

## NIRSpec Pipeline Concept: A High Level Description

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### **Abstract.**

NIRSpec is a multi-object spectrograph (up to  $\sim 100$  objects) with a large field of view ( $\sim 10'$  square) and a detector response covering nearly a factor of 10 in wavelength ( $0.6 - 5 \mu\text{m}$ ). It will be employed on a segmented off-axis telescope in deep space. The combination of these factors results in a number of unique challenges for the calibration of the NIRSpec instrument. In this paper we outline some of these challenges and present a high-level concept of the NIRSpec pipeline data reduction sequence.

### **1. Why is NIRSpec so special?**

In general, the goal of the spectrophotometric calibration of any astronomical instrument is to convert — for every field point, wavelength, and “observing mode” (i.e. combination of filter, grating and band) — the number of electronic counts registered in the detector electronics (measured in digital numbers or DN) to the signal received from the astronomical source (measured in  $\text{erg/s/cm}^2/\text{\AA}$  or similar units). In the case of a multi-object spectrograph (MOS) in general, and NIRSpec on board JWST in particular, there are a number of effects that make this calibration particularly challenging:

1. At variance with a traditional long slit spectrograph, every detector pixel in a MOS must be calibrated for its response over the entire spectral range, because spectra from a large number of celestial objects can illuminate the same detector pixel, albeit at different wavelengths. For a MOS, therefore, the “flat field” response map is a three-dimensional data cube that “stacks” the two-dimensional, ( $2\text{K} \times 4\text{K}$ ) pixel response maps along the wavelength dimension. In principle, the wavelength axis must be sampled at the spectral resolution of the instrument (up to 2700 in the case of NIRSpec). Possible simplifications of this approach, which would otherwise result in rather large and impractical calibration reference files, must be sought.
2. The two-dimensional NIRSpec field of view (FOV), combined with the use of reflection gratings and the NIRSpec design (see Figure 1), causes light to hit the dispersive elements at rather large (and varying) incidence angles. This leads to a significant curvature of the projected slit apertures on the NIRSpec detectors: while each individual shutter aperture is essentially tilted with respect to the dispersion axis, the tilt angle varies significantly across the FOV. This complicates calibration and data reduction because each shutter spectrum must be rectified differently.
3. Unlike for ground-based MOS, for NIRSpec the telescope PSF is a strong function of wavelength: the FWHM varies nearly by a factor of 10 between the blue and red ends of the NIRSpec spectral range. On the other hand, NIRSpec uses only a single imaging scale for its entire wavelength range, and the Micro-Shutter Array (MSA) offers only a single physical slit width. Although the shutter width (200 mas) has been carefully selected to optimize throughput and resolution across the entire

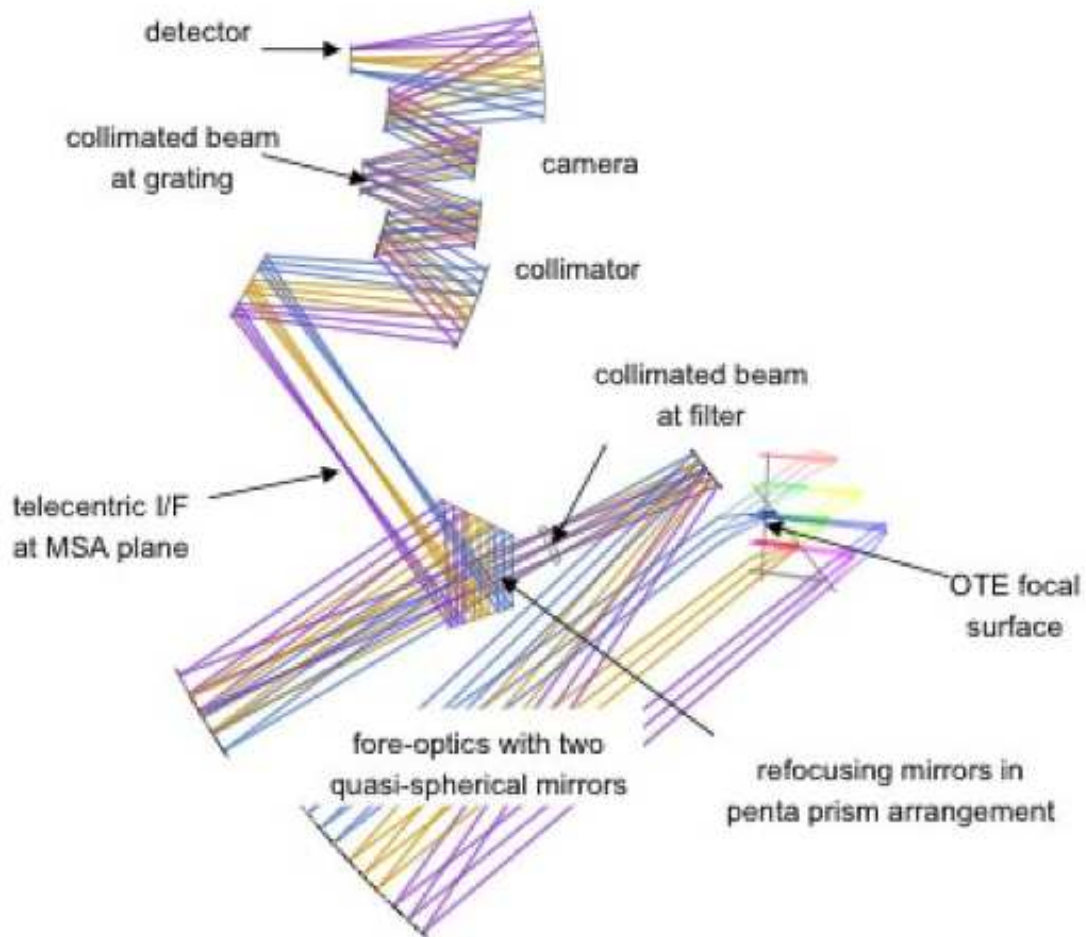


Figure 1: NIRSpec optical layout.

spectral range, the fraction of light that passes through an MSA shutter (or fixed slit) is nevertheless a strong function of wavelength. In principle, the slit throughput can be accurately modeled, but this approach requires exact knowledge of the source shape and position within the shutter. Given the faintness of targets and the limited accuracy of the target acquisition process, such a priori knowledge is not generally available. Note that the slit loss variations with wavelength are most pronounced for a point source, while in the case of a source that uniformly illuminates the entire shutter or slit, a very small correction for chromatic slit loss is needed. Another effect that has consequences similar to those of chromatic slit loss are diffraction losses due to the finite size of the NIRSpec optics behind the MSA, in particular the gratings. The diffraction pattern depends on wavelength, source shape and position within the slit, and thus the amount of light that is diffracted outside the NIRSpec optical train is difficult to predict. Because both these effects — the geometric light loss due to “cutting off” the PSF at the shutter/slit, and the diffraction losses in the optical train behind the MSA — have similar consequences, we refer to them here collectively as “chromatic slit loss”.

4. Because of the large field of view, use of a purely reflective optical train, and deployment behind a fast, off-axis telescope, optical distortion is significant in NIRSpec. The resulting plate-scale variations across the aperture provide additional challenges for the spectrophotometric calibration because one must account for the varying solid angle seen by both detector pixels and MSA shutters.

The complexity of the effects discussed above, combined with the limited testing facilities on ground and stringent efficiency requirements in orbit, leads to an approach for NIRSpec calibration which relies heavily on optical modeling of the instrument. Wherever possible, we will attempt to construct parametric descriptions of the instrument features that will be tested, verified, and optimized at every stage from sub-system to instrument level to in flight operations. The requirements for the instrument performance simulator are thus intimately connected to the design of the NIRSpec pipeline.

Here we provide a brief, high level summary of the steps involved in processing NIRSpec spectra. In particular, we address the operations that must be carried out on raw data to render them in a form suitable for scientific analysis.

## 2. Pipeline goals

The main product of the NIRSpec pipeline is a rectified, finely sampled “window” for each open MSA shutter. This window is a two-dimensional array, sized to capture all the (dispersed) light entering the collimator/camera optics through the shutter under consideration for the specific observing mode. Once processed by the pipeline, all rows in the final extraction window have the same, uniform wavelength scale, i.e. all columns correspond to the same wavelength and the spectral sampling is constant along rows and the same for all extraction windows belonging to a common observing mode. The value of each element (pixel) in the window is the astrophysical flux, calibrated in absolute terms. It should be noted that there is no one-to-one correspondence between array elements in the final extraction window and detector pixels.

One extraction window is produced for each open shutter, regardless whether it contains objects or background, but each window is marked accordingly on the basis of the information provided by the observer. The correct procedure to subtract background light depends on the size and shape of the source, as well as on the structure and spectrum of its surroundings. Therefore, background subtraction from the extracted spectra is left to the observer, who will select the background windows most suitable to his needs. However, for quick-look purposes, the pipeline computes an average background by combining all available background windows, or only those specifically associated by the observer to one target, and subtracts it from the extracted object spectrum. The window is then collapsed in the spatial direction and a one-dimensional spectrum is produced, which is further corrected to compensate for the chromatic slit loss (using the correction computed for a point source). Since, however, the latter correction depends crucially on the geometry of the target and on its exact position within the slit, the produced one-dimensional spectrum should only be used for a first assessment of the overall quality of the data (quick-look). Scientific analysis should be carried out on the full two-dimensional final extraction window.

## 3. The NIRSpec pipeline

The pipeline is a series of operations that need to be carried out on detector raw data to remove instrumental signatures and to convert counts to absolute flux units. For NIRSpec, and MOS instruments in general, it is convenient to split these operations in two groups: 1) those that depend solely on pixel coordinates on the detector; 2) those that depend on

pixel coordinates, wavelength of the incident light and location of the (undispersed) source in the field of view.

The first group includes dark current, linearity and bias level corrections, all of which are independent of the disperser and filter used, as well as pixel-to-pixel variations in the response of the detector (hereafter “P-flat”), for which the wavelength dependence is expected to be negligible within each passband, as suggested by preliminary analyses. Operations belonging to this group can be applied to the raw data frame as a whole and are not discussed further here because they are all similar to those routinely carried out for the instruments on board the HST.

The second group includes corrections for sensitivity variations (on both global and local scale), geometric distortion (affecting the flux, spatial scale and wavelength of each pixel) and absolute flux calibration. Operations of this type are more logically executed at the level of the extraction window because they depend on which specific MSA shutter is used. These steps are conceptually not different from those normally carried out with traditional ground-based single and multi-object spectrographs, and include: removing large scale variations in the uniformity of the detector’s response, both as a function of position and wavelength (usually referred to as L-flat); tracing the spectrum in the aperture and rectifying the wavelength scale and the spatial axis (spectral extraction); assigning a wavelength to each pixel in the extracted spectrum (wavelength calibration); correcting the measured count rate to account for field and wavelength variations in the throughput of the optics and dispersing elements, such as the grating blaze function (flux calibration); registering the measured count rates with those of a reference spectrophotometric standard (absolute calibration).

In reality, however, the complexity of NIRSpec (see Introduction) and the constraints imposed by having the MSA in the optical train have serious repercussions on the pipeline flow and on the calibration of the instrument, both on the ground and in orbit. In particular, some of the steps in the second group indicated above must be carried out simultaneously, since they require calibration measurements that are intertwined and cannot be otherwise obtained separately.

An example of two calibration steps that must be executed together is the correction for large scale flat field uniformity and throughput variations. The former is the so called L-flat, i.e. the measure of the low-frequency variations in the response of the detector, whereas the term ‘throughput’ here refers to the transmission of all the reflective and dispersive elements along the optical path. Both depend on field angle (or pixel position) and wavelength, and both are characterized during ground calibration of the individual components and at the integration level. This calibration information could in principle be used to determine the total sensitivity as a function of wavelength and field angle for any observing mode. However, while the wavelength dependence can be accurately described by a model, validated by ground calibration measurements, the dependence of the throughput on field angle is much more difficult to predict analytically and will have to be determined empirically. Furthermore, such a determination requires a proper knowledge of the L-flat, which may not be attainable with the required level of accuracy during ground calibration (because, after integration, the detectors cannot be uniformly illuminated due to the presence of the MSA in the optical path).

It is, therefore, advisable to determine simultaneously the combined effect of throughput and detector response on the overall sensitivity variations of the instrument, as a function of wavelength and field position, since they collectively affect the response of each pixel as a function of wavelength. To this purpose, NIRSpec is equipped with an internal continuum calibration lamp, of known spectrum, that uniformly illuminates the MSA. The lamp can be used to simultaneously measure on the detector, during thermal vacuum and in flight, the combined response (i.e. DQE + throughput) as a function of wavelength and position. Time constraints do not permit such measurements to be obtained for each individual shutter, but a suitable subsample may be sufficient. The result would be a series of

extraction windows uniformly spread across the detector, each containing the same known spectrum, which completely cover the detector at least for some wavelengths.

With measurements of this type, it is possible to derive the low-frequency detector response variation, both spatial and spectral, folded with the low frequency spectral and field variation of the throughput. It is useful to visualize this calibration file in the form of a three-dimensional array, with X and Y along the detector's coordinates and Z scaling with wavelength. Since it is expected that any variations in the overall instrument response, with position or wavelength, are very slow and thus suitable to be interpolated via a low-order polynomial, it is only necessary for the pipeline to know the form and parameters of this function in order to apply the correction. The advantage of the approach mentioned above, over the separate measurement of the detector L-flat and individual throughput of the components, is that it can be easily repeated in flight, for a subset of the exposures, to verify the temporal stability of the sensitivity.

#### 4. Conclusions

Although space limitations do not allow us to address in detail the many individual tasks of the NIRSpec pipeline, we offer in Figure 2 a schematic conceptual outline of the steps needed to deal with the MSA data. It is obvious from the complexity of the tasks at stake that, in order to efficiently carry out the calibration of the NIRSpec data, an innovative approach will be needed that departs in more ways than one from that routinely used for HST data. In particular, the pipeline will have to rely more heavily on optical modeling of the instrument and the reference files will, in most cases, be replaced by tables of coefficients that represent the best fitting parameters of those models. Furthermore, the multiplicity of observing modes makes it almost impossible to test and derive reference files for each and every observational setup during the ground campaign. Therefore, developing and validating an end-to-end simulator of the scientific performances of NIRSpec becomes a pressing need in order to pave the road to the smooth and manageable commissioning and calibration of the instrument.

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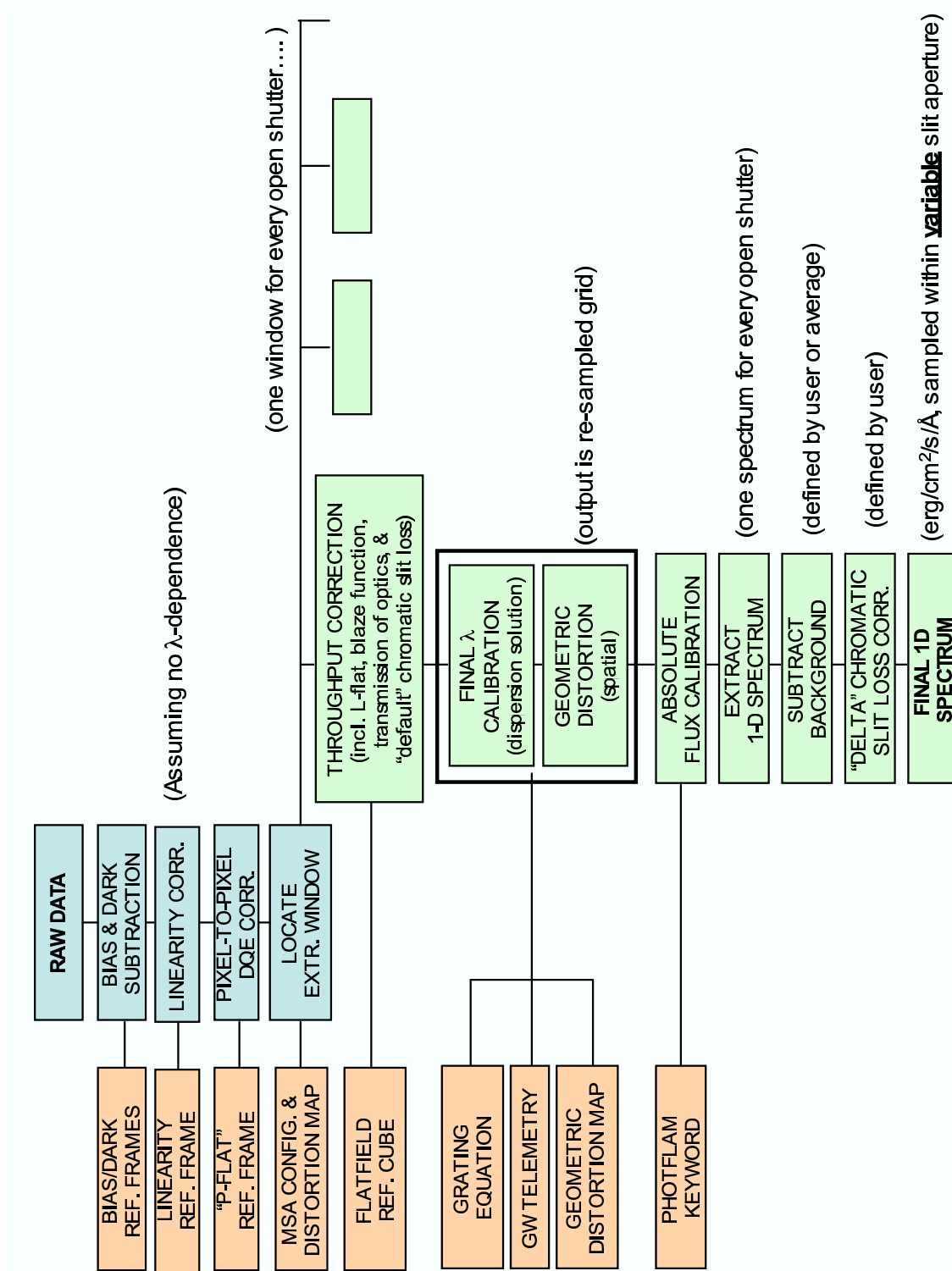


Figure 2: Schematic conceptual outline of the NIRSpec pipeline.