NIRCam WFSS Deep Galaxy Observations

The article outlines an example science use case for Wide Field Slitless Spectroscopy observations with JWST NIRCam, including descriptions on how to apply the ETC and APT tools.

Science motivation

The science case we describe here is loosely based on The Exploring the End of Cosmic Reionization survey, which is a GTO program designed to explore the evolution of the intergalactic medium and of the circumgalactic environment at the tail end of reionization. It aims to:

- Measure the correlation between HI Lyman alpha opacity and galaxy overdensity.
- Identify the host systems of metal absorption systems at z>5 in the quasar spectra to investigate the chemical enrichment and the ionization state of the gas in and around young galaxies.
- Characterize the nature of the quasar host galaxies and the surrounding large scale environment, and to measure their central black hole masses.

This science case is based on this program and outlines the process of selecting a grism and filter combination to achieve these science goals, general mosaic design, and use of the JWST Exposure Time Calculator (ETC) and JWST Astronomers Proposal Tool (APT).

For the purpose of this use case, the Exploring the End of Cosmic Reionization survey will perform a census of emission-line galaxies at 5.3<z<7.0 with [OIII]4959, 5007 Å + Hβ 4861 Å and at 3.7<z<5.1 with Hα 6564 Å. The survey is aimed to reach an imaging depth of m~26.5 ABmag at 3.5μm and to detect an emission line with a flux of 10^{-17} erg/cm^2/s at the 10-sigma level. The fields will be selected around known z>6 quasars from the literature and are therefore pre-defined.

The NIRCam Wide Field Slitless Spectroscopy (WFSS) mode allows one to obtain R~1600 slitless observations (~10Å/pixel) between the wavelengths of 2.5 and 5 μm and using two separate modules. Module A and module B are essentially mirror copies of the same instrument, offering the same observing capabilities and which can be used at the same time. Each module can simultaneously obtain imaging in the short wavelength (SW) channel (0.5<λ<2.3 μm) and WFSS grism observations in the long wavelength (LW) channel (2.4<λ<5 μm). The long wavelength channel in each module consists of a 2040 × 2040 pixel detector with a field of view of 2.2' × 2.2', with the two modules separated by 45 – 48'' on the sky. NIRCam is required to obtain spectroscopy of these high redshift sources as the emission lines are expected to be in a wavelength range that is not within the reach of NIRISS WFSS (0.8 – 2.2 μm). This project does not have an a-priori list of targets and is therefore better suited to NIRCam than NIRSpec. Each NIRCam module offers two different grisms which can be used in combination with a medium or wide band filter to limit the effective wavelength range of these grisms. The use of filters reduces the amount of spectral overlap between different objects. It also reduces the amount of dispersed background light. See NIRCam WFSS Recommended Strategies.

Choice of grism cross filter

Each NIRCam module provides a set of row- (GRISMR) and a column-direction (GRISMC) grisms. These can be used to obtain spectra of sources along different orientations to mitigate the effect of contamination. Observations obtained using multiple orientations can also be essential to unambiguously identify bonafide emission lines. Due to the reduction in the effective field of view when crossing either grism with a filter, there are no ways to assume that every source in the field can be dispersed along different directions. In Figure 1, we show one example of the reduced effective field of view for GRISMR combined with the F356W filter.

Alternatively, one can overlap the full-spectrum field of view from Module A and Module B by using a large pointing offset. The overlapping field will have GRISMR spectra dispersed in opposite directions from each module. In this way, the observer can maximize the area of overlap containing full spectra dispersed in two directions, at the expense of reduced depth for the areas without overlap.

**Figure 1. Field of view of the GRISM R / F356W Combination**
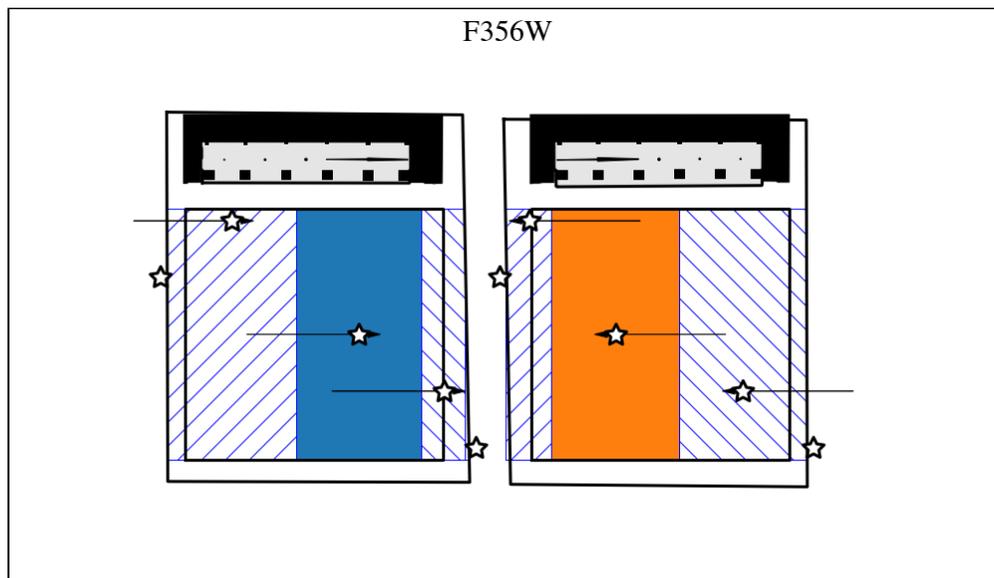
The NIRCam Module A and B LW detectors are shown (black squares), along with larger area covered by the NIRCam optics including the footprint of the coronagraph. The areas marked with solid colors are fields of view where full spectra are generated for sources in GRISM R/F356W observations. Sources within the hashed regions will generate truncated spectra. Positions of sources are shown as stars, and the extent and direction of their dispersed spectra are shown as black arrows. The wavelength increases from left to right in Module A (left panel) and right to left in Module B (right panel). Similar figures for other combinations of grisms and filters are shown in NIRCam WFSS Field of View.

APT mosaic strategy

The goal is to obtain deep spectroscopic observations of Lya emitters around known z>6 quasars. Each field will be covered by four overlapping pointings which, when combined will be deep enough to detect faint Lya emission lines. Unlike other JWST instruments, the 10 NIRCam detectors (2 LW and 8 SW) are split between two different modules (A and B) which are separated by a large (~45") gap. In order to obtain a contiguous mosaic, 4 intramodule primary dithers are required to fill the SW detector gaps. Larger offsets are then required to fill the large gaps between the 2 LW channels. In addition to this, 3 standard subpixel dithers are added to help mitigate the effects of bad pixels as well as to improve the final spatial sampling in the final combined images. Altogether, this yields a total of 12 dithered exposures. A larger area can be covered by observing each field 4 times and offsetting each visit by a quarter of a single LW field of view (i.e., ~60''). By allowing the data to be taken ~6 months apart, the position angle (PA) of 2 of these 4 overlapping visits can be 180° apart, ensuring that the central area, containing the z>5 quasars, will be observed with the GRISMR of each module pointing in different directions and the maximum depth of this survey. There will be a small area of overlap (approximately 210 pixels (15'') wide by 2040 pixels (132'') high) for an area of about 0.57 arcmin^2 where objects will produce full spectra in two different directions. This is illustrated in Figure 2 where we show a single NIRCam pointing in panel (A). Adding a second observation that is flipped 180° and offset by about half of the size of the LW field of view results in the pattern shown in panel (B). Adding another identical pair of exposures but now offset in the other direction results in what is shown in panel (C). The black arrow points to the narrow region near the center of the field where we can expect objects to produce fully dispersed spectra in both directions. In this example, we have decided to offset each pointing so that the 45'' gap between the Module A and Module B LW channels is filled. A portion of the observations will be to full depth. Other portions will be observed at either 1/2 or 1/4 depth. In this example, as well as the other example below, we show the location of a source as a black dot in each module and the resulting dispersed spectrum as a black line. The source location corresponds to a wavelength of approximately 4 µm. The spectra span a range of 3.1 – 4.1 µm, as F356W is being used. We use different hashed patterns so that we can readily see overlapping observations taken using different spectral dispersion directions. The hash patterns are arbitrary and are not related to the actual dispersion direction but are useful to distinguish the different dispersion orientations.

Figure 2. Observation pattern using GRISM R only
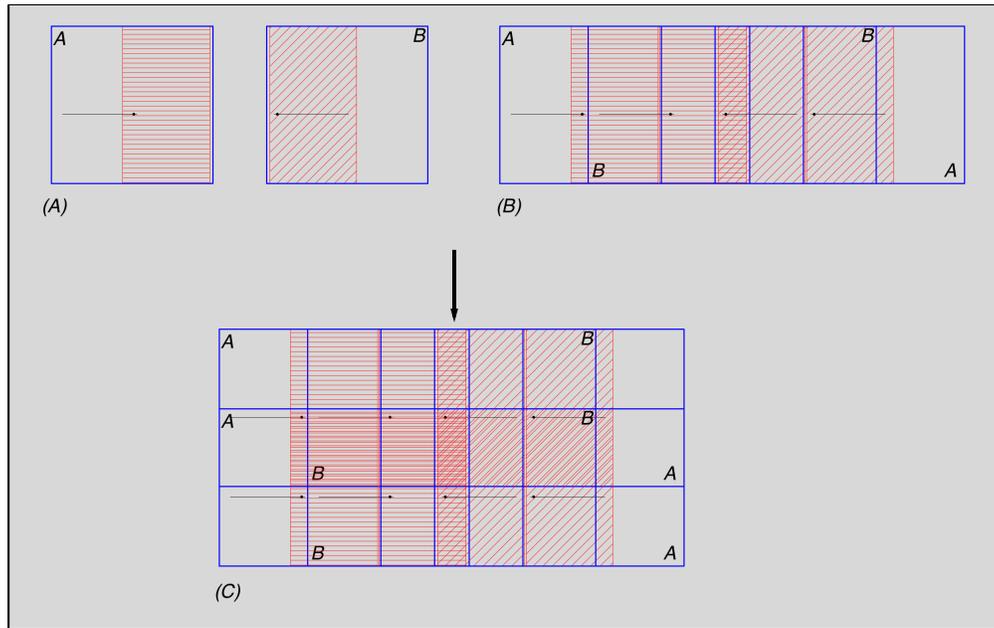
Observation pattern using 4 GRISM R pointings. Different dispersion directions are indicated using different shading so that areas where objects will be observed using multiple dispersion directions can be readily seen. Panel (A) shows a single pointing. Panel (B) shows two pointings, offset by 1/2 of the field of view (FOV) of a single LW channel and flipped 180°. Panel (C) shows the final, 4 pointings mosaic. There is a small portion of the field which is observed in all 4 pointings and using 2 different dispersion directions (black arrow). It is in the center of a shallower band which is observed in 2 of the 4 pointings but again using two different dispersion directions.

It is difficult to obtain a contiguous mosaic of dispersed spectra with different dispersion directions. We illustrate this further by showing alternative possible choices using GRISM C observations (Figure 3), an alternative use of the GRISM R (Figure 4), and finally using a combination of GRISM R and C observations (Figure 5). The gap between the two modules and the relative directions of the dispersed spectra in each module result in mosaics with either non-contiguous coverage or regions where objects will only produce spectra dispersed in a single direction. To satisfy our science case, we picked the pattern shown in Figure 2 because it gives the best compromise between a deep uniform coverage of the field around the quasars while also allowing multiple orientation slitless spectroscopy at the center of the field.

**Figure 3. Observation pattern using GRISM C only**
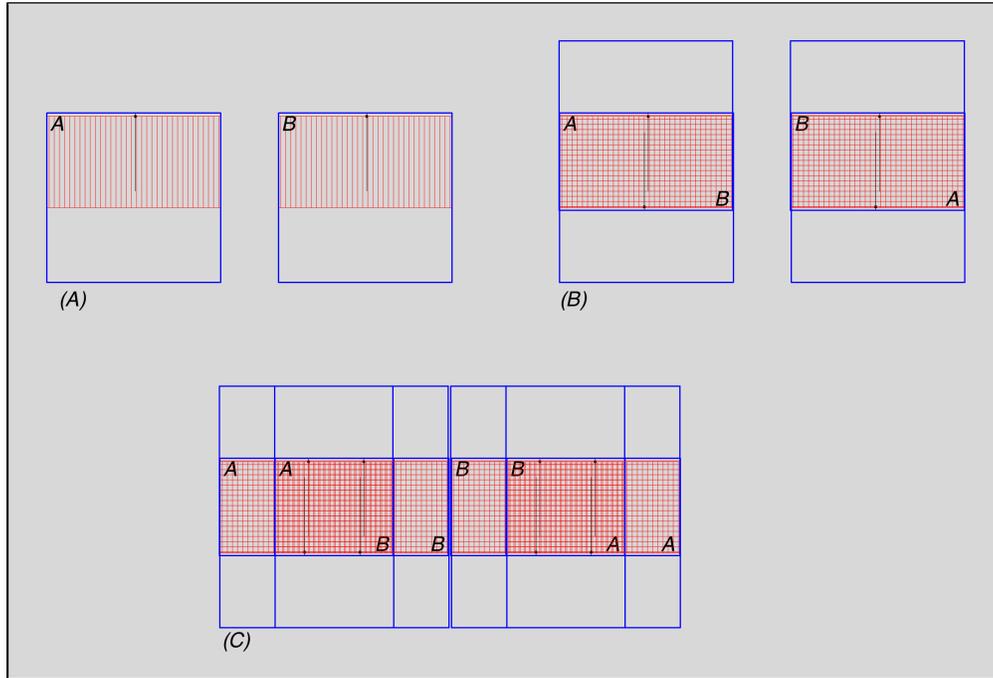
Observation pattern using 4 GRISM C pointings. Using sets of offsets GRISM C exposures flipped 180° would allow us to obtain contiguous coverage of our field, but in this particular example the deepest coverage would be on each side of the center of the field. Panel (A) shows a single GRISM C/F356W exposure. Panel (B) shows how two exposures, flipped 180° and offset to overlap the effective field of view would allow us to obtain different slitless dispersion for every source. Panel (C) shows an option were we repeat the exposures shown in Panel (B) but offset them to cover the gap between Module A and Module B.

Figure 4. Observation pattern using GRISM R to increase number of sources observed with multiple dispersion directions
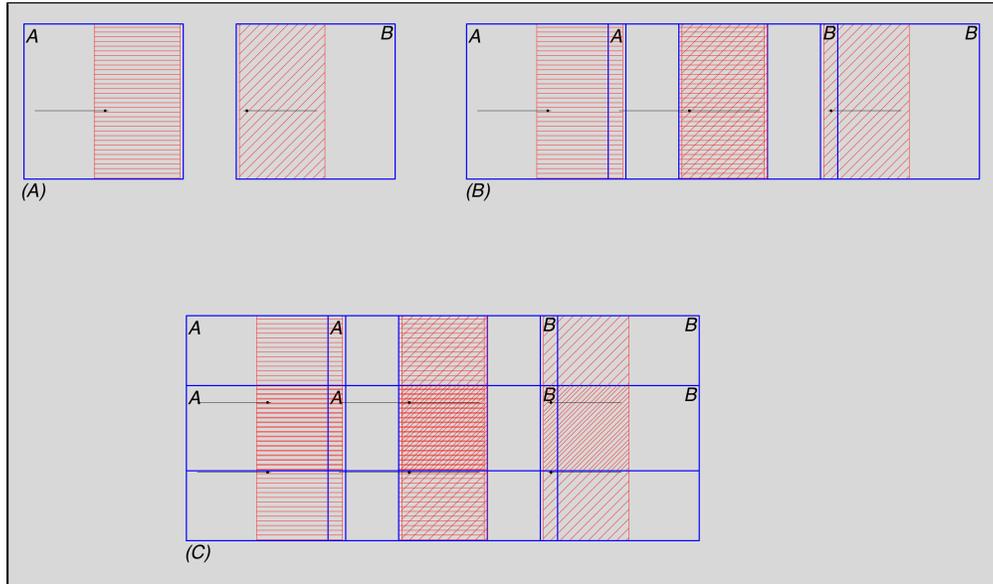
In this example, we again only use the GRISM R grisms (Panel A). We however offset a second exposure so that the field of view of Module A and B overlap. We then add another two exposures to reach our full depth (Panel C). This example has the advantage of allowing for a larger area where multiple dispersion directions will be used but has the disadvantage of not producing a contiguous set of observations.

Figure 5. Observation pattern combining GRISM R and GRISM C
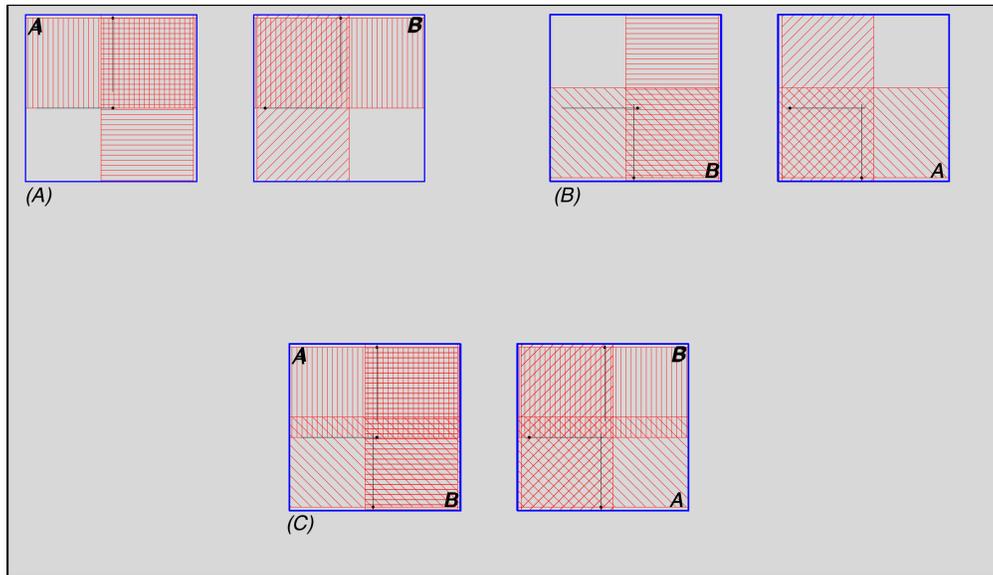
In this example, we combine a GRISM R and GRISM C exposure, (Panel A). The area of overlap of the two grisms is relatively small, covering about 1/4 of the field. We can however do the same thing by observing the same field with a position angle that is flipped 180°, (Panel B). By offsetting these two sets of observations we can obtain spectra with multiple dispersion directions for a large portion of each module. As shown in Panel C, approximately half of the field will be observed using different dispersion directions.

Determining the exposure time

For this project, we want to detect an emission line with a flux of 10^{-17} erg/cm^2/s at the 10-sigma level. We also want our F356W, F115W and F200W imaging to be deep enough to detect faint, partially-resolved (~0.3'' across) z>3 galaxies. We design the required observations using the Exposure Time Calculator (ETC).

Spectroscopic exposure time

We are interested in detecting emission lines which will originate from unresolved star forming regions. We therefore set up a scene with an unresolved point source with an emission line.

In ETC, create a new workbook. Click on Load. In the Calculation tab, click on the NIRCam tab and select Grism Wide Field (Figure 6).

Figure 6. Select NIRCam Grism Wide Field observation in the ETC
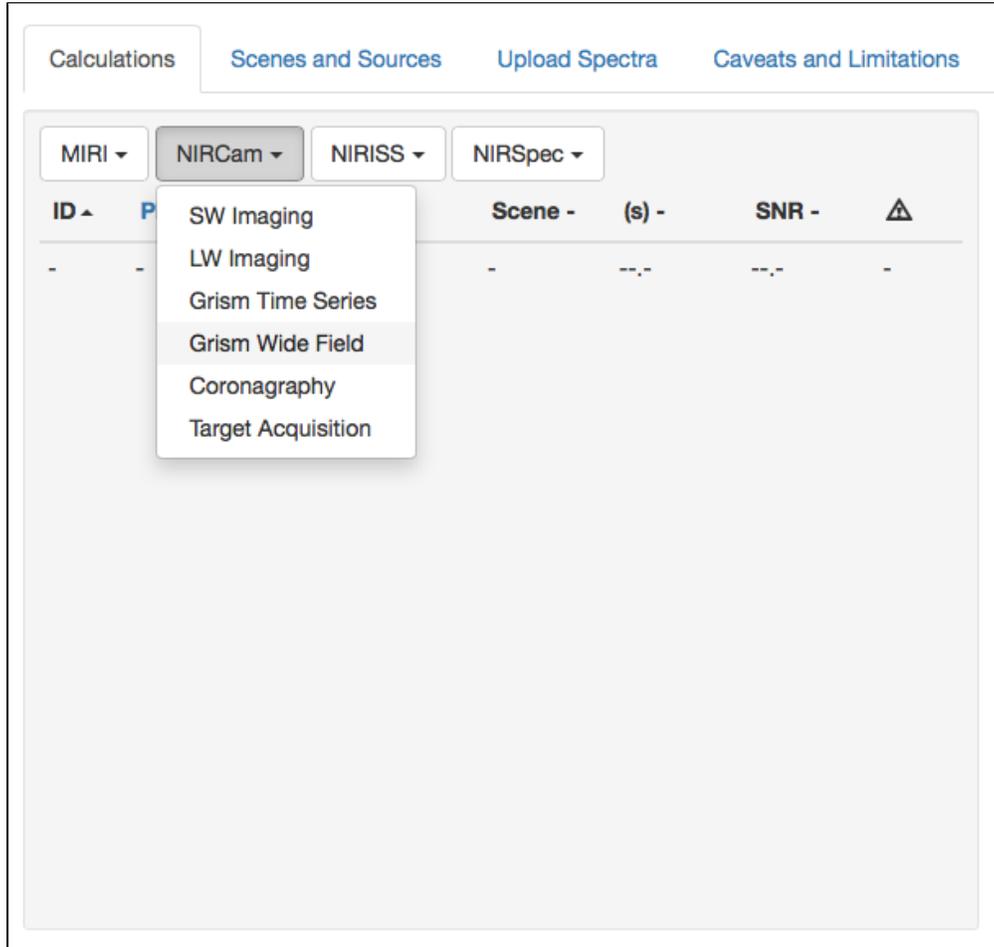
Click on the Scenes and Sources tab. Select Scene 1 in the Select a Scene box, and then click on "default source from 1" in the Select a Source box (Figure 7).

Figure 7. Initialize ETC scene and source
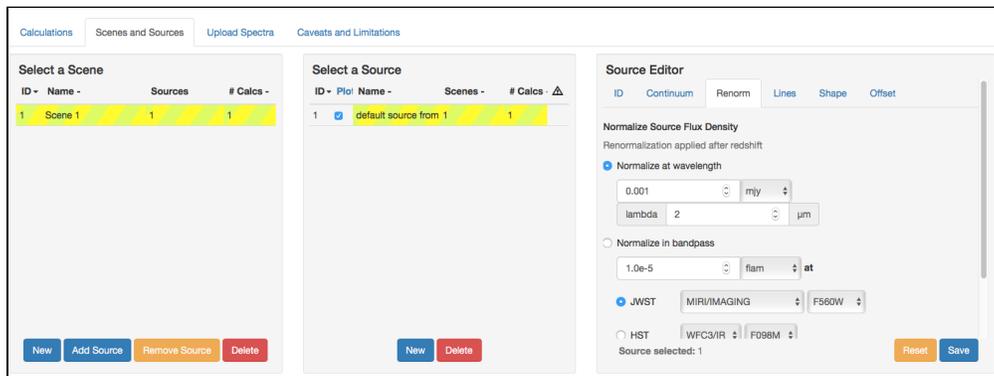
We want to edit this source. In the Source Editor box, click on Normalize in bandpass, select abmag and enter 26.5 in the input box. Select NIRCam/LW_IMAGING and select the F356W filter. Select Renorm and select Do Not Renormalize. Click on Save (Figure 8). We can set the size of this galaxy. Select the Shape tab in the Source Editor, click on Point (Figure 9).

Figure 8. Set the source magnitude

Figure 9. Select point source
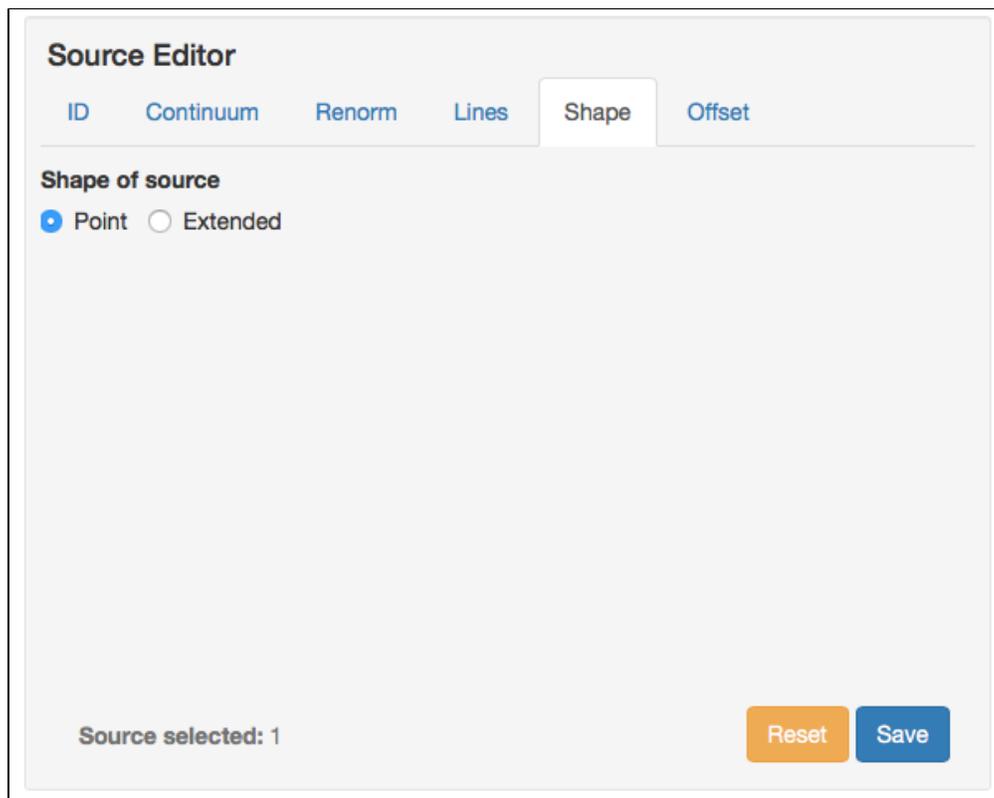
Add an emission line. Under Source Editor, select the Lines tab, enter a name under Line Name, a wavelength of 3.6 µm for the line center, 200 km/s for the line width and 1e-17 erg/cm^2/s for the line strength. Click on Add. Click on Save (Figure 10).

Figure 10. Add an emission line
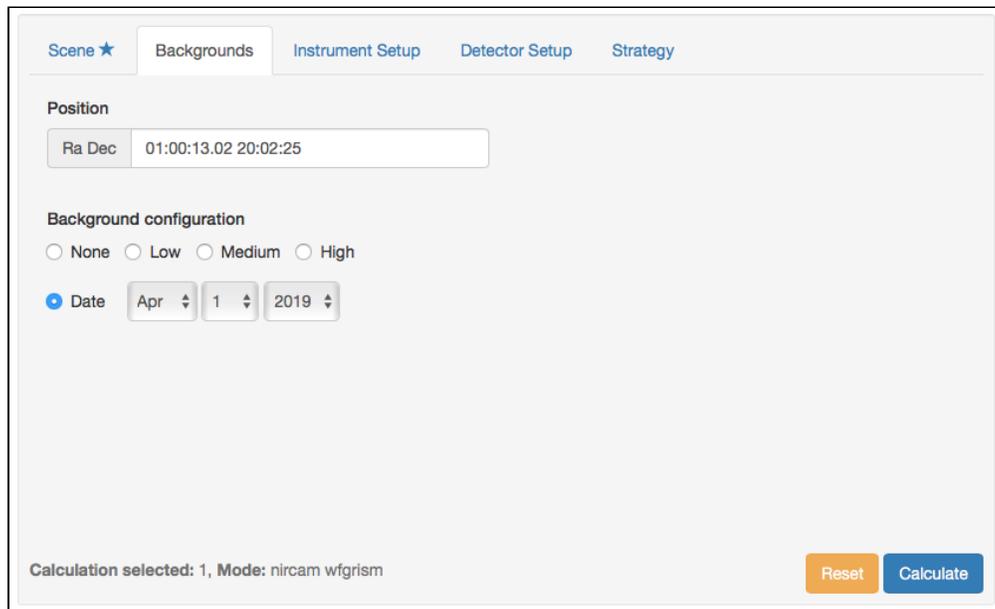

Select the Calculations tab. Under Instrument Setup, select GRISM (row-dispersed) and F356W for the filter, (Figure 11).

Figure 11. Select GRISMR and the F356W filter
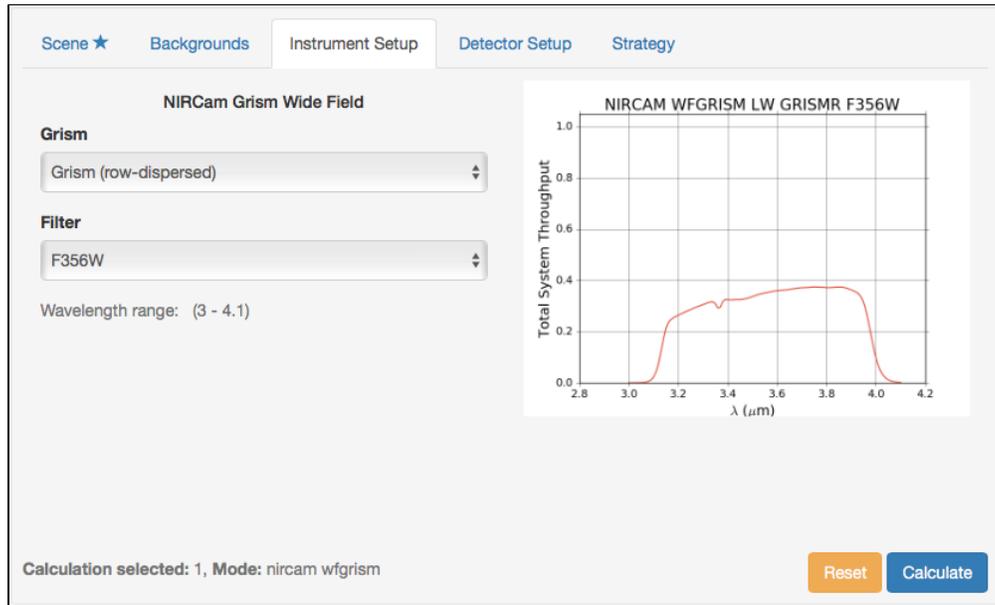
Select Backgrounds and enter the coordinates of the field, and a background condition or a date, (Figure 12).

**Figure 12. Under Backgrounds, set the source coordinates (RA, Dec) and observation date**

We now want to find a total integration time. Under Detector Setup, select 6 groups, 1 Integrations and 1 Exposures using the DEEP8 Readout Pattern. This corresponds to an integration time of 1170.31 s. Click on Calculate, (Figure 13).

Figure 13. Under Detector Setup, set the readout specifications

We can examine the SNR as a function of integration time by selecting a range of numbers of exposures. This can be done using the Expand tab at the top of the screen and selecting Expand Integrations. Start with a value of 1, a step size of 1 and 7 Iterations. This will create new calculations with integration times varying from 1170.31 to 8192.15 s. One can select all the entries and select SNR in the Plots box to see a plot of the SNR as a function of wavelength for these varying integration times. Change the X scale from 3.5 to 2.7 micron to zoom on the emission line (Figure 14). Based on our emission line detection requirements (10-sigma), we conclude that a total integration time of approximately 8000 s is required.

Figure 14. Spectroscopy Signal-to-Noise results for a range of exposure times
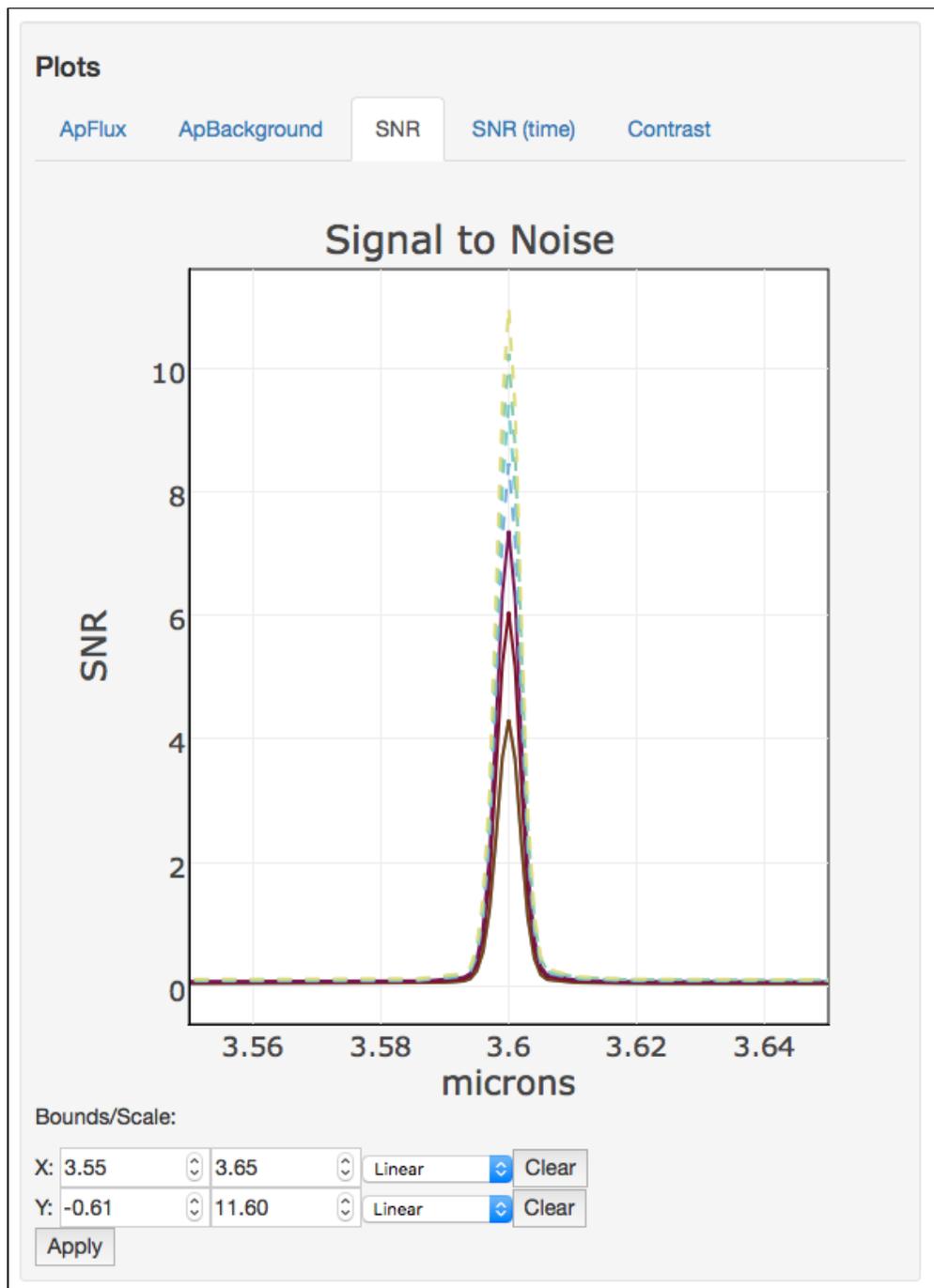
Direct Imaging Exposure Time

We would like to extract spectra in galaxies as faint as AB mag 26.5. We can estimate the integration time required using the F356W filter in a manner similar to that shown above. We simply create a new scene and point source with continuum flux of 26.5 but omit the emission line. We also change our source from a point source to a 0.15'' by 0.15'' 2D gaussian extended source, the expected size of galaxies at z~3 (e.g., Ferguson et al. 2004). Doing so, we can readily verify that a short integration time of ~500s results in a SNR of 3.6.

We also plan to obtain imaging using the SW filters F115W and F200W, splitting the exposure time equally between the two (e.g., 4000 s in each). These images will be obtained at the same time as the LW slitless observations and each filter will be used for half of the total exposure time spent using the GRISMR/F356W. Following the same procedure as above, we can make a copy of the last Calculation and switch from NIRCam lw_imaging to NIRCam sw_imaging. We select a Detector Setup that results in a total exposure time of approximately 4000 s (10 GROUPS, 2 INTEGRATIONS, DEEP8 pattern). The ETC confirms that the expected SNR of a small AB mag 26.5 galaxy would be approximately 3.8.

Note while default sizes were used for the photometric aperture and sky annulus in these calculations, we generally recommend different aperture sizes for SW and LW calculations, given the different pixel sizes and PSF widths. See NIRCam Imaging Sensitivity for details.

Choice of Readout Pattern

The choice of a readout pattern is predicated on the details of how we plan to observe our field. Given our 4 intramodule dithers and 3 subpixel dithers, each of the four pointings we are planning will be split into 12 different exposures. In this example, we settled on approximately 8000 s per pointing. This exposure time will be split in two exposures of 4000s each so that we can observe with the SW channel at the same time but using two different filters (F115W and F200W). Our desired integration time, per exposure, is therefore 333 s. An optimal readout pattern for this survey is one that allows as many groups as possible (given data volume limits), with the fewest number of dropped frames between groups. This will maximize our ability to detect and correct for cosmic rays and saturation of bright sources in the field. Using a SHALLOW4 readout pattern with 6 groups allows us to achieve this (see detector readout patterns: integration times). Using this choice of readout pattern, we obtain a total exposure time of 3865 s in each of the SW F115W and F200W filters, and a total of 7730 s in the LW GRISMR/F356W exposures.

References

Ferguson, H. C., Dickinson, M., Giavalisco, M., et al. 2004, ApJL, 600, L107
The Size Evolution of High-Redshift Galaxies

JWST technical documents