The JWST Exposure Time Calculator: Observing strategies

Klaus Pontoppidan, pontoppi@stsci.edu

This document specifies the basic observing strategies for the three-dimensional JWST Exposure Time Calculator (the 3D ETC). The general observing strategy concept is defined in Pontoppidan et al. (2013 to be submitted to Soccer). Briefly, an observing strategy describes how the ETC calculates a total signal-to-noise ratio () of an observable (photometric point, extracted spectrum or integrated line flux) from two-dimensional maps (scenes) of pixel-by-pixel signal and variance , as well as a covariance matrix describing any inter-pixel correlations. The pixel-by-pixel variances are the diagonal elements of . An observing strategy consists of 1) set of input parameters that could, in principle, be accessed by the user, and 2) a numerical recipe for calculating the correlation mapping, describing a linear mapping between a vector of coefficient weights , and the variance of the photometric measurement .

In general, the ETC will output a two-dimensional (pixel-by-pixel) noise and signal map. The ratio of this map will be a signal-to-noise per pixel map. The observing strategy generates additional outputs based on the pixel-by-pixel maps and any inter-pixel correlations. These secondary outputs are those listed under each observing strategy.

Text coded in RED indicates features that are planned, but not yet implemented in the engine.

# Aperture (region) photometry (ImagingApPhot)

## Rationale

This is the basic data extraction method for any imaging mode, and is still applied in many, if not the majority, of science applications using photometry. This is likely a workhorse strategy for the ETC. The one addition to the classical prescription is the addition of a region for the sky measurement that is elongated along the fast-read direction. This, in particular for the 2RG detectors, may help to suppress the correlated noise inherent in these detectors.

## Inputs

* Choice of source OR x, y coordinate offset from the POV center.
* Aperture radius (with point source-optimal default values, depending on filter).
* Sky annulus radii, inner and outer (also with default values).
* Switch for using optimal aperture radius.
* Shape of sky region – circular or rectangular along fast-read direction.

## Outputs

* Total signal in aperture in e-/s.
* Total background in aperture in e-/s (split into different background components – thermal, scattered light, zodi, galactic and other sources in scene).
* Fraction of source signal enclosed in aperture.
* Scalar signal-to-noise ratio

## Coefficients

A is the set of detector pixels inside the aperture, while B is the set of pixels in the sky region. K is a scalar that is applied to the total flux in the aperture to account for any source flux that is not included in the aperture. It is a complication that K has to be calculated (although this can be relatively easily done), however, it actually drops out of the S/N ratio.

Note that it is a requirement that the regions A and B have no overlap, so the input parameters must be constrained to not allow this eventuality.

## Potential issues

In defining a circular region on a pixelated detector, a decision has to be made in how to treat pixels that are not fully enclosed by the circle. Currently, pixels with centers within the radius are fully included.

The term ***aperture*** is overloaded in the ETC, but is a standard astronomical term for this type of analysis. That is, a user interface using the term ***aperture photometry*** for this strategy will be more likely to be understood correctly by most astronomers, than if another term is used.

# Aperture spectral extraction for single slits (SpecApPhot)

## Rationale

Rather than having a two-dimensional extraction aperture, a spectrum only requires one dimension to specify the aperture size. However, the higher dimensionality of the 3D ETC allows for a dependence of the aperture size on the wavelength and size of the PSF. This can be important for broad-band spectroscopic modes, such as the NIRSpec prism. As opposed to the optimal extraction strategy described below, this is likely the strategy of choice for extended sources.

## Inputs

* Choice of source OR angular offset from the POV center in the cross-dispersion direction.
* Aperture radius in angular units (arcseconds or pixels) OR in units of the point source FWHM or equivalent. The second option allows for the aperture to grow with the PSF size and is anticipated to be the standard strategy for point sources.
* Inner and outer annulus radii in angular units OR in units of the point source FWHM or equivalent (must be the same as the unit of the aperture radius).
* Switch for optimal choice of aperture radius. I.e., pick the radius that gives the highest S/N ratio. The default for point sources will be optimal.
* Dither pattern from a list of canned patterns.

## Outputs

* S/N ratio as a function of wavelength over the range covered.
* Detected source signal in e-/s as a function of wavelength.
* Detected background signal within the aperture in e-/s as a function of wavelength, broken down into components (thermal, scattered light, zodi, galactic and other sources in the scene.

## Coefficients

The coefficients are conceptually the same as for aperture photometry. The difference is that the aperture region may change with wavelength, creating a separate set of coefficients for each pixel column (if the dispersion direction is along rows). If x is the pixel column:

## Potential issues

No current issues.

# Aperture spectral extraction for NIRSpec MSA (MSASpecPhot)

## Inputs

* Choice of source OR angular offset from the POV center along the MSA cross-dispersion direction.
* Aperture radius in angular units (arcseconds or pixels) OR in units of the point source FWHM or equivalent. The second option allows for the aperture to grow with the PSF size and is anticipated to be the standard strategy for point sources.
* Dither pattern from list of canned patterns TBD.
* Switch for optimal choice of aperture radius. I.e., pick the radius that gives the highest S/N ratio. The default for point sources will be optimal.

## Outputs

* Separate output structure for every dither as well as the combined dithers.
* For each dither and combined dither:
  + S/N ratio as a function of wavelength over the range covered.
* For the combined dither:
  + Detected source signal in e-/s as a function of wavelength.
  + Detected background signal within the aperture in e-/s as a function of wavelength, broken down into components (thermal, scattered light, zodi, galactic and other sources in the scene.

## Coefficients

## Potential issues

# Optimal spectral extraction for single slits (SpecOptPhot)

## Rationale

It is becoming standard to extract spectra for point sources using the optimal extraction algorithm from Horne 1986. This is applicable if the spatial shape of the spectral image is known to some reasonable accuracy. If this is the case, the optimal extraction method requires no choice of free parameters, making it highly appropriate for data reduction pipelines, including the JWST pipelines.

## Inputs

* Choice of source OR angular offset from the POV center in the cross-dispersion direction.
* Dither pattern from a list of canned patterns.

## Outputs

* S/N ratio as a function of wavelength over the range covered.
* Detected source signal in e- per second as a function of wavelength.
* Detected background signal in e-/pixel/s as a function of wavelength, broken down into components (thermal, scattered light, zodi, galactic and the contribution from other sources at the source (x,y) coordinate).

## Weights

The optimal extraction weights access the profile of the source spectrum at each wavelength, P, defined such that:

Then the optimal flux density at dispersion pixel x is (adapted from Horne 1986):

In a real observation, it is not possible to estimate the profile from the data, at least not on a column-by-column basis, because of noise[[1]](#footnote-1). However, within the ETC, we of course have a noise-less estimate of the flux rate per pixel. Thus, using that the profile is normalized, we can rewrite the optimal expression to:

Leading to the following expression for the coefficients:

## Potential issues

In the classical version, optimal extraction is only valid for point sources. There is nothing preventing one from applying it to an extended source, but this requires pre-existing knowledge of the source profile. This can be calculated from the data, but assumes that the source extent does not change with wavelength, which is rarely the case in realistic applications.

It is still unclear exactly which approach is to be taken in the JWST pipelines, although some sort of optimal extraction approach seems likely. Future maintenance of the strategies should ensure that there is reasonable equivalence.

# Aperture spectral extraction for IFUs (IFUApPhot)

## Rationale

This is the equivalent of imaging aperture photometry for IFU spectroscopic modes. The difference is that the IFU observation consists of a number of separate slices (slits). For NIRSpec/IFU, the number of slices is 30, for the MIRI IFUs, the number of slices vary from 12 to 22, depending on channel. The ETC will create a stack of dispersed detector images, one for each spectral slice. A pixel from any plane in the stack may be used for the extracted spectrum.

## Inputs

* Choice of source OR offset in angular units from the FOV center.
* Aperture radius in fixed angular units (in arcseconds or pixels) OR in units of the point source FWHM or equivalent. The latter option allows for the aperture to grow with the PSF size.
* Sky annulus radii, inner and outer in the same units used for the aperture radius.

## Outputs

* S/N ratio as a function of wavelength over the range covered.
* Detected source signal in e- per second as a function of wavelength.
* Detected background signal within the aperture in e- per second as a function of wavelength, broken down into components (thermal, scattered light, zodi, galactic and other sources in scene).

## Coefficients

In principle, the formula for the coefficients is the same as for aperture slit spectroscopy. However, now the sets A and B are more complicated and include potentially non-contiguous pixels from a three-dimensional cube (slice, cross-dispersion offset and wavelength).

The arguably easiest way to determine A and B, given a the aperture and annulus parameters is to create a map:

# Aperture spectral extraction for nodded IFU observations (IFUNodApPhot)

## Rationale

Some IFU observations will be self-calibrated by nodding, that is, offsetting to a position in which the target is moved sufficiently far away in the FOV that the two nods can be subtracted to get rid of background. The nod could leave the target within the FOV (for point sources or compact sources), or it could offset the target completely out of the FOV.

## Inputs

* Dither pattern from a canned list of patterns. Currently supported is a single nod off-source.
* Choice of source OR offset in angular units from the FOV center.
* Aperture radius in fixed angular units (in arcseconds or pixels) OR in units of the point source FWHM or equivalent. The latter option allows for the aperture to grow with the PSF size.

## Outputs

* S/N ratio as a function of wavelength over the range covered.
* Detected source signal in e- per second as a function of wavelength.
* Detected background signal within the aperture in e- per second as a function of wavelength, broken down into components (thermal, scattered light, zodi, galactic and other sources in scene).

## Coefficients

# Aperture line spectroscopy

## Rationale

Line spectroscopy can be seen as a specialization of other spectroscopic strategies. Specifically, it is possible to envision an aperture extraction and an optimal extraction version of line spectroscopy. The simplest strategy is that using aperture extraction.

## Inputs

* Line center
* Line width in velocity
* Redshift
* Doppler velocity shift
* Integrated line flux (defines an emission line) or center optical depth (defines an absorption line)
* All inputs relevant for the parent spectroscopic strategy.

## Outputs

* Scalar signal-to-noise ratio of the integrated line.
* Signal-to-noise ratio per pixel as a function of velocity (plotted over a range of -3xFWHM to +3xFWHM).
* Line-to-continuum ratio at peak line flux/depth.

## Weights

## Potential issues

# Coronagraphic photometry

## Rationale

The coronagraphic observing strategy is pending a coronagraph working group white paper.

## Inputs

* Off-axis source (x,y).

## Outputs

* Raw contrast in units of occulted star flux.
* Contrast profile: Flux of faint source detectable as a function of separation

## Weights

TBD

Table of strategies along with supported observing modes

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Strategy | Supported modes | Number of input parameters | S/N output | Source signal output | Background output | Raw contrast |
| Aperture photometry | NIRCam imaging, NIRISS imaging, MIRI imaging, NIRSpec imaging |  | ✔ | ✔ | ✔ |  |
| Aperture slit spectroscopy | NIRCam grism, NIRISS slitless spectroscopy, NIRSpec fixed slit, NIRSpec MSA, MIRI LRS |  | ✔ | ✔ | ✔ |  |
| Optimal slit spectroscopy | NIRCam grism, NIRISS slitless, NIRSpec fixed slit, NIRSpec MSA, MIRI LRS |  | ✔ | ✔ | ✔ |  |
| Aperture IFU spectroscopy | NIRSpec IFU, MIRI IFU |  | ✔ | ✔ | ✔ |  |
| Aperture line spectroscopy | All spectroscopic modes |  |  |  |  |  |
| Coronagraphy | NIRCam coronagraphy, MIRI coronagraphy |  |  | ✔ | ✔ | ✔ |

1. Some times the profile is measured by assuming that it is independent of wavelength, allowing for a low-noise estimate to be calculated by averaging the 2D spectrum along the dispersion direction. This is the standard approach in the ESO spectroscopic pipelines. [↑](#footnote-ref-1)