux in a spectrum spread over a few pixels in the cross-dispersion direction falls into the
brightest pixel. They also assume a readout scheme in which \( n_r = 2 \) frames are obtained in between resets (the first frame establishes the zeropoint and the second obtains a measurement); thus each pixel is exposed to flux for a total of \((n_r + 1)t_{\text{frame}}\) or \(3t_{\text{frame}}\) for the minimum assumed \( n_r = 2 \). Note that because only two reads in between resets leaves the first and last \( t_{\text{frame}} \) as “dead time”, this readout scheme does not necessarily optimize the S/N for a given target – generally the largest \( n_r \) that does not saturate in a frame time should be used. More details on how to optimize readout schemes and S/N for bright targets are available in the technical Jakobsen’s memo and also the Technical Report “NIRSpec Subarrays for Planetary Transits and Other Bright Sources” by J. Tumlinson (JWST-STScI-001601).

Table 3.1 Approximate bright limits for the NIRSpec gratings and various subarrays.

<table>
<thead>
<tr>
<th>( \Delta i )</th>
<th>( \Delta j )</th>
<th>( R = 100 )</th>
<th>( R = 1000 )</th>
<th>( R = 2700 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2048</td>
<td>2048</td>
<td>14.6</td>
<td>11.4</td>
<td>10.3</td>
</tr>
<tr>
<td>2048</td>
<td>256</td>
<td>13.8</td>
<td>10.6</td>
<td>9.5</td>
</tr>
<tr>
<td>2048</td>
<td>64</td>
<td>12.5</td>
<td>9.3</td>
<td>8.2</td>
</tr>
<tr>
<td>2048</td>
<td>32</td>
<td>11.9</td>
<td>8.7</td>
<td>7.6</td>
</tr>
<tr>
<td>128</td>
<td>8</td>
<td>8.0</td>
<td>4.8</td>
<td>3.7</td>
</tr>
</tbody>
</table>

“Spoilers” are non-science targets in the field of view that are bright enough that some light gets through the closed micro-shutters. The micro-shutters have a finite contrast owing to the imperfect blocking of light by the array material and by the very small gaps between micro-shutter “doors” and the “egg crates” into which they fit. Micro-shutters are expected to have a contrast ratio exceeding 2000 by specification, but ground testing of flight candidate arrays suggests, first, that most shutters have contrast of \( 8000 \to 10000 \), and second, that some shutters have “low contrast” in the range \( 500 \to 2000 \). When converted to magnitudes, these contrast ratios roughly approximate the brightness differential between science targets and “spoilers” in the field that can be tolerated without too much interference. For example, a MOS observation targeting faint galaxies with \( AB \sim 25 \) can tolerate stars in the field as bright as \( AB \sim 17 \) before these stars potentially overwhelm the faint target sources. In normal circumstances where the shutters have contrast of 10000, magnitude differentials up to 10 mag can be tolerated, though for low-contrast shutters the differential can drop to 6.7. Low-contrast shutters will need to be taken into account and avoided during the planning of MSA observations and it is expected that the MSA planning tool will be able to identify low-contrast shutters for the user, who can then plan around them if necessary. Excessively bright sources can also be placed behind the bars that separate MSA quadrants, if necessary.

These considerations apply to the IFU slitlet spectra as well, since they spread across the detectors in the vertical direction. It will be therefore necessary to take into account bright sources that might fall into the MSA FOV even for IFU observations. The fixed slits have a dedicated detector area and should not suffer from spoilers in the MSA field.

The bright limits for target acquisition with undispersed images through the two imaging filters (F110W and F140X) are imposed in a similar fashion; the target magnitude is limited by the requirement to avoid 60000 e- saturation in the time required to obtain a useful TA image. For TA,
it is necessary to obtain at least three frames to remove cosmic ray hits, followed by a reset, so that each pixel is exposed to flux for \( t_f \). P. Jakobsen has calculated the bright limits for a single frame to be \( AB = 18.1 \) in the broad F140X filter and \( AB = 16.8 \) in the narrow F110W filter (ESA-JWST-AN-3032). Thus, for a three frame + reset image, the limits are 1.5 mag fainter, or \( AB = 19.6 \) for F140X and \( AB = 18.3 \) for F110W. Reference stars for target acquisition will generally not be useful if they are brighter than these limits, and may saturate at even fainter magnitude if longer exposures are used to ensure adequate counts are collected on fainter reference stars; that is, for 10 frame times, the bright limits are \( 2.5 \log(10/4) = 1 \) mag fainter.

### 3.10 Geometric Distortion

**Figure 3.10-1** Illustrations of the geometric distortion at the MSA plane, relative to the sky (upper panel); nine reference points are shown at the OTE focal plane (left), and at the MSA plane (right). The lower panels show the
relative change in the platescale (arcsec/mm), with respect to the mean, over the field. This is a “local” effect of the optical distortion in the system.

The various image planes of NIRSpec do not map linearly to one another, owning to optical distortion in the elements between them and to non-normal incidence of light onto these surfaces. That is, an imaginary grid with square angles at one plane will appear distorted at any of the other planes. As a consequence of this, the platescale (as defined to be, e.g. the ratio between arcsec on the sky and mm on the MSA or FPA) changes over the FOV. These effects are quantifiable given good knowledge of the instrument, and must be taken into account when planning observations. Some early quantitative information on these effects is shown in Figure 3.10-1.

### 3.11 Other Instrument Characteristics

There are a number of additional considerations worth mentioning when planning NIRSpec observations and the reduction of its science data. Most of these are currently only understood at conceptual level, and a detailed investigation of these "features" will need to await the flight model test campaign in late 2010. Here, we mention them for completeness, and as a reminder for any ensuing discussions of data reduction pipelines, observation planning tools, etc.

1) NIRSpec is an all-reflective spectrograph, except for the filters in the FWA, which are made of CaF2 (or BK7 in the case of the target acquisition filters F110W and F140X). Because the index of refraction for all optical materials is wavelength-dependent, the position of a source on the MSA will vary slightly, but noticeably, with wavelength. This so-called "chromatic aberration" may be important for the target acquisition procedure, depending on the actually measured shifts in the as-built flight model. In terms of the photometric calibration of NIRSpec, the resulting variations in slit loss are folded into the computation of the chromatic slit loss (see Sec. 3.3).

2) Although very stringent cleanliness requirements are enforced for the NIRSpec optics and the JWST observatory in general, there is a non-zero chance that thin layers of molecular contamination will be present on some optical surfaces. Among the most critical contaminants for NIRSpec are hydrocarbons that have a strong absorption feature at 3.4 μm, and thus can potentially reduce NIRSpec sensitivity at this wavelength.
4 MAJOR FUNCTIONAL ELEMENTS

4.1 Focal Plane Assembly

4.1.1 DESIGN AND FUNCTIONALITY

The NIRSpec focal plane assembly (FPA) shown in is contains two closely butted HAWAII-2RG sensor chip arrays (SCAs) manufactured by Teledyne Imaging Systems (TIS). Each SCA has 2048 x 2048 pixels that can be addressed individually and read out in a non-destructive way.

![Diagram of NIRSpec Focal Plane Assembly](image)

**Figure 4.1-1** Design principle of the NIRSpec Focal Plane Assembly (FPA).

The light-sensitive portions of the two SCAs are separated by a physical gap of no more than 3.144 mm which – given the mean image scale at the FPA of 5.66"/mm in the dispersion direction – corresponds to 17.8" on the sky. In imaging mode, the gap region will simply be obscured behind the gap between MSA quadrants. In dispersed mode, the detector gap will – in general - cause loss of spectral information over a range in wavelength that depends on the location of the target and the dispersive element used. The “lost” information can be recovered by dithering the targets as described in Section 7.3.3.

Because thermal stability is crucial for good performance of NIR detectors, the FPA is mounted to a thermal strap that connects to a dedicated radiator. In this way, the NIRSpec SCAs can be cold-loaded, and maintained at a stable operating temperature using heaters controlled by a thermal control circuit. The specified operating temperature is in the range 30 - 40 K.
4.1.2 SIDECAR ASIC AND OPERATIONAL CONSTRAINTS

The System for Image Digitalization, Enhancement, Control, and Retrieval (SIDECAR) ASIC is used for detector readout and control. It is a special-purpose electronic device individually matched to its corresponding FPA. There are no known operational constraints on the SIDECAR ASIC at this time. However, there exists a possibility that new tuning (or “personality”) files will be needed for each operating temperature. This issue is being tracked. There are no plans to run more than one microcode executable. More information about ASIC commanding and telemetry is available in the SIDECAR ASIC Interface Requirement Document (RD 15).

![SIDECAR ASIC](image)

**Figure 4.1-2** SIDECAR ASIC

4.1.3 DETECTOR SYSTEM PERFORMANCE

The characteristics of the NIRSpec SCAs are a crucial element for the performance of the whole instrument. Parameters such as dark current, read noise, and quantum efficiency are strongly tied to the overall NIRSpec sensitivity (see RD 5 for the details of the NIRSpec sensitivity calculation). Therefore, the requirements for these parameters as summarized in Table 4-1 are at the limit of what is technologically feasible.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array size</td>
<td>Two SCAs with 2048 x 2048 pixels each</td>
</tr>
<tr>
<td>Pixel size</td>
<td>18 mm x 18 mm</td>
</tr>
<tr>
<td>Wavelength range</td>
<td>0.6 mm – 5.0 mm</td>
</tr>
<tr>
<td>Quantum efficiency 0.6 mm – 1.0mm</td>
<td>&gt; 70%</td>
</tr>
<tr>
<td>Quantum efficiency 1.0 mm – 5.0mm</td>
<td>&gt; 80%</td>
</tr>
<tr>
<td>Total noise (incl. electronics)</td>
<td>&lt; 6 e⁻ (in MULTIACCUM 22x4)</td>
</tr>
</tbody>
</table>

Table 4-1 Performance requirements for the NIRSpec detectors.
<table>
<thead>
<tr>
<th>Dark current</th>
<th>&lt; 0.01 e⁻/s/pixel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full well capacity</td>
<td>60,000 e⁻</td>
</tr>
<tr>
<td>Operational temperature range</td>
<td>30 – 40 K</td>
</tr>
</tbody>
</table>

In order to verify these requirements, and to develop a good understanding of NIRSpec performance even before cryogenic tests at instrument level, an extensive test program is underway to characterize these parameters as well as reasonably possible before launch.

### 4.1.4 DIRECTIONS AND COORDINATES

The relative orientation of the two SCAs with respect to the optical bench and their pixel numbering scheme is illustrated in . SCA-2 is located closest to the optical bench. Note that the dispersion direction runs along FPA rows (i.e. constant $j$ coordinate), while FPA columns (constant $i$ coordinate) follow the cross-dispersion direction. Note that there are two orientations: 1) “official NIRSpec” in which rows are parallel the dispersion direction, and 2) “detector level”, where exposure configurations are done. Note that we will use $i$ and $j$ consistently in both.

![Sketch of the FPA geometry](image)

**Figure 4.1-3** Physical orientation and pixel numbering convention for the NIRSpec FPA. This figure follows official NIRSpec usage in which rows run parallel to the dispersion direction. Note that both SCAs are rotated 90 degrees (SCA#1 counterclockwise and SCA #2 clockwise) with respect to the detector level orientation which is described in the next session and that is used for configuring an exposure.

### 4.1.5 READOUT PATTERN

In order to increase the readout speed and maintain low power consumption, each SCA is read out via four output channels. Each channel comprises a region of 512x2048 pixels as indicated in Figure 4.1-3 and Figure 4.1-4 with
channel I reading from $j = 1$ to 512 and from $i = 1$ to 2048
channel II reading from $j = 513$ to 1024, and from $i = 1$ to 2048
channel III reading from $j = 1025$ to 1536, and from $i = 1$ to 2048
channel IV reading from $j = 1537$ to 2048, and from $i = 1$ to 2048.

Pixels located in the first and last four columns and rows (i.e. $i,j < 5$ and $i,j > 2044$) are insensitive to light and can only be used as reference pixels to track the behavior of the readout electronics. Due to design constraints, channels II and III do not have reference pixels along the slow scan direction. Note that the fast readout (HDIR) runs along the cross-dispersion axis. However, its direction varies between the four channels. The slow readout (VDIR) runs parallel to the dispersion axis.

**Figure 4.1-4** Schematic of the readout scheme for the NIRSpec SCAs. The depicted orientation is used for configuring the detector system for an exposure. The coordinate system ($i,j$) is consistent with official NIRSpec usage (see fig 4.1-2), in which FPA rows (constant $j$) run parallel to the slow readout (dispersion) direction, and FPA columns (constant $i$) run parallel to the fast readout (cross-dispersion) direction. The ASIC keywords VDIR and HDIR indicate the slow and fast scanning direction respectively. The values in the figure represent the baseline during ground testing.

**4.1.6 THE MULTIACCUM READOUT SCHEME**

Before and after each integration, the ASIC resets each pixel in sequence. During an integration the ASIC will nondestructively sample at regular intervals the charge that accumulates in each pixel. This illustrates this “up-the-ramp” readout scheme. The ability to sample pixels multiple times reduces the impact of read noise, improving signal-to-noise for faint sources. Regular sampling also facilitates cosmic ray correction and measurement of detector non-linearity.

In full-frame mode, the ASICs will clock and read pixels with a regular cadence to keep the SCAs and their analog electronics as stable as possible thermally. To help maintain thermal stability, pixels will be read, even if the FPE later discards the data. Past experience with similar devices,
e.g. HST/NICMOS, shows that changing the readout rate causes variations in temperature and in detector behavior; calibration then becomes a complicated function of recent usage. For NIRSpec, the goal is to avoid such problems by regularly clocking and reading the SCAs whenever possible. The exception to this rule is the subarray mode, which will require a nonstandard clocking cadence. Each MULTIACCUM exposure is defined by eight parameters, listed in . Note that the “subarray” parameters are also used in full-frame mode, in which case they take on the expected values of NROWS=NCOLS=2048 And ROWCORNER=COLCORNER=1 (see also Table 4-4).

Table 4-2 ASIC configuration parameters for an individual exposure. Only ROWCORNER and COLCORNER can have different values for the two ASICs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFRAMES</td>
<td>Number of frames that are read and coadded per group.</td>
</tr>
<tr>
<td>GROUPGAP</td>
<td>Number of frames that are read and dropped per group.</td>
</tr>
<tr>
<td>NGROUPS</td>
<td>Number of groups per integration.</td>
</tr>
<tr>
<td>NINTS</td>
<td>Number of integrations per exposure.</td>
</tr>
<tr>
<td>NROWS</td>
<td>Number of pixel rows in the subarray (Di in figures)</td>
</tr>
<tr>
<td>NCOLS</td>
<td>Number of pixel columns in the subarray (Dj in figures)</td>
</tr>
<tr>
<td>ROWCORNER</td>
<td>Row coordinate of subarray origin (i in figures).</td>
</tr>
<tr>
<td>COLCORNER</td>
<td>Column coordinate of subarray origin (j in figures).</td>
</tr>
</tbody>
</table>

Observers will generally choose from a limited set of detector readout patterns. This simplifies observation planning, onboard script generation, instrument calibration, and pipeline processing. Table 4-3 lists the readout patterns that are currently defined. These patterns are sufficient for most NIRSpec science applications. Additional readout patterns can be defined and added to this set, if necessary, but we do not envision that users will define their own.
Table 4-3 NIRSpec detector readout patterns.

<table>
<thead>
<tr>
<th>Name</th>
<th>NFRAMES</th>
<th>Group Time (s)</th>
<th>GROUPGAP</th>
<th>Maximum NGROUPS</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRS</td>
<td>4</td>
<td>42.94704</td>
<td>0</td>
<td>250</td>
<td>Default pattern</td>
</tr>
<tr>
<td>NRSRAPID</td>
<td>1</td>
<td>10.73676</td>
<td>0</td>
<td>1000</td>
<td>For bright sources</td>
</tr>
</tbody>
</table>

4.1.7 SUBARRAY MODE

The NIRSpec detectors have a subarray mode in which only a contiguous rectangular subset of pixels is read from each SCA. In this case, a single output channel is used. The following constraints apply to the size and location of the subarrays:

- only one rectangular subarray is allowed per SCA.
- subarray size must be identical for both SCAs.
- subarray dimension must be a power of two along each dimension, e.g. 64 x 256 pixels.
- a subarray must contain at least 1024 pixels.
- neither dimension may be smaller than 8 pixels.

Depending on their size and location subarrays may or may not have reference pixels. Note that the subarray location in the two SCAs may be set independently.

Figure 4.1-6 illustrates the readout pattern in subarray mode.
Subarray mode is advantageous for bright sources that would cause pixel saturation within the minimum full-frame readout time. The time to reset or to read a subarray is

\[ T_{\text{frame}} = 10 \text{ms} \left( \Delta_j + 12 \right) \left( \Delta_i + 1 \right), \]

where \( \Delta_i \) (ASIC parameter NROW) and \( \Delta_j \) (ASIC parameter NCOLS) are the subarray size in pixels in the dispersion ("i" in the figures of this section), and cross-dispersion direction ("j"), respectively. Note that for full frame mode, \( \Delta_i = 2048 \) and \( \Delta_j = 512 \) (because four amplifiers are used in parallel), yielding a full-frame readout time of \( t_{\text{frame}} = 10.7368 \text{ s} \). To assess saturation risk, note that pixels accumulate charge for at least 2-3 \( t_{\text{frame}} \), depending on location in the subarray.

Fixed slit spectroscopy with NIRSpec will use subarray mode by default because most of the detector area will not be illuminated, and many of the high-contrast measurements require maximum dynamic range. Table 4-4 lists the six subarrays that are used in fixed slit mode (see Section 4.2.9 for the shape and location of the fixed slits on the MSA). When in subarray mode, the rest of the detector area may still be exposed to light, either through the fixed slit apertures, failed-open micro-shutters, or possibly an all-open MSA. In order to avoid the negative effects of saturation, it is possible to periodically reset the entire SCA after the sub-array has been read without leaving the subarray mode (see RD 9 for details).

**Table 4-4** Summary of NIRSpec subarrays for fixed slit spectroscopy.

<table>
<thead>
<tr>
<th>Subarray name</th>
<th>COLCORNER ((j_0)) SCA1, SCA2</th>
<th>ROWCORNER ((i_0))</th>
<th>Height [pixels] ((\Delta_i, \text{Cross-Dispersion}))</th>
<th>Width [pixels] ((\Delta_j, \text{Dispersion}))</th>
<th>(T_{\text{frame}}) [seconds]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FULL</td>
<td>1, 1</td>
<td>1</td>
<td>2048</td>
<td>2048</td>
<td>42.2094</td>
</tr>
<tr>
<td>ALLSLITS</td>
<td>890, 902 (TBR)</td>
<td>1</td>
<td>256</td>
<td>2048</td>
<td>5.49132</td>
</tr>
<tr>
<td>S200A1</td>
<td>911, 1073 (TBR)</td>
<td>1</td>
<td>64</td>
<td>2048</td>
<td>1.55724</td>
</tr>
<tr>
<td>S200A2</td>
<td>951, 1033 (TBR)</td>
<td>1</td>
<td>64</td>
<td>2048</td>
<td>1.55724</td>
</tr>
<tr>
<td>S200B1</td>
<td>1061, 923 (TBR)</td>
<td>1</td>
<td>64</td>
<td>2048</td>
<td>1.55724</td>
</tr>
<tr>
<td>S400A1</td>
<td>993, 991 (TBR)</td>
<td>1</td>
<td>64</td>
<td>2048</td>
<td>1.55724</td>
</tr>
<tr>
<td>S1600A1</td>
<td>1044, 972 (TBR)</td>
<td>1</td>
<td>32</td>
<td>2048</td>
<td>0.90156</td>
</tr>
</tbody>
</table>
4.2 **Micro-Shutter Assembly**

4.2.1 **DESIGN AND FUNCTIONALITY**

The Micro-Shutter Assembly (MSA) is mounted on the NIRSpec Optical Assembly (OA) through a mounting bracket as shown in Figure 4.2-1. This bracket is also used to mount the Integral Field Unit (IFU). Light passes through the open shutters of the MSA in the direction of the red arrow.

![Micro-shutter assembly mounted on the NIRSpec optical assembly.](image)

Figure 4.2-1 Micro-shutter assembly mounted on the NIRSpec optical assembly.

Figure 4.2-2 shows that the MSA is composed of three layers: the Cover Layer, the Mechanism Layer, and the Mosaic Integration Layer. The Cover Layer is the layer closest to the light source. It provides contamination protection for the MSA, and it also acts as a light baffle. The Mechanism Layer contains the launch lock and magnet arm motors, mechanisms, and resolvers. The Mosaic Integration Layer contains the four micro-shutter quadrants, substrates, daughter boards, and MSA connector bracket.
Figure 4.2-2: Micro-shutter assembly layers (top) and the assembled subsystem with cardinal directions labeled (bottom). NOTE: The inset photo showing the direction of light through the shutters is incorrect. In fact light enters through the “back side”, or “magnet arm side” of the shutters and exits through the “front” or “detector” side. See Figure 4.2-5 for the correct orientation.
The MSA consists of a $2 \times 2$ arrangement of quadrants (see Figure 4.2-3). Each quadrant has 365 shutters along the dispersion axis and 171 shutters along the spatial axis. Pairs of quadrants are separated by approximately 9 mm (22.88") along the dispersion axis and 13.95 mm (36.1") along the spatial axis. Within each quadrant, the shutter pitch is approximately 0.26" along the dispersion axis and 0.51" along the spatial axis. The open area of an open shutter is approximately $0.20" \times 0.45"$. The “walls” separating individual shutters are approximately 0.06" wide. The sizes in Figure 4.2-3 are given in minutes of arc. In this figure, the optical bench is located on the left at the MSA plane (with the IFU aperture located closest to the optical bench) and on the right when projected onto the FPA plane (with the IFU aperture located away from the optical bench). The orientation of Figure 4.2-3 is therefore rotated 90º clockwise from the orientation of the MSA in Figure 4.2-2 when facing the front (magnet arm side) of MSA.

Figure 4.2-3: Schematic view of the MSA layout, projected onto the detector plane. The location of the fixed slits and the IFU are illustrative only.

4.2.2 NORMAL OPERATIONS

4.2.2.1 Shutter Orientation: Rows and Columns

To understand the normal operation of the MSA, it is important to first understand the relative orientation of the magnet arm, shutters, and light direction. Figure 4.2-2 shows that the magnet arm is located close to the light source. The shutters are oriented so that light enters the back side (magnet arm side) of the shutters, and exits out the front side (detector side). The back side of the shutters is sometimes referred to as the “egg crate” side.

Figure 4.2-4 shows a conceptual drawing of the MSA looking from the magnet side. (Note that this figure is correct for the MSA but predates some changes to the details of the other apertures; namely, the addition of the fifth fixed slit and the change to a square IFU aperture.) There are four quadrants, each containing 365 rows and 171 columns, and the numbering of the rows and columns in each quadrant are identical with shutter (1,1) located in the upper left-hand corner of each quadrant. Every shutter has a row electrode and a column electrode so that it can be uniquely
addressed. The 365 row electrodes are attached to the “egg crate” on the magnet side of the MSA. The 171 column electrodes are attached to the “shutter paddles” on the detector side of the MSA.

Note that there is some potential for confusion in the labeling of the MSA rows and columns. The rows of shutters on the MSA device quadrants run in the cross-dispersion direction and columns of shutters run in the dispersion direction. This usage is rotated 90 degrees with respect to the coordinate systems of NIRSpec’s detector SCAs (Section 4.1.3) and, significantly, with respect to conventional astronomical usage in which rows run along with the dispersion direction, so that dispersed spectra run parallel to rows. It is important that the correct usage be observed when referring to the MSA device itself, as is done extensively throughout this section and in some places elsewhere in this document. Where the MSA labeling system is being used, this document will refer to “MSA rows” or “MSA columns”. Outside this section, when referring to dispersed spectra, the detector, or when speaking in general astronomical terms, the convention that rows run in the dispersion direction will be used.

![Micro-shutter assembly quadrant orientation](image)

**Figure 4.2-4** Micro-shutter assembly quadrant orientation.

### 4.2.2.2 Array Latching Procedure

The MSA shutters are opened and closed by sweeping a permanent magnet across the array. In the orientation depicted in Figure 4.2-3, the magnet arm sweeps upward to open shutters, and
downward to close them. The magnet arm is located on the front side of the MSA; i.e., towards the sky. As the magnet sweeps upwards away from the NIRSpec OA, its magnetic field pulls on the magnetic stripes on the shutter doors and swings the shutters open into their “egg crates”.

As shown in Figure 4.2-5, the open shutters are latched and held open by electrostatic forces until they are electronically released. Positive voltages are applied to the 365 row electrodes (+V₂), and negative voltages are applied to the 171 column electrodes (-V₁). The voltages described below for opening and addressing an array are nominal voltages. Since each array is unique, each quadrant uses an individually optimized voltage in the range from ±12 to ±36 V.

During the latching process, the front side electrodes (171 column electrodes) are nominally set to V₁ = -20 V before the magnet starts to move, and the back side electrodes (365 row electrodes) are nominally set to V₂ = +26 V as shown in Figure 4.2-6.

**Figure 4.2-5** Electrostatic latching of shutters.

At the end of the magnet arm’s movement, all of the shutters are fully open and latched. The array is now ready for a Release or an Address cycle. Figure 4.2-6 shows a single quadrant with all shutters closed (top), going to partially latched (middle), going to all shutters open and latched (bottom).
4.2.2.3 Array Releasing Procedure

A Release cycle closes all of the shutters as the magnet arm moves downward back to its Primary Park position. An Address cycle closes only those shutters that have been commanded to be closed, and leaves open the shutters that have been commanded to stay open.

Shutter release must be synchronized with the downward sweep of the magnet for two reasons. First, the magnet dampens the spring action of the shutters and keeps the shutters from slamming into the light shields on the front of the array and causing damage to the light shields. Second, the magnetic field helps to pull shutters that are to be closed away from the back wall. This is important because just setting the voltages of the 365 row and 171 column electrodes to 0 V does not necessarily release the shutters.

During a Release cycle, the magnet arm is swept downward across the shutters back to its Primary Park position. When the trailing edge of the magnet is 2.6 mm ±0.530 mm past the first row of shutters, the voltages on all of the columns are driven to 0V. The voltage on the first row is also switched to and left at 0V as shown in Figure 4.2-7.

**Figure 4.2-6** Array latching procedure.
Figure 4.2-7 Array releasing procedure.

As the magnet sweeps by the rest of the array, the row voltages are switched to 0V when they are 2.6 mm ±0.530 mm behind the magnet. When the magnet arm reaches its Primary Park position, all of the row voltages and the column voltages will be set to 0V, and the array will be fully closed. Figure 4.2-7 shows a single quadrant with all shutters latched open (top), going to partially closed (middle), going to all shutters released and closed (bottom).

4.2.2.4 Array Addressing Procedure

During an Address cycle, all of the 365 row voltages are nominally set to +32V, and all of the 171 column voltages are nominally set to -32V as shown in Figure 4.2-8. These are the “Address” voltages that help keep shutters from being pulled away from the back wall by the magnetic field. The magnet arm is swept downward across the shutters back to its Primary Park position. When the trailing edge of the magnet is 2.6 mm ±0.530 mm past the first row, the voltages on the individual 171 columns are either set to 0V if the shutter in a column on the first row should be released, or left at -32V if the shutter in a column of the first row should be remain open.

The voltage on the first row is then pulsed to 0V for 2 ms or greater, and then returned back to +32V. This process is repeated across the entire array. When the magnet arm reaches its Primary Park position, the array has been fully addressed. All row and column voltages are then nominally set to lower “Hold” voltage levels of +16V and -16V, respectively. Figure 4.2-8 shows a single quadrant with all shutters latched open (top), going to partially addressed (middle), going to all shutters addressed (bottom).
4.2.2.5 MSA Magnet Arm Positions

The Micro-Shutter Flight Software (MSFSW) can command the magnet arm to three different holding positions for the magnet arm: Launch Lock position, Primary Park position, and Secondary Park position. For each of these positions, Table 4-5 lists the typical application, the state of the IFU aperture (open or blocked), the nominal state of functioning shutters (open or closed), and the script parameter.

Table 4-5 Magnet Arm Positions

<table>
<thead>
<tr>
<th>Arm Position</th>
<th>Script Parameter</th>
<th>IFU Status</th>
<th>Array Status</th>
<th>Typical Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Lock Position</td>
<td>IFU</td>
<td>open</td>
<td>closed</td>
<td>IFU spectroscopy, Launch lock</td>
</tr>
<tr>
<td>Primary Park Position</td>
<td>HOME</td>
<td>blocked</td>
<td>any state</td>
<td>MOS, Fixed slit spectroscopy, protected imaging, Dark</td>
</tr>
<tr>
<td>Secondary Park Position</td>
<td>FAR</td>
<td>open</td>
<td>open</td>
<td>Imaging</td>
</tr>
</tbody>
</table>

Note that:

1. The Secondary Park (Alternate Park) position is “above” Quadrants 1 and 2; i.e., farthest from the optical bench, so that all shutters are opened during a sweep to the Secondary Park.
position. The Micro-shutter Control Electronics (MCE) will command all shutters to open when moving the magnet arm to the Secondary Park position.

2. The Launch Lock and Primary Park arm positions are between the optical bench and Quadrants 3 and 4, so that any set of shutters may be closed during the sweep to either of these positions. Nominally, all shutters are closed when moving to the Launch Lock arm position.

3. The IFU aperture is blocked only when the magnet is in the Primary Park position.

4. The launch lock can be engaged or disengaged multiple times, but only if the magnet arm is in the Launch Lock position.

5. When a resolver reports that the magnetic arm has reached the commanded position, the MSFSW sets a telemetry value that indicates success. If the arm does not reach the commanded position within the allowed time interval, the MSFSW sets a telemetry value that indicates failure.

4.2.3 SPECIFYING A CONFIGURATION

Months before a visit executes, an observer uses the NIRSpec Observation Planning Tool (NOPT, see Section 5.3) to create an MSA configuration file (or to specify a pattern) for each exposure. Given a spacecraft pointing and orientation, the NOPT calculates where potential targets with precisely known coordinates will project onto the MSA. Note that each target has a different offset from the center of the nearest shutter, which affects throughput and calibration accuracy. The observer can use optimization algorithms in the NOPT to select the target subset(s) to observe in any given exposure.

MSA configuration files for a period of up to ten days are bundled together and uplinked to the spacecraft in a compressed format. When a particular configuration file is needed, the scripting engine uncompresses the specified configuration file before sending a command to the Flight Software (FSW) to transfer the configuration to the MCE. Transfer of an entire bitmap will take approximately two minutes. Transfer of a bitmap to the MCE may not be done in parallel with other script commands.

The MCE has 16 bitmap buffers that can hold 16 different patterns. Each buffer represents the desired (not actual) state of all MSA shutters. After the MCE is powered up, the MSFSW can upload configuration information and 16 patterns to the MCE. This capability allows the MCE to load its bitmap buffers with predefined patterns, reducing memory and bus usage. These predefined patterns include a small number of “checkerboard” patterns that are used to calibrate the optical distortion between the MSA and the FPA. These patterns can be easily uploaded from the ground.
There are no “all open” or “all closed” predefined array patterns. Instead, the actions of opening all of the shutters and closing all of the shutters are handled by unique commands from the MSFSW to the MCE.

### 4.2.4 LAUNCH LOCK OPERATIONS

The MSS (Micro-Shutter Subsystem) magnet arm must be locked in launch position to prevent movement during transportation and launch. It can then be unlocked once it reaches its destination or after launch. Locking (closing) and unlocking (opening) the magnet arm uses similar operations.

The launch lock, shown in Figure 4.2-9, is a rotating cam that moves a pawl in and out of the path of the magnet arm actuator. There are special features on the cam that will open and close the two limit switches as the cam rotates. When the launch lock is closed (locked), the closed limit switch is depressed by the special feature on the cam, so it reads CLOSED. In this position, the cam does not depress the open limit switch, so the open limit switch reads NOT OPEN. When the launch lock is opened (unlocked), the cam rotates and immediately releases the closed limit switch. At this point, the closed limit switch now reads NOT CLOSED. The cam continues to rotate until a special feature on the cam depresses the open limit switch, which then reads OPEN.

A single driver operates either the magnet arm motor or the launch lock motor. Therefore, a command to select the launch lock motor is first sent to the MCE, followed by a command to set the current level for the launch lock motor. Then, to unlock the magnet arm, a command from the MSFSW is sent to the MCE to open the launch lock, seen in Figure 4.2-9. The FSW will then wait a predetermined time period for the launch lock closed limit switch to indicate NOT CLOSED, and the open limit switch to indicate OPEN. If these two limit switches do not go to these values during the time period, the FSW will timeout and will mark the command as failed.
The MCE hardware also has a hardware timeout that will be slightly longer than the FSW timeout. If for some reason the FSW sends the command to lock or unlock the launch lock but then loses communication with the MCE, the MCE will stop the motor current when its hardware timeout is reached.

It is expected that opening the launch lock will be performed by ground control under real-time monitoring. It is also expected that the launch lock will be opened only once after launch, and that it will not be opened or closed again in orbit.

As a precaution to ensure that the launch lock is really locked, the magnet arm should be commanded to move out of the launch lock position after it is locked. If the resolver counts do not change, then the launch lock locked position is confirmed. This additional check has been added since there is a very small probability that a break could occur in the launch lock spring that is required to move the launch lock pawl into the locked position. If this condition occurs and the launch lock is in the unlocked (OPEN) position, then when a user sends a command to the FSW to close the launch lock, the limit switches could indicate that the launch lock is CLOSED, but the pawl of the launch lock would not move into position. This would leave the magnet arm unlocked. Again, the probability of the spring breaking is very small, but the consequence of moving or launching the MSA without the magnet arm locked is very high.
4.2.5 DETECTION OF FAILED OPEN/CLOSED SHUTTERS

Micro-Electro-Mechanical Systems (MEMS) devices are subject to stiction, which keeps the devices from operating as designed. There are several known causes for stiction, and probably even more causes that are unknown. The MSA works very well, but as the shutters are operated, some of them can stick open or stick closed. Stuck closed shutters are not too harmful to science operations, but stuck open shutters can cause serious problems with stray light.

It is possible that up to ~15% of the shutters will be permanently closed either because they are stuck closed, or they were stuck open and have been plugged during the flight array screening and testing procedures. Similarly, a few shutters may be permanently stuck open. The number of inoperable shutters is expected to increase over the course of the mission.

The present state of the four flight quadrants (as of February 2010) are shown in Figure 4.2-10. Here the failed closed shutters are shown in black, the failed open shutters in white, and the operable shutters in orange.

Unfortunately, the MCE does not have a means of verifying that commanded shutters behave as commanded. There are no sensors on the shutters to determine whether a shutter is open or closed. Therefore, the only way to detect failed shutters is by taking a flat-field image through the all-open (for stuck closed) or all-closed (for stuck open) MSA using the lamps of the Calibration Assembly (CAA). An automated calibration pipeline on the ground will monitor shutter operability by comparing commanded and actual shutter states for every image of an internal lamp. Inoperable shutters will be indicated in the tool that observers will use to plan MSA observations.
Figure 4.2-10 MSA Shutter maps for the flight quadrants (as of Feb 2010). At the top, operable shutters are colored grey, while failed closed are black. The bottom panel shows the failed open shutters in white.
4.2.6 MSA HEAT-UP PROCEDURE

Testing indicates that over time, MSA shutters can become curled up much like a potato chip. Deformed shutters can wedge into their egg-crate walls and stick in this open state, causing loss of fidelity to the planned MSA configuration. Testing has shown that heating the MSA to 260 K, holding the temperature for 15 minutes, and then cooling back down releases the majority of stuck open shutters. Heating the arrays up to 260 K may be returning the shutters back to their original configuration, thus freeing up stuck open shutters.

The MSA is equipped with prime and redundant heaters on each quadrant that may be used to heat up the entire MSA to 260 K in order to release shutters that have become stuck open during on-orbit operations. The required frequency of the heat-up cycles is not known with certainty due to limited statistics and variability from one array quadrant to another. Originally, the best estimate of the required frequency for the heat-up cycles at this time was every 2000 open/close cycles of the shutters. Recently, however, flight quadrant Q1-18-132 was cycled and then had permanently stuck open shutters plugged. After 2,000 more cycles, only two shutters became stuck open. If this recent test is any indicator, then a heat-up procedure may only need to be run when there is noticeable and unacceptable degradation of science data. It is expected that this procedure will be done through the on-board scripts.

Before the heat-up cycle begins, it is important to move the FWA to its OPAQUE position to keep infrared stray light from going out of the NIRSpec instrument back down to the pick-off mirror and so to the rest of the observatory. The GWA should be rotated to its G140H position so that the long-wavelength end of the thermal emission spectrum is dispersed off the detectors; all of the MSA shutters should be closed (ALLCLOSED); and power to the MSA magnet arm motors should be turned off through MSFSW commands.

The nominal heat-up procedure is as follows:

1. Set the MCE heater voltage level for each quadrant. Since every quadrant is unique, the MCE provides the capability of using different heater voltage levels for each quadrant. Note that for each quadrant, either the prime or redundant heater may be used, or both of these heaters may be used simultaneously to increase the power.

2. Send a command to the MCE to switch the heater power on to all four quadrants. This command will not start the heating process at this point since the heaters have not yet been enabled.

3. Send a command to the MCE to start the hardware watchdog timer for the specified amount of time (about 5 minutes). At the same time, start the FSW watchdog timer for half the MCE hardware watchdog timer (about 2.5 minutes).

4. Send a command to the MCE to enable the heaters on all four quadrants.
5. When the MSFSW watchdog timer times out, it will send another command to the MCE to restart the MCE hardware watchdog timer for specified period of time (another 5 minutes).

6. The FSW will repeat this process until the specified number of timing intervals has been completed.

7. When, during the heat-up time period, the MCE detects that the temperature of a quadrant has reached 260 K, it will turn off that quadrant’s heaters. It will perform this action for each of the four quadrants.

8. For optimum performance, the quadrants should be held at 260K for 15 minutes. Therefore, when the on-board script “sees” that the MCE has turned off a quadrant heater, it will send another command to the MSFSW to start the heat-up all over again for that quadrant. The on-board script will continue to send these commands until 15 minutes have passed since the MCE first turned off the heaters to the quadrant. The on-board scripts will need to perform this timing function for each of the four quadrants.

9. Once all of the commanded quadrants have been heated at 260 K for 15 minutes, the FSW will send a command to the MCE to disable the heaters.

10. The user sends a command via the FSW to the MCE to turn off the power to the heaters.

11. After the quadrants have cooled down within their operational temperature range, the user sends a command via the FSW to the MCE to perform a zero-volt sweep.

If for some reason, the MSFSW loses communication with the MCE while the heaters are turned on, the MCE hardware watchdog timer will automatically turn the heaters off when it times out (nominally after 5 minutes).

Table 4-6 shows the heat-up and cool-down times for three levels of total heater power (all four quadrants). These values are based on the latest thermal analysis done in March 2008. Thermal stability of the MSA is being tested now. So far, results from optical tests show that when the MSA is heated to 260 K and cooled back down, it has thermal stability in the X-Y direction of ≤ 1.8 microns rms. Further tests are planned that should improve the accuracy and resolution of the measurements. These results also are based on cool-down for about 24 hours.

Table 4-6 MSA heat-up and cool-down times versus heater power.

<table>
<thead>
<tr>
<th>Heater Power (W)</th>
<th>Time to Heat Up to 260 K (minutes)</th>
<th>Time to Heat Up to 260 K and Cool Down to 50 K (hours)</th>
<th>Time to Heat Up to 260 K and Cool Down to 32 K (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>26.3</td>
<td>2.0 hrs</td>
<td>6.4 hrs</td>
</tr>
<tr>
<td>18</td>
<td>13.3</td>
<td>1.7 hrs</td>
<td>5.6 hrs</td>
</tr>
<tr>
<td>24</td>
<td>9.0</td>
<td>1.6 hrs</td>
<td>5.2 hrs</td>
</tr>
</tbody>
</table>
Although the MSA heat-up and cool-down times are shown in Table 4-6, the real criteria for when the NIRSpec instrument can resume normal operations depends on the sensitivity of the MSA thermal stability to slight temperature variations, and the thermal effects on the detectors from heating the MSA. If the MSA must return to its original starting temperature to achieve the required thermal stability, then the cool-down period may be longer than the values in Table 4-6. Also, if the detectors experience a temperature increase, it may take more time to reestablish thermal stability in the detector system, especially if the temperature increases beyond the set point of the temperature controller.

4.2.7 MSA ELECTRICAL SHORTS AND MASKING

There are four types of shorts that can occur in the MSA: column-to-column shorts (“171 side” or “front-side”), row-to-row (“365-side” or “back-side”) shorts, and row-to-column (“front to back”) shorts, and “tri-state” shorts of unclear origin. These shorts can occur through the bulk material of the substrate or through surface effects (contamination, etc). These shorts can occur due to the close spacing of the rows and columns, and due to electrically conductive particulate contamination that can be generated during the operation of the MSA. The incidence of these shorts tends to be higher early in the life of the MSA, and then drops over time.

4.2.7.1 Column-to-Column Shorts

If adjacent columns are electrically shorted, shutters should be addressed in pairs along the 171 column side rather than deactivate both columns (making them permanently closed). Specifically, if two columns are shorted together (for example columns 50 and 51 of 171 columns), and we want to address a shutter in column 50 to be open, then the adjacent shutter along the cross-dispersion direction in column 51 will also be opened. Since the columns are addressed in pairs, the two shorted columns have the same voltage so there is little to no increase in current. Making the data identical for these pairs (either ones or zeros) is up to the user.

Another means to mitigate this problem is implemented in hardware using masks. A “zero potential mask” can be sent to the MCE that keeps the rows and/or columns that are shorted at a constant zero volt potential.

4.2.7.2 Row-to-Row Shorts

Shorts can also occur between two adjacent MSA rows, which is generally unacceptable because of straylight degradation of the spectra through two open shutters along the dispersion direction of the grating. In this case, both the addressed shutter in the row and the adjacent shutter in the next row will open. Although this is a compromise, it is thought to be better than masking both rows and converting them to a permanently closed inoperable state.

Since each row is set to the same voltage, shorts between rows do not cause a measurable increase in current. Therefore, it is not possible to detect a row-to-row short by monitoring current increases. The presence of a short must be detected by taking an image. Once a short has been detected, the specific rows affected can be isolated by a simple algorithm during debugging.
4.2.7.3 Row-to-Column Shorts

Shorts can also occur between a row and a column. This is the worst type of short because the voltage difference between a row and column can get as high as 72V during addressing. The current can increase and be detected by the MSS current monitor in the MCE. The MCE will turn off power to a quadrant if the array current exceeds 10 mA for \( \geq \) 300 seconds, and it will set a sticky over-current shutdown bit in the telemetry. The MSFSW will report the error in its telemetry, will automatically send an ABORT command to the MCE to stop any command processing, and will set its INHIBIT CMD flag to inhibit further processing of commands from the on-board scripts. Ground intervention is then required to debug the over-current problem.

During debug operations, the short can be isolated using the same simple algorithm as used for row-to-row shorts. Once the specific shorted row and column have been isolated, a mask can be loaded into the MCE from the MSFSW that prevents this row and column from being latched or addressed at all because the specific row and column voltages are always kept at zero volts. Masking of the shorted row and column is necessary because these shorts can draw high current.

4.2.7.4 Short Mitigation and Masking Engineering Activities

The NIRSpec Ops Working Group has designed algorithms for detecting and masking shorts that will be implemented in the on-board scripts. The use of these scripts would be triggered by an increase in trended voltage telemetry coming off the MSA, or by a discrepancy between a planned MSA configuration for a science observation and the configuration that was actually obtained.

In brief, these scripts use a row-by-row and column-by-column search procedure to identify shorted pairs of adjacent rows, columns, or shorts between rows and columns. The scripts use the existing “zero-potential” and “tri-state” masks to avoid rediscovery of shorts that are known and already masked. If more than 10 new shorts are found, this is an indicator of a serious unanticipated problem and the script will exit by safing NIRSpec. If less than 10 new shorts are found, these will be masked and the updated mask file will be sent to the ground for analysis. The short detection script will also identify the so-called tri-state shorts but will not automatically mask them. There is a command flag to safe NIRSpec in the event that the script completes the search for shorts (both “zero-potential” and “tri-state”) without identifying any shorts, which indicates an unanticipated problem. This is regarded as unlikely.

Ordinary row-to-row, column-to-column, or row-to-column shorts are automatically masked by this detection activity, while tri-state shorts are not. For replacing the on-board tri-state mask or for restoring or updateing the zero-potential masks on board there is a separate activity for uploading masks only.

Row-to-row and column-to-column shorts are unlikely to trigger the on-board safety limits, so the decision to mask them is largely concerned with their impact on science operations, as described above. They can be masked or not masked and in either case will be planned around using the MSA planning tool, which will contain the latest shorts mask. Row-to-column shorts can draw
unsafe current, so they should be masked routinely. Tri-state shorts have no clear-cut origin; they will need to be masked if they are discovered to draw unsafe current.

More details about the operational impacts of shorts can be found in the technical report “MSA Short Detection and Mitigation” by J. Tumlinson (JWST-STScI-001736), which preserves a record of NIRSpec Operations Working Group discussions on this issue.

4.2.8 OPERATIONAL CONSTRAINTS

A complete list of MSS operational constraints is documented in the *NIRSpec Micro-Shutter Subsystem Fault Protection Plan* (JWST-PLAN-009670). This plan will be used by ISIM to incorporate the MSS operational constraints with the operational constraints of the rest of the Science Instruments.

4.2.9 SLIT APERTURES FOR SINGLE-OBJECT SPECTROSCOPY

The NIRSpec MSS plane will also have a set of permanently open slit apertures for single-object, high contrast observations of astronomical targets. As indicated in Figure 4.2-3, these “fixed slit” apertures are located in the gap between the MSA quadrants. Physically, they are simply cutouts in the metal frame used for mounting the MSA quadrants. The approximate locations for the IFU and all slits except B_200 are illustrated in Figure 4.2-10, while their physical (in the MSA plane) and angular (projected on the sky) dimensions are listed in Table 4-7.

![Figure 4.2-10: Left panel: Arrangement of fixed slits and the IFU aperture in the MSA plane. Some of the IFU virtual slits can be seen in blue to the right of the MSA plane, in addition to the circular cutout around the IFU aperture and four of the five slits. The fifth slit is located far to the left outside the region shown here. Right panel: Layout of IFU slitlets in the field of view. This figure does not show S1600A1, which is only recently added to the design in place of the small upper left slit in the left panel.](image-url)
Table 4-7: Names and dimensions of the fixed slit apertures

<table>
<thead>
<tr>
<th>Slit name</th>
<th>Width [µm]</th>
<th>Length [µm]</th>
<th>Width [arcsec]</th>
<th>Length [arcsec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S200A1</td>
<td>78.6</td>
<td>1274.2</td>
<td>0.200</td>
<td>3.2</td>
</tr>
<tr>
<td>S200A2</td>
<td>78.6</td>
<td>1274.2</td>
<td>0.200</td>
<td>3.2</td>
</tr>
<tr>
<td>S400A1</td>
<td>157.3</td>
<td>1453.5</td>
<td>0.400</td>
<td>3.65</td>
</tr>
<tr>
<td>S1600A1</td>
<td>637.1 (TBC)</td>
<td>637.1 (TBC)</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>S200B1</td>
<td>78.6</td>
<td>1274.2</td>
<td>0.200</td>
<td>3.2</td>
</tr>
<tr>
<td>IFU window</td>
<td>Circular with diameter 2.0 mm</td>
<td>Elliptical with axes 5.176&quot; x 5.084&quot;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3 Integral Field Unit

The benefit of an Integral Field Unit (IFU) is the ability to obtain the spectrum of a contiguous, extended area on the sky. This is achieved by optically re-arranging all spatial resolution elements within the field of view into a virtual long slit, either by means of optical fibers or, as in the case of NIRSpec, by “image-slicing” techniques as illustrated in Figure 4.3-1. The resulting virtual slit can then be dispersed without confusion by neighboring spatial elements. In the case of NIRSpec, a 3" x 3" square field of view (within the ~5" circular window) is dissected into 30 slices of 0.1” width and 3” length each.

Figure 4.3-1 Illustration of the principal idea behind integral-field spectroscopy (from VLT/SINFONI).
4.3.1 OPTICAL DESIGN

A conventional IFU optical design, indicated schematically in Figure 4.3-2 includes the following optical components:
1) a **pick-off mirror** re-directs the light from the telescope focal plane into the IFU optics.
2) two **re-imaging mirrors** form a magnified image of the input field onto the image slicer.
3) the **image slicer** consists of 30 stacked mirror surfaces that are all curved and tilted with respect to each other such that the image is split into 30 individual “slitlets”, each of which is directed onto a dedicated pupil mirror.
4) each slitlet beam hits a **pupil mirror** that forms an image of the slitlet aperture. The pupil mirrors are curved and tilted such that the slitlet images are aligned to form a single long slit.
5) the **slit mirrors** are also curved and tilted such the output beams, from all image points in all slitlets, are directed towards the spectrometer entrance pupil.

**Figure 4.3-2** Illustration of the “standard” image-slicing IFU design.

In the “standard” IFU configuration, the sub-slit images created by the pupil mirrors are formed on the surfaces of the slit mirrors. However, the design of the NIRSpec IFU (see Figure 4.3-3 and Figure 4.3-4) is different in that the slit mirrors cannot be located in a focal plane. Instead, they are followed by an additional final mirror, the **output fold mirror**, which will create a virtual image of the slits at the nominal focal plane.
4.3.2 OPERATIONAL CONSTRAINTS

The NIRSpec IFU has no moving parts, and there are, in principle, no operational constraints associated with its use. However, this implies that the IFU entrance aperture is always open, and any light entering it will be transformed into a virtual long slit which, when dispersed, fills nearly the entire active detector area. It is thus mandatory that when the IFU is not in use, the entrance aperture is blocked. This is achieved by “parking” the MSA magnet in a position that obscures the IFU window. This position is, in fact, the default park position for the MSA magnet, and will be used for all NIRSpec modes except IFU mode.
When NIRSpec is in IFU mode, the MSA magnet must obviously be parked such that it does not obscure the IFU window. For this purpose, a secondary magnet position is defined. The FSW has to ensure that this position is used whenever NIRSpec enters IFU mode.

### 4.4 Filter Wheel Assembly

#### 4.4.1 DESIGN AND FUNCTIONALITY

The main structural components of the filter wheel assembly are shown in Figure 4.4-1:

1. a mechanism support structure provides the structural interface to the optical bench via three isostatic mounts and contains the torque motor, the central ball bearing, sensors to monitor the wheel position and temperature, and the harness connectors.
2. a spring-operated ratchet mechanism holds the wheel in place with good angular repeatability.
3. the filter wheel structure holds seven transmission filters and one element that doubles as an instrument shutter to the telescope side and a coupling mirror for the CAA on the NIRSpec side. The filters are described in detail in the next section.

![Figure 4.4-1](image)

**Figure 4.4-1** Main components of the filter wheel sub-assembly.
4.4.2 OPTICAL ELEMENTS

The eight filter wheel elements and their main applications are summarized in Table 4-8. All filters have a clear aperture diameter of 66 mm. All the filters except F140X and F110W are made of CaF$_2$ and are 10.15 mm thick. Both F110W and F140X are made of BK7G18 and are 8.9 mm thick. In order to avoid ghost reflections, the filters are tilted by 5.3º with respect to the optical axis in the spatial direction.

Table 4-8 Summary of the NIRSpec filters.

<table>
<thead>
<tr>
<th>Name</th>
<th>Bandpass</th>
<th>Average Trans.</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>F140X</td>
<td>0.8 µm &lt; λ &lt; 2.0 µm</td>
<td>&gt; 85%</td>
<td>target acquisition (BB-B)</td>
</tr>
<tr>
<td>F110W</td>
<td>1.0 µm &lt; λ &lt; 1.2 µm</td>
<td>&gt; 90%</td>
<td>target acquisition (BB-A)</td>
</tr>
<tr>
<td>F070LP</td>
<td>λ &gt; 0.7 µm</td>
<td>&gt; 80%</td>
<td>MSA/IFU/SLIT over 0.7µm ≤ λ ≤ 1.2µm</td>
</tr>
<tr>
<td>F100LP</td>
<td>λ &gt; 1.0 µm</td>
<td>&gt; 80%</td>
<td>MSA/IFU/SLIT over 1.0µm ≤ λ ≤ 1.8µm</td>
</tr>
<tr>
<td>F170LP</td>
<td>λ &gt; 1.7 µm</td>
<td>&gt; 80%</td>
<td>MSA/IFU/SLIT over 1.7µm ≤ λ ≤ 3.0µm</td>
</tr>
<tr>
<td>F290LP</td>
<td>λ &gt; 2.9 µm</td>
<td>&gt; 80%</td>
<td>MSA/IFU/SLIT over 2.9µm ≤ λ ≤ 5.0µm</td>
</tr>
<tr>
<td>CLEAR</td>
<td>λ &gt; 0.6 µm</td>
<td>&gt; 80%</td>
<td>alignment tests at optical wavelengths also MSA/IFU/SLIT with PRISM on GWA</td>
</tr>
<tr>
<td>OPAQUE</td>
<td>n/a</td>
<td>n/a</td>
<td>shutter, used for calibrations with the CAA</td>
</tr>
</tbody>
</table>
Figure 4.4-2 Transmission curves for the six NIRSpec filters. The top four curves are for F070LP, F100LP, F170LP, and F290LP (all measured at cryogenic temperatures). The lower two curves show the transmission for F110W (left) and F140X (right).

The OPAQUE position prevents light from the JWST telescope from reaching the MSA. It will be used for dark current measurements, and whenever NIRSpec is not being used. In addition, it has a flat mirror mounted on the back side (i.e. facing the MSA) which is aligned such that the beam from the CAA will be directed exactly as if it had originated from the telescope. In other words, behind the FWA, shape and direction of the optical beams from CAA and telescope are indistinguishable.

The CLEAR position serves mainly to support the instrument alignment and verification procedures at ambient conditions, using measurement devices at visible wavelengths. It can potentially be used for scientific applications if the JWST wavefront error below 0.7 μm is acceptable.

The two finite bandpass filters F140X and F110W are mainly used during the target acquisition procedure to obtain the acquisition images that allow centroiding of the reference stars (see Section 6). The different widths of the two filters allow greater flexibility in the luminosities and dynamical range of reference stars. To facilitate cross-calibration between NIRSpec and NIRCam, the transmission curve of F110W is substantially similar to the corresponding NIRCam filter.

Finally, the four long-pass filters are used in conjunction with the respective gratings to avoid confusion due to overlapping spectral orders. Their transmission curves are shown in Figure 4.4-2.

4.4.3 FWA RUN-IN AND CHARACTERIZATION

Two operational activities have been defined to maintain the effective operations of the FWA. These two activities apply also to the very similar Grating Wheel Assembly (GWA), as described in the next subsection.

FWA “Run-in”: The FWA mechanism contains a high-grade lubricant that will need to be distributed evenly throughout its sealed chamber before the FWA can be used in normal operational modes. The engineering activity has been defined to accept a request for 1 to 50 full
wheel rotations in either the forward or reserve directions, or in both directions as the likely default choice. The activity can be executed separately for the forward and reverse directions for flexibility in scheduling these short visits. Thermal constraints during run-in may limit the number of iterations to be performed at a given time; this possible constraint will be investigated during ground testing. This activity is planned to occur shortly after launch of JWST during mission commissioning, and should not need to be done again.

FWA “Characterization”: This activity is intended to record reference data of wheel movement and control characteristics (current, voltage, and position over time) after launch and run-in to establish a reference data set for future troubleshooting. This engineering activity moves the wheel to each position in sequence, in either the forward or reverse direction as requested, and dumps the mechanism’s high capacity buffer for inspection on the ground. It is planned to allow the forward and reverse characterizations separately so that one full rotation can potentially be executed within different observatory slews. The activity is the same whenever it is done.

4.4.4 OPERATIONAL CONSTRAINTS

Preliminary constraints on FWA operations are defined as of November 2009; flight model testing will finalize these constraints. Note that many of these constraints apply also to the GWA (4.5.4).

1) Disturbance after FWA or GWA movement: After a FWA (or GWA) movement a settling time for observatory pointing stabilization is needed before science exposures can be taken.
2) The FWA (and GWA) should not be operated at temperatures intermediate between the nominal “ambient” and “cryogenic” ranges, because the ICE implements distinctive configuration tables that do not apply at intermediate temperatures.
3) The sum of the two motor coil currents shall not exceed 640 mA, otherwise the ICE will switch off motor drive current, and abort wheel movement.

4.5 Grating Wheel Assembly

4.5.1 DESIGN AND FUNCTIONALITY

The mechanical design of the GWA is very similar to that of the FWA. Hence, the main structural components of the GWA (Figure 4.5-1) have similar tasks:

1) a mechanism support structure provides the structural interface to the optical bench via three isostatic mounts and contains the torque motor, the central ball bearing, sensors for monitoring the mechanism position and temperature, and the harness connectors.
2) a spring-operated ratchet mechanism holds the wheel in place with good angular repeatability and provides additional torque to minimize power consumption of the motor.
3) the grating wheel structure holds the eight optical elements described in the next section.
4.5.2 OPTICAL ELEMENTS

The GWA contains eight optical elements: one flat mirror, one double-pass prism, and six blazed reflection gratings. The gratings and the mirror are made from gold-coated Zerodur-0, a glass ceramic with a low coefficient of thermal expansion (CTE). The prism is made from CaF₂, also with a gold-coated reflective surface. The spectral resolution, central wavelengths, and main scientific applications of the optical elements in the GWA are summarized in Table 4-9.

Table 4-9: Optical elements of the GWA

<table>
<thead>
<tr>
<th>Name</th>
<th>Resolution</th>
<th>Peak Efficiency</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>G140M</td>
<td>R~1000</td>
<td>~ 1.3 μm</td>
<td>For MSA/IFU/SLIT over 0.6μm ≤ λ ≤ 1.8μm</td>
</tr>
<tr>
<td>G235M</td>
<td>R~1000</td>
<td>~ 2.2 μm</td>
<td>For MSA/IFU/SLIT over 1.7μm ≤ λ ≤ 3.0μm</td>
</tr>
<tr>
<td>G395M</td>
<td>R~1000</td>
<td>~ 3.7 μm</td>
<td>For MSA/IFU/SLIT over 2.9μm ≤ λ ≤ 5.0μm</td>
</tr>
<tr>
<td>G140H</td>
<td>R~2700</td>
<td>~ 1.3 μm</td>
<td>For MSA/IFU/SLIT over 0.6μm ≤ λ ≤ 1.8μm</td>
</tr>
<tr>
<td>G235H</td>
<td>R~2700</td>
<td>~ 2.2 μm</td>
<td>For MSA/IFU/SLIT over 1.7μm ≤ λ ≤ 3.0μm</td>
</tr>
<tr>
<td>G395H</td>
<td>R~2700</td>
<td>~ 3.7 μm</td>
<td>for MSA/IFU/SLIT over 2.9μm ≤ λ ≤ 5.0μm</td>
</tr>
<tr>
<td>PRISM</td>
<td>R~100</td>
<td>~ 2.5 μm</td>
<td>for MSA/IFU/SLIT over 0.6μm ≤ λ ≤ 5μm</td>
</tr>
<tr>
<td>MIRROR</td>
<td>n/a</td>
<td>n/a</td>
<td>Mirror for undispersed images</td>
</tr>
</tbody>
</table>
The “as designed” grating parameters are listed in Table 4-10:

Table 4-10: Grating design parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>G140M</td>
<td>3.6</td>
<td>40 – 90</td>
<td>95.4035</td>
<td>4.20006</td>
<td>&gt; 62.6</td>
<td>&gt; 77.4</td>
</tr>
<tr>
<td>G235M</td>
<td>3.7</td>
<td>40 – 90</td>
<td>56.8767</td>
<td>4.20258</td>
<td>&gt; 65.9</td>
<td>&gt; 78.3</td>
</tr>
<tr>
<td>G395M</td>
<td>3.8</td>
<td>40 – 90</td>
<td>33.8221</td>
<td>4.10143</td>
<td>&gt; 68.0</td>
<td>&gt; 79.2</td>
</tr>
<tr>
<td>G140H</td>
<td>10.0</td>
<td>60 – 90</td>
<td>252.267</td>
<td>8.80284</td>
<td>&gt; 63.5</td>
<td>&gt; 77.8</td>
</tr>
<tr>
<td>G235H</td>
<td>10.0</td>
<td>60 – 90</td>
<td>150.291</td>
<td>8.75437</td>
<td>&gt; 64.0</td>
<td>&gt; 78.3</td>
</tr>
<tr>
<td>G395H</td>
<td>10.3</td>
<td>60 – 90</td>
<td>89.4088</td>
<td>8.80105</td>
<td>&gt; 67.2</td>
<td>&gt; 79.4</td>
</tr>
</tbody>
</table>

Figure 4.5-2 shows the expected efficiency curves for all six gratings.

Figure 4.5-2 Expected efficiency curves for the NIRSpec gratings for the nominal blaze angles (as listed in Table 4-10) and ± 0.2° deviation. From top to bottom the gratings are G140, G235, and G395, with the medium-resolution gratings (M) on the left, and the high-resolution gratings (H) on the right. These curves will be updated as soon as the actual performance of the flight gratings has been measured.
4.5.3  GWA RUN-IN AND CHARACTERIZATION

Two operational activities have been defined to maintain the effective operations of the GWA. These two activities apply also to the very similar Filter Wheel Assembly (FWA), as described in the previous subsection.

GWA “Run-in”: The GWA mechanism contains a high-grade lubricant that will need to be distributed evenly throughout its sealed chamber before the GWA can be used in normal operational modes. The engineering activity has been defined to accept a request for 1 to 50 full wheel rotations in either the forward or reserve directions, or in both directions as the likely default choice. The activity can be executed separately for the forward and reverse directions for flexibility in scheduling these short visits. This activity is planned to occur shortly after launch of JWST during mission commissioning, and should not need to be done again. Thermal constraints during run-in may limit the number of iterations to be performed at a given time; this possible constraint will be investigated during ground testing.

GWA “Characterization”: This activity is intended to record reference data of wheel movement and control characteristics (current, voltage, and position over time) after launch and run-in to establish a reference data set for future troubleshooting. This engineering activity moves the wheel to each position in sequence, in either the forward or reverse direction as requested, and dumps the mechanism’s high capacity buffer for inspection on the ground. It is planned to allow the forward and reverse characterizations separately so that one full rotation can potentially be executed within different observatory slews. The activity is the same whenever it is done.

4.5.4  OPERATIONAL CONSTRAINTS

Preliminary constraints on GWA operations are defined as of November 2009; flight model testing will finalize these constraints. Note that many of these constraints apply also to the FWA (4.4.4).

1) Disturbance after FWA or GWA movement: After a GWA (or FWA) movement a settling time for observatory pointing stabilization is needed before science exposures can be taken.
2) The GWA (and FWA) should not be operated at temperatures intermediate between the nominal “ambient” and “cryogenic” ranges, because the ICE implements distinctive configuration tables that do not apply at intermediate temperatures.
3) The sum of the two motor coil currents shall not exceed 640 mA, otherwise the ICE will switch off motor drive current, and abort wheel movement.
4.6  **Re-focus Mechanism**

4.6.1  **DESIGN AND FUNCTIONALITY**

The Re-focus Mechanism Assembly (RMA) provides a means to ensure that the images of the sky are properly focused when projected onto the MSA plane. While the internal NIRSpec optics are expected to be extremely stable, the exact position of the OTE focus will not be known until after launch when the telescope has undergone its initial fine-phasing, and the ISIM structure has reacted to gravity release and cooldown. The main purpose of the RMA is to accommodate this initial focus uncertainty.

In principle, the OTE focus position can drift with time after the initial phasing campaign as the telescope alignment changes, either between or after subsequent re-phasing campaigns. However, it is currently planned that the OTE focus will always be maintained at the initial position as defined by the NIRCam focus. Barring severe changes in the alignment between the science instruments due to ISIM structure deformation, it should therefore not be necessary to exercise the NIRSpec RMA after the initial focusing of NIRSpec. This is crucial for the target acquisition (TA) procedure, because a change in NIRSpec focus results in changes to the various distortion tables used by the TA software (see Chapter 6).

The working principle of the RMA is illustrated in Figure 4.6-1. It consists of two flat mirrors mounted in a penta-prism arrangement on a baseplate (a.k.a. “sled”) which can be moved along the refocusing direction, resulting in a shift of the focal position which should coincide with the plane of the MSA shutters. The penta-prism design has a number of important operational benefits:

1. the lateral image position is independent of RMA position.
2. no additional wavefront error is introduced by changing the RMA position.
3. Large adjustment range, easily accommodating the budgeted OTE focal plane variations of up to 25mm.

The mechanical implementation of the RMA is shown in Figure 4.6-2. The sled is driven by a cryogenic, geared stepper motor, an eccentric shaft assembly mounted on ball bearings, and a connecting lever transmitting the motion from the eccentric shaft to the sled.
Figure 4.6-1 Working principle of the RMA. The penta-prism design assures a stable image position.

Figure 4.6-2 Design of the RMA structure.
The eccentric rotation through the lever will allow a linear displacement of the sled as illustrated in Figure 4.6-3. The total stroke of the sled is 6 mm and it is performed by a half rotation (180°) of the eccentric shaft. The small angular tilt experienced by the connecting lever during one revolution makes it possible to mount it to the sled by an intermediate flexural section, thus avoiding use of an additional ball bearing.

The eccentric shaft can be driven in open loop in both directions. Since the eccentric drive concept allows a continuous rotation of the eccentric shaft for a full 360° without running into restricted areas, end stops and end-switches are not required. Two Hall effect sensors are used to monitor the launch and the nominal focus position.

In order to minimize the torque on the gear output shaft generated by the launch vibrations, the RMA is launched with the sled positioned at the end of its range, i.e. the -3mm (TBC) position in Figure 4.6-3.

**Figure 4.6-3** Schematic of the RMA translations scheme. Note that the launch position is at -3mm (TBC), the end of the adjustment range.
4.6.2 STRATEGY FOR FINDING “BEST FOCUS”

For most spectroscopic applications, maximizing signal-to-noise ratio in the extracted spectrum is more important than maximizing image quality. If necessary, spectrograph focus should be adjusted to maximize sensitivity, even if image quality at the detector suffers. The MSA and FPA are designed to be conjugate focal planes, so that the best COL/CAM focus at the FPA should correspond to the best OTE/FOR focus at the MSA (and hence maximum throughput). If this ideal is achieved, then maximizing image quality at the FPA will yield optimum spectrograph sensitivity.

If the MSA and FPA are not conjugate focal planes, due to design or manufacturing errors, then it might be necessary to maximize encircled energy at the FPA, rather than image quality at the FPA. However, encircled energy is likely to be a weak function of focus because MSA apertures are relatively large compared to the PSF. In this case, maximizing image quality at the FPA is an equally valid approach. Regardless of how optimum focus is actually determined during the data analysis (i.e. via MSA throughput or FPA image quality), the procedure to obtain the required data will be the same. Since the magnitude and number of steps in a typical sweep will not be known until FM testing, this procedure uses generic values for the sweep position input array DELTA.

A) Set-up:
1) Configure MSA to all open or bright object mask configurations
2) Move FWA to F140X
3) Move GWA to MIRROR
4) Move RMA to reference position
5) Sort input sweep positions, 0, then increasing positive values, then increasing negative values, e.g. DELTA = “-10, -5, 0, 5, 10” will sort to DELTA = “0, 5, 10, -10, 5”.
6) Move RMA to start position of sweep (generally the current DELTA = 0 position).

B) Focus sweep:
7) Configure FPE/ASIC for full-frame exposure
8) Configure SCEPs
9) Obtain exposure (full-frame, MULTIACCUM, user input parameters)
10) Clean-up SCEPs and memory
11) Move RMA to next sweep position in sorted DELTA array.
12) Repeat 7) - 11) until full sweep range is covered

C) Clean up:
13) Move RMA to reference position (new focus position will not be known immediately)
14) Move filter wheel to OPAQUE position

The focus quality can vary with field angle, and the “best focus” will therefore represent a compromise over the field of view. Focus measurements should therefore be obtained at multiple field positions on the MSA. External point sources (i.e. a pinhole mask during ground testing and stars during in-orbit operations) will be positioned within the central acceptance zone of a shutter,
but they cannot all be perfectly centered. The goal is to maximize global image quality across the field of view.

Because the baseline plan is to focus NIRSpec only once at the beginning of the mission, there is no need for onboard scripts to autonomously analyze the data and to determine the optimum focus. Instead, the data obtained during will be downlinked and the NIRSpec instrument scientists will spend a few days analyzing them. After the best focus position has thus been determined, a command to move the RMA to the best focus position will be uplinked to the spacecraft. This procedure will be used again if NIRSpec needs to be refocused later in the mission, which should be rare if it happens at all.

4.6.3 OPERATIONAL CONSTRAINTS

The periodic telemetry of the ICSW will contain two different counters for the Refocus Mechanism Assembly:

1. A counter corresponding to the value stored last time the RMA reference position has been detected. This counter is updated each time the RMA Hall sensor signal is above a table defined threshold (this is independent of the command “Go to reference position”).
2. A counter giving the number of user-commanded increments (nominally, this corresponds to the current position of the RMA).

The positional accuracy depends on backlash in the RMA motor and gear, currently given as 0.75° worst case for the launch position and 0° in mid-stroke position.

The RMA does not operate in closed-loop, i.e. there is no feedback on whether a commanded movement has actually been executed. It is therefore necessary to reacquire the position index of the RMA reference position from time to time. This is why the focus sweep procedure includes the step “Go to reference position”.

It has been noticed in ground testing of the NIRSpec Demonstration Model (DM) that the RMA may have a preferred direction of travel, e.g. the mechanism may move more accurately to a certain position from one direction than from the other. It is not known if this behavior will occur in the Flight Model (FM), but the issue is being tracked and will appear as an RMA operational constraint in this document at a later time, if necessary.

4.7 Calibration Assembly

The purpose of the calibration assembly (CAA) is to enable on-orbit calibration and monitoring of a number of important instrument parameters such as (i) the geometric distortion between the MSA and the FPA, (ii) the response as a function of both field angle and wavelength, and (iii) the dispersion of the various spectral elements.

Because its light beam does not pass through the NIRSpec filter wheel (see Section 4.7.3), the CAA has to provide passband filters that closely mimic the NIRSpec filters. In addition, the wide
wavelength range of NIRSpec, the multitude of available spectral modes (i.e. the combination of passband and spectral resolution), and the different calibration goals add to the complexity of the CAA design. Other key drivers for the design of CAA are the following:

- a high level of uniformity of the output beam.
- light sources with a wide optical bandwidth (0.7 to 5 μm).
- light levels that are adequate for achieving the calibration goals in a reasonable amount of time without saturating the detector.
- low power dissipation.
- thermal stability under all operational conditions.
- light sources that are electrically redundant.
- a near-parallel light path through the spectral filters to avoid chromatic variations of the signal level.
- volume, and mass limits
- lifetime requirements

4.7.1 MECHANICAL AND OPTICAL DESIGN

The design drivers listed above lead to a CAA implementation which has the following features:

- An integrating sphere to provide the optical uniformity.
- Eleven light source assemblies (or “telescopes”) feeding light into the integrating sphere.
- Each telescope contains two redundant lamps, dedicated filters for the correct bandpass, and a set of lenses that ensure that the beam from either lamp passes through the filter at the correct angles and evenly illuminates the integrating sphere.
- Each lamp uses a bulb-enclosed Tungsten filament, operated at a temperature of ~ 1800K.

Figure 4.7-1 shows a schematic of the CAA sub-assembly, and the detailed design of the feeder telescopes is shown in Figure 4.7-2.
Each CAA lamp has two identical filaments in order to provide redundancy. It is not possible to operate both filaments simultaneously. If one fails or degrades beyond operability, recovering the lost capability will require switching to the redundant ICE, since no cross-straps are available to operate the failed CAA lamps with the primary ICE. Since this switch from one side to another of the ICE is a major change to NIRSpec operations, CAA filament lifetimes should be considered a limited resource and be preserved as much as reasonably possible consistent with science needs and other instrument constraints.
4.7.2 LIGHT SOURCES

The NIRSpec CAA contains 11 light sources that are nearly identical in their mechanical design, but differ in their passband characteristics and signal levels. The passbands and expected signal levels of the 11 light sources are summarized in Table 4-11.

**Table 4-11** Summary of CAA light sources. Note that the intensities are integrated over the CAA exit aperture.

<table>
<thead>
<tr>
<th>Source name</th>
<th>Wavelength range [μm]</th>
<th>Min. spectral intens. $[10^{13} \text{ ph}/(s \cdot sr \cdot \mu m)]$</th>
<th>Max. spectral intens. $[10^{13} \text{ ph}/(s \cdot sr \cdot \mu m)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLAT 1</td>
<td>1.0 – 1.8 (Band I)</td>
<td>1.0</td>
<td>40.0</td>
</tr>
<tr>
<td>FLAT 2</td>
<td>1.7 – 3.0 (Band II)</td>
<td>0.6</td>
<td>25.0</td>
</tr>
<tr>
<td>FLAT 3</td>
<td>2.9 – 5.0 (Band III)</td>
<td>0.4</td>
<td>15.0</td>
</tr>
<tr>
<td>FLAT 4</td>
<td>0.7 – 1.4 (Band 0.7)</td>
<td>2.0</td>
<td>40.0</td>
</tr>
<tr>
<td>FLAT 5</td>
<td>1.0 – 5.0 (Broadband)</td>
<td>0.01</td>
<td>1.0</td>
</tr>
<tr>
<td>LINE 1</td>
<td>1.0 – 1.8 (Band I)</td>
<td>1.0</td>
<td>40.0</td>
</tr>
<tr>
<td>LINE 2</td>
<td>1.7 – 3.0 (Band II)</td>
<td>0.6</td>
<td>25.0</td>
</tr>
<tr>
<td>LINE 3</td>
<td>2.9 – 5.0 (Band III)</td>
<td>0.4</td>
<td>15.0</td>
</tr>
<tr>
<td>LINE 4</td>
<td>0.6 – 5.0 (Broadband)</td>
<td>0.01</td>
<td>1.0</td>
</tr>
<tr>
<td>REF</td>
<td>1.3 – 1.7</td>
<td>5.0</td>
<td>40.0</td>
</tr>
<tr>
<td>TEST</td>
<td>0.5 – 5.5</td>
<td>$5.0 \times 10^9 \text{ ph}/(s \cdot sr)$</td>
<td>$50.0 \times 10^9 \text{ ph}/(s \cdot sr)$</td>
</tr>
</tbody>
</table>

There are five continuum sources (“FLAT”) that are optimized for calibration of the instrument response for all wavelengths and field angles (the “spectral flat field”). Their filaments are operated at temperatures around 1800 K and basically provide blackbody spectra. The various continuum sources differ predominantly by the long-pass filters that are needed to prevent order overlap. These filters are identical to (and have the same purpose as) the order-sorting filters on the NIRSpec filters wheel. The filters in FLAT1-4 are long-pass only; the emission spectra of these lamps run all the way to the detector cutoff at the red end. FLAT5 has no filter, and runs all the way to the detector cutoffs at both ends. Note that FLAT1-5 are too bright to be used in imaging mode.

In addition, the CAA carries four spectral line sources that allow calibration of the dispersion over the various NIRSpec bands. Because of the design constraints on power consumption and heat load, gas discharge lamps commonly used in ground-based instruments are ruled out for NIRSpec. Instead, the CAA uses Fabry-Perot type interferometric filters that provide a number of well-defined transmission peaks over the respective passband. An example spectrum for the Band I line source is shown in Figure 4.7-3. Because the exact transmission peaks of such interferometric filters are prone to be temperature-sensitive, the filter temperature will be monitored with thermistors. There are only long-pass filters on LINE1-3; their emission spectra run all the way to the detector cutoff at the red end. Like FLAT5, LINE4 has no filter and runs all the way to the detector cutoff at both ends.
The NIRSpec CAA also carries a spectral reference source (SRS) which provides an absolute wavelength standard in the form of a rare-earth filter which has a few narrow absorption lines between 1.3 and 1.7 μm. The last source, labeled TEST source, is used for exposures with NIRSpec in imaging mode. For this purpose, it does not include any spectral filters but instead a small aperture to attenuate the lamp output to avoid saturating the detector. This source therefore shows different units and values for its intensity in the table above.

![Figure 4.7-3 Transmission spectrum of the LINE1 filter.](image)

### 4.7.3 OPTICAL PATH

The optical path of the CAA beam is shown in Figure 4.7-4. The light emanating from the integrating sphere is reflected via two flat mirrors (CAL1 and CAL2) onto one of the mirrors of the RMA before it hits the backside of the OPAQUE position in the filter wheel, which is occupied by a low-power spherical surface that acts as the CAL3 mirror. From this point onwards, the path and beam shape is identical to the nominal one coming from the OTE.
4.7.4 OPERATIONAL CONSTRAINTS

As of November 2009, the following operational constraints are defined for the flight model CAA:

1) The lamps have a “turn-on time” of three seconds before they reach full performance.
2) The four CAA Line filters will experience a temperature increase while operating the corresponding lamp. This will cause a change in their transmission characteristics. To maintain the stability of the wavelength solution, the maximum lamp-on time for the line sources is 100 seconds, after which the lamp must remain off for at least 1000 seconds to ensure the temperature stability of the Fabry-Perot filters.
3) Owing to this temperature drift in the CAA Line filters, calibration of their wavelengths should adopt the telemetered telescope temperature at the start of the exposure.
4) There is no “wait time” required between powering on the CAA and switching on the lamps.
5 PREPARING NIRSPEC OBSERVATIONS

5.1 Finder Image

The NIRSpec target acquisition algorithm uses 8 – 20 reference stars observed through the MSA to precisely position the science targets within the micro-shutters. This procedure imposes strict requirements on the relative astrometry between these reference stars and the science targets. We expect that only space-based observations at high angular resolution will be sufficient to meet the error budget requirements for the standard NIRSpec target acquisition algorithm (see next Section). Imaging data from HST’s cameras have sufficient astrometric accuracy, and NIRCam should also satisfy these requirements. For this reason, NIRSpec users will be required to provide either verified astrometry from HST images (or another validated source) or to obtain NIRCam pre-imaging of their target fields as part of their program. As of October 2009, NIRCam has defined special mosaic patterns for this purpose; the imaging data need not be taken at precisely the same telescope roll angle provided the full NIRSpec field of interest is covered. The logistical scheme for planning and scheduling the pre-imaging visits and obtaining the necessary astrometry are TBD.

5.2 Reference Stars

At present the basic TA procedure assumes that the user has provided between 8 and 20 reference stars, with relative astrometry that meets the strict requirements mentioned just above. The reference stars are also subject to the bright limits imposed in Section 3.9. The algorithm for using the reference stars to perform the target acquisition is described in Section 6.

5.3 The NIRSpec Observation Planning Tool

The NIRSpec Observation Planning Tool (NOPT) is the primary software tool used by general observers (GOs) to select the astronomical objects that are to be observed in a given exposure. The main purpose of the NOPT is to provide an accurate, and visually accessible, projection of the MSA shutter grid onto a given scene on the sky in order to allow the GO to evaluate a given telescope orientation with respect to the target alignment in the respective micro-shutter. For this, the NOPT has to incorporate the precise coordinate transformation between the MSA and sky planes, taking into account the significant distortion of the combined optical system of OTE and NIRSpec fore optics. A detailed description of the foreseen capabilities and features of the NOPT can be found in an STScI study note (RD 8).

In brief, at Phase 2 the GO specifies a tentative telescope roll angle (which is, to a large degree, defined by the scheduling of the observation) and a NIRSpec pointing, expressed as the desired right ascension and declination of a fiducial point in the NIRSpec field of view. The observer also provides a catalog of potential targets with very precise (< 5 mas) relative coordinates. The targets may be grouped into a limited number of priority bins.
The NOPT then either displays an image of the region (if available) which must be corrected for all distortion effects, or a schematic view of the input target distribution. In addition, the NOPT overlays the boundaries of the active area of the MSA. Note that individual shutters are much too small to visualize in an image of the entire field of view. For each astronomical target, the NOPT then evaluates whether it is located in the “acceptance zone” (approximately the inner half of a shutter for which the slit loss is small and well-defined). The NOPT provides a summary report for the given pointing, listing the number of “good” targets, warning about possible overlapping spectra, and flagging targets affected by failed shutters in the vicinity.

The GO can use the NOPT to search for a better solution by varying the pointing and/or exploring the available range of roll angles. After the tool has provided a subset of suitable targets, the GO can zoom in on individual targets to inspect their position within the micro-shutter, and may edit the target list by adding or rejecting targets from the catalog.

As output, the NOPT specifies the desired “optimal” telescope pointing and roll angle for a specific MOS observation, including any planned dithers. In addition, it provides, for the specified pointing and orientation, the location of the reference stars as measured in the tangential coordinate system on the sky, i.e. relative to the fiducial point in the NIRSpec field of view. Finally, the NOPT creates an MSA configuration file that specifies one open aperture for each accepted target in the final list. The apertures will have a default shape (e.g. the three shutter long “slitlet” further described in Section 7.3.3), but the GO can alter individual apertures depending on the shape of the objects, e.g. for extended galaxies. To aid the data analysis pipeline, the NOPT will flag each shutter as target or background, either via a default classification or following a manual classification by the GO.

As of February 2010, the detailed requirements for the NOPT are still in development; the minimum capabilities of the NOPT that are mandatory to enable the GO to prepare and set up NIRSpec MOS observations are described in RD 6.
6 NIRSPEC TARGET ACQUISITION

6.1 Overview

The purpose of the NIRSpec target acquisition (TA) procedure is to fine-tune the JWST pointing such that a given set of astronomical targets is imaged precisely onto the grid of shutters at the MSA\(^1\). The problem is illustrated in Figure 6.1-1. The TA procedure, i.e. the entire sequence of events following the spacecraft slew to the target field, up to the completion of the pointing correction that places the science targets accurately within their intended apertures, must be executed without human intervention. In particular, the NIRSpec on-board software\(^2\) must autonomously derive the positions of a set of bright reference stars in a dedicated, short, undispersed exposure (the “acquisition image”) and from these, must derive the necessary pointing corrections.

![Figure 6.1-1](image)

**Figure 6.1-1** The MSA projected onto the target field during ground preparation. Science targets are indicated in blue and the brighter reference stars in red.

For this purpose, the on-board software uses a set of stored coordinate transformations between the various optical planes of the sky-OTE-NIRSpec optical train, which take into account the

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1 Note that the method described here can be equally applied to observations with the IFU and the fixed slits, although simpler (“peak-up”) methods may be developed for these observing modes.

2 The on-board software consists of two components, the C++ based “Flight Software” and the JavaScript-based “Activity Description Scripts”. For details, see RD 6.
magnifications and distortions of the various optical modules. The required accuracies of these transformations listed in this document have been derived and quantified in RD 2. Calibrating the coordinate transformations for the full OTE/NIRSpec system is only possible in orbit, and requires dedicated (and non-trivial) observations of well-understood astrometric star fields. These observations and their analysis are time-consuming, and will significantly degrade NIRSpec and JWST efficiency if they must be done frequently.

In addition, the correct transformation must be available at least a few months before the actual observation. This is because a General Observer (GO) must be able to decide on the optimal MSA configuration for a given telescope orientation. For this purpose, the GO will use the “NIRSpec Observation Planning Tool” (NOPT) described in 5.3. Using the same coordinate transformations, the NOPT projects the (properly distorted) MSA grid onto a given scene on the sky. Based on this projection – and only with this projection - the GO can decide which subset of targets fall into the acceptable area of a shutter, and can define the corresponding MSA configuration(s) to be used for this observation.

It is important to realize that the above planning stage relies on existing images of a given sky field. Because the sensitivity and spatial resolution of these images must be comparable to that of NIRSpec, they will most likely come from prior observations with NIRCam, but at this stage, alternative image sources such as HST or even ground-based telescopes are not ruled out. It should also be understood that the achievable accuracy of the planning stage is limited by the relative astrometric calibration of these “finder images”. That is to say, the field orientation and the plate scale of the finder image must be known very accurately in order to precisely derive the relative distances and orientations between the science targets and the reference stars so that the user can judge their placement on the shutter grid (using the NOPT). This is why one of the requirements in this document specifies the NIRCam astrometric calibration. Note specifically that this does not imply the need for very precise absolute astrometry of the finder images: any offset in the assumed field center will be corrected by the TA process because it is indistinguishable from a telescope pointing error.

For all these reasons, it should be clear that the optical train Sky-OTE-NIRSpec (or NIRCam) should be as stable as possible over timescales of many months. Many of the requirements specified in RD 6 in are driven by this stability aspect.

The saturation limits of the NIRSpec detectors impose limits on the magnitude of the reference stars for target acquisition. The bright limits for undispersed images through the two imaging filters (F110W and F140X) are calculated by requiring that less than 60000 e⁻ accumulate in a full frame time of 10.6 sec. These limits are AB = 20.6 in the broad F140X filter and AB = 18.3 in the narrow F110W filter (ESA-JWST-AN-3032), assuming that the image is obtained with three frames plus a rest (see Section 3.9). Reference stars for target acquisition will generally not be useful if they are brighter than these limits, and may saturate at even fainter magnitude if longer exposures are used to ensure adequate counts are collected on fainter reference stars; that is, for 10 frame times or 100 sec, the bright limits are 2.5 mag fainter.
6.2 Required Accuracy

The driving requirement for the TA precision is the photometric calibration accuracy of NIRSpec observations. In order to guarantee that the slit losses occurring at the MSA can be well-calibrated, the placement of the science targets within their respective shutter must be controlled to better than 10% of the shutter width. This corresponds to a target acquisition error no larger than 20 mas.

The detailed error budget for the NIRSpec TA procedure is explained in RD 6. The coordinate transformations between the image planes of sky, MSA, and FPA are important error sources. Of particular interest in this context is the stability of the plate scale (i.e. the magnification) of the OTE between and across its frequent re-phasing campaigns, because the relative distances between the reference star images in the OTE focal plane must be accurately known. Note specifically that this is not a requirement on the absolute telescope pointing, because any zero-point (i.e. boresight) offset will be corrected by the TA procedure.

6.3 Target Acquisition Procedure

The baseline procedure for NIRSpec TA is schematically outlined in Figure 6.3-1. The procedure and its rationale are described in detail in RD 1 and RD 6. In short, after the initial spacecraft slew to the target field, a short exposure with the internal continuum lamp is used to illuminate the fixed slits on MSA, and to infer the exact tilt of the imaging mirror in the grating wheel from the location of the slit images on the detector.

Then, two images of the sky through the all-open MSA are taken, separated by a spacecraft slew corresponding to half the micro-shutter pitch (about 120 mas in $x$ and 250 mas in $y$). Both images are processed by the on-board TA software to correct for pixel-to-pixel response variations (“flat fielding”), and to determine the precise locations of a set of reference stars. These locations are initially measured in pixel coordinates and must be transformed by the software into the distortion-free, tangential coordinate system on the sky, before they can be compared to the desired “ideal” positions. This coordinate transformation requires precise knowledge of the combined distortion effects of OTE and NIRSpec, as well as the measured tilt of the imaging mirror.

Finally, comparing the measured reference star positions on the sky with the “ideal” positions as specified by the observer during the planning stage will allow the software to compute the final corrective spacecraft slew, and to communicate it to the attitude control system (ACS).

The baseline procedure makes two somewhat pessimistic assumptions, namely that the mirror tilt can not be inferred from telemetry, and that the pixel-to-pixel response variation of the NIRSpec detectors is higher than expected, so that flat-fielding of the detector data is needed before centroiding of the reference star images. Figure 6.3-2 then shows the “best case” TA procedure which will be adopted in case those two assumptions turn out to be overly pessimistic.
Figure 6.3-1 Baseline flow for NIRSpec TA activities

Figure 6.3-2 “Best case” flow of NIRSpec TA activities. This procedure assumes accurate telemetry for the imaging mirror tilt, and FPA pixel-to-pixel response variations below 10% rms.
7 NIRSPEC OPERATIONS

7.1 Terms and Definitions

Each JWST guide star acquisition defines a new NIRSpec field. A NIRSpec field includes all instantaneous fields-of-view that can be accessed without acquiring new guide stars. One or more astronomical targets observed simultaneously constitute a target set. A single NIRSpec field may contain multiple target sets, each observed at disjoint times. A particular target or target set is selected by opening the appropriate shutters in the micro-shutter array (MSA) or by placing a target in the integral-field unit (IFU) or in one of the fixed slits. For slitless spectroscopy, the target set is the entire field-of-view.

An association consists of all data obtained with a particular grating and MSA configuration, as well as the reference image if available. Reference images may be part of multiple associations (e.g., each with a different grating). Multiple associations may contain the same target set (e.g., each with a different grating). A new target set implies a new association, even if no motion of the GWA is required. Reduced data will be combined into a merged product for multiple associations with the same grating and the same target or target set. An association may contain sub-aperture dithers that move targets within the aperture.

Between two consecutive detector resets, nondestructive reads yield an integration. At each dither location, multiple integrations may be recorded, forming an exposure. A single exposure may not span two sub-aperture dither locations.

NIRSpec observing programs will contain hierarchical arrangements of the aforementioned elements, as illustrated in Table 7-1. A NIRSpec observing program may contain multiple NIRSpec fields. Each NIRSpec field may contain multiple target sets. Each target set may use multiple MSA configurations. Each MSA configuration may use multiple gratings, forming multiple associations. Each association may contain multiple sub-aperture dither locations. The exposure at each sub-aperture dither location may contain multiple integrations. The detailed interrelationships between associations, visits, observations, and their corresponding data products are presently (February 2010) under review at STScI.

<table>
<thead>
<tr>
<th>Table 7-1 Hierarchy of Data Associations for a NIRSpec Visit</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIRSpec Field (same guide star, potentially one visit)</td>
</tr>
<tr>
<td>Target Set 1</td>
</tr>
<tr>
<td>Assoc 1</td>
</tr>
<tr>
<td>Grating 1</td>
</tr>
<tr>
<td>Assc 7</td>
</tr>
<tr>
<td>Grating 1</td>
</tr>
</tbody>
</table>
7.2 **Observatory Constraints**

The OTE and ISIM must remain in the shadow of the sunshield at all times, in order to maintain a stable temperature and to minimize scattered light from the Earth and Moon. This orientation constraint defines an annular field of regard that is accessible to the observatory at any particular time of year, as depicted in Figure 7.2-1. Accessible targets will be 85° to 135° from the Sun.

All targets within 5° of the ecliptic pole (e.g., the Large Magellanic Cloud) are continuously observable. Nominal roll increments by approximately 1° per day. A particular orientation of the field of view is available for only 10 days a year. Calibration fields will preferentially be chosen near the ecliptic pole in order to maximize scheduling windows and available orientations.

A target in the ecliptic will be observable for 50 days every 6 months. Nominal roll alternates every 6 months between two values that differ by 180°. Roll about the optical axis of the primary mirror must be within 5° of nominal (corresponding to maximum coverage by the sunshield). The allowed orientations for a particular field of view in the ecliptic will therefore be limited to two 10° ranges separated by 180°. Targets at intermediate ecliptic latitudes will have constraints between the limits described above for the ecliptic pole and equator. We do not expect that it will be necessary for the NIRCam preimage for a particular NIRSpec observation to be obtained at the same roll angle, provided that the NIRCam imaging adequately covers the NIRSpec field.

Solar radiation pressure on the sunshield produces a torque on the observatory, which is balanced by changing the spin rate of the reaction wheels. Reaction wheel speeds are kept within operational limits by using thrusters to unload momentum and by using scheduling to balance the expected torques. The torque on the observatory increases as the roll deviates from nominal. Long observations will therefore have to be performed at nearly nominal roll angle to avoid interruptions due to angular momentum unloading.

![Figure 7.2-1: Schematic of observatory field-of-regard limitations](image-url)
7.3 Observations of External Targets

NIRSpec observes both Internal and External targets to obtain science and calibration data. Internal targets are observed with the filter wheel set to the OPAQUE position, yielding dark and internal lamp exposures (see Section 7.4). External targets are observed with the filter wheel set to any position except OPAQUE, yielding exposures of the NIRSpec field of view, as described in this section. External observations include (but are not limited to) spectroscopic science data, acquisition images, calibration spectra, pointed sky flats, and parallel sky monitoring.

There are four main observation types (OPMODE) for external targets:

- Imaging (IMAGE)
- Single-Object Spectroscopy (FIXEDSLIT)
- Multi-Object Spectroscopy (MSASPEC)
- Integral Field Spectroscopy (IFU)

After guide star acquisition and in most cases NIRSpec target acquisition (see Section 6), NIRSpec scripts observe external targets using the following sequence of activities:

- Send MSA configuration filename or fixed pattern name to the MCE
- Move filter wheel to OPAQUE to prevent unnecessary detector illumination
- Configure MSA (use the ALLCLOSED pattern for IFU or FIXEDSLIT)
- Move filter wheel to the requested position
- Optionally, take a confirmation image (except when OPMODE=“IMAGE”)
- Move grating wheel to the requested position
- Configure signal chain electronics for requested exposure and take exposure

Note that a separate confirmation image is not possible for imaging observations.

7.3.1 IMAGING MODE

Imaging mode (grating wheel set to MIRROR) is intended mainly for target acquisition, confirmation images, and instrument calibration observations. The ever-present MSA grid limits the photometric and astrometric precision that can be achieved in imaging mode. Nonetheless, images will be needed frequently during normal operations. Images of external targets will be used for the following purposes:

- Target acquisition images to measure reference star positions and calculate pointing and orient corrections,
- Confirmation images to record the final position of science targets in the science apertures,
- Parallel-mode (NIRSpec as a secondary instrument) imaging observations to monitor PSF and geometric distortion as a function of time and position in the field of view.
Table 4-8 defines the filters that can be used in imaging mode. Wide (F110W) and extra-wide (F140X) acquisition filters accommodate fields of view with brighter or fainter reference stars. For imaging mode, the default number of integrations per exposure is one.

7.3.2 SINGLE-OBJECT SPECTROSCOPY MODE

For spectroscopic observations of isolated objects of interest such as a nearby star, a galaxy nucleus, or a high-redshift quasar, NIRSpec will essentially be used as a long-slit spectrograph. The nominal MSA state in this observing mode is “all closed”. The target is placed in any of the permanently open slit apertures described in Section 4.2.9. Full wavelength coverage for the “standard” 0.2" wide aperture can be achieved by alternating between the A_200_1 and A_200_2 slit apertures shown in Figure 4.2-10 because they are separated by slightly more than the distance corresponding to the physical gap between the two SCAs.

Although in single-object mode, the spectra only fill a very small fraction of the NIRSpec detectors, for targets that do not saturate pixels within a couple of frame times (i.e. tens of seconds), the default detector readout scheme is full-frame readout. This is for two reasons: i) maintaining the standard readout mode optimizes thermal stability and reduces the risk of undesired electronic effects, and ii) it leaves open the possibility to observe a second target anywhere in the NIRSpec FOV “for free” by opening a shutter in the MSA. However, for bright targets such as planet searches around nearby stars, it is mandatory to use sub-array mode in order to avoid pixel saturation. Table 4-4 lists the subarray types that are defined for FIXEDSLIT observations. All other observations types for external targets (IMAGE, MSASPEC, IFU) and all confirmation images use FULL frame readout.

7.3.3 MULTI-OBJECT SPECTROSCOPY MODE

7.3.3.1 Background Subtraction

Much of the primary JWST science is concerned with studying the most remote and exceedingly faint galaxies approaching the sensitivity limit of NIRSpec. In this regime, the dispersed signal from the science target is comparable to the signal from the Zodiacal and scattered light backgrounds entering the MSA shutter. In order to ensure optimal photometric accuracy at these very faint magnitudes, great care must be taken to measure and subtract the unwanted background signal underlying the feeble target signal of interest. The well-proven ‘long slit’ approach to this problem is to measure the local background in the immediate vicinity on each side of the target, and carry out the background subtraction as early as possible in the data reduction sequence, preferably already in raw count form. Note that even if background light entering the NIRSpec optics were uniform over the entire FOV, modest errors in the large-scale calibration of NIRSpec would introduce an error when subtracting the background spectrum measured in one part of the NIRSpec FOV from a target (plus background) spectrum measured elsewhere in the field. This shortcut can only be assumed to work for bright targets where the background correction is less critical.

3 In this case, the NOPT will need to be linked into the planning of the fixed slit observation.
Figure 7.3-1 Schematic illustrating how the MSA will be used for faint galaxy surveys using the concept of “slitlets” that are three micro-shutters long. Note that a failed open shutter precludes use of the entire shutter row.

The baseline NIRSpec multi-object usage scenario developed by the NIRSpec Instrument Science Team is illustrated in Figure 7.3-1: each science target is positioned in a dedicated “slitlet” consisting of three adjacent micro-shutters. During a given exposure, one shutter contains the target, and two neighboring shutters in the cross-dispersion direction (along the same row of the MSA device) measure the adjacent background. It is important to point out that micro-shutters that have failed in the open state essentially “block” the entire row of micro-shutters for use in a slitlet (along a column of the MSA device), while shutters failed in the closed state can be tolerated as long as they are not used in the slitlet directly.

The slitlet approach has another important advantage: using spacecraft small-angle motions (SAMs) in the direction along the slitlet, all objects can be simultaneously moved up or down in the slitlet by one shutter (modulo small and uncritical differences due to the field distortion), as illustrated in Figure 7.3-2.

Figure 7.3-2 Schematic illustrating the baseline approach of observing faint NIRSpec targets. In this case the two unoccupied shutters are used to estimate the background for the target shutter.
This not only improves the accuracy of the background subtraction, but also dithers the object spectrum on the detector between sub-exposures so that bad detector pixels can be corrected. Moreover, this observing scheme can be easily implemented in an automated manner without a need to reconfigure the MSA. The NIRSpec sensitivity limits quoted in Section 3.7 have been calculated assuming this approach.

7.3.4 INTEGRAL-FIELD SPECTROSCOPY MODE

Integral-field spectroscopy delivers spectral information for every pixel in a two-dimensional field. It is thus most powerful for spatially extended sources. Because the aperture of the NIRSpec IFU is only about 3"×3", even compact sources have to placed rather carefully within the aperture. This implies that the baseline NIRSpec IFU observation will be preceded by a “standard” target acquisition identical to that for a MOS observation. The only difference to MOS observations is that only a single science target is to be observed. In principle, therefore, there is no need for a complicated target set optimization using the NOPT. Instead, the observer simply has to provide accurate coordinates for a set of reference stars, and to define the spacecraft pointing that will place the target within the IFU aperture.

In order to improve the spatial sampling of the IFU, and to be able to correct for bad pixels, it is planned to dither the target within the IFU aperture, i.e. to obtain multiple exposures with intermittent small-angle manoeuvres (SAMs) of a few tenths of arcsec slew amplitude. In some cases, the target might be small enough that the nominal large-angle slew accuracy of the spacecraft is sufficient to place the target “blindly” within the 3"×3" IFU aperture, and hence TA can be skipped. Whether this is indeed possible will depend on the actual performance of the ACS.

7.3.5 NIRSPEC DITHERING STRATEGIES

Dithering of spectroscopic observations is necessary to improve coverage of the sky, cover gaps between detector segments, correct for pixel-to-pixel response fluctuations on the detector, and to improve the pixel-space sampling of the point- and line-spread function of the instrument. NIRSpec has defined general dithering strategies that accomplish these goals for each of the major spectroscopic modes separately. Details of these strategies and their implementation for each mode are contained in the corresponding dithering study “NIRSpec Dithering Strategies” (RD 13).

NIRSpec dithering patterns have been defined in the general form being proposed for all the JWST science instruments, in which there are “primary patterns” and “secondary patterns”. Large-scale “primary patterns” use motions of several pixels up to tens or arcseconds and generally serve the purpose of improving coverage on the sky and/or using different detector regions for the same object to mitigate detector effects. “Secondary patterns” generally have the purpose of improving spectral or spatial pixel-space sampling, and so generally have smaller motions of fractions of a pixel up to a few pixels. Generally secondary patterns can be nested within primary patterns and so executed at each primary position. This terminology is adopted in the descriptions of the NIRSpec patterns below; further details are contained in RD 13.
7.3.5.1 Fixed Slit Dithering Strategies

The dithering patterns for the “long” fixed slits (that is, excluding the big square) break cleanly into a primary pattern that occupies a few positions along the slit to place the spectrum on different detector regions for mitigation of pixel-to-pixel response variations. The user will specify the primary pattern by requesting a specific number of positions within the slit; the choices are one position (i.e. no dither), 2, 3 or 5 positions, as shown in the Figure 7.3-3. Because it is intended for high-precision spectroscopy of bright targets, no dither patterns have been defined for S1600A.

The secondary pattern for the fixed slits is composed of subpixel shifts in the spatial dimension, or in the spectral dimension, or both. These subpixel shifts are specified to produce optimal pixel-phase sampling of the PSF and LSF. The user specifies a secondary pattern simply by answering yes or no in each case. The two secondary motions can be combined by answering “yes” for both (at right). The secondary pattern will always be executed at each of the primary positions.

There is an optional special purpose dither defined for observations in the A_200_1 fixed slit. Spectra obtained with the R = 2700 gratings will be missing data at wavelengths that fall into the gap between SCA segments (see Figure 3.5-3). These wavelengths can be completely recovered with a separate exposure in the A_200_2 slit with a dither in between the two slits. The exposures in the second aperture will be executed after the complete pattern is observed in the first slit, and the combination of primary and secondary motions chosen by the user will be executed in both apertures identically.
Figure 7.3-4 Screen capture from the Astronomers’ Proposal Tool (APT) planning window for MIRI mosaics. This method should work very well for enabling NIRSpec users to cover extended objects with the IFU, as a primary dither pattern.

7.3.5.2 IFU Dithering Strategies

The IFU allows full spatial and wavelength coverage of a 3x3” area of sky (Section 4.3). IFU observations require dithering for all the usual reasons, but the division of the aperture into “slitlets” and their layout on the detector require special dithering patterns for the IFU.

The IFU is well suited to map out a large (> 3”) extended object or field, such as a Galactic star-forming region or a nearby galaxy using a pre-planned pattern of 3x3” apertures or a regular grid. For this type of “dither”, to keep planning and implementation simple, we envision the user defining a primary pattern of positions on the sky using a simple tool in the Astronomer’s Planning Tool, as shown in Figure 7.3-4. The pattern of fields on the sky is specified by a central position and by 6 additional parameters that describe the size of the grid, the degree of overlap in x and y, the skew in x and y, and the orientation of the whole set. For NIRSpec IFU as for MIRI these will be the only selectable parameters of the large-scale primary pattern. Individual subpositions in the grid can be omitted if the user desires, but the positions cannot be chosen individually or arbitrarily. NIRSpec instrument scientists may define optimal degrees of overlap later on.

We anticipate that the full IFU primary pattern will be executed with a single grating / filter setting (choice of band), followed by a grating change and then another walk through the pattern. The alternative, to obtain all three bands at one position before moving to the next, requires approximately MxN more movements of the grating and filter wheels, where M and N are number of rows and columns in the large-scale pattern.

In cases where the user desires to use the IFU for mapping very large regions (greater than 1 arcmin or so), more than one guide star must be used and so more than one visit is created for the primary pattern. Dividing the user-defined primary pattern into the optimal number of visits is a
task for the planning software and ground system, not NIRSpec or its operational scripts.

Figure 7.3-5 Illustration of “slitlet” stepping as a secondary dither pattern for the IFU. Each slitlet is labeled to show its correspondence to the correct “virtual slit”.

The secondary dither patterns for the IFU consist of two types of motions that can mitigate detector effects and improve spectral and spatial sampling of the data. To accomplish the former purpose, we have defined “slitlet stepping” dithers that move the IFU field of view in the dispersion (x) direction by a fixed number of IFU slitlet widths. As shown in Figure 4.2-10, the IFU slitlets are arranged such that adjoining or nearly adjoining slitlets fall on different regions of the detector. Moving the target by a few slitlets can then move the spectrum of a point on the sky by many pixels in the cross-dispersion (the y direction in Figure 4.2-10) direction. This slitlet stepping principle is illustrated concretely in Figure 7.3-5, where an extended object with a bright knot is dithered by one slitlet in each direction to show its movement in the cross-dispersion direction. The spectrum of the bright knot will be obtained on different sets of detector pixels for each exposure. We envision asking the user to select this pattern by specifying the number of slitlets to move, from 0 (which results in no dither motion), 1, 3, or 5 slitlets.

Moves as small as one full slitlet in x (as shown here) can accomplish this purpose. However, since the FWHM of the JWST PSF occupies 100, 130, and 163 mas at 3, 4, and 5 μm, respectively, light from the same position on the sky overlaps significantly with multiple slitlets, which are 100 mas wide. Thus to obtain independent measurements at different positions it is desirable to move over by at least 300 mas or 3 slitlets. For users interested in the longest wavelengths who seek to
minimize the overlap of the PSF between slitlets, we have defined patterns with offsets of up to 5 slitlets. For N slitlet offsets, only 30 – N slitlets will be covered at both dither positions, so the effective exposure time will be reduced at the edges of the field. Some users may not be able to tolerate this loss of coverage but still want improved spectral sampling. For them, we recommend a one-slitlet offset, for a total of three options: 1, 3, or 5 slitlet offsets in x. Note that for any choice of 1, 3, or 5 slitlets, two positions will be observed; one at the fiducial position (selected by the user to optimize the whole field) and the other 1, 3, or 5 positions away. Though it will be rarely used in practice, there should be an option to not execute slitlet stepping at all. Which option to adopt will be the user’s choice based on their desired coverage of the field, S/N requirements, and observing time request.

![Diagram](image)

**Figure 7.3-6** Examples of secondary dithers for the IFU, and their combinations. Each pair of apertures represents the two positions observed for a given combination of slitlet step and sub-pixel shifts in x and y. These pairs show how slitlet steps can be combined with subpixels secondary shifts for optimal sampling. The subpixel shifts are 0.15” (~1.5 pixel) in the spatial direction and/or 0.5 slitlet (0.05” or ~0.5 pixels) in the spectral dimension. See text for discussion.

Since the dispersed light from the IFU cannot be moved around on the detector, there is no need for the sort of spectral or wavelength-gap covering dithers planned for the fixed slits and MSA. However, the user may want to increase the sampling of the spatial and spectral resolution elements and average out subpixel variations in sensitivity. Spatial subpixel dithers should closely parallel those defined for the fixed slits - the basic pattern is to observe with an offset of 0.15” as a secondary pattern (in addition to any slitlet stepping). The value of 0.15” (~1.5 pixels) is chosen to minimize overlap between the PSF in the two positions, which is especially important for bad-pixel avoidance when the slitlet stepping option is not chosen. For subpixel shifts in the spectral dimension, the simplest approach is to observe at 0.05” offsets (~0.5 pixel, ~0.5 slitlet widths) as a secondary pattern (in addition to any slitlet stepping), with or without the sub-pixel spatial dithers.
In contrast to the fixed slits, the IFU will often be used to cover an extended object on the sky. So in most cases a number of dithering moves will be done in a large-scale tiling pattern and overheads will be incurred already before any subpixel dithers are added. Also, if slitlet stepping is done to mitigate detector effects the center regions of the field will be observed multiple times. In light of these two effects it is most efficient to combine the slitlet stepping and subpixel dithers into single moves if the user chooses to include both types of dithers.

Figure 7.3-6 illustrates several combinations of slitlet and subpixel secondary patterns. In the combined scheme, the slitlet steps illustrated in Figure 7.3-5 would occur over 1 slitlet (or 3 or 5) plus one half slitlet (the slitlets are \( \approx 1 \) pixel or \( \approx 100 \) mas wide). Thus the steps would be 1.5, 3.5, or 5.5 slitlets over in \( x \) if the user chooses to include the subpixel shifts and 1, 3, or 5 slitlets in \( x \) if they do not. It also makes sense to combine the subpixel spatial dithers with the slitlet motions in the same fashion, so that 1.5, 3.5, or 5.5 slitlet motions in \( x \) would be combined with \( \approx 0.15'' \) (\( \approx 1.5 \) pixel) offsets in the \( y \) (spatial) dimension (see Figure 5). These combinations are far more efficient than using 2 to 4 subpixel pointings at each slitlet step (as for the fixed slits), since the slitlet step motions are being done anyway.

The secondary dithers described here are intended to deliberately shift light on the detector pixels by a specific angular offset. However, the optical distortion of the field across the detector, the “tilt” of the IFU apertures with respect to the \( y \)-coordinate of the detector, and curvature of the spectra mean that there is not an exact and uniform correspondence between position on the sky and pixel space. The effect of these non-uniformities is that a shift, say in the dispersion direction as for the slitlet stepping, will also move the spectrum in the \( y \)-direction in some places and so change its spatial sampling in pixel space even though this was not strictly desired. This is like an unintentional dither. These complications cannot be avoided; their magnitude and dependence on location will not be known until the flight instrument is tested. Nevertheless, it is important to implement the capability to achieve deliberate shifts of known size on the sky to ensure the general purpose of dithering, help calibrate these distortion effects, and enable adaptation if necessary. It is for these reasons that the shifts are usually described here in arcsec or slitlets rather than pixels.

7.3.5.3 MSA Dithering Strategies

The MSA is the key technology that enables NIRSpec’s unique MOS capability; as a unique device it presents challenges to the design of dither patterns. MSA dithering is needed for all the usual purposes of dithering described above, but it is complicated by the complexity of the device as it will fly. The very high degree of configurability of the MSA allows the user to realize a slit mask for an arbitrary set of positions on the sky. Departures from an “ideal MSA” caused by failed open or closed shutters ensure that a given configuration cannot be shifted by a fixed offset in either dimension and always recover the same pattern of open apertures. Therefore, there is only a small set of restricted circumstances in which predefined dither patterns will be feasible. Outside this small set of dither patterns that can be “canned”, the burden of planning for observations of targets in different places on the array, or exposures separated by small motions on the scale of a single shutter, will fall on the MSA configuration planning software.

The “slitlet” strategy for MSA dithers is illustrated in Figure 7.3-1 and 7.3-2. In brief, each target is assigned a 3x1 shutter slitlet by the planning software. During the observation exposures are
obtained at each of the three positions in turn with dithering motions of the spacecraft in between the exposures. This simple strategy should provide an excellent background subtraction for faint targets. Since each target is assigned a slitlet at planning time, the shutters used are predetermined to be functional. This simple scheme can also be generalized to slitlets of arbitrary shape and size, within reasonable limits (e.g. 5x1 slitlets for extended targets, 2x2 for bright targets with uncertain astrometry. To minimize reconfigurations of the MSA and movements of the FWA / GWA, the three positions will be observed in a grating before moving to the next grating (if more than one is selected), and all gratings and the set of dithers will be observed before reconfiguring the MSA.

Ideally the user would be able to request that a given pattern of open shutters be shifted by a large number of shutters across the array to use different detector regions, with a guarantee that all targets remain in the “sweet sport” within a shutter. However, failed shutters and geometric distortion of the image across the field mean that shifted patterns will not recover all the targets – some will fall behind failed closed shutters or will fall outside the acceptance zone because of distortion. For this reason, large shifts will need to be planned in advance to observe each target in two places on the array as part of the optimization of the MSA configuration. We envision that the planning software will assist the user in planning large shifts as part of the optimization step, with a set of center positions and their corresponding MSA configurations as the output.

Figure 7.3-6 An illustration of using the MSA to cover three regions of a Galactic supernova remnant with a complicated shape. This is the “generic” strategy for dithering the MSA.

A second MSA “dithering strategy” is not really a strategy, but a generic capability to observe a large set of positions within a field with small motions separating observations with different MSA configurations. The unique configurability of the MSA enables a very wide range of scientific investigations of objects on the sky of arbitrary shape and size. Predefined dither patterns will generally not work for programs that choose to depart from the simple strategies described above, or for programs that intend to observe large extended objects. In these cases the burden will fall on the user and on the MSA planning tool to define separate MSA configurations that accomplish the
purpose of dithers by obtaining data on a given set of targets at different positions on the array. To capture this general case with a minimum of complexity, overheads, and mechanism movements, we plan to implement a capability to observe multiple MSA configurations that refer to the same target acquisition and guide star but which are separated by small angle motions (~< 20”). Within this limit these motions are constrained only by the needs of the science program; they can be less than a shutter pitch, or many shutters away, or anything in between. An illustration of such an application is shown in Figure 7.3-6, where a schematic view of the MSA field is overlaid on a supernova remnant. This capability will be implemented in the on-board scripts and planning software to permit efficient coverage of target sets that cannot be covered in a single MSA configuration at a single central position, owing to failed shutters and/or overlapping spectra.

7.4 Internal Calibration Observations

Internal calibration observations are obtained with the filter wheel in the OPAQUE position. When the filter wheel is in the OPAQUE position, a mirror on the back of the filter wheel reflects any light from the CAA calibration assembly into the optical path. Internal observations will produce Dark exposures if the CAA lamps are off and Lamp exposures if the CAA lamps are on.

Observers must specify a Readout Pattern (NRS or NRSRAPID), the Number of Groups per integration (maximum depends on choice of Readout Pattern), and the Number of Integrations (maximum of 235).

7.4.1 DARKS

Darks are obtained with the CAA lamps turned off. NIRSpec scripts obtain dark observations using the following sequence of activities:

- Move filter wheel to OPAQUE
- Configure MSA to ALLCLOSED with magnet in HOME, if not already in this state
- Configure electronics for requested exposure and take exposure

The grating wheel is not moved for dark observations.

7.4.2 LAMPS

Internal lamps exposures are obtained with a CAA lamp turned on. The maximum time the LINE lamps can be on for a single exposure is limited to 100 seconds, after which they must be turned off for at least 1000s in order to avoid shifts of the emission peaks due to heat-up of the filter. NIRSpec scripts obtain internal lamp observations using the following sequence of activities:

- Move filter wheel to OPAQUE to select the CAA
- Send MSA fixed pattern name or configuration filename to the MSFSW
- Configure MSA
- Move grating wheel to the requested position
- Turn on the requested lamp
- Configure electronics for requested exposure and take exposure
• Turn off the lamp

Table 7-2 lists the allowed operating modes (OPMODE), gratings, and MSA configurations for internal lamp exposures. The FIXEDSLIT operating mode is not allowed because for internal targets it is redundant with the MSASPEC operating mode.

Table 7-2: Grating and MSA as a function of OPMODE for internal lamp observations

<table>
<thead>
<tr>
<th>OPMODE</th>
<th>GRATING</th>
<th>MSA STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMAGE</td>
<td>MIRROR</td>
<td>ALLOPEN or configuration file</td>
</tr>
<tr>
<td>MSASPEC</td>
<td>Any, except MIRROR</td>
<td>Any pattern or configuration file</td>
</tr>
<tr>
<td>IFU</td>
<td>Any, except MIRROR</td>
<td>ALLCLOSED</td>
</tr>
</tbody>
</table>

7.5  Engineering Operations

7.5.1  MOVE TO A FOCUS REFERENCE POSITION

One of the activities defined within the engineering main script (NRSENGMAIN) called with ENGTYPE=FOCUS_REF is to command the ICE software (ICSW) to move the RMA in a specified direction (FORWARD or REVERSE) to a specified reference position (LAUNCH or MID_STROKE). This engineering operation is useful when the RMA location is unknown (for example, during commissioning) or lost (for example, if the ICSW is restarted, which resets the focus counter). Two Hall sensors in the RMA assembly define the two reference positions, so this operation does not use the detectors or any mechanism other than the RMA. After successfully moving the RMA to the MID_STROKE reference position, the script resets the focus counter to zero.

7.5.2  FOCUS MEASUREMENT, ADJUSTMENT, OR SWEEP

In addition to locating the RMA reference position as described above, there are three other types of focus activities that can occur during normal operations: focus measurements will be used to monitor long-term trends in the focus quality. If the focus degrades significantly, a focus sweep will be used to determine the new best focus. Finally, a focus adjustment will be used to move the RMA to the newly determined best focus.

All these are executed via the NRSENGMAIN script with ENGTYPE=FOCUS. The script moves the RMA from its initial position to a number (up to 20) of specified positions per call, and takes a focus exposure at each specified position. The RMA offsets are specified via the DELTA parameter and must be given in motor steps, relative to the initial position before the first exposure. When specifying DELTA, forward slashes are used to separate multiple RMA offsets (for example, DELTA="-10/0/10"). All values must be between -9200 and +9200 motor steps (the full stroke in either direction). The value DELTA = “0” specifies the initial RMA position. DELTA may not contain duplicate values (for example, DELTA=“5/-5/5”).
In order to avoid unnecessary RMA travel, the sequence of RMA offsets as specified in DELTA does not determine the actual sequence of RMA moves. Instead, the script always begins by taking an exposure at the initial RMA position. Then, if DELTA contains at least one positive value, the script sorts all positive values in increasing order and moves the RMA monotonically in the forward direction, stopping at each specified position to take an exposure. Next, if DELTA contains at least one negative value, the script then moves the RMA once in the reverse direction to the most negative RMA offset and then moves the RMA monotonically in the forward direction to each negative RMA offset to take an exposure. Finally, if DELTA contains more than one RMA offset, then the script moves the RMA back to the initial position and takes a final exposure.

Which type of focus activity (measurement, adjustment, or sweep) is controlled by the way the DELTA parameter is used. In case only the RMA start position is specified (DELTA="0"), a single focus exposure is taken without moving the RMA, providing the data needed to measure the current image quality. If DELTA contains a single nonzero value, the RMA is moved once, adjusting the focus. In this case, focus exposures are taken at the initial and final positions, providing the data needed to measure the change in image quality. Finally, if DELTA contains more than one value, the RMA is moved sequentially to each of the specified positions. Regardless of the number of positions and initial direction that are fed to the scripts, a sweep will always end in the initial position. The initial position ("0") will be added by the script as a last entry in the DELTA array if necessary. Focus exposures are taken at each RMA position, providing the data needed to measure image quality as a function of RMA position. Table 7-3 gives some examples of actual RMA offset sequences and their purpose.

Table 7-3: Examples of RMA offset sequences

<table>
<thead>
<tr>
<th>DELTA</th>
<th>RMA Offset Sequence</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;0&quot;</td>
<td>0</td>
<td>Measurement</td>
</tr>
<tr>
<td>&quot;+3&quot;</td>
<td>0, 3</td>
<td>Adjustment</td>
</tr>
<tr>
<td>&quot;-3&quot;</td>
<td>0, -3</td>
<td>Adjustment</td>
</tr>
<tr>
<td>&quot;0/3&quot;</td>
<td>0, 3, 0</td>
<td>Sweep</td>
</tr>
<tr>
<td>&quot;-3/0&quot;</td>
<td>0, -3, 0</td>
<td>Sweep</td>
</tr>
<tr>
<td>&quot;-3/3&quot;</td>
<td>0, 3, -3, 0</td>
<td>Sweep</td>
</tr>
<tr>
<td>&quot;-3/0/3&quot;</td>
<td>0, 3, -3, 0</td>
<td>Sweep</td>
</tr>
<tr>
<td>&quot;0/3+6&quot;</td>
<td>0, 3, 6, 0</td>
<td>Sweep</td>
</tr>
<tr>
<td>&quot;-6/0/-3&quot;</td>
<td>0, -6, -3, 0</td>
<td>Sweep</td>
</tr>
<tr>
<td>&quot;-3/+3/-6/6&quot;</td>
<td>0, 3, 6, -6, -3, 0</td>
<td>Sweep</td>
</tr>
</tbody>
</table>

The script obtains identical focus exposures at every RMA position in a focus measurement, adjustment, or sweep. In all cases, the target is an external field of point sources. The grating wheel will be set to MIRROR for imaging. Observers must specify any filter except OPAQUE, a Readout Pattern (NRS or NRSRAPID), the Number of Groups per integration (max. depends on choice of Readout Pattern), and the Number of Integrations (maximum of 235). In addition, observers may provide a single MSA configuration for all of the exposures. If no MSA configuration is specified, the script will move the magnet arm to the FAR position and use the ALLOPEN fixed pattern for the focus exposures. In either case, the filter wheel will be moved to OPAQUE while the MSA is being reconfigured to prevent unnecessary illumination of the detector.
7.6 **NIRSpec Operational Constraints**

- to be completed, will contain global (i.e. instrument-level) operational constraints, when these are known from ground testing.
8     NIRSPEC MISSION SCENARIO

8.1  Number of Visits and Target Acquisitions

The design lifetime of JWST is 5 years. The observatory is designed to be available for science observing 90% of those 5 years, i.e. all activities related to observatory and telescope maintenance such as angular momentum management, re-phasing of the primary mirror, and slews to a new target field will not occupy more than 10% of time. We will also assume that NIRSpec is the primary instrument 1/3 of the available science time. This means that we will be actively observing with NIRSpec 30% of a year or roughly $1.0 \times 10^7$ seconds per year.

Table 8-1 lists the assumed distribution for the various types of NIRSpec science visits, i.e. short, medium and long. The last column in Table 8-1 lists the likely number of Target Acquisition (TA) sequences associated with each of these visits. We assume that NIRSpec will have to execute a TA sequence at least once every 10,000 s. The reason for this assumption is the possibility of thermally induced drifts in the ISIM structure, which can lead to changes in the relative alignment between the FGS and NIRSpec on timescales longer than 10,000 s. Such drifts would, of course, invalidate the alignment of the NIRSpec targets within their shutter (or slit) apertures.

However, even for visits shorter than 10,000 s, we assume that two TAs are needed. The reason is that most observers will want to eliminate the spectral gap caused by the physical gap between the two SCAs. This can be achieved by splitting the observation in two exposures, separated by a slew of the telescope by ~ 20” in dispersion direction. Bridging the detector gap in this way is very costly, both in terms of overheads and mechanism usage, because with the current specifications for the attitude control system (ACS), such a slew can only be executed to an accuracy of about 20 mas. This implies that another TA procedure is required following the telescope slew, hence two TAs are assumed even for visits shorter than 10,000 s. For medium and long visits, the 20” telescope slew can be inserted after any 10,000s interval when another TA is needed anyway because of the image drift mentioned above.

In all likelihood, a fair fraction of science projects can tolerate a small gap in the resulting spectra. However, the exact fraction is difficult to estimate. By assuming the worst case, i.e. that all short visits require two TAs, one avoids placing implicit constraints on the science selection process.

Table 8-1  Observation types

<table>
<thead>
<tr>
<th>Type of Observation</th>
<th>Fraction of NIRSpec</th>
<th>Time per visit [s]</th>
<th>Number of Visits / year</th>
<th>Number of TAs / visit</th>
<th>Number of TAs / year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>10%</td>
<td>5,000</td>
<td>200</td>
<td>2</td>
<td>400</td>
</tr>
<tr>
<td>Medium</td>
<td>60%</td>
<td>20,000</td>
<td>300</td>
<td>2</td>
<td>600</td>
</tr>
<tr>
<td>Long</td>
<td>30%</td>
<td>100,000</td>
<td>30</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>$1.0 \times 10^7$</td>
<td>530</td>
<td>-</td>
<td>1300</td>
</tr>
</tbody>
</table>
8.2 **Mechanism Usage Estimates**

In this section we discuss the expected mechanism usage throughout the JWST mission. For routine science operations, mechanism usage – to first order – scales with the total number of NIRSpec visits. For a conservative estimate, therefore, the highest plausible fraction of short visits similar to the “bright star survey” scenario discussed in Section 8.3.1 should be assumed, because this maximizes the total number of NIRSpec visits. However, for mechanism usage estimates, only the total number of NIRSpec TAs per year is relevant, as will become clear in the following discussion.

For simplicity, we assume that the sequence of events between subsequent TAs is always the same: the TA is followed by a series of science exposures taken in a dither pattern (see below) and, possibly, through different gratings. The end of the sequence is marked by a final “clean-up” which puts the filter wheel in the closed position and the MSA to “all closed”.

**Target Acquisition:**

The general procedure and event sequence for a NIRSpec TA has been described in Section 6. We assume that the starting conditions are as follows: FWA in OPAQUE, GWA in an arbitrary position, and the MSA in “all closed”. For a conservative estimate of lamp usage, we use the “baseline” TA procedure which requires illumination of the fixed apertures via the CAA lamps in order to measure the exact position of the imaging mirror in the GWA. Note that whether or not this exposure is actually needed has no impact on the FWA usage numbers, because the starting condition already has the FWA in OPAQUE, so this image can be taken without a dedicated FWA move.

We will further assume that the observer always needs to protect against bright stars in the field of view, so that a full MSA magnet sweep (up and down) is required to obtain the TA image. This again is somewhat conservative, because for fields without bright stars, the MSA magnet can, in principle, be left in the “up” position for the acquisition image, and the downsweep can be directly used to obtain the science configuration, thus saving a full magnet cycle. At the end of the TA sequence, after the corrective telescope has been executed, and after a confirmation image has been obtained, the FWA will again be placed in OPAQUE in order to protect the detector during the following MSA reconfiguration which leaves the optical train open for up to 20s.

**Science sequence:**

For simplicity, we assume that all NIRSpec observations – regardless whether they are “short”, “medium”, or “long” - are identical in the sense that the observer wants to study the science object(s) over the full NIRSpec wavelength range. This implies that following a successful target acquisition, a spectrum is taken in each of the three NIRSpec bands.

Moreover, we assume that the position sensors on the GWA are sufficiently accurate that dedicated wavelength calibration exposures are not required after a GWA move. In the case that this baseline assumption is not correct, the “worst case” scenario foresees a dedicated wavelength calibration exposure with the CAA at each GWA position. In principle, this implies two additional moves of the FWA per science exposure because the CAA can only be used if the FWA is in the OPAQUE
position. For the first science exposure, however, the FWA is already in OPAQUE because that is the exit configuration following TA. Effectively, there are therefore 5 FWA moves needed for every science sequence in the “worst case” scenario.

Note also that each NIRSpec band has a dedicated lamp with an emission line spectrum over the appropriate wavelength range. This means that each CAA lamp source is used for only two (out of six) NIRSpec gratings, and hence only once per sequence.

**Dithering Strategy:**
In Section 7.3.3.1, we described a strategy to subtract the sky background from NIRSpec exposures by alternating the target location between three adjacent open shutters. Moving the target within such a three-shutter “slitlet” does not require any actions within the NIRSpec optics, i.e. except slewing the telescope and starting/ending the respective detector exposures, no internal mechanisms are used. For estimates of mechanism usage, this procedure can therefore be ignored.

However, in order to improve the correction of small-scale, pixel-to-pixel response variations of the detector, one should ideally move the entire set of three-shutter “slitlets” to at least a few positions over the detector array, in what is commonly called a “dither pattern”. Unfortunately, this is costly in terms of efficiency and lifetime considerations because it requires a new MSA configuration for each dither position, and possibly even a new TA procedure if the slew amplitude is too large to guarantee sufficient accuracy.

The most efficient way of completing a dither pattern while covering the entire NIRSpec spectral range is to cycle through all NIRSpec gratings at a given dither position. This minimizes the number of telescope slews and MSA configurations. On the other hand, it increases the number of movements for both wheel mechanisms and the number of CAA cycles by a factor equal to the number of positions in a dither pattern.

The number of dither positions is therefore an important parameter for estimates of the mechanism usage. Unfortunately, it is also very difficult to predict because it depends critically on the detector performance and the science requirements of the given observation. For the moment, we assign a free parameter $n$ to the number of dither positions.

**Clean-up:**
We assume that at the end of each science sequence, the MSA will be returned to its “all closed” state in order to protect the NIRSpec detectors during the subsequent telescope slews, and – more importantly – to minimize the “hold open” times for the MSA shutters in case of prolonged NIRSpec inactivity after the science exposure, e.g. when another SI is used. Therefore, this step is definitely needed at the end of a NIRSpec visit, i.e. after the last of the science sequences. On the other hand, most sequences in a long NIRSpec visit can be continued by directly configuring the MSA to the TA configuration, without going to “all closed” first. However, for simplicity and to add some conservatism, we plan for this step to be added to the end of each sequence. Table 8-2 then summarizes the expected number of mechanism cycles for a typical NIRSpec science visit.
Table 8-2: Mechanism usage per NIRSpec visit. The parameter $n$ denotes the number of dither positions in a typical NIRSpec visit.

<table>
<thead>
<tr>
<th>Type of activity</th>
<th>FW moves</th>
<th>GW moves</th>
<th>MSA magnet sweeps (up-down)</th>
<th>CAA cycles per lamp (on-off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Acquisition</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Science sequence (baseline)</td>
<td>$3 \times n$</td>
<td>$3 \times n$</td>
<td>$n$</td>
<td>-</td>
</tr>
<tr>
<td>Science sequence (worst case)</td>
<td>$5 \times n$</td>
<td>$3 \times n$</td>
<td>$n$</td>
<td>- N</td>
</tr>
<tr>
<td>Clean up</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Total (baseline)</td>
<td>$3(n+1)$</td>
<td>$3n + 1$</td>
<td>$n+2$</td>
<td>1 N</td>
</tr>
<tr>
<td>Total (worst case)</td>
<td>$5n+3$</td>
<td>$3n + 1$</td>
<td>$n+2$</td>
<td>1 N</td>
</tr>
</tbody>
</table>

**Calibration sequences:**
For a detailed list of the on-orbit calibration activities, see RD 7. Here, we briefly summarize those calibration sequences that are most intensive in terms of the required mechanism usage. These are primarily the internal “spectral flat” measurements described in Sec. 8.3.2 which rely on repeated MSA reconfigurations and CAA on-off cycling, and an almost identical sequence with the emission line lamps to derive the dispersion solution. The most efficient way of executing these measurements is to cycle through all gratings and both kinds of lamp for a given MSA configuration. We assume that ca. 40 long-slit positions are required to construct accurate calibration reference files, and that these observations must be performed twice a year. This yields the totals listed in Table 8-3.

Table 8-3: Mechanism usage for NIRSpec on-orbit calibration observations.

<table>
<thead>
<tr>
<th>Type of Calibration</th>
<th>FW moves</th>
<th>GW moves</th>
<th>Magnet sweeps</th>
<th>CAA cycles (on-off)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cont.</td>
</tr>
<tr>
<td>Spectral Flat</td>
<td>$10 \times 6 \times 40$</td>
<td>$10 \times 6 \times 40$</td>
<td>$10 \times 40$</td>
<td>$10 \times 2 \times 40$</td>
</tr>
<tr>
<td>Dispersion Solution</td>
<td>$10 \times 6 \times 40$</td>
<td>$10 \times 6 \times 40$</td>
<td>$10 \times 40$</td>
<td>-</td>
</tr>
</tbody>
</table>

**Lifetime usage:**
To estimate the lifetime usage for each mechanism we simply multiply the number of mechanism moves per integration by the number of sequences per year (i.e. TAs/yr as listed in Table 8-1) and the nominal mission lifetime in years (5). For the dither parameter, we assume $n=2$, i.e. two positions on each side of the detector gap. Table 8-4 then list the total for all four mechanisms on
NIRSpec, and compares them to their lifetime requirements. The “worst case” estimates which include the dedicated wavelength calibration exposures are summarized in Table 8-5.

Table 8-4 “Baseline” Estimate for 5-year on-orbit lifetime usage of mechanisms for n=2.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>lifetime cycles</th>
<th>Qualification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Science</td>
<td>Calibration</td>
</tr>
<tr>
<td>FWA</td>
<td>5 × 1300 × 9</td>
<td>2400</td>
</tr>
<tr>
<td>GWA</td>
<td>5 × 1300 × 7</td>
<td>2400</td>
</tr>
<tr>
<td>MSA</td>
<td>5 × 1300 × 4</td>
<td>400</td>
</tr>
<tr>
<td>CAA</td>
<td>Cont. Line</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 × 1300</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>800</td>
</tr>
</tbody>
</table>

Table 8-5 “Worst case” Estimate of on-orbit lifetime usage of mechanisms for n=2.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>lifetime cycles</th>
<th>Qualification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Science</td>
<td>Calibration</td>
</tr>
<tr>
<td>FWA</td>
<td>5 × 1300 × 13</td>
<td>2400</td>
</tr>
<tr>
<td>GWA</td>
<td>5 × 1300 × 7</td>
<td>2400</td>
</tr>
<tr>
<td>MSA</td>
<td>5 × 1300 × 4</td>
<td>400</td>
</tr>
<tr>
<td>CAA</td>
<td>Cont. Line</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 × 1300</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>5 × 1300 × 2</td>
<td>800</td>
</tr>
</tbody>
</table>

8.3 “Hot” Use Cases

In order to assess the thermal stability of the NIRSpec optics and the dissipated power during normal science operations, it is useful to define observational sequences that represent the “worst case” scenario with respect to the usage of lamps and mechanisms. Two such sequences have been identified: the “bright star survey” constitutes the most challenging scenario for science observations, while the “spectral flat field” is the worst-case calibration sequence. Because lamp calibrations are internal to NIRSpec, and can be done in parallel with other SIs, the “spectral flat field” has more flexibility in the duty cycles of the various mechanisms, e.g. by introducing wait times into the sequence. For the bright star survey, similar wait times would immediately produce a loss of NIRSpec (and JWST) efficiency. Both scenarios are briefly described in the following.

8.3.1 BRIGHT STAR SURVEY

The “bright star survey” use case describes a sequence of numerous short observations of relatively bright (stellar) sources within an extended area of the sky. Each of these observations consists of
two exposures, separated by a spacecraft dither (and an MSA reconfiguration) in order to recover the spectral information lost in the gap between the two SCAs. The dither amplitude is assumed to be small enough that no additional TA sequence is required. The observation sequences are separated by small angle spacecraft slews in order to “mosaic” a larger field. The highly repetitive nature of the observations is evident in Figure 8.3-1 which describes the (overly simplistic) case of equal exposure times for all science targets. In principle, the number of repeated observing sequences (i.e., pointings in the mosaic) can be arbitrarily high, but for the purpose of studying the thermal impact of such a scenario, one can assume that the total time spent on this activity does not exceed 100,000s. This limits the number of repeats to about 25.

8.3.2 SPECTRAL FLAT FIELD

Because NIRSpec is a multi-object spectrograph, each detector pixel is potentially exposed to any wavelength between 0.6 and 5.0 μm. In order to calibrate and monitor relative variations of instrument throughput\(^4\) versus field position and wavelength, it is therefore crucial to measure the

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\(^4\) Here, “throughput” includes the transmisson of all mirrors, filter, grating, MSA, and the QE of the detector pixel itself.
response of every detector pixel across the entire spectral range. The conventional method of obtaining such calibration data for imaging instruments is to take a series of “monochromatic” flat field exposures. For NIRSpec, this approach is only possible on the ground, and only at the detector subsystem level because once the MSA is integrated into NIRSpec, there is no longer a “clean” optical path to the detector.

NIRSpec therefore must be calibrated in this respect via the “spectral flat field” method in which light from a long-slit aperture is dispersed across the detector. By stepping the long-slit aperture across the field of view, one can construct the same data cube as obtained from many monochromatic flat field images. Note that such a spectral flat field must be obtained for all configurations (i.e. R100 and all bands in R1000 and R2700) because the grating efficiency curve is folded into the “flat field” response.

The outcome of this method is a “flat field reference cube” for each NIRSpec configuration, normalized to an average value of one to correct the relative response variations. The absolute calibration will then be performed using astronomical standard stars in a few field positions. While initial measurements will be done during the on-ground test campaign, the final calibration cubes can only be obtained in flight because the actual OTE throughput (both spatially and as a function of wavelength) must also be folded into the reference file. In practice, we foresee the following procedure to obtain this calibration data (see Figure 8.3-2):

- open an entire column of shutters (in cross-dispersion axis) to form a long-slit aperture
- expose with appropriate continuum lamp until sufficient S/N is reached. Note that the required integration time (denoted T in Figure 8.3-2) depends on the spectral resolution, wavelength, and the available flux from the calibration lamp. For some configurations, it might be as long as 1000s.
- move long slit by ~ 20 shutters in the dispersion direction, and repeat until FOV is covered
- go to next observing mode, i.e. move GWA to next grating or the prism
- repeat the entire sequence for all remaining dispersive elements

Figure 8.3-2 Schematic of the spectral flat field calibration sequence.

Because of the frequent mechanism movements, and potentially long usage times of the calibration lamps, the spectral flat field has been identified as the most challenging activity from a thermal stability point of view.
8.4  NIRSpec Observing Efficiency

The observing efficiency of JWST is required to be better than 70%, i.e. the time spent collecting photons from science targets must be at least 70% of actual time passed. All other spacecraft activities are collectively regarded as overheads. By far the largest contributor to overheads is the time spent re-pointing the telescope, both during large-angle slews and small-angle maneuvers (SAMs). Therefore, the efficiency budget depends critically on the assumed number of visits during the mission lifetime which, in turn, depends on the distribution of visit lengths, i.e. the assumed science program of JWST.

For this reason, RD 12 describes three different science use cases with different assumptions for the number of short, medium, and long visits for each SI, and provides overhead estimates for each of them. The NIRSpec usage scenario described in Table 8-1 is identical to the “SI Teams Use Case” in RD 12. Given the various activities executed during a “typical” NIRSpec visit as summarized in Table 8-2, and accounting for the on-orbit calibration activities, RD 12 arrives at internal NIRSpec overheads of about \(29 \text{ min per NIRSpec visit}\).

Given that the average NIRSpec visit has a duration of 314 min (see Table 8-1), this implies a NIRSpec overhead fraction of 29/314 \(\approx 10\%\), i.e. the NIRSpec efficiency is well within the FRD requirement of 85%.

9  NIRSPEC DATA PROCESSING

9.1  Data Management System and Science Data Archive

The Data Management System (DMS) is part of the Science and Operations Center. It processes the science data downlinked from the Solid State Recorder onboard JWST. The science data then progresses through a series of data processing levels, as outlined in Table 9-1.

The software that produces Level 1 and Level 2 data handles all instruments, but each instrument has unique calibration reference files (e.g., darks). NIRSpec specific software (described in section 9.2) will be needed to produce Level 3 and Level 4 NIRSpec data. At launch, calibration reference files will be based on models and ground test data. Calibration reference files will be updated with data from commissioning and from routine monitoring over the lifetime of the mission.

Data products at every level will be stored in the Science Data Archive. Archive users may download Level 1 and higher data products and the associated science data calibration software. Archive users may rerun the pipeline software with non-standard parameters.
Table 9-1 Science Data Processing Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 0</td>
<td><strong>Recorded Science Data</strong> - Downlinked files containing packets of compressed pixel data, as stored by ISIM on the Solid State Recorder. Data from a particular integration may be spread across multiple files.</td>
</tr>
<tr>
<td>Level 1</td>
<td><strong>Raw Exposure Data</strong> – FITS file containing up-the-ramp image data for an exposure that may consist of multiple integrations. Relevant packets are extracted from recorded science data files, uncompressed, and assembled into one image sequence per integration. Engineering telemetry and calibration keywords are added to the FITS header.</td>
</tr>
<tr>
<td>Level 2</td>
<td><strong>Count Rate Images</strong> – Up-the-ramp image sequences are fitted to create a count rate image, an uncertainty image, and a data quality image for each integration. The slope fitting procedure removes cosmic rays, bias drifts, and dark current.</td>
</tr>
<tr>
<td>Level 3</td>
<td><strong>Processed Science Exposures</strong> – Count rate images are processed to remove instrumental signatures, extract spectra, and convert to physical units. Measurements from contemporaneous calibration exposures (e.g., science target locations in the reference image) are used when creating processed science exposures. Data from multiple integrations are combined.</td>
</tr>
<tr>
<td>Level 4</td>
<td><strong>Combined Science Exposures</strong> – Associated science exposures (e.g., dithers) are combined.</td>
</tr>
</tbody>
</table>

### 9.2 Pipeline Overview

The goal of pipeline calibration is to accurately convert the number of electrons registered at the detector into the signal from the observed astronomical source for every observing mode at all spatial field points and wavelengths. In the case of NIRSpec, and for multi-object spectroscopy in particular, proper and complete data calibration can be challenging. A general outline of the NIRSpec pipeline calibration philosophy is presented here, but a more detailed account of calibration input reference files and pipeline reduction is included in RD 7 and RD 11.

#### 9.2.1 Pipeline Input Data

The inputs into the NIRSpec data reduction pipeline will consist of the raw .fits files from the up-the-ramp MULTIACCUM science exposures (see section 4.1.6), input reference and calibration files, and instrument telemetry from data header keywords. A brief description of each of these is given below:

- **Raw .fits files**
  - Input raw data files – The raw NIRSpec data files for initial pipeline processing will be 3-D data-cubes. The x and y dimensions are pixel data from individual detector reads, and the z dimension is the multiple detector readouts recorded in time during the MULTIACCUM up-the-ramp integrations.
The x and y dimension of every raw .fits file will be surrounded by 4 reference pixels \((i, j < 4, i, j > 2044)\) which are insensitive to light and will be used to monitor drifts in the properties of detector readout electronics.

- **Calibration Files and Reference Model Inputs:**
The NIRSpec data reduction pipeline will require inputs from previously generated calibration files and reference models, including

- Detector Bad Pixel Masks (calibration file) – Characteristic “hot”, “warm” or “cold” pixels inherent in the detector will need to be identified prior to launch, and monitored periodically during the lifetime of the mission.
- Darks and Biases (calibration files) – Input files for the bias and dark current generated by each pixel per unit time (and possibly as a function of temperature around the nominal operating conditions). These frames will likely be re-observed occasionally to test for dark current and bias stability.
- Detector Linearity response (reference model) – A set of coefficients which model the detector flux linearity response, characterized during I&T by illuminating pixels with a calibrated light source. The derived linearity relationship can be finalized on-orbit by observing standard astronomical sources that span a range of known brightness levels at a few pixel locations.
- P-Flat (calibration file) – The response flat for calibrating out pixel-to-pixel effects in MSA data. Because the bars around shutters block light in an MSA all open configuration, the P-flat calibration files should be generated during ground characterization of the detector. The stability of the P-flat can be monitored in orbit using the flat field calibration lamps in the CAA.
- Extraction box location (reference model) – A model of the box size and location for extracting out smaller detector field regions for pipeline processing of individual MSA spectra (or IFU / Longslit Spectra).
- IFU and Long Slit flats (calibration files) – In these observing modes, each detector pixel will measure a fixed wavelength of light, so flat field files at every grating setting (spectral resolution and wavelength range) will be acquired using the calibration lamp for pipeline reduction reference. The accuracy and stability of these flat fields will be checked occasionally by repeating observations of the flat field calibration lamps for IFU and Long Slit flats.
- The MSA Flat and Throughput model (reference model) – Spectral images acquired with different MSA slits open will illuminate each pixel with a different wavelength of light, so every detector pixel in the NIRSpec MSA observing mode must be calibrated for response over the entire spectral range. As a result, the flat field and throughput response for MSA mode is a three-dimensional model data-cube that “stacks” the multiple 2-D spatial pixel response maps along the wavelength dimension. The MSA throughput data-cube will consist of polynomial models constructed by interpolating over spectral flat field calibration lamp images acquired by stepping “longslit” columns (= a row of the MSA device) of open shutters across the MSA field of view. These calibration files will be re-observed occasionally to check for MSA throughput model stability.
- Geometric distortion (reference model) – The spatial geometric distortion of MSA slits
needs to be corrected to ensure proper flux calibration from differences in effective slit sizes. The geometric distortion over the MSA field will be measured during AIT, and monitored by observing an astrometric reference sky field.

- Wavelength calibration (calibration files) – At the present time, because of the non-repeatability of the grating wheel mechanism positioning with respect to the FPA, a wavelength calibration spectrum will be observed using the appropriate LINE source lamps in the CAA (§4.7.2) every time the grating wheel mechanism is moved. These wavecals are the only calibrations that must be obtained during the science visit. The wavelength calibration will be verified using the grating equation with the absolute grating position determined from instrument telemetry header keywords.

- Absolute flux calibration (reference model) – once the instrument throughput has been accurately rectified, NIRSpec data can be converted onto an absolute flux scale by multiplying by a constant calibration factor. This absolute calibration factor will be derived by multiple observations of spectro-photometric standards and will be repeated to test for stability over the course of the mission.

9.2.2 DATA REDUCTION OVERVIEW

The early processing steps for NIRSpec data involve the collapse of the raw data cube into a two-dimensional, single frame, count rate image. This count rate image is then processed through steps which extract the slit data, remove the instrumental signature, spatially and spectrally rectify the data and absolutely flux calibrate the spectra. The present outline for NIRSpec pipeline calibration is to execute these tasks in three segments: the initial processing will be general for all JWST instruments (CALWebb), and the subsequent steps are more instrument or mode specific (presented here as CALNIRSPCECA and CALNIRSPECB, following HST terminology). A very general outline of these processing steps is included below. However, the NIRSpec data structures are complicated (particularly the MSA), so a more detailed description of the challenges associated with NIRSpec pipeline calibration has been left to RD 7 and RD 11.

**CALWebb** – The early steps of the NIRSpec pipeline reduction will be carried out under the hypothesis that there are strong similarities between the detectors and their readout modes for all JWST instruments. All JWST data will be acquired using up-the-ramp, MULTIACCUM readouts and the raw .fits files will have the same initial structure. For all instruments, the end product of the early processing of the raw .fits datacube is a single collapsed count rate image, generally with units of detected counts/s. The processing steps encompassed by the CALWebb pipeline include:

- **Masking bad pixels** (Input: bad pixel mask file) – A data quality (DQ) and variance plane is generated for each input image, and flag values from the bad pixel mask file are added to the DQ image.

- **Correction for reference pixels** - Reference pixels track detector voltage changes, and this step allows for correction of time dependent drifts of the signal offset.

- **Dark and Bias** Correction (Input: dark and bias image files) – Subtracts the dark reference images, readout-by-readout for MULTIACCUM observations, from the science data.

- **Linearity Correction** (Input: linearity model table/polynomial coefficients) - The linearity correction step corrects the integrated counts in the science image for the intrinsic non-linear response of the detectors
Cosmic Ray Rejection and count rate image creation - Identify and flag pixels suspected of cosmic ray hits, apply the proper weight to the single reads, and combine the data from all readouts into a single count rate image by estimating the slope of the ramp.

For the reference pixel correction and cosmic ray rejection steps, instrument or detector-specific flags could be set to define guidelines for applying these corrections (using header keywords for instrument and detector parameters). The instrument teams are investigating optimal methods for correcting reference pixels and rejecting cosmic rays. Further definition of the CALWebb pipeline for the early processing steps for all JWST instruments is being done at STScI.

CALNIRSPECA – The initial instrument specific steps of the data reduction pipeline focus on removing instrumental signatures from the data, rectifying the data onto a common spatial and spectral grid, and absolutely flux calibrating the spectra. These steps concentrate on pipeline calibration of NIRSpec data associations acquired on a given target set for each grating and MSA configuration (or IFU/Long Slit):

- **P-Flat correction** – correct pixel-to-pixel response variations for MSA data. (Input: P-Flat Image)
- **Data extraction** - Extract from the full frame image individual slit spectra into smaller 2D image for processing in further steps. (Input: model for slit extraction window for each observing mode).
- **Correction for throughput variations** – Full flat field correction and throughput variation are merged into this single step to correct the response of each detector pixel for flux loss as a function of wavelength, field angle and detector sensitivity. This includes flat field correction for IFU and Long Slit modes, and L-Flat and 3D flat model for MSA mode. (Inputs = MSA 3D flat model, IFU/Longslit Flat field, including throughput corrections for vignetting and detector sensitivity)
- **Correction for geometric distortion** - Because of geometric distortion in MSA mode, slits can have different effective slit areas over the full spatial field and light loss from preferentially long wavelengths can be problematic. A differential throughput correction to correct for geometric distortion may need applied. (Input: MSA geometric distortion model).
- **Wavelength Calibration and Spectrum Rectification** - The dispersion direction for NIRSpec data is not parallel to detector rows, and spectral tilting varies with wavelength along the dispersion direction. To rectify the wavelength scale into a common grid, the NIRSpec pipeline will resample data onto a finer pixel scale in a way that conserves flux. The absolute wavelength calibration is derived using the wavelength calibration image acquired contemporaneously with the science, and checked using the grating equation with instrument telemetry on the grating positioning (Input: wavelength rectification model, wavelength calibration image).
- **Absolute Flux Calibration Rectification** - Once instrument throughput and spatial/spectral rectifications are properly taken into account, the conversion of flux into absolute physical units consists of multiplying pixel values by a constant. (Input: spectro-photometric reference calibration value).

CALNIRSPECTB – NIRSpec data may be acquired with spatial dithers to cover the wavelength gap between the detectors (on order of 20") dithers for covering extended objects with the IFU, or
identical target sets using multiple grating settings. As a result, a higher level data pipeline is likely needed to merge multiple associations into one data product. The CALNIRSPECB data reduction pipeline will encompass these next level reduction steps. The details of tasks in CALNIRSPECB are under study; processing steps incorporated into the CALNIRSPECB pipeline might include:

- Extracting spectra from 2D reduced, calibrated images (output from CALNIRSPEC A).
- Merging spectra from spatially dithered data, such as acquired with different MSA configurations or Long Slits to cover the wavelength range lost because of the detector gap, or slightly different IFU pointings.
- Mosaicing data to create a larger spatial IFU field.
- Merging spectra acquired with different gratings.

The output from the NIRSpec data reduction pipeline will be rectified, flux calibrated (possibly extracted/mosaiced) spectral data of multiple MSA targets, IFU datacubes or Long Slit spectra. All output pipeline products will have data quality and variance planes that have been propagated through all processing steps. In practice, the pipeline calibration of JWST data products may be merged into an object-oriented processing philosophy rather than instrument specific. The general outline for NIRSpec reduction (described above) will be preserved, but common modes for JWST instruments (such as Long Slit spectroscopy, IFU spectroscopy) may be merged into a single pipeline flow to simplify and take advantage of cross instrument commonalities. In this case, NIRSpec-specific calibration files, reference model inputs and instrument specific header keywords and telemetry will be accessed using calibration pipeline keywords and data processing settings. The CALWebb procedure outlined above may represent the first seed of a more extended structure able to satisfy the general needs of the JWST mission.
# APPENDIX A - TABLE OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACS</td>
<td>Attitude Control System</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application-specific integrated circuit</td>
</tr>
<tr>
<td>CAA</td>
<td>Calibration Assembly</td>
</tr>
<tr>
<td>CS</td>
<td>Continuum Source</td>
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<tr>
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