Updated GRISM Configuration

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1 Introduction

Current HST configuration files for the NICMOS, ACS and WFC3 grisms have been based on the aXe configuration file methodology. These files describe how spectra are physically dispersed for individual orders when using a particular detector and instrument. With new instruments on the horizon, such as JWST NIRCAM, the current aXe method to describe the grism dispersion needs to be generalized. Here we introduce an update, or extension, of this calibration format

2 The problem

The goal of the Grism configuration file is to allow a user to go back and forth between what are essentially two coordinate systems: an image+wavelength coordinate system and a dispersed spectrum coordinate system. Fundamentally, this is akin to the WCS transformation functions pixtosky and skytopix which allow a user to go back and forth from units on the sky to detector pixels, allowing for corrections such as geometric distortions and other effects. Users are isolated from the details of how these systems are corrected from and to and are simply provided with a set of functions or modules to perform the required transformation. Similarly to the WCS coordinate transformation problem, when dealing with dispersed spectra, we are interested in knowing where light that would otherwise be on a pixel at coordinates x,y on the detector will be dispersed to in the dispersed frame. Since the dispersion is wavelength dependent, the wavelength of the light is one of the input parameter to compute this. Users can be fully isolated from how this operation if performed as long as an appropriate function f or module to implement the transformation

$$x', y' = f(x, y, \lambda) \tag{1}$$

is provided. In the Equation above, (x,y) refers to the pixel coordinate in the incident image and (x',y') to the pixel coordinates on the dispersed image, while λ is the wavelength of the incident light.

3 Current aXe format

The aXe configuration file format to describe the dispersion of spectra was developed back in 2000 to be used with the ACS grisms and prisms. All of these instruments dispersed the light in the x-direction (in the case of the ACS/HRC grism, with a large angle). The actual parametrization of this dispersion was done using two-dimensional polynomials which allowed for field dependence of the function $f(x, y, \lambda)$. A set of two dimensional polynomials were introduced to do the job of the function f described above. These polynomials, given a pixel at coordinates (x,y) on the detector allowed to compute the wavelength of a region of the dispersed spectrum that was a given distance along the trace. At the time, the distance along the trace was chosen to be one of the driving variable of these polynomials to allow for some flexibility when spectra were strongly non-linear (as in the case of the WFC3 UVIS grism for example).

This is described in some details in WFC3-ISR-2016-XX from Pirzkal et al. The whole physical dispersion of a grism are described using only two polynomials: DYDX and DPDL. The first one, DYDX, allows to compute the offset in the y-direction if the trace as a function of an offset in the x-direction. The second polynomial, DLDP, allows a user to to compute the wavelength of the light incident on a pixel, along the trace. Having defines were the trace is located using the DYDX polynomial, one can compute the wavelength after computing the pathlength along the trace, which is computed using:

$$\Delta p(x_0, y_0, \Delta x) = f(\Delta x) = \int_0^{\Delta x} \sqrt{1 + (\frac{dy}{dx})^2} dx \tag{2}$$

where $\frac{dy}{dx}$ is the first derivative, or slope, of the trace.

The aXe software takes care of computing the path length for users.

The specific manner in which the dispersion is described in the aXe configuration files stems from the fact that these were designed for *extracting* spectra.

Unfortunately, there are several serious drawbacks and limitations to the way dispersers are parametrized:

- The description of the trace, DYDX, implicitly assumes that the trace is non degenerate in the x-direction. A spectrum dispersed vertically on the detector can therefore not be described this way.
- Parametrizing the wavelength calibration as a function of path length along the trace requires code to perform the integration shown in Equation 2 . This can be a computationally expensive integral.
- For the purpose of generating simulated spectra, it is actually the reverse relation DPDL that is required. That is, a way to compute how far light at a given wavelength will be dispersed.

4 Solution

Modern instruments such as NIRCAM as well as modern simulation code will benefit from a generalization of the Grism configuration file and we describe how this can be done by expanding the current aXe configuration file in two crucial ways: First, the description of the grism dispersions should not be assumed to be a function of the x-coordinate but rather more generalized one (which we will call t) which can be predefined to span the range $(0, 1)$. How the coordinate t maps or not to physical quantities such as x, y and λ will be determine on an instrument/disperser basis and is something transparent to the user. In the orginal aXe configuration format, t was chosen to be p the pathlength along the trace, with the caveats we described above.

The physical dispersion and wavelength calibration of the trace of a single spectral order can be fully described using three functions:

$$\hat{x} = x' - x = f_x(x, y; t) \tag{3a}$$
$$\hat{y} = y' - y = f_y(x, y; t) \tag{3b}$$
$$\lambda = f_\lambda(x, y; t) \tag{3c}$$

Using these function, a user or extraction software can trivially computed the location and wavelengths along the trace. However, and in addition to the Equations 3, we also require the reverse functions to be also defined:

$$t = f_x^{-1}(x, y; \hat{x}) \tag{4a}$$
$$t = f_y^{-1}(x, y; \hat{y}) \tag{4b}$$
$$t = f_\lambda^{-1}(x, y; \lambda) \tag{4c}$$

Note that in addition to the reverse functions, the *numerical inverse* functions could be provide. This would allow for code that relies on going back and forth between the imaging and the dispersed reference frames repetitively without loss of precision. In cases of simple polynomials, the *inverse* and reverse functions would be identical. Specific applications will drive the use of either the reverse or *inverse* functions.

While the use of a variable t might seem unnecessary, it avoids assuming that the spectra can be described well using λ alone, as is the case with some prisms for example. This set of 6 functions allow users and code to relate any of the x,y,λ,$\hat{x}$, and $\hat{y}$ variable to one another in an efficient manner. In the description above, we made no assumption as to how the functions f_x,f_y, and f_λ are implemented.

5 Implication for calibration

The functions f_x,f_y, and f_λ (Eq. 3) can be determined in a manner that is similar to past ACS and WFC3 calibration efforts. As long as calibration or

observational data exist to measure both the physical location of the trace and the position of known emission lines, one can uniquely determine these relations. The aXe configuration files have relied on a two-dimensional description of the field dependence of these functions but that is not technically required. Other approaches, such as interpolated lookup tables are also possible (although solutions near the edges of detector might be better extrapolated using a smooth two-dimensional fit). The details of how Equations 3 are implemented will not have an impact on users who will simply be provided with code to compute the Equations 3.

The reverse functions functions f_x^{-1},f_y^{-1}, and f_λ^{-1} (Eq. 4) can be trivially derived from Equations 3 if the latter are expressed as simple polynomials of order less than 3. However, a better approach is to actually calibrate and implement Equations 4 independently of Equations 3 using the original data. In another word, the equivalent of fitting y versus x and then doing a separate fit of x versus y rather than trying to invert the fit of y versus x.

This ensures that any errors in the calibration of Equations 3 are not further propagated into Equations 4.

6 Example Workflow and use

6.1 Extraction

A very basic example of how to perform the transformation from and to the (x,y,) to the (x',y') coordinates are illustrated in Figure 1. In the case when we wish to determine the position of a pixel (x',y') where the light at wavelength λ of an object at pixel (x,y) is dispersed to, we may proceed by using $f_x^{-1}(x, y, \lambda)$ to compute t, followed by $f_x(x, y; t)$ and $f_y(x, y; t)$ to compute (x',y'). The reverse operation, that is determining the wavelength of a pixel (x',y') on a dispersed spectra can be done by first using $f_x^{-1}(x, y; \hat{x})$ to compute t followed by $f_\lambda(x, y; t)$ to compute λ.

7 Scope

The parametrization we described concentrated on a single spectrum. That is, a specific spectral order obtained using a specific dispersive element on a specific detector of a specific instrument and, finally, telescope. These functions are essentially the basic quanta to describe the dispersed trace and it wavelength calibration. The actual configuration file or system will need to allow for multiple orders (beams in the aXe world), detectors (e.g. ACS, NIRCAM), and so forth. Other important values such as the derivative of the trace dispersion or wavelength dispersion can be provided as part of the overall module. Depending on the specifics of the calibration these can be pre-calibrated or computed on the fly by the calibration module. We also did not include a discussion of other physical calibrations such as sensitivity or P and L flat-fielding, which should be allowed. Some of the latter might be beam specific, some might be detector

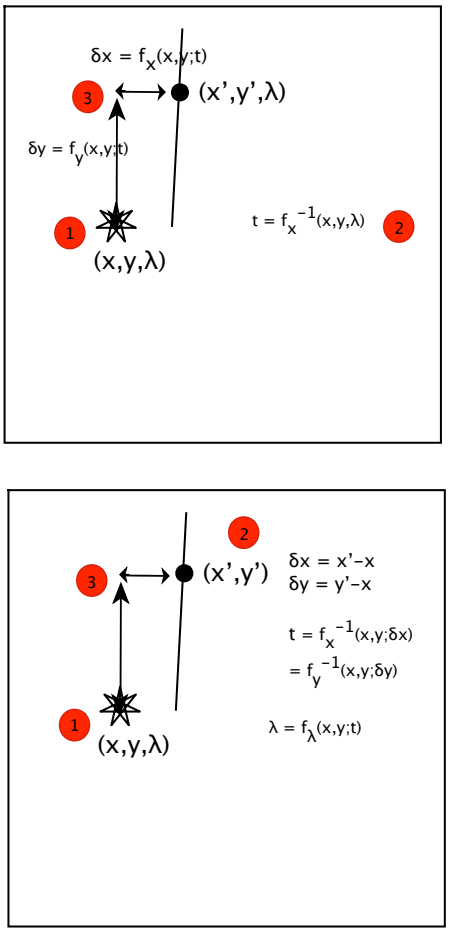

Figure 1: Illustration of implementing a more generalized transofoarmation from (x,y,λ) space (direct image) to dispersed (x',y') space (grism image). As long as functions to describe the dispersion do no assume either x- or y- direction dispersions, the processes of simulating or extracting spectra can be the same no matter what direction spectra are actually dispersed in.

specific and so a clear hierarchical definition will be necessary to keep things organized.

8 Acknowledgments

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