JWST Near Infrared Spectrograph (NIRSpec) Operations Concept Document

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1 Instrument overview

1.1 Basic description

NIRSpec is a multi-object dispersive spectrograph covering a field-of-view (FOV) of > 3 x 3 arcmin, capable of observing >100 sources simultaneously.

The region of sky to be observed is transferred from the JWST optical telescope element (OTE) to the spectrograph aperture focal plane (AFP) by a pick-off mirror (POM) and a system of fore-optics which includes a filter wheel for selecting bandpasses and introducing internal calibration sources. The nominal scale at the AFP is ~2.5 arcsec/mm.

Targets in the FOV are normally selected by opening groups of shutters in a micro-shutter array (MSA) in *aperture patterns* to form slits. In addition to the apertures defined by the MSA, there are several fixed-slits in the AFP that can be used for high-contrast spectroscopy. There may also be in integral-field unit (IFU) that uses a small part of the FOV for integral-field spectroscopy. Other apertures may be provided for calibration purposes, although their number and size are constrained by the availability of detector area.

These slits are re-imaged onto a mosaic of NIR detectors (the focal-plane array: FPA) by a collimator, a dispersing element (gratings or a double-pass prism) or an imaging mirror, and a camera. The image scale on the FPA is nominally either 5.56 arcsec/mm or 4.00 arcsec/mm, depending on the choice of detector vendor (100 mas per detector pixel in both cases).

The basic elements of the spectrograph are illustrated schematically in Fig. 1.1 which shows both the optical subsystems and associated mechanisms.

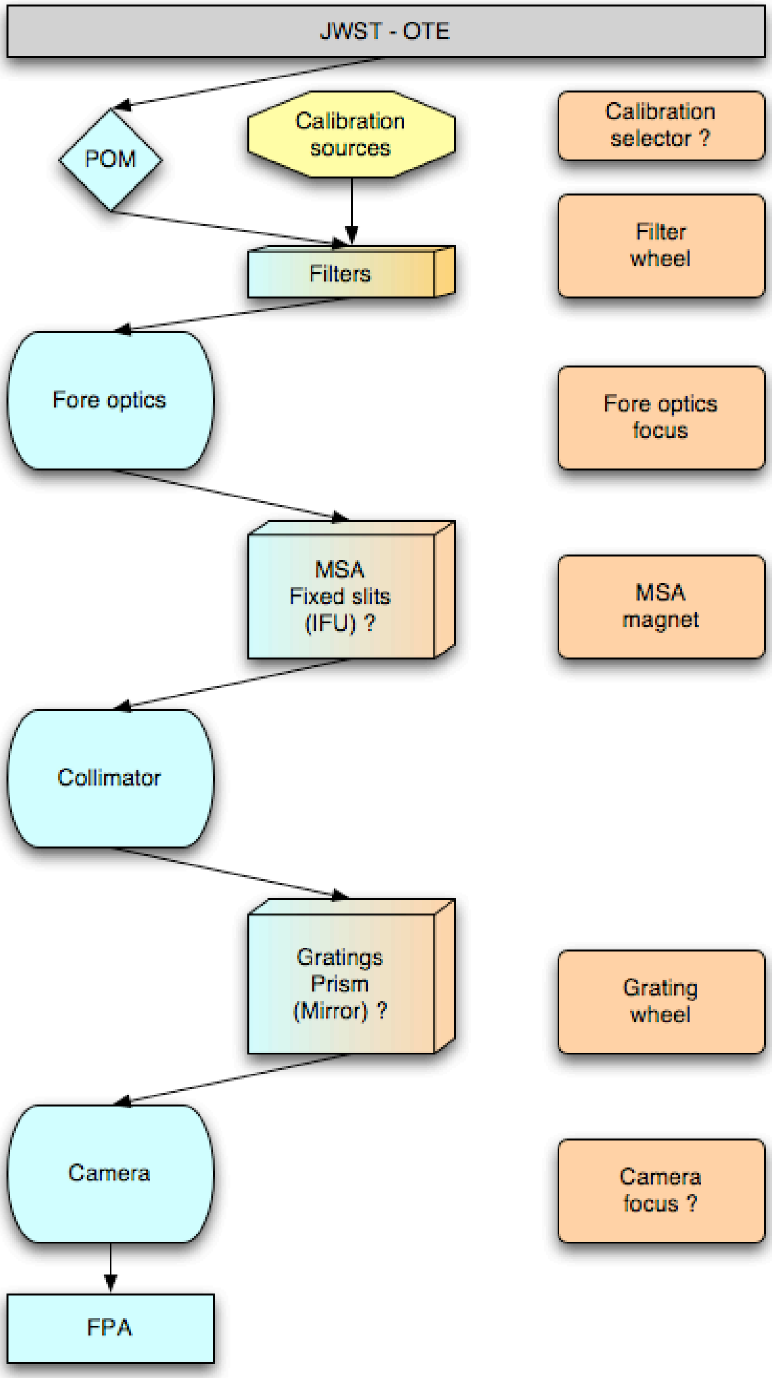

Figure 1.1 A schematic view of NIRSpec showing the main optical elements/subsystems on the left and the mechanisms on the right. The optical flow is from top to bottom (OTE to the detector FPA), The principal opto-mechanical elements are in the centre. The calibration unit contains a number of continuum and line sources together, possibly, with a selector mechanism to feed the light into the optical path via a diffuser on the filter wheel. The actual arrangement of focus mechanisms is TBC.

1.2 Optics

There are three basic optical subassemblies: the fore-optics, the collimator and the camera; the latter two of which at least are three mirror anastigmats (TMA). One or more of these are provided with focus mechanisms.

The fore-optics project a part of the JWST FOV onto the AFP through selectable filters. This optical mapping will introduce optical distortions in a pattern that needs to be mapped to an accuracy that ensures that selected targets over the entire NIRSpec FOV can be placed to high precision with respect to both the fixed slits and the slits defined by the MSA.

The MSA itself consists of a mosaic of subunits producing a final array which, with inter-unit gaps and space for fixed slits and other apertures, defines the NIRSpec FOV. The complete MSA array consists of approximately 1k x 0.5k (TBC) shutters measuring approximately 100 x 200 μm (spectral x spatial direction). The filling factor of the opening shutters is >70% (85% goal).
The smallest configurable element of the MSA is a shutter. In the open configuration, a shutter passes light from the fore-optics to the collimator. In the closed configuration, a shutter prevents light from directly entering the collimator. Occasionally, shutter reconfiguration fails, leaving a shutter temporarily unset. Permanently failed shutters cannot be reconfigured. As illustrated in Fig. 1.2, a fixed support grid with light shields separates individual shutters in the MSA.

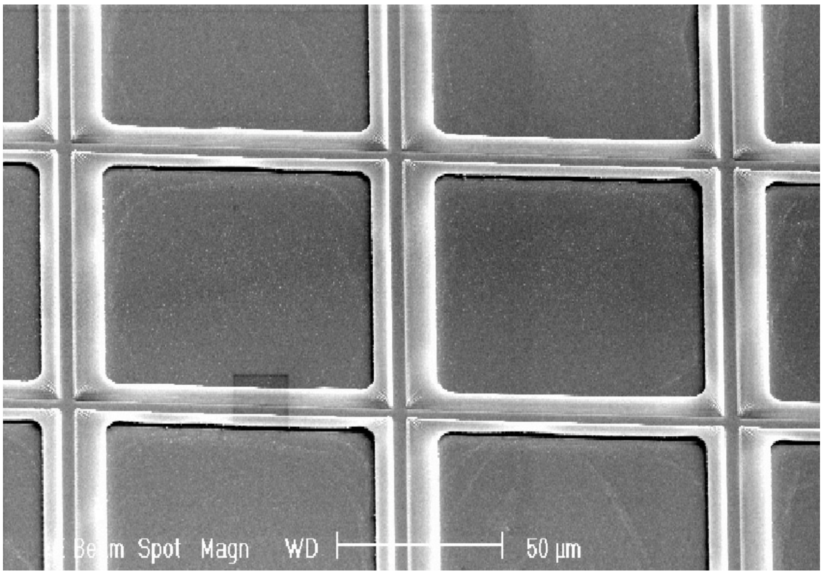

Figure 1.2 An electron micrograph of a prototype MSA showing individual shutters with their light shields

The fixed slits are placed in the AFP between sub-units of the MSA. They are arranged in such a way as to allow two (several TBC) slit widths in a manner that provides redundancy in the case of a failure in the MSA configuration mechanism. The entrance aperture for the IFU will also be located somewhere between MSA sub-units.

The collimator provides a parallel beam to the dispersing elements and the imaging mirror and projects a pupil onto them. Table 1.1 shows the three wavebands for the R=1000 spectroscopy.

Band	Coverage (μm)	Nominal slit width (mas)
I	1.0 – 1.8	200
II	1.7 – 2.9	200
III	2.9 – 5.0	200 or 420

Table 1.1 The three wavebands for the R=1000 spectroscopy and their nominal slit widths.

The camera images the dispersed or undispersed AFP onto the detectors (FPA). The detector array consists of a mosaic of sub-units, each 2k x 2k, forming an array of 2k x 4k 100mas pixels.

The collimator/camera re-imaging system introduces optical distortions between the AFP and the FPA that need to be mapped to a precision sufficient to enable successful multi-target acquisition.

1.3 Mechanisms

1.3.1 Filter wheel

The filter wheel mechanism allows the selection of one of long-pass and bandpass filters used for spectroscopic order-sorting and imaging/target acquisition respectively and a (parfocal) clear position. An opaque closed element that also serves as a diffuser for the calibration sources occupies one of the positions.

1.3.2 Fore-optics focus mechanism

A focus mechanism may be introduced into the fore-optics in order to focus the image from the OTE onto the AFP.

1.3.3 Micro-shutter Array

The MSA consists of approximately 1000 (spectral) by 500 (spatial) individually addressable shutters that can be used to define a variety of science and calibration apertures. The open shutter width and height is approximately 200 and 450 mas, respectively, while the pitch size is 250 and 500 mas, respectively. Sweeping a magnet across the surface of the MSA opens all properly functioning shutters. Individual shutters may then be addressed and closed electronically. The nominal aperture pattern for multi-object spectroscopy is a single shutter for all bands although observers will have the option of choosing different aperture patterns and longer apertures can be used whenever possible without causing spectral overlap. Longer apertures will also be required for spatially resolved spectroscopy of extended sources. Standard patterns of open and closed shutters will be needed for calibration purposes.

1.3.4 Grating wheel

The grating wheel allows the selection of one of five (six TBC) gratings, a double-pass prism and a mirror. Three gratings are used for first-order coverage of the three NIRSpec wavebands at R~1000. Two (three TBC) gratings are used for higher resolution (R~3000) in conjunction with the fixed-slits or the IFU. The prism gives R~100 resolution over the entire NIRSpec bandpass but can, optionally (TBC), be blocked below 1 μm with one of the filters. Although the goal is to have the stability and precision of repositioning of the grating wheel sufficient to preclude the need for positional or wavelength calibration within a sequence of observations of a particular target field on the sky throughout a sequence of dithers and mirror/disperser changes, this may not be physically possible. Therefore, it is currently assumed that this rotational uncertainty will have to be calibrated every time the grating wheel is moved. There is a higher requirement on the positional stability of the mirror used for target acquisition which may mean that it is located separate from the grating wheel.

1.3.5 Camera focus

A focus mechanism may be introduced into the camera in order to focus the image from the AFP onto the FPA.

1.3.6 Calibration select?

Calibration light is injected into the spectrograph from a diffuser placed in one position in the filter wheel. The selection of a particular lamp source will be made electrically/mechanically (TBC).

1.4 Lamps

Continuum and line internal calibration sources are needed for flat-fielding, geometric calibration and for wavelength calibration. It is likely that several continuum sources will be required to cover the full NIRSpec wavelength range. If line sources are constructed from filtered continuum sources, several different sources or filters will be required.

1.4.1 Continuum

Band I

Band II

Band III

Prism

1.4.2 Line

Bands I+II+III, Prism combined or separate (TBC)

2 Detectors

Only one detector mode, MULTIACCUM, is needed to fully enable the NIRSpec science program. MULTIACCUM's user selectable parameters, and their baseline values, are listed in **Error! Reference source not found.**. In the following paragraphs, we define a lexicon for discussing detector readout and then discuss MULTIACCUM readout in more detail.

For consistency in discussing detector readout modes within the JWST Project, we adopt the lexicon currently used by the GSFC ISIM team. Some key phrases are defined as follows.

READ (vb)	The act of clocking and digitizing pixels in an SCA. The word "read' is a verb.
SAMPLE (n)	The result of a single analog to digital (ADC) conversion of the voltage of a pixel.
FRAME (n)	The result of sequentially clocking and digitizing all pixels in a rectangular area of an SCA. "Full frame readout" means to digitize all pixels in an SCA, including reference pixels. "Sub frame readout" might mean for example to digitize only a 128x128 pixels^2 area.
EXPOSURE (n)	The end result of resetting the detector and then non-destructively sampling it one or more times over a finite period of time. This is a unit of data for which signal is proportional to intensity.
EXPOSURE TIME (n)	The time argument in the expression $N_{e^-} = f\, t_{exposure}$, where N_{e-} is the number of electrons collected, f is the detected flux in electrons per second, and $t_{exposure}$ is the exposure time in seconds.

2.1 MULTIACCUM readout

In MULTIACCUM Readout the array is read out non-destructively at intervals during the exposure. By combining these multiple non-destructive samples on the ground, it is possible to "average out" much of the read noise. NIRSpec is limited to downlinking a full frame read every 50 seconds by bandwidth limitations. Therefore, every 50 secconds NIRSpec will send to the solid-state recorder for later downlinking either one read or the average of four reads.

One advantage of MULTIACCUM mode is that cosmic rays can be rejected using ground-based software and samples taken before and after a cosmic ray hit are still useable. In this case, the optimal exposure time is determined not by how long it takes for a specified fraction of pixels to be hit by cosmic rays but by how long it takes for other noise sources to dominate. For broadband imaging, this will typically be the time required for a given exposure to become background limited. For NIRSpec spectroscopy, exposure time will be influenced by the time required for exposures to become dominated by shot noise on detector dark current. Regan & Stockman 2001 discuss how MULTIACCUM type readout facilitates exposure times longer than 1000 seconds and greatly increase the signal-to-noise ratio obtainable in a fixed amount of time. The advantages of this approach have also been demonstrated on-orbit by HST's NICMOS instrument.

There are two user-selectable parameters for NIRSpec's implementation of MULTIACCUM mode: nframe, the number of frames per group, and exptime, the exposure time. All other parameters are either held fixed or can be derived from nframe and exptime.

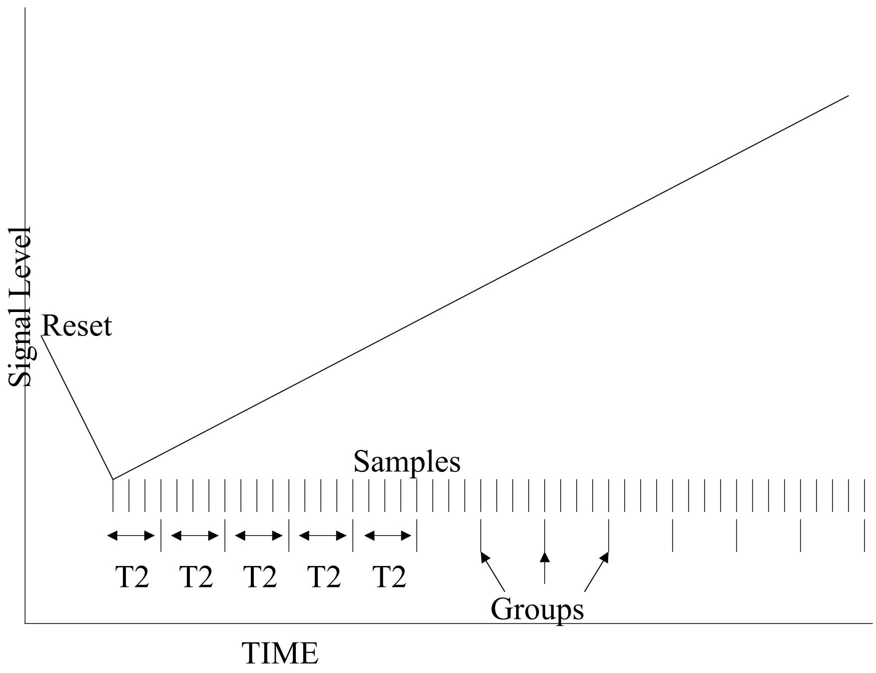

Figure 2-1 In MULTIACCUM mode, each pixel is reset and then non-destructively sampled many times during an exposure. Here we consider the nominal NIRSpec multiaccum mode where there are four samples in each group. The exposure time is the time difference between the first sample in the 0th group and first sample in the last group. The time interval between samples, t_1, is equal to the non user-selectable frame time. The constant time interval between sample groups, t_2, is user-selectable. For NIRSpec t_2 is nominally 50 seconds. The overhead associated with finishing the last group of samples is not included in exposure time.

MULTIACCUM mode operates by time-tagging each frame averaging the frames in a group and sending the average for each group to the SSR for downlinking to the ground. Subsequent processing, which may include cosmic ray rejection, fitting the slope, and reference pixel correction is performed on the ground. There is a small amount of overhead associated with finishing the last group of samples. This overhead is not part of the exposure time.

Pseudo-code for implementing MULTIACCUM mode could appear as follows. We anticipate that the actual implementation will deviate somewhat from this example. Nonetheless, it does convey the overall idea of how we anticipate the data will be taken.

```
n_samples = nsamp0; /* Set up for zeroth group */
reset_array;
For (j=0; j<n_groups; j++){
  For (i=0;i<n_samples; i++){
    group_sum += sample;
  }
  send_to_ssr(group_sum/n_samples);
  group_sum =0;
  wait_until_next_group; /* Groups are linearly spaced. */
}
```

Following the NICMOS model, users will select MULTIACCUM patterns from a suite of available patterns. To facilitate cosmic ray rejection, the time interval between groups, t_2, will be constant within any one pattern. This will ensure uniform sampling of the integrating signal.

2.2 Subarray readout

Most IR photometric calibration standards are too bright for observation in the minimum exposure time of 12 seconds for full frame readout even when dispersed by the gratings. These calibration observations are essential for achieving NIRSpec's science goals. In addition, there are NIRSpec programs for observations of galactic objects in which the objects themselves, or acquisition targets, are brighter than can be observed in a MULTIACCUM full-array minimum integration time of 12 seconds. Sub-arrays are needed to permit shorter integration times. Only one sub-array is needed at a time to fulfill the science requirements.

In SUBARRAY readout, only pixels that fall within a specified area of the SCA are digitized. Each pixel within the subarray region is reset and then non-destructively sampled using a MULTIACCUM pattern. The frame time, or the time required to digitize all pixels within the subarray, is a function of the size of the subarray box and is not user-selectable. The user-selectable parameters for Subarray readout are as follows.

TEXP	Exposure time. Selected from a set of SUBARRAY readout patterns
NSAMP	Number of frames per group. Selected from a set of readout patterns.
X1	x pixel coordinate of first column read out in sub-array. The column shift register is the fast shift scanner. Due to the layout of the SCA's multiplexer, x1 is constrained to be an integral multiple of 4. In other words, x1 modulus 4 = 0.
Y1	y pixel coordinate of first row read out in sub-array. The row shift register is the slow scanner. For consistency is constrained to be an integral multiple of 4.
XSIZE	Length of a X side of the subarray. Size must be an integral multiple of 4.
YSIZE	Length of a Y side of the subarray. Size must be an integral multiple of 4.

The overhead for each subarray readout should be small relative to the exposure time. This overhead should not be larger than 50% for the smallest subarrays.

2.3 Use of reference pixels

NIRSpec's SCAs will incorporate specially engineered reference pixels. Although they do not respond to light, the reference pixels have been engineered to electronically mimic a regular light-sensitive pixel. Using reference pixels, it should be possible to calibrate-out bias drifts and many other artifacts having a timescales longer than approximately 1/10 of the frame read time and longer. Examples of the artifacts that might be calibrated out include

HST/NICMOS's "pedestal drifts" and SIRTF/IRAC's "first frame effect". The reference pixels in NIRSpec's SCAs should be sampled and digitized in exactly the same manner as the light sensitive pixels.

Although it is too early to say exactly how reference pixels will be used, it is clear that data from a large number (≥100) pixels will need to be combined in order to avoid adding noise to the data. Operations that aim to fit structure in frames should ideally be performed on a Frame-by-Frame bases. For this reason, NIRSpec's reference pixels should be treated in precisely the same manner as any other pixel. They should be digitized in exactly the same way and the resulting data should be downlinked to the ground. Sophisticated spatial-averaging (see Rauscher et al. 2003) and other processing can be performed on the ground if SCA testing shows this to be useful. The electronics and data system should therefore make no special provisions for reference pixels beyond ensuring that they are read out with the data in the same manner as any "normal" pixel.

2.4 Integration times

For many NIRSpec observations, long dark-current-limited MULTIACCUM exposures will be the norm. The palette of readout patterns will provide patterns appropriate to the following general classes of observation:

- Acquisition imaging
- Calibration lamp exposures
- Detector limited spectroscopy

The spectrograph's detectors will be operated synchronously with the same time between SCA resets. This is needed because in R=1000 mode the spectrograph will be detector noise limited and asynchronous operations can add additional noise (see NICMOS for examples). In this case, the best sensitivity is obtained with the longest possible exposures (see Regan & Stockman 2001). For the R=1000 mode, we baseline exposure times of t=2000-8000 seconds.

Exposure type	Exposure time (sec)	Number of groups	Time between groups (sec)	Number of Samples per group
Acquisition	72-1000	6	0-200	1
Cal Lamp	60-1000	2-20	0-50	1
Science	50-20000	Exp-time/50	0	4,1

Note that the general science observation exposure times are only constrained to be a multiple of 50 seconds. This is because we are storing and downlinking the groups every 50 seconds. Therefore, dark current calibrations do not need to be taken that exactly match the exposure time of the science program. Instead we can extract the matching exposure time from the long dark exposure and use that to subtract from the science image.

Some NIRSpec programs may require exposure times shorter than the t=12 seconds minimum for MULTIACCUM. In these cases, sub-array readout will be used. Sub-array exposure times can be very short. However, it is important not to use such short exposure times that strongly time dependent persistence arising from ephemeral charge traps renders calibration impossible. Until more is known about NIRSpec's detectors, we therefore baseline a minimum sub-array exposure time of 40 ms. We anticipate that the subarray minimum exposure time will be updated when it can be informed by testing of flight-candidate detectors.

2.5 Detectors electronic gain value

The amount of amplification that is needed to convert the output voltage from the SCA to a voltage that is applied to a digital to analog converter is known as the gain. For NIRSpec we plan to operate with only a single value of the gain. Because digital to analog converters have a fixed number of bits of accuracy (16 is assumed here), for some low noise detectors it is not possible to both Nyquist sample the read noise and be able to represent in 16 bits the full well of the pixel. Therefore, many instruments have two or more gain settings which trade-off effective read noise and dynamic range.

There are several reasons why this does not apply in the case of NIRSpec. Because NIRSpec is being optimized for faint source targets, larger dynamic ranges are not required. In addition, tuning the detectors for smaller full wells for the pixels will lead to lower dark current (a primary limit on the sensitivity of the instrument). Finally, lab testing of JWST detectors has shown that the read noise on a single read will not be below 8 e^-. With a single sample read noise of 8 e^- one only needs a gain setting of just under 4 e^-/ADU to not add quantization noise. Therefore, if we are conservative and use a gain setting of 2 e^-/ADU, we can easily represent up to 128K e^- and very well sample the single sample read noise.

2.6 Idle patterns

An "idle pattern" refers to the clocking sequence that controls a detector while it is not being used for an exposure. It can serve to ensure that the detector wells do not fill up and induce persistent charge in science and/or calibration exposures. It can also serve to stabilize the detector temperature by keeping the power through the detector relatively constant during and between exposures. The NIRSpec idle pattern(s) should consist of a sequence of resets and reads within a TBD reset pattern. The reset pattern may consist of resets at well-defined intervals, or a continuous flush. In any case, the choice of reset pattern should be informed by the results of ground based testing using realistic NIRSpec detectors.

3 Observing Strategies

NIRSpec has a small number of observing modes each of which can be quite complex. In this section we describe the various observing modes and associated observing strategies.

3.1 Definition of terms

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. Different target sets may be used for target acquisition and science observations. A particular 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.

Each move of the grating mechanism defines a new *association*. A target set may be observed in multiple associations. From a commanding and data analysis perspective, a new target set implies a new association block, even if no motion of the grating mechanism is required. For multi-object spectroscopy of a particular target set, each association may include multiple *MSA configurations*. In this case, the field-of-view is adjusted to move the targets from previously opened shutters into newly opened shutters.

For each association or MSA configuration, *sub-aperture dithering* may be used to move targets within an aperture. Between two consecutive detector resets, nondestructive reads yield an *image sequence*. At each dither location, multiple image sequences may be recorded. A single image sequence may not span two sub-aperture dither locations.

NIRSpec observing programs will contain hierarchical arrangements of the aforementioned elements. Each NIRSpec observing program may contain multiple NIRSpec fields. Each NIRSpec field may contain multiple target sets. Each target set may be observed in multiple associations. Each association may include multiple MSA configurations. Each association or MSA configuration may involve multiple sub-aperture dither locations. At each dither location, multiple image sequences may be obtained.

3.2 General assumptions

3.2.1 Types of science observations

Separate observing strategies may be defined for each of the following types of NIRSpec science observations:

- Slitless spectroscopy
- Spectroscopy with fixed-slits
- Multi-object spectroscopy with the multi-shutter array (MSA)
- Imaging spectroscopy with the integral-field unit (IFU)

NIRSpec imaging will be used primarily for target acquisition and calibration. NIRCam will obtain science images, yielding higher throughput, better sampling, and an unobstructed field-of-view.

3.2.2 Image stability in the Aperture Focal Plane

Roughly a third of the science observing time with NIRSpec will likely be devoted to deep exposures that last about a day per association. We assume that the grating mechanism will normally remain stationary for the duration of these exposures, but interspersed target acquisitions should be allowed, if necessary. Each new target acquisition implies a full set of contemporaneous calibrations, significantly reducing overall observing efficiency. Therefore, science target location errors in the aperture focal plane should not increase significantly on any timescale from seconds (*image jitter*) up to a day (*image drift*). Similarly, a sequence of dithers within 20 arcsec of the initial pointing should not significantly increase target location errors. Errors in target location may grow for the following reasons:

- Variations in spacecraft roll angle about a single FGS guide star
- Cumulative errors in achieving requested dithers up to 20 arcsec
- Temporal changes in the mapping between spacecraft and NIRSpec roll angles
- (Thermal) drift in relative FGS and NIRSpec position in the OTE focal plane

For a given target acquisition, we assume that the average target will drift by less than 6.4 mas (2σ), regardless of the number of dithers within 20 arcsec of the initial location (see section 4 for details).

3.2.3 Grating wheel repeatability

We assume that contemporaneous calibration will be needed to compensate for mechanical residuals in the grating wheel location. The mirror element is used during target acquisition. Successful target acquisition requires knowledge of the mirror orientation with an accuracy corresponding to 0.05 detector pixels rms (5 mas on the sky). Science observations use a dispersing element. Successful wavelength calibration of science observations requires knowledge of dispersing element orientation with an accuracy corresponding to approximately 0.1 detector pixels rms. If the grating wheel is not repeatable with an accuracy of 0.05 detector pixels, then contemporaneous calibration exposures will be required for every target acquisition and for most science observations. Contemporaneous calibrations reduce operational efficiency and significantly complicate flight software development and testing. Nonetheless, it seems likely that contemporaneous calibrations will be required.

3.3 MSA apertures

An *MSA configuration* can be specified as a 1024 x 512 bit array, with each bit set only if the corresponding shutter is supposed to be open. This fully bit-mapped representation requires 64 KB per MSA configuration. This is a significant fraction of the on-board MSA data storage allocation for an entire week. A typical week will require a few hundred MSA configurations, so a more compact representation is needed.

One possibility is to uplink compressed bit-maps. An MSA configuration with 100 apertures typically compresses down to ~1 KB, depending on the generic algorithm. Compression becomes less effective as the number of shutters in the minority state increases. Decompression requires roughly 30 MIPS-seconds, corresponding to 15 seconds for a processor allocation of 2 MIPS.

As an alternative to generic compression, a tailored encoding scheme can be used to represent compactly all typical shutter configurations, but also allow arbitrary MSA configuration, if necessary. Encoding will be at least a factor of 2 more compact than generic compression and decoding will be less computationally expensive, but the ground and on-board software may be somewhat more complicated.

As an example of a possible encoding scheme, each aperture could be described by an *aperture type,* a *shutter state flag*, an optional *reference shutter*, and optional *aperture data.* A 3-bit aperture type would select between 8 possible aperture types. A 1-bit shutter state flag would indicate whether a particular aperture definition specifies shutters to close or shutters that should remain open. A total of 21 bits would be needed to specify the reference shutter. A reference shutter need not be at the center of an aperture. The following apertures types are probably sufficient to describe all desired science and calibration configurations. Aperture data for each type are listed in parentheses.

- Rectangular aperture (height, width, orientation)
- Circular aperture (radius)
- Bit-mapped tile to repeat across MSA (size of tile [power of 2], tile data)
- Bit-mapped MSA sub-array (size of sub-array, sub-array data)

The aperture type and aperture data together describe the pattern of shutters to open or close, relative to the reference shutter, which need not be open. Portions of an aperture that extend off the MSA would be ignored. Individual shutters may be open in one aperture and closed in another overlapping aperture, so the ordering of aperture definitions in the *aperture list* is important. Aperture definitions later in the list have higher precedence, so the last requested state for a given shutter prevails. This probably means that a fully bit-mapped array must be constructed before sending commands to the MSA electronics.

Although aperture shape parameters allow commanding flexibility, calibration accuracy will vary depending on the requested *aperture size*. A limited number of commonly used rectangular aperture sizes will have *primary calibration* data. For other aperture sizes, *secondary calibrations* of varying accuracy will be determined on a best effort basis.

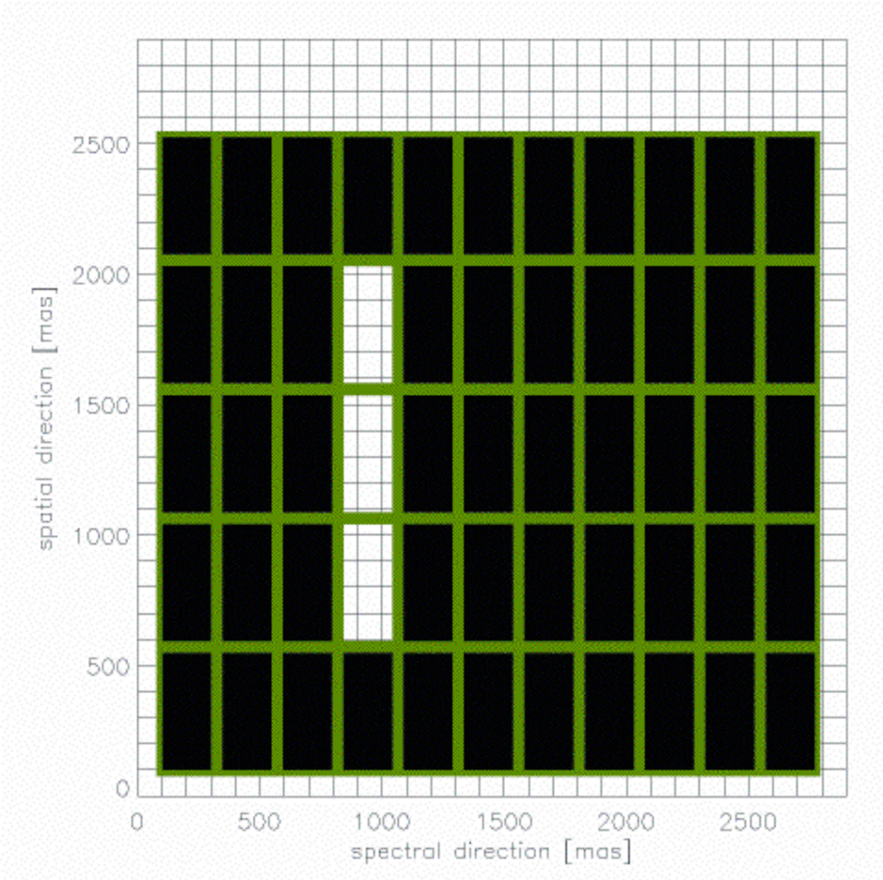

Figure 3-1 shows a segment of the MSA with shutters opened to form a 1x3 aperture. The MSA segment is projected onto the grid of detector pixels.

3.4 Aperture selection and field coverage

The MSA shutter array can be used to create slit apertures within most of the NIRSpec field of view. A typical aperture shape is shown in figure 3-1. For a randomly distributed science target set typically only one object can be placed at an optimal position (i.e. the center) in its slit. All other targets will be misplaced by up to half the shutter size due to the fixed spacing of the MSA. The slit efficiency is a strong function of the exact positioning of the target within the slit, the target PSF and the wavelength (see Figure 4.1). In order to meet the requirements on spectrophotometric fidelity and overall sensitivity of NIRSpec, only objects in a central "target zone" within a shutter can be accepted for observations. First calculations show that this target zone, providing roughly uniform throughput, will be approximately half the size of the shutter width. It is assumed that most of the remaining throughput variations can be eliminated by sub-shutter dithering (see next paragraph). With this set-up the full FOV of the MSA can be covered with two pointings, offset by half a shutter width in spectral direction.Sub-Aperture dithering

Because multiple shutters are opened to create apertures, a target in the aperture may be partially occulted by the MSA grid in the spatial direction. Furthermore, the exact location of the science target in the "target zone" will create small variations in throughtput (order of 5%). Dithering within an aperture is one way to improve flux calibration, despite throughput losses caused by the fixed nature of the MSA grid. Comparing the number of photons detected at different sub-aperture dither positions provides empirical constraints on source extent and positioning of the source with respect to the MSA grid. These two empirical constraints are sufficient to permit accurate flux calibration, assuming point-source throughput as a function of position in the aperture is calibrated adequately. Accuracy may be further improved by using images of the field-of-view obtained with NIRSpec, NIRCam, or some other high angular resolution camera.

Sub-aperture *dither patterns* are chosen to provide adequate constraints on source extent and sub-aperture position with respect to the MSA grid. Increasing the number of sub-aperture dither positions generally improves flux calibration, but then read noise is higher because increasing the number of dithers effectively limits exposure time at each location and thus the number of non-destructive reads for each exposure. Observers typically optimize S/N ratio, subject to a constraint on flux calibration accuracy, rather than the converse. Thus, typical observations will employ the minimum number of sub-aperture dithers and MSA reconfigurations required to achieve the absolute flux calibration goal. For exposure times shorter than a few thousand seconds, some observers may prefer not to dither at all. For longer exposure times, cosmic rays effectively limit the number of non-destructive reads, so sub-aperture dithering can be employed without penalty.

3.5 Operational constraints

The detectors cannot be damaged by bright illumination, but the dark rate of individual pixels depends on their recent illumination history. Pixels subjected to bright illumination will have a significantly elevated dark rates for hours after the event. An elevated dark rate will compromise observations of faint sources, which are limited by detector noise. To prevent inadvertent bright illumination, NIRSpec should effectively be shuttered when not in use.

Setting the filter wheel to the closed/calibration position is the simplest and most effective method of protecting the detector. The closed/calibration position places a diffuser in the optical path, instead of a filter. The opaque diffuser prevents external light from illuminating the detector. The diffuser face of the calibration position connects the calibration source module with the spectrograph optics. Closing the MSA would protect much of the detector, but sources in the fixed slits would still illuminate the detector. Selecting a grating, rather than the mirror, would not adequately protect against bright illumination.

3.6 Activity Sequences for an Association

Associations may contain target acquisitions, contemporaneous calibrations, and science observations. The sequence of possible activities is described below. Certain activities may be skipped or repeated, depending on the science goals and observing configurations for a particular association. Instrument performance will affect the need for certain calibration observations.

Instrument mechanisms may be in any configuration at the start of an association. The filter wheel may be in the calibration position, which blocks external light, but the filter wheel may also be in some other position, depending on the preceding activities. Similarly, the MSA may be in any configuration. To maximize operational efficiency, reconfiguration commands should require negligible execution time when a mechanism is already in the requested state. Flight software logic within an association is also simplified when a mechanism command that requires no mechanism motion incurs no significant overhead penalty.

3.6.1 Measure mirror orientation

The goal of target acquisition is to position targets in the desired location in the aperture focal plane. A target acquisition image of the field-of-view constrains the position of targets on the focal plane array (FPA), but additional calibration observations are required to map positions on the FPA back to positions in the aperture focal plane. Image distortion between the aperture focal plane and the FPA will be measured as part of the annual calibration program. But if the mirror orientation does not repeat precisely, global image shifts are still possible each time the mirror is selected.

If the mechanical residual error in mirror positioning leads to global shifts larger than 0.1 detector pixel (2□) along the spectral axis, mirror orientation will have to be measured during target acquisition. Operational overhead will be significantly increased if mirror orientation must be measured as part of every target acquisition. Precise mirror repeatability is a goal of the instrument design, but for now the operations plan must allow for the possibility that mirror orientation will have to be measured during every target acquisition.

3.6.2 Select imaging mode

Some fields-of-view will contain objects bright enough to leave a persistent image in the detector, if observed too long in imaging mode. In such cases, observers may elect to use *protected imaging mode*. If a field-of-view contains no *bright objects*, observers will typically use *unprotected imaging mode*. Observers will use the *observation-design tool* (ODT) to specify any bright objects that should not be allowed to illuminate the detector while in protected imaging mode. Because failure to block light from a bright object will not permanently harm the detector, flight software will not be responsible for choosing between protected and unprotected imaging mode. Similarly, flight software will not be responsible for validating requested MSA configurations in protected imaging mode.

Unprotected imaging mode is achieved using the following activity sequence:

A. Command the desired filter into the optical path

B. Open all the MSA shutters

C. Command the mirror into the optical path

D. Protected imaging mode is achieved using the following activity sequence:

E. Command the filter mechanism to the dark/calibration setting, blocking external light

F. (Slew the telescope to the desired field-of-view)

G. Open all the MSA shutters

H. Close the specified shutters around the bright objects

I. Command the mirror into the optical path

J. Command the desired filter into the optical path

A request for protected imaging mode implies that the filter wheel should be used as a shutter before the telescope slews to the requested field-of-view. This adds complexity to the flight software. The radius of shutters to close around a bright object will depend on the brightness of the source and the duration of the exposure. It may be necessary to close additional shutters to block bright diffraction spikes. The ODT will generate a complete description of the required MSA configuration.

3.6.3 Target acquisition

The goal of target acquisition (TA) is to position a set of *acquisition targets* accurately in the aperture focal plane. Due to the time delay between JWST and the ground based control center the TA has to be carried out by an automatic on board procedure. As discussed in the previous section, this may also involve the measurement of the exact mirror position. Accurate target acquisition requires multiple acquisition targets or dithered measurements of fewer acquisition targets. Here we adopt a strategy involving multiple targets observed at one pointing. In order to avoid image shifts introduced by different filters we recommend that the target acquisition should be carried out with the same filter as used in the spectroscopic observations. The use of special bandpass filters for acquisition (to aid brightness estimation) will require an extra term in the pointing error budget representing a constraint of filter wedge and distortion performance.

The target acquisition procedure includes a brightness test for acquisition targets. The observer will use the ODT target acquisition tool to estimate expected brightness through the acquisition filter. With an event-driven commanding philosophy, no science data will be obtained for a visit with a failed acquisition. Success criteria for acquisitions should be fairly strict because revisiting a field-of-view is less expensive than wasting a full day observing the wrong targets. Because failed acquisitions will frequently be followed by repeat visits, failed acquisitions should return all available diagnostic information. The details of the target acquisition are discussed in section 4.

3.6.4 Direct image

After target acquisition, science targets should be near their expected locations in the aperture focal plane; typical positional errors are estimated to be15 mas (1σ, TBR). The MSA configuration will have to be changed from the acquisition target configuration to the initial science target configuration. MSA reconfiguration will require a magnet sweep to open all of the shutters, after which the appropriate shutters can be closed to form science apertures. While the MSA is open and the mirror is still in the optical path, bright objects in the field-of-view could be imaged on the detector, leading to a temporary increase in detector dark rate. If this is the case then the MSA reconfiguration has to be done in *protected mode*. This protection strategy assumes that leaving and then returning to a particular filter moves targets in the aperture focal plane by less than 5 mas (2σ, TBR).

The accuracy of flux calibration and wavelength calibration in the data processing pipeline depends on how well target positions are known. Therefore observers will be strongly encouraged to follow each target acquisition with a direct image of their science targets through the configured MSA (“through slit” image). The data reduction pipeline will use this direct image to optimize data extraction and calibration.

3.6.5 Disperser selection

After finishing all preparatory imaging, the mirror is replaced by the desired dispersing element in the optical path.

3.6.6 Wavelength calibration

After pipeline data processing, every extracted spectrum will have an associated wavelength scale. Wavelength accuracy will depend on NIRSpec mechanical characteristics and the availability of calibration data. Wavelength dispersion and zero-point will be measured across the detector for each disperser, as part of the annual calibration program. Global wavelength shifts are still possible each time a disperser is selected, if the grating wheel does not repeat precisely.

Disperser orientation will have to be measured each visit, if mechanical residual error in grating wheel leads to global shifts larger than 0.2 detector pixel (2σ) along the spectral axis. Precise disperser repeatability is a goal of the instrument design, but for now the operations plan must allow for the possibility that disperser orientation will have to be measured each time a new dispersing element is selected. Some science programs will not require accurate wavelengths, but poor calibration degrades the archival value of data. Thus, contemporaneous wavelength calibration measurements will be the default every time a new dispersing element is selected. The wavelength calibration observations may be suppressed only when necessary to achieve the primary science goal of the observing program. Wavelength calibration measurements are useful even when the MSA has all shutters open because the fixed-slits provide information about disperser orientation.

3.6.7 Science observations

Science observations can begin once all preparatory acquisition and calibration activities complete successfully. Data at the first and any subsequent MSA configurations are obtained using the following activity sequence:

A. Command the desired order blocking filter into the optical path

B. Obtain one or more exposure(s)

C. Perform a sub-aperture dither, if necessary

D. Repeat steps B-C until the requested sub-aperture dither pattern is completed

Most visits will use sub-aperture dithers along the spatial and spectral axis to reduce throughput non-uniformity caused by the MSA grid.

Dithers beyond a shutter size are useful for several reasons. The gap between detectors corresponds to 20 arcsec (TBR) on the sky, so a dither of this magnitude is required to obtain complete wavelength coverage. Large scale dithers also help to minimize the impact of detector noise, MSA and detector defects etc. Dithers larger than 50 mas arcsec will generally move targets out of the current apertures defined by the MSA. The MSA must then be reconfigured to open apertures around the new target locations. The reconfiguration will occur with the grating in the optical path, rather than the mirror, significantly reducing the impact of bright objects in the field-of-view. Nonetheless, a protected MSA reconfiguration activity should be used in the precence of bright objects.

4 Target acquisition

4.1 General assumptions

Target Acquisition (TA) will be necessary to place the science targets at their intended positions within the slits defined by the MSA configuration or in one of the fixed slits. After their program has been selected by the TAC, the observer will be provided with the range of position angles (PA) which can be used for a given observation. The observer will then pick the desired PA for the observations and prepare a list of acquisition targets. To prepare this list, the observer needs to have access to accurate relative astrometric information over the whole NIRSpec field of view. We assume that the user knows the relative astrometric reference frame with respect to the JWST guide star frame to within < 0.5 arcsec to enable a satisfactory starting position for the TA. The telescope scheduler will ensure that an observation in the queue is only carried out if the desired roll angle is available for the full time slot. The absolute pointing accuracy of the telescope is sufficient to place any target in NIRSpec's field of view within about 1" of the MSA slits, and to arrive at a roll angle to within 20 arcsec of the commanded value. The purpose of the target acquisition procedure is to place the acquisition targets at the desired AFP positions to a very high precision.

4.2 Target acquisition goals

4.2.1 Motivation

Science observations will be carried out after placing the science targets onto a pre-configured MSA slit mask. In general, the MSA can be configured so that any randomly placed target is within an area of the size of one shutter around the center of each slit. However, at least for the shorter wavelength bands, the standard observing procedure will be to cover an area on the sky with two exposures offset by half the width of an MSA shutter, selecting only targets which fall within the central 50% of the slit. With the nominal MSA shutters, the TA will therefore attempt to place as many objects as possible within the central 123 mas x 447 mas wide strip of the shutter. We refer to this strip as the "target area". For long wavelength bands, this target area might be larger. Since the shortest wavelength bands will place the more stringent requirements on TA, only this band will be discussed from now on. Errors in the TA will lead to objects being placed outside the target area. Such errors in the pointing will have two effects. First, outside the target area, the slit efficiency will be a strong function of the position of the targets. Random offset in the pointing will therefore lead to random errors in the photometric fidelity of the spectra. The overall goal for NIRSpec is to reach a photometric accuracy of 10%. We assume here that the photometric error introduced by an error in the TA has to be less than 5% to reach the overall photometric goal. The second effect of errors in the TA is that the overall efficiency of the spectrograph decreases because the average slit throughput for randomly place science targets will decrease. The goal is to limit the loss of efficiency to less than 10%. Both effects depend strongly on the exact shape of the PSF and diffraction effects on the MSA. We therefore propose a purely geometrical goal for the TA in section 4.2.2 which can be used to derive requirements on components of the telescope which are independent of the PSF. In section 4.2.2 and 4.2.3, we demonstrate that with our current estimates of the PSF, this geometrical goal implies a photometric fidelity and throughput efficiency compatible with the stated goals.

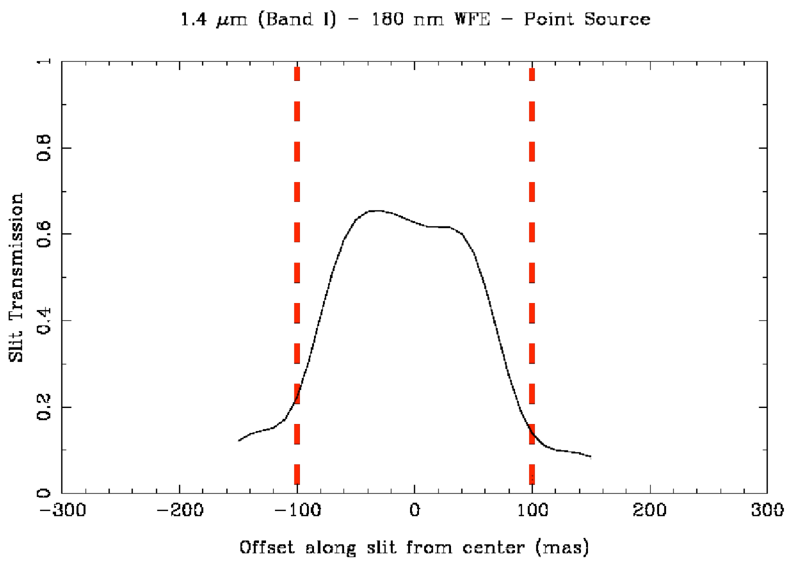

Fig. 4.1. **Slit efficiency as a function of position within the slit. The solid line shows the slit efficiency as a function of offset from the slit center for a slit composed of a single MSA shutter with an effective aperture size of 180x360 mas. The curve was computed in Fourier approximation, assuming a 20% oversizing of the spectrograph optics and including a realistic OTE and instrument WFE (Jakobsen, 2003).**

4.2.2 Geometrical definition of successful TA

TA will attempt to align the pre-configured MSA with the acquisition targets. Slits will in general be 1 or more MSA shutters long (see figure 3.1) and individual MSA shutters are themselves elongated. Errors in the pointing along the slit have therefore much less impact on both photometric accuracy and efficiency of the spectrograph then pointing error across the slit. Therefore, pointing errors discussed below are one-dimensional errors in the dispersion direction of the spectrograph, with the <u>assumption that pointing in the spatial direction is at least as good as in the spectral direction</u>. The target area for TA is therefore a strip 50% the size of the separation of MSA shutter, i.e. 123 mas. Errors in the TA will lead to some acquisition targets being located outside their intended target area. A target acquisition will be considered as failed if the misalignment between MSA and acquisition targets is such that more than 25% of randomly placed objects are shifted outside the target region within each slit. The goal of the TA procedure is for this to occur in less than 5% of all cases. This leads to a requirement of one-dimensional 2σ errors in the TA procedure of less than 31mas, or a 1σ error of about 15mas.

4.2.3 Impact of TA error on photometry

The advantage of the geometrical definition of TA goals is that it is easily testable and independent of the optical performance of the telescope for which requirements are set

elsewhere. However, it is important to test whether the TA goals and existing specification for the PSF are consistent with the photometric goals for NIRSpec.
The science requirement is to achieve a 1σ photometric accuracy of 10%. In order to achieve this, photometric errors added by error in the TA must be less than 5%. Slit transmission for point sources is a strong function of the position within the slit. The variations are larger for shorter wavelengths. Therefore, we investigate here the effect of TA errors on the slit transmission in band I at $\lambda=1.4$ μm. Figure 4.1. shows the slit throughput for point sources as a function of position for a MSA shutter with a transmissive part 180 mas wide. It can be seen that within the central 50% of the slit, slit efficiency is fairly constant. Similar calculations for the nominal shutter size (200 mas wide) show that pointing offsets of 15mas from the target area lead to photometric variations of about 5% in throughput (TBC). Therefore, the geometrical pointing requirement as defined in 4.2.2. satisfies the photometric goals for NIRSpec.

4.2.4 Impact of TA on spectrograph efficiency

The average efficiency of the spectrograph for randomly placed science targets decreases by about 5% (TBC) with the nominal observing strategy, well within the goals.

4.3 Target acquisition procedure

4.3.1 Required input

The success of the TA depends on input that has to be prepared by the observer well in advance. The observers pick a desired PA for their observations within the constraints provided by the observatory. Using these constraints, they will supply desired positions of an acquisition target set on the MSA. The TA will attempt to place the acquisition targets at these positions. It is the responsibility of the observer to ensure that that, by placing the acquisition target set as requested, a subsequent science target set will be located correctly in the MSA configuration. Acquisition targets can be science targets or other objects in the field. It is therefore not possible for the SOC to check the consistency of the provided input.

Specifically, the observer must provide the following information:

- The desired PA
- An acquisition target set to be used for target acquisition
- The MSA configurations that define the aperture mask for each science target set to be observed in the visit
- Specification of whether the acquisition targets should be used to adjust offsets and roll angle, or offsets only
- An optional target acquisition MSA configuration to be used if there are any bright objects in the target field of view.
- Exposure time for target acquisition images
- Filter to be used for target acquisition

TA without roll angle adjustment can, in general, only place a single object onto a slit with sufficient accuracy when not near the geometrical center of the acquisition target set. It is therefore mostly useful for fixed slit or IFU observations.

The list of acquisition targets will consist of desired x and y coordinates on the MSA, and a magnitude within the NIRSpec acquisition filter. The sky coordinates of the acquisition targets must be provided using a standard definition which applies both for point sources and slightly extended sources, e.g. center of gravity.

The aperture mask will consist of a list of x and y coordinates for the shutters on the MSA that will be opened for the spectroscopic observation (this will be in the form of a compressed 1-bit image: see section 3.3).

4.3.2 TA imaging

The core of the TA procedure is the imaging of the target field through open shutters and then to perform an automatic procedure to determine necessary adjustments in the telescope pointing. Accurate position measurements on these images requires that images be automatically reduced. This reduction includes flat fielding (TBC), distortion correction (TBC) and cosmic ray (CR) removal. The computer needs access to a flat field reference file (TBC) and to a distortion map (TBC).

4.3.3 Object locating algorithm

Positions and fluxes of the objects must be measured automatically. Opaque bars between the MSA shutters will complicate these measurements. The positions of these bars relative to the detector will not accurately be known and will therefore not be taken into account *a priori*. Instead, the TA will rely on the recognition and rejection of outliers amongst the measured positions (see below). Algorithms such as the "sliding checkbox" used for HST STIS are available, but their performance for this application needs to be tested. At this point, the baseline is to use a simple *center of gravity* algorithm because of its robustness.

4.3.4 Computation of pointing adjustment

The final step in the TA procedure is to compare the measured positions of the acquisition targets with their expected values. The on-board software will determine the best set of offsets in x, y and, roll and place the acquisition targets as close a possible to their intended position on the MSA. In some cases, not enough acquisition targets will be available to determine the three offset parameters. In such cases, the observer can specify that roll offsets are assumed to be zero. This option will mostly be used for observations with the fixed slits.

4.3.5 Detailed TA steps for MSA observations

The procedure as outlined above requires a large number of individual steps that are detailed below. It is assumed that, if the imaging mirror is located on the grating wheel, the position of the MSA relative to the detector has to be calibrated during each TA procedure . This procedure can be carried out while the telescope is slewing to the target region. Once it arrives, imaging for the determination of pointing offsets starts.

As soon as the commanded pointing offsets have been carried out, the science exposure starts.

The specific sequence of events is the following:

A. Telescope is commanded to go to field

B. Telescope slews.

C. During the slew, NIRSpec is configured for target acquisition and the position of the MSA relative to the detector is calibrated. This consists of the following steps:

  1. Rotate the grating wheel into mirror position. NIRSpec is now in imaging mode.
  2. Rotate filter wheel to dark/calibration position

3. Turn on appropriate continuum lamp
4. Take short exposure
5. Read a window on the detector that is centered on the alignment slits.
6. Send image to computer
7. Turn off lamp
8. Computer analyzes the images and computes position of MSA relative to detector.
9. Configure MSA for imaging of acquisition targets: all MSA shutters are opened (optionally shutters around bright objects are closed (protected mode)).
10. Filter wheel is moved to selected TA filter

A. After the telescope arrives at the target field, a multiaccum exposure is taken. This is nominally a reset followed by three non-destructive reads of the detectors.

B. Images are sent to computer

C. For each image, computer

1. Combines the reads to form a cosmic ray free image
2. Divides image by flat
3. Determines COG of targets
4. Computes position of objects from COGs
5. Fits offsets (Δx and Δy in pixels) and orientation $\Delta\theta$ to difference between measured and expected coordinates.
6. If specified by observer, instead only determine Δx and Δy in pixels
7. Converts Δx, Δy and $\Delta\theta$ to slew commands using distortion map
8. Identify and remove outliers in the measured positions (TBC). These outliers might be caused by residual cosmic rays or the partial masking of sources by the MSA inter-shutter bars,
9. If too few acquisition targets are left, abort observations and return command to scheduler.
10. Using the previously computed position of the MSA relative to the detector, the offset Δx pixel and Δy pixel are computed
11. Commands offset Δx pixel, Δy pixel, $\Delta\theta$ (TBC)

D. Telescope slews to final position

E. MSA is configured for first science target set.

F. Science observations start. The first image in the science sequence will in most cases be an undispersed image to be used to aid the extraction of spectra.

4.3.6 Target acquisition for fixed slits

Target acquisition for the fixed slits will be identical to the target acquisition for the MSA slits. In particular, target acquisition images through the open MSA will also be used to place the target on the fixed slits. Any observation, which uses the MSA, can be used to simultaneously place science targets onto one or several fixed slits. The target acquisition procedure does not need to know whether the acquisition aims to do so or not.

4.3.7 Target acquisition in case of MSA failure

If all the shutters of the MSA fail to open, fixed slits are still available for spectroscopy. However, TA cannot use imaging through an open MSA configuration. It is clear that the absolute pointing accuracy of the telescope is not sufficient to place objects in the slit. A small clear opening in the AFP could be used for TA in the case of such a failure. The size of such an aperture would need to be large enough that the spacecraft pointing accuracy places objects into this aperture with high probability. The TA would be similar to the one using the MSA but would use only a single reference object and therefore would not provide any estimate for the current roll angle. Therefore, the absolute roll angle accuracy of the telescope pointing has to be accurate enough to move an object to the fixed slit without roll angle adjustment. Assuming that the offset between placing the reference object into the clear aperture and placing the target into the fixed slit is 5 arcsec, the absolute roll angle accuracy needs to be better than 20 arcsec. Error budget for TA

The final placement of the science targets within the slits depends on both the accuracy of the TA procedure and the accuracy of the science and acquisition target coordinates. Errors in the TA lead to a shift of all slits relative to their intended targets. It, therefore, cannot be traded with the accuracy of the science target coordinates. The final achievable accuracy in relative coordinates of the science targets requires that errors in the TA itself are less than the 15mas goal set above. The assumption that the relative coordinates of science targets are accurate to about 1/10th of a NIRCam image pixel (i.e. 6mas), leads to a goal for the accuracy of the TA proper of $\sqrt{15^2 - 6^2}$ mas = 13.7 mas. The error budget shown in table 4.1 leads to an 1_ TA error of 12.5 mas, which leaves some small margin of safety. The accuracy of the TA critically depends on the number of acquisition targets used. In table 4.1, the total error budget is listed when using 1 and 10 acquisition targets. It can be seen that the TA requirements cannot be achieved when only a single acquisition target is used. It is necessary that the on-board TA software is able to extract and process at least on the order of 20 acquisition targets, because only a subset of the initially extracted stars will actually be used to compute the offsets.

Individual entries in the error budget are described below. The purpose of this budget is to suggest one way of allocating error allowances so that the TA goals can be achieved. The rationale for each estimate is given here and can serve as a guide to derive instrument and telescope requirements.

4.3.8 Errors in acquisition target input coordinates

We assume that astrometry for both acquisition targets and science targets will be extracted from images of the target field, either with NIRCam or by other means. Errors in the relative astrometry between acquisition and science targets will therefore include the random error in position measurement and also uncorrected distortions in the image. Based on experience with the ACS on HST, a 10 mas relative astrometry should be conservative for high enough signal-to-noise ratio NIRCam images, but reaching this accuracy from the ground will be challenging.

4.3.9 Accuracy of centering through MSA shutters

Object positions in high signal-to-noise ratio images can routinely be measured to an accuracy of 1/5th to 1/10th of the pixel size. However, NIRSpec target acquisition requires that positions be measured on images of the target field through open MSA shutters. The situation is illustrated in figure 4.1, which shows the MSA patterns projected onto the detector grid. Differences in scale will lead the MSA and detector grids to be aligned in some part of the image and to be out of phase in other parts. The position of acquisition targets will be measured from such images through open shutters. These position measurements will then in turn be used to compute necessary offsets. The achievable accuracy is limited by the relatively large projected pixel sizes of the detector and by the impact of the bars between shutters of the MSA on positional measurement. As discussed above, the position of the bars will not be predictable and therefore no attempt will be made to correct for them.

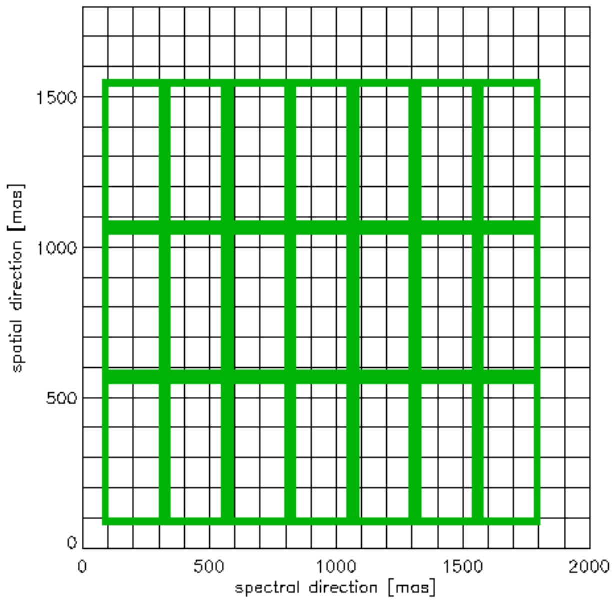

Figure 4-1 MSA shutter array projected onto the grid of detector pixels.

The accuracy of position measurements can be estimated by simulating imaging through open MSAs in Fourier approximation (Freudling 2002, ST-ECF ISR NGST 2002-04). The difference between the *center of gravity* of objects measured on the detector and measured on the sky can be used to estimate expected systematic and random errors for position measurement of a single point source. These experiments show that:

- Systematic position errors depend on the position of objects relative to the MSA grid. For objects close to the bars between shutters, they are on the order of 20mas when 200mas wide shutters are used. The total area covered by the gaps between shutters is about 25%. Therefore only about 25% of all reference targets will be heavily biased.
- Systematic errors are significantly smaller at longer wavelengths and for slightly extended objects. Therefore, unless ruled out by signal-to-noise ratio or other considerations, target acquisition will be carried out at the longest wavelengths.
- A 10% pixel-to-pixel flatfielding error adds about 5mas to the position measurement errors.

Both the systematic errors and the random errors for the position of a single acquisition target are as large as or larger than the total TA error budget. The TA requirement can therefore not be reached with a single acquisition target. Using more than one acquisition target will allow the identification of outliers in the measured coordinates by comparing the measured relative coordinates with their expected values. These outliers can then be removed with a sigma-clipping algorithm. This procedure becomes more important when the shutter size is large. Rejecting outliers will allow the reduction of errors to nearly the value that can be achieved by imaging without the MSA, i.e. a typical 1σ errors of about 15mas. Assuming that the accuracy of the final pointing offset computed from the positions of the acquisition targets scales with the number of acquisition targets, N, as $1/\sqrt{N}$, a minimum of about 10 acquisition targets (after outlier rejection) will be required. Some of the initially specified targets will be rejected by this sigma-clipping or because of other image defects such as hot pixels or cosmic ray residuals. Assuming that these two effects will affect 30% and 10% of all objects respectively, it will be necessary to specify a target set of about 16 sources for a successful TA.

Alternatively, if fewer than 10 bright enough acquisition targets are available, a small dither pattern of target acquisition images can be obtained. Typically, the pattern will consist of 16 points. The position of the acquisition target(s) will be determined for each image of the dither pattern, and an average position will be computed. The software to measure positions on the individual image can be identical to the one used when multiple acquisition targets. The same algorithm will run on the individual images sequentially and therefore does not require any additional storage space.

4.3.10 Computation of acquisition target coordinates on the MSA

Positions of the acquisition targets measured on the detector have to be compared to positions of the MSA slits. The computation requires knowledge of the coordinate transformation between MSA and detector. Two sources of error contribute to uncertainties in this transformation. One is the limited knowledge of the exact position of the mirror if it resides on the grating wheel. This uncertainty translates into an overall shift between the detector and the MSA. It will therefore affect all acquisition target positions by the same amount and cannot be compensated for by observing additional acquisition targets. It is therefore essential that the errors in the positioning are significantly smaller than the total error TA allowances; the value of 5mas is used in the error budget. A design of NIRSpec with a fixed mirror could reduce this error to effectively zero.

A second source of error is the calibration of distortions between detector and MSA. The impact will depend on the position of the acquisition targets on the detector. While observing additional acquisition targets can reduce the impact of residual distortion on the TA accuracy, these residuals also impact on the target coordinates itself. Residual distortion must therefore be small. The error budget used the 5mas accuracy goal from the calibration plan (Kuntschner et al., 2003). The error on the mean position of all reference stars was taken to scale as $1/\sqrt{N}$.

4.3.11 Computation of necessary slew and roll adjustment

The necessary slew and roll adjustment to be carried out by the telescope will be computed from the difference between slit and object positions on the detector. Our limited knowledge of distortions between MSA and a sky reference system limit the accuracy of this calculation. The error in this value again depends on accurate calibration and is taken from the calibration plan to be 7.1mas. This number results from the residuals of calibrating the distortions between sky and detector, and MSA and detector. Note that this accuracy has to be achieved at any time during the whole calibration cycle. The error on the mean position of all reference stars was assumed to scale as $1/\sqrt{N}$.

4.3.12 Slew errors

Finally, an error will be associated in carrying out the slew. Since the target acquisition exposure time will be short, it is assumed that changes in the positioning during the observations will be negligible. For the same reason as above, errors in carrying out the pointing offsets must be small and were assumed to be 5mas both for the shifts and rolls.

4.3.13 Stability

The accuracy of the pointing will deteriorate during long science exposures due to drifts in the pointing. They include offsets and roll angle drifts. Both of them enter the pointing error budget. Drifts in x and y should be small because they can only occur due to a change in the relative alignment of the FGS and NIRSpec. Given the expected stability of the ISIM structure this should be a very small term, assumed to be 2mas. Roll stability is a different issue. Once we perform TA with a specified roll any changes in spacecraft roll will be rotations about the star used for guiding in the FGS. If we assume a maximum distance of a guide star from the center of the NIRSpec field of view to be 600”, then the positional shift due to roll angle drift of Δr is 600 arcsec x sin(Δr). This lead to a maximum 5 mas shift for a roll angle uncertainty of 1.7 arcsec. This value is listed in the column for “single acquisition target”.

4.3.14 Impact of distortions on science targets

The impact of residual distortions between sky and MSA on the acquisition targets has been taken into account in section 4.4.4. In addition, the residuals will lead to errors in the assumed location of the science targets on the MSA. This error is more serious because it affects individual science targets and therefore does not decrease with the number of acquisition targets used.

Table 4.1.

Error Budget for Target Acquisition			
Budget	includes	1 σ error **single reference star**	1 σ error average of **all acquisition targets**
random errors of **reference star coordinates** relative to average target position	distortions in NIRCam or ground based image, measurement errors	10	3.2
measurement of positions of reference stars on detector	bias due to MSA, random error, flatfielding error	15	4.7
conversion of star position on **detector to** star position on **MSA**	bulk shift calibration (mirror)	5	5.0
	residual distortions MSA-detector after correction	5	1.6
computation of necessary **slew** from position of reference star on MSA	residual distortions after correction between MSA - sky, includes telescope + NIRCam optics including TA filter	7.1	2.2
errors in carrying out slew	error in initial position,	5	5.0
	stability during observation	2	2.0
	roll angle setting	5	2.5
	roll angle stability	5	2.5
impact of residual distortion on individual science targets	residual distortions between sky and MSA	7.1	7.1
total target acquisition error		**23.5**	**12.5**

(cyan) errors independent of number of reference stars

(yellow) numbers are the maximum and mean effect on any object within the field

4.4 Errors in science target coordinates

4.4.1 Impact on observations

Even if the TA shifts the MSA aperture mask exactly to its intended position, the errors in the coordinates of the science targets will lead to individual objects being scattered around their intended positions within the slits because of uncertainties in the coordinates of individual targets. These uncertainties are not strictly part of the error budget since they do not originate within the observatory. It will be up to the observer to design an appropriate dither strategy to compensate for these errors.

4.4.2 Generation of acquisition target list

The sensitivity of NIRSpec is such that, for most parts of the sky, it will be easy to find the required 16 acquisition targets. Under some circumstances, science targets themselves could be used as acquisition targets.

5 Calibration

5.1 General assumptions

The basic goal for NIRSpec is to determine for each observed target the intensity of radiation as a function of wavelength and position along the spatial direction of the slit. To accomplish this goal the raw data must be calibrated to convert it from counts per pixel to flux per wavelength. This section describes the overall calibration concept for NIRSpec. The overall goal of the calibration concept is to allow for an optimal extraction of the signal and to ensure that all NIRSpec observations can meet the calibration requirements on throughput, wavelength and spatial accuracy with minimal calibration-time investment. The SOC will provide the calibration reference files needed for the operation of the spectrograph and the data-reduction pipeline. In order to achieve the calibration accuracy, the observer may have to apply a specific observing strategy (e.g., dither pattern). Non-standard observing strategies will be treated on a “best effort” basis. However, it is the sole responsibility of the observer to determine the resulting calibration accuracy. The observations from which the default calibration reference files are produced separate into those that are science program specific and those that result from the regular monitoring of the general instrument characteristics. In-orbit monitoring calibrations serve mainly as verification of the instrument model derived from extensive pre-flight calibrations. The monitoring calibrations are carried out at regular time intervals that are determined by the stability of the instrument characteristic in question. The science program specific calibrations are carried out together with the science observations at regular time intervals that are determined by the stability of the instrument. The overall calibration philosophy is to minimize the science program specific observations. The NIRSpec calibrations will include the following areas: detector characteristics, optics, sensitivity, geometric and wavelength calibrations.

5.2 Calibration operations

There are five fundamental observing modes for NIRSpec which need to be considered in the calibration concept: (1) Slitless spectroscopy, (2) Spectroscopy with fixed slits, (3) Multi-object spectroscopy with the MSA, (4) Imaging spectroscopy with the IFU and (5) Imaging (mirror selected in place of dispersing element; only used for target acquisition).

The calibration process will provide the reference files necessary to perform target acquisition, to reduce and interpret science data, and to monitor the functioning of the instrument in each of these modes.

In order to allow for an efficient and simple calibration strategy, only a limited set of observing modes (see section “Observing Strategies”) will be supported. It is anticipated that individual science programs may not need to achieve this accuracy and observers may therefore want to optimize their observing strategy towards their individual goals. A second key ingredient of an efficient calibration strategy is the stability of NIRSpec. Science specific calibrations should only be needed to initialize the zero points in the data reduction pipeline for a given observation. The general monitoring calibration program will provide all other calibration information. This implicitly assumes that the overall instrument characteristics change only on timescales much longer than the duration of a single science program (e.g., distortion mapping from the sky to the MSA and through to the detectors). Should NIRSpec not reach such a high degree of stability then the science specific calibrations will have to include more instrument characteristics and need to be repeated at regular time intervals during observations. This will result in a decrease of instrument efficiency that may result in a violation of the Level 2 requirement of 70% prime exposure time on scientific targets.

The overall calibration strategy should be designed such that a failure of one detector or the MSA unit does not critically affect the calibration needed to operate the fixed slits or the IFU.

5.3 Scientific calibration requirements

In the following, we list the current assumptions on the calibration accuracies for the final data products that are derived from the scientific requirements (see e.g., Kuntschner et al. 2003). These requirements are defined for multi-object spectroscopy with the MSA. However, we currently assume the same requirements for all spectroscopic observing modes. Future versions of this document may define specific calibration requirements for each observing mode. For example, the spectrophotometric accuracy can be relaxed for the slitless mode. Where a requirement is given as a function of wavelength, the relevant sampling is assumed to be the size of one resolution element (FWHM) of the dispersive element. For spatial requirements, the sampling is assumed to be the pixel size at the detector level. All requirements are applicable to fully reduced and calibrated data, i.e. the end product of the data-reduction pipeline. We note that a fully reduced spectrum may be assembled from multiple (dithered) exposures.

- *Wavelength calibration accuracy*: The combination of systematic and relative errors in the wavelength calibration will be smaller than 1/7 (rms) of the resolution element (FWHM) for a given grating/prism, over the full wavelength range and at least 95% of the FOV.
- *Spectrophotometric calibration accuracy*: Assuming no Poisson noise in the signal, multiple observations of the same target with different MSA, fixed slit or IFU configurations will provide repeatability for the flux of better than 5% (rms) for at least 95% of the FOV. The relative flux uncertainty as a function of wavelength will be better than 5% (rms).
- *Spatial calibration accuracy*: The spatial coordinate along the slit or over the IFU FOV will be known and mappable with a low-order polynomial function to better than 20mas (rms) with respect to the coordinate frame defined by the acquisition. This accuracy will be met at all wavelengths, over at least 95% FOV.
- *Spectral PSF shape calibration accuracy*: The first moments of the line spread function (i.e. FWHM + asymmetry modeled by e.g., a Gauss-Hermite series) will be known and mappable with a low order polynomial over at least 95% of the FOV to better than 5% (rms) along the dispersion direction at all wavelengths.
- *Spatial PSF shape calibration accuracy*: The FWHM of the spatial PSF will be known and mappable with a low order polynomial over at least 95% of the FOV to better than 5% (rms) at all wavelengths.

The fixed slits and the IFU are assumed to be located in regions of the FOV where the knowledge of the parameters listed above is not degraded from the calibrations requirements.

The calibration requirements for the imaging mode can be derived from the Target Acquisition requirements (see Section 4).

- *Photometric calibration accuracy*: Assuming no Poisson noise in the signal, multiple observations of the same target at different locations will provide a repeatability of the overall flux better than 5% (rms) for at least 95% of the FOV (TBC).
- *Spatial calibration quality*: The astrometry will be known and mappable with a low order polynomial to better than 20 mas (rms) with respect to the coordinate frame

defined by the acquisition targets. This accuracy will be met for all filters and at least 95% of the FOV.

5.4 Calibration types

NIRSpec will be able to produce all required performance and calibration data using a combination of the following calibration types.

- Pointed calibrations: Dedicated observations of astronomical objects. For some observations, an accurate target acquisition may be needed.
- Sky calibrations: Observations of typical sky (i.e. background) regions. Normal telescope pointing will be sufficient.
- Lamp calibrations: Internal continuum and line lamp observations.
- Dark calibrations: Observations with the light path blocked.
- Auto and Opportunistic calibrations: The calibrations make use of the science data itself (auto) or are extracted from another set of suitable science observations (opportunistic). These calibrations do not require specific observations.

Pointed and sky calibrations require NIRSpec to be the primary instrument, while dark and lamp calibrations are suitable to be carried out in parallel mode. Lamp calibrations when NIRSpec is not prime could be a problem for the other instruments since there is not a level 2 requirement to prevent light from one instrument interfering with another.

5.5 On-board calibration lamps

NIRSpec will be equipped with internal line and continuum lamps. The purpose of these lamps is to provide convenient and efficient means to carry out routine calibrations such as the wavelength zero point, flat fielding and the exact determination of the grating wheel position. The light from the calibration lamps is inserted into the main NIRSpec beam at the filter wheel by a back illuminated diffuser that also serves to block off the external light path. In the following, we list the main calibration tasks for which the internal lamps will be used:

- Gain calibration of the detectors (cont. lamp)
- MSA to FPA registration for imaging, including the calibration of the imaging mirror position and the verification of the distortion model (cont. lamp)
- Throughput calibrations for the MSA shutters, the conventional slits (i.e. slit function) and the IFU (cont. lamp)
- Pixel-to-pixel flat-field calibration for the imaging mode (mainly detector pixel-to-pixel sensitivity, cont. lamp)
- MSA to FPA registration for spectroscopy, e.g., wavelength zero point, wavelength dispersion and wavelength trace calibration (line lamp, cont. lamp)
- Pixel-to-pixel flat-field calibration of the spectrographic stage of the spectrograph (mainly detector pixel-to-pixel sensitivity as function of wavelength, cont. lamp)

Safe and efficient operations:

The wavelength zero point and the dispersion solution derived from the internal line lamps will be directly applicable to the science data, although the light path cannot include the order blocking filters on the filter wheel. This may imply that copies of the long pass filters will have to be installed in the line calibration system. The same is true for the continuum lamps.

The brightness of the signal produced by the calibration system must be predictable. Preplanned power settings and exposure times must result in a data quality that satisfies the needs of the exposure.

It will be possible to use the calibration system with any allowed spectroscopic mode and produce a signal that satisfies the calibration requirements.

The system must not produce under-exposed data nor exceed saturation levels or cause a signal that affects subsequent exposures (i.e. image persistence).

Any combination of lamp, power level, optical mode, wavelength, and detector that can cause damage or spoil subsequent observations will be identified, documented and its use avoided.

The calibration subsystem will be designed in such a way that it can be used in parallel with other JWST science instruments. It will be possible to make internal calibration exposures while another SI is observing e.g., dark calibrations. This requires that stray light from does not escape NIRSpec and that any stray light originating outside NIRSpec is blocked.

The exposure time required to produce the signal needed for wavelength calibration purposes will be shorter than or equal to 60s.

The line lamps will produce > 10 unambiguously identifiable lines, pseudo-uniformly covering the full wavelength range of each dispersing element with a S/N > 30 (peak, per pixel) in each of the lines (line/continuum contrast > 80%). Emission line calibration lamps are preferred for calibration the wavelength scale. If absorption line sources are used, it must be demonstrated that the lamp(s) are appropriately filtered such that they can be used for all spectroscopic modes.

The continuum lamps will provide a S/N > 100 over the full wavelength range of each dispersing element in less than 1000s. Both types of calibration lamps will illuminate the entire FOV uniformly to within 25%. Illumination variations on scales of 5 arcsec will be <1% to allow for illumination calibrations. The stability of the line lamps will be such that an external re-calibration will not be needed more often than once per month (goal once per year). The required signal for both lamps will be achieved within the exposure times listed above over the nominal five year JWST lifetime.

5.6 Science program specific calibrations

The science program specific calibration will consist of the following types:

1) Determination of exact mirror position for TA
2) "Through slit" images of the science target(s) after a successful TA
3) Wavelength zero point calibration

During standard operations, the science specific calibrations will be obtained during/after each target acquisition. The resulting files will then be used to facilitate the on-board TA sequence and initialize the data-reduction pipeline for the set of data obtained for this target set. If the instrument and the telescope show a high degree of stability during a visit, then no further science specific calibrations need to be obtained. Since a given visit may include a complex combination of telescope and instrument operations (e.g., small dither steps, MSA re-configurations, grating and filter wheel moves) it may be necessary to re-obtain a "through slit" image and/or wavelength zero point calibrations. The frequency of these calibrations should be minimized by the design of the spectrograph.

In order to calculate the exact position of the imaging mirror (<5mas rms at the FPA), the aperture focal plane will carry special apertures which allow the determination of the offset in the x and y direction on the detectors. This can be achieved with e.g., "L" shaped slits slightly tilted with respect to the detector columns and rows to allow sub-pixel offset accuracies. It is assumed that the fixed slits in combination with extra vertical slits (i.e. perpendicular to the dispersion direction) can be used for this mirror-offset calibration. Each detector should have its own calibration slit. The flight software will provide the means of measuring the mirror offset and injecting the result into the target acquisition procedure. Note that the purpose of the mirror position calibration is to achieve sub-pixel (i.e. <0.05 pixel) accuracy while the intrinsic repeatability of the grating wheel is assumed to be better than one detector pixel (rms).

In the following, we provide an outline of science specific calibration steps at the beginning of a visit. It is assumed that the telescope has already reached the target field with a precission of ~1arcsec (rms).
The TA sequence is carried out (see section 4). After a successful TA sequence the following calibration steps need to be carried out (it is assumed that the imaging mirror is still selected in the optical path and has not been moved since its position calibration):

"Through slit" image:

A. Set-up MSA to science configuration for target set (fully open in slitless mode)
B. Select appropriate order blocking filter in filter wheel
C. Take short (exposure time user selectable, TBC) exposure and prepare for downlink of data

Wavelength zero point calibration:

A. Select closed/calibration position in filter wheel
B. Select appropriate dispersing element in grating wheel
C. Select and switch on the matching line lamp for this dispersing element
D. Take short exposure
E. Switch off line lamp
F. Select appropriate order blocking filter

After this sequence the science specific calibrations are determined and science observations proper can start. The "through slit" and wavelength zero point calibrations can be carried out independently from each other. If the "through slit" image is not taken right after a target acquisition then an additional grating wheel move (mirror position) needs to be inserted.

In order to avoid image persistence on the detectors, the calibration operations have to be performed such that no bright source can be "seen" by the detectors. This may result in an extra filter wheel move to block the light path with the diffuser during MSA re-configuration. Furthermore, MSA configurations used for external calibration tasks must ensure that no unwanted bright source can be seen by the detector.

5.7 General monitoring calibrations

The monitoring calibrations of the instrument need to be scheduled at regular time intervals so that they can be used for all regular science programs regardless of the time when they are carried out and the duration of the program.

Although NIRSpec offers only a limited number of observing modes, the monitoring calibrations need to be performed, in principle, for a prohibitively large set of MSA configurations (e.g., 1024 x 512 shutters). Therefore, the key to a realistic and efficient calibration strategy is a highly stable and well behaved spectrograph where parameters such as geometric distortions, sensitivity and wavelength solution change only smoothly across the FOV and thus a rather coarse sampling of the parameter space (e.g., 16 independent spatial points over the full FOV) is sufficient to calibrate the full system in accordance with the default calibration requirements.

Since JWST will carry an "active" mirror design which will need regular (monthly, TBC) re-phasing we expect the need for frequent re-focusing of NIRSpec. The impact of the mirror re-phasing on this calibration concept can be very severe if, for example, the distortion model has to be re-determined. Details of the effects of mirror re-phaseing will be incorporated into the calibration concept as soon as they become available.

The target acquisition procedure in particular demands an accurate knowledge of the distortions in the spectrograph. The optical distortions from the MSA to the FPA need to be known and mappable over the full FOV to an accuracy better than 5mas (rms). The distortions from the FPA to the sky need be known and mappable over the full FOV to an accuracy better than 5 mas (rms). Bulk shifts introduced by the incorrect knowledge of the placement of the mirror in the grating wheel need to be smaller than 5 mas (rms).

Furthermore, the small scale flat-field (FF) calibration strategy relies on an extensive *pre*-flight calibration of the detectors. A determination of the full pixel-to-pixel FF as a function of wavelength is extremely time consuming on orbit (required flat field accuracy of order of 1-2% rms, Kuntschner et al. 2003).

In terms of JWST operations, it is important to separate the monitoring calibrations into the those that are capable of being carried out in parallel with other JWST instruments and those where NIRSpec is required to be the primary instrument. The loss in science time without parallel capabilities is estimated to be at least 3% of total NIRSpec time. If more frequent dark calibrations are necessary then this value will increase significantly. The following tables list the calibration tasks that will need to be carried out by the overall calibration monitoring program. The tables give basic information about the calibration tasks, their frequency and the approximate time consumption as fraction of NIRSpec science time. Calibrations that can be derived from the science data themselves are not listed here. For a more detailed discussion of the calibration concept see Kuntschner et al 2003.

5.7.1 Parallel capable calibrations

Measurement	Type	Frequency per year	Time consumption
Dark current	Dark	2	3.04 %
RN determination	Dark	2	0,00 %
RN verification	Dark	52	0.25%
Hot pixels	Dark	120	0.00%
Shutter throughput	Continuum lamp	12	0.07%
Conventional slit throughput	Continuum lamp	2	0.00%
Small scale flat field	Continuum lamp	12	0.34%
Geometric distortions	Continuum lamp	1	0.00%
Spectral trace	Continuum lamp	1	0.03%
Dispersion solution	Continuum lamp	1	0.15%
Gain	Continuum lamp	2	0.02%

5.7.2 Calibrations which require NIRSpec as primary instrument

Measurement	Type	Frequency per year	Time consumption
Linearity	Pointed	1	0.10%

Image persistence	Pointed	12	2.28%
PSF	Pointed	1	0.34%
Image anomalies	Pointed	1	0.90%
Photometric response	Pointed	1	1.02%
Geometric distortions	Pointed	1	1.43%
Line spread function	Pointed	1	0.27%
Line lamps	Pointed	1	0.08%
Shutter contrast	Pointed	1	0.01%
Large scale Flat Field	Sky	12	1.61%

5.8 Scheduling of calibrations

The regular science specific calibrations will be automatically attached to the science programs without the need of user interaction. The user will be able to schedule additional science specific calibrations provided the TAC grants the necessary time. The monitoring calibrations will be scheduled by the SOC on regular time intervals determined by the stability of the instrument characteristic in question.

6 Usage estimates

In the following section we look at several scenarios for the usage of NIRSpec. These scenarios are needed to determine the thermal load induced by NIRSpec in the ISIM and to determine the expected number of on-orbit cycles of the mechanisms.

6.1 Thermal worst case

The worst-case thermal load from mechanism heat is for a spectroscopic survey of bright sources. In this case there is not a lot of integration time between mechanism moves for the heat load to average out. For this worst case analysis we are assuming that only the average load over 24 hours is important and that any heat loads on shorter timescales are damped by the thermal mass of the NIRSpec bench and optics.

For this spectroscopic survey we assume that the user wants to have a total integration time of 30 minutes on-source. This will be at a single grating wheel position. We also assume that the user will want to configure the MSA three times to get both good sampling of their spectra and to average over the gaps between the two detectors. In Table 6.1 we detail the tasks that have to be performed at the start of an observation.

Table 6.1 – Start of visits tasks

Task	Time Required[1]	Filter wheel moves	Grating Wheel moves	MSA reconfiguration	Calibration Lamp
Slew/settle on new target	20 min (assumed)	0	0	0	0
Acquire guide star	GSAcqTime[2]	0	0	0	0
Take acquisition image	36 sec + FWTime[3]+ GWTime[4] + MSATime[5]	1	1	1	1
Calculate offset	10 sec	0	0	0	0
Move to correct location	DitherTime[6]	0	0	0	0

After the observation has been setup each visit in the survey would have the tasks shown in Table 6.2.

[1] We assume that all mechanism moves are done serially.
[2] This is the time to get into fine lock on the guide star.
[3] This is the time to move the filter wheel.
[4] This is the time to move the grating wheel.
[5] This is the time to reconfigure the micro-shutter array.
[6] This is the time to perform a small angle maneuver maintaining fine lock on the guide star.

Table 6.2 - Tasks in a Visit for Bright Spectroscopic Survey

Task	Time Required[7]	Filter wheel moves	Grating Wheel moves	MSA reconfiguration	Calibration Lamp
Configure for 1st observation	FWTime + GWTime + MSA_time	1	1	1	1
Observe	10 min	0	0	0	0
Dither in spectral dimension (10 arcseconds)	DitherTime	0	0	0	0
Configure MSA	MSATime	0	0	1	0
Observe	10 min	0	0	0	0
Dither in spectral dimension	DitherTime	0	0	0	0
Configure MSA	MSATime	0	0	1	0
Observe	10 min	0	0	0	0

We then assume that the survey is of regions of the sky that are reasonably close by. Therefore, the slew and settle time will be small for all subsequent visits. Because a new guide star will have to be acquired for each visit, there will still be the overhead of the guide star acquisition. In Table 6.3 we show the tasks and their times in subsequent visits. Note that all of the times are the same as in Table 6.1 except the slew and settle time.

Table 6.3 - Tasks for visit setup after the first visit in a survey.

Task	Time Required	Filter wheel moves	Grating Wheel moves	MSA reconfiguration	Calibration Lamp
Slew/settle on new target	MinSlewTime	0	0	0	0
Acquire guide star	GSAcqTime	0	0	0	0
Take acquisition image	12 sec (minimum exp time)+ FWTime+ GWTime+ MSATime	1	1	1	1

[7] We assume that all mechanism moves are done serially.

Calculate offset	10 sec (assumed)	0	0	0	0
Move to correct location	DitherTime	0	0	0	

Now the worst-case thermal load for a day occurs when we spend the entire day doing the subsequent visits for a large survey. In this case we will have one subsequent visit start for each visit. The total time for this would be

Time = 30min + 2xFWTime + 2xGWTime + 4xMSATime + 3xDitherTime + GSAcqTime + 22sec

Now when we make the assumptions show in Table 6.4, we get a total time for one visit of 45.6 minutes (0.032 days). Therefore, if we divide the number of actuations of a mechanism in one visit by 0.032 we come up with the peak load in a day. *This yields 63 moves of the filter and grating wheels and 126 configurations of the micro-shutter array for the worst-case day.*

Table 6.4 - Assumptions for worst-case thermal load

Parameter	Value
DitherTime	60 seconds
FWTime	30 seconds
GWTime	30 seconds
MSATime	30 seconds (worst case for this situation)
GSAcqTime	2 min

6.2 Mission lifetime usages

For the 5-year design lifetime of NIRSpec, we will assume that NIRSpec is the primary instrument 1/2 of the time. When will also assume that the observatory meets its requirement of doing science observing 70% of the time. This means that we will be actively observing with NIRSpec 35% of a year or 1.1 x 10^7 seconds per year. We will also make a conservative estimate of the breakdown between types of science observations. To be conservative we are using the highest possible fraction of short observations that we think will be scheduled. This is conservative because short observations have the largest impact on the lifetime usage of the mechanisms. The three basic types of NIRSpec observations are detailed in Table 6.5.

Table 6.5 - Observation types

Type of Observation	Fraction of NIRSpec Time	Total Time for one visit	Number of Observations in a year
Science short	0.10	3K	370
Science medium	0.60	20K	330
Science long	0.30	100K	33

For each type of science visit we assume the following type of observations. For the short observations we make the worst-case assumption that the observer will want to obtain a full spectrum from 1 to 5 microns. Since this will require three grating settings and a mirror move for acquisition, there will be a total of four grating wheel moves. We also assume that the observer will want no gap in their spectra caused by the gap in the detectors so there will be three MSA configurations for each grating setting. Because we can use the same MSA configuration after a grating wheel move this will require only a total of seven MSA configurations. When we add one for target acquisition we get a total of eight MSA configurations. The filter wheel will have to change four additional times to match the two extra grating settings. Each new grating requires one move to move to closed/calibration to take a wavecal exposure and another move to the blocking filter. Adding in the five-filter wheel moves for standard target acquisition yields a total of nine filter wheel moves. The calibration lamp will have to be turned on an additional two times for the two additional grating wheel selections. Adding in the two cycles of the lamp for target acquisition yields four lamp cycles per visit.

For the medium science visit we assume that the observer only wants two grating settings and wants no gaps in the spectra due to detector gaps. This yields two less filter wheel moves, one less grating wheel move, two less MSA configurations, and one less lamp cycle than the short science visit.

Finally, for the long science visit we assume that only one grating setting is used which yields two less filter wheel moves, one less grating wheel move, two less MSA configurations, and one less lamp cycle than the medium science visit. The totals for each type of visit are shown in Table 6.6

Table 6.6 – Mechanism moves for each visit

Type of Observation	Number of filter wheel moves	Number of grating wheel moves	Number of MSA configurations	Number of calibration lamp cycles
Science short	9	4	8	4
Science medium	7	3	6	3
Science long	5	2	4	2

To determine an estimate of the usage of each mechanism we now just have to multiply the number of years times the number of visits per year times the number of mechanism moves per visit for each type of science program. In Table 6.7 we total the sums for all four mechanisms on NIRSpec for a five-year mission.

Table 6.7 – Estimate of on-orbit (5 year) lifetime usage of mechanisms

Type of Observation	Number of filter wheel moves	Number of grating wheel moves	Number of MSA configurations	Number of calibration lamp cycles
Science short	5*370*9	5*370*4	5*370*8	5*370*4
Science medium	5*330*7	5*330*3	5*330*6	5*330*3
Science long	5*33*5	5*33*2	5*33*4	5*33*2
Total cycles	29K	13K	25K	13K

7 Data Flow

7.1 Data Flow Concept

This concept assumes that the observer will interact with an Observation Design Tool (ODT) that will transform science requirements into formalized descriptions of target sets, the content of spacecraft visits - as lists of activities - and the organization of the resulting data stream into associations. The preparation of this plan will require prior scheduling information in order to select a roll angle (or a small range thereof) for the optimum MSA configuration (mask) design for the scientific target sets.

The visit specifications form the input data for the generation of the command uploads. Once the commands are resident in the spacecraft, they will trigger a sequence of operations that will result in the acquisition of data. Some of these data are used autonomously (e.g., for target acquisition) and some are packaged directly for downlink. The combination of the visit specifications and their associated target sets, the downlinked data and their descriptors constitute a complete package for ingest into the JWST NIRSpec archive. The process is completed by a pipeline reduction/calibration that produces final output products for the observer.

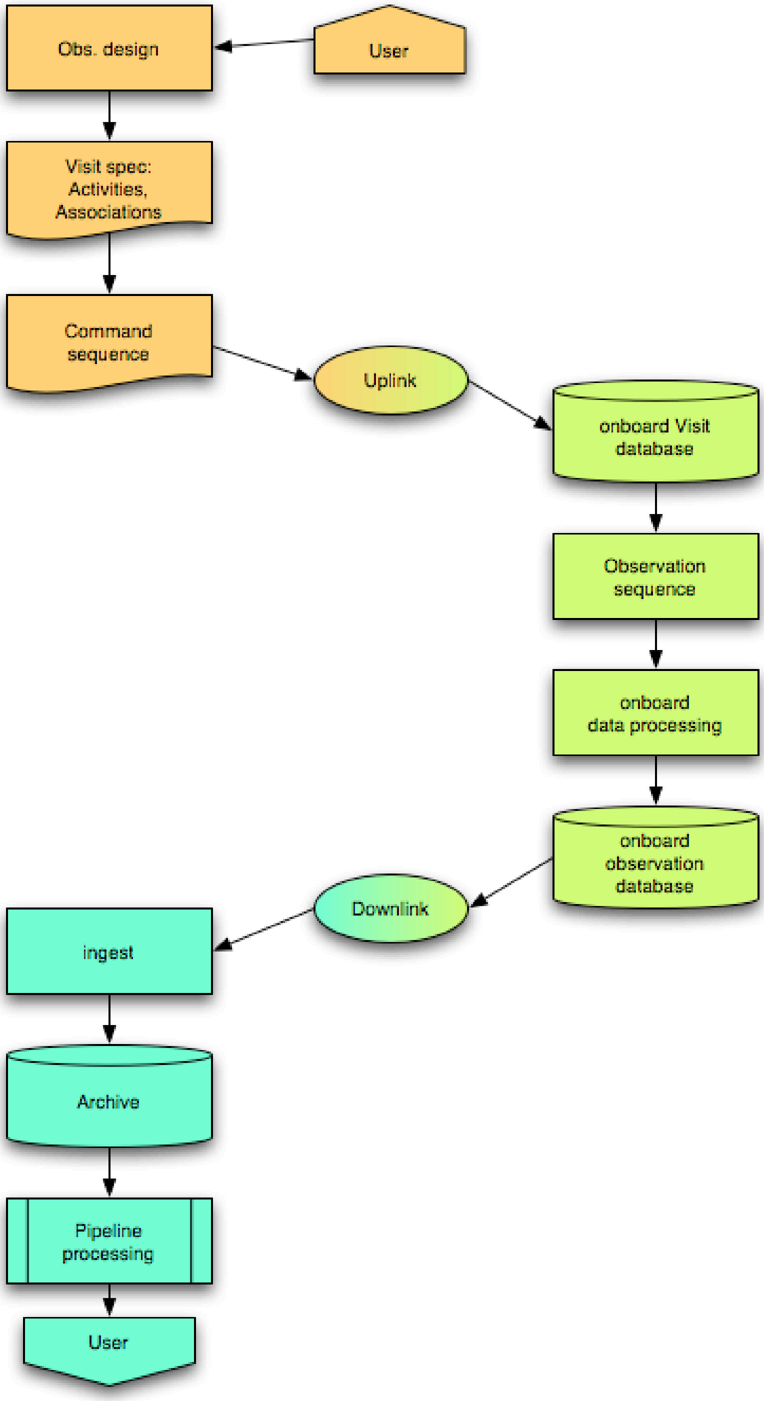

Figure 7-1 A schematic view of the NIRSpec Data Flow from observation design to pipeline processing.

7.2 Flow elements

These sections describe the nature of the process in the form of input/output and functional descriptions for each component.

7.2.1 Observation Design Tool (ODT)

Input: approved Phase I scientific proposal and allocated observing time (including, for NIRSpec, an approximate calendar)

Output: Visit specifications and associated target set masks

Function: The observer will use lists of required targets to design optimum sets of input aperture patterns (MSA configurations or fixed slit positions) for acquisition and scientific target sets. These mask designs will be restricted by a pre-allocated calendar that defines spacecraft roll angle ranges. The observer will choose a target acquisition (TA) strategy and a dither pattern for each target set based on requirements for spectrophotometric accuracy etc. The ODT will have access to the NIRSpec calibration database to enable properly calibrated observation design (e.g. the optical distortion of the OTE + NIRSpec foreoptics).

7.2.2 Visit specification (VS)

The VS captures the results of the ODT in the form of MSA configurations, dither patterns, exposure times and TA strategy. In the particular case of NIRSpec, the VS will demand to be carried out by the observatory within a specified time slot in order to match the roll angle requirement of the mask.

There will be standard specifications to provide various calibration functions. Some of these will be implemented as part of the observatory-wide calibration plan; others will be included at the request of the observer.

The size of the VS is dominated by the description of the MSA configuration. This is an approximately 1000 x 500 one-bit array representing open or closed shutters. For typical MSA configurations, this can be represented by a compressed (lossless) file.

7.2.3 Command uplink and store

Input: Science and calibration specifications from all instruments; spacecraft calendar and constraints

Output: Command stream stored in onboard database

Function: The NIRSpec VS are processed, along with similar structures from the other instruments, into a commanding stream that is uplinked to the spacecraft and stored.

7.2.4 Observation

Input: contents of onboard visit database; spacecraft and instrument status

Output: FPA readouts, instrument status, telescope status and pointing

Function: NIRSpec will require autonomous TA. Any TA images acquired must join the downlinked data stream.

The NIRSpec data format is 2 x 2k x 2k pixels = 8Mpixels = 16MB @ 16 bits depth.

The entire array is used in all MSA-based science modes.

TA modes and some observation modes (i.e., fixed-slit) may employ FPA windowing.

Detector is read continuously => each pixel read every 12s

N:1 averaging on-board as required (N=4-6)

For N=4, this produces 2.7Mbit/s for downlink

As an upper limit, this results in 29GB of NIRSpec data per day of continuous observation.

7.2.5 Onboard processing

Input: FPA readouts

Output: Position and roll offset data for TA, N:1 averaged FPA readouts for downlink

Function: Support of autonomous functions; reduction in data volume

7.2.6 Data downlink and store

Data downlinked after every N:1 averaging

7.2.7 Archive ingest

Input: Spacecraft telemetry; VS and target set library

Output: Populated science and engineering archive

Function: Data identification, sorting and formatting; recognition and grouping of data into associations defined by ODT

7.2.8 Pipeline processing

Input: Science data from archive grouped into associations; calibration database

Output: Calibrated data products

Function: Provide data in a form for immediate scientific use. Ensure that all relevant associated data are attached: original VS and target sets, spacecraft and instrument parameters.

8 List of Acronyms

Acronym	Description
AFP	Aperture Focal Plane
CR	Cosmic Ray (event on detector)
DRM	Design Reference Mission
FF	Flat Field
FGS	Fine Guidance Sensor
FOV	Field of View
FPA	Focal Plane Array
GOG	Center of Gravity
IFU	Integral Field Unit
JWST	James Webb Space Telescope
MSA	Micro-Shutter Array
NIRCam	Near-Infrared Camera
NIRSpec	Near-Infrared Spectrograph
ODT	Observation Design Tool
OTE	Optical Telescope Element
PA	Position Angle (of FOV on sky)
POM	Pick-off Mirror
SI	Science Instrument
SOC	Science Operations Center
TA	Target Acquisition
TAC	Time Allocation Committee
TMA	Three-Mirror Anastigmat
VS	Visit Specification