

# FOC $f/48$ Wavelength Calibration

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M. Voit  
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## ABSTRACT

*This report describes the program undertaken to calibrate the wavelength scale of the FOC  $f/48$  long-slit spectrograph. The calibration proceeds in two steps. We first remove the camera distortion by rectifying the reseau grid in an internal flat-field image from the same visit. Then we compute the transformation that takes the observed spectral lines to their desired positions. Because the camera distortion is time-dependent, we describe how to make custom calibration files as needed.*

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## 1. Introduction

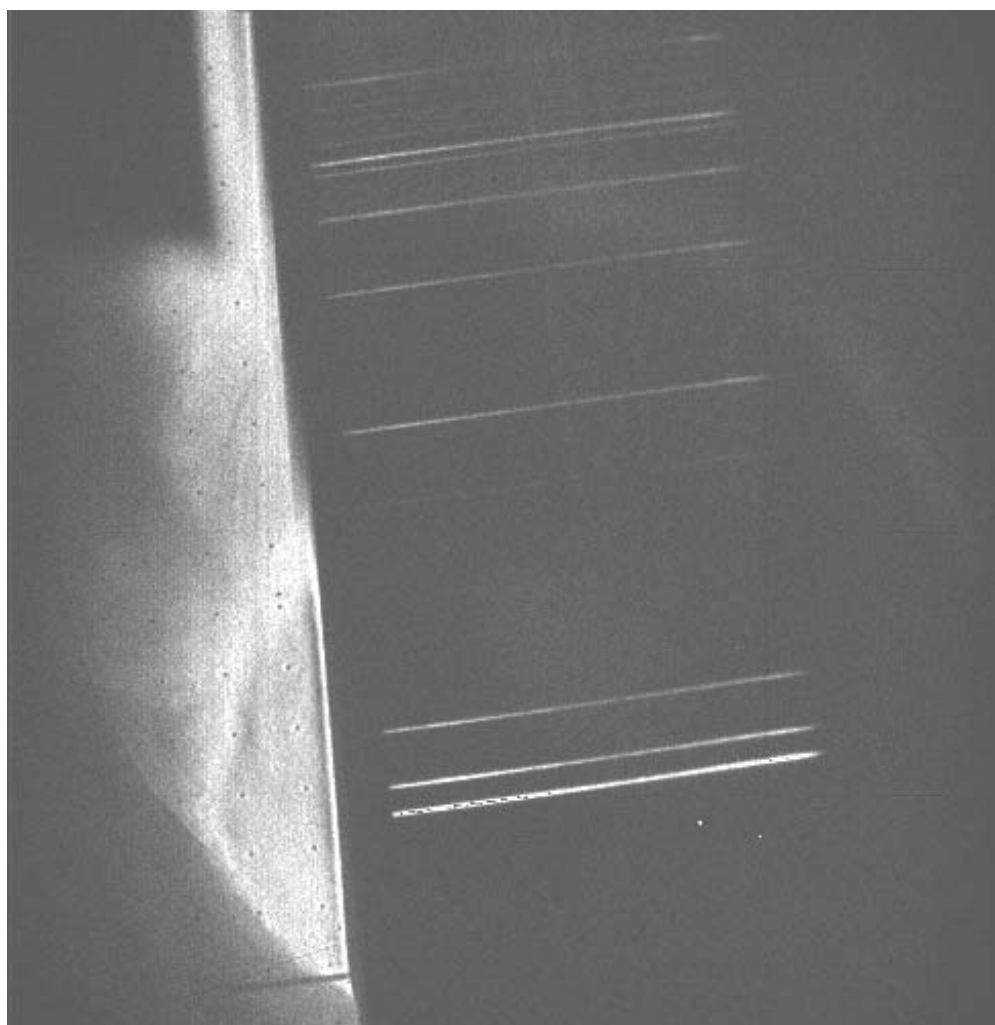
The recommissioning of the  $f/48$  spectrograph has reintroduced long-slit spectroscopic capability to HST for Cycle 5 GTOs and Cycle 6 GOs. This mode of the FOC had been calibrated in the pre-COSTAR era but has not been calibrated since. Now that the  $f/48$  spectrograph is back in use, we need to remeasure its wavelength scale in order to produce a new generation of spectrographic calibration files. This ISR describes the program (proposal 6199) we executed to calibrate the  $f/48$  long-slit spectrograph. Section 2 outlines the relevant data. Section 3 shows how we corrected for the geometric distortion of the imaging camera. Section 4 presents our calibration of the wavelength scale, and Section 5 discusses the accuracy of the calibration.

## 2. Calibration Observations

Our target for calibrating the  $f/48$  wavelength scale was the bright planetary nebula NGC6543, an emission-line object wide enough to fill the 12 arcsecond slit length of the spectrograph. We observed NGC 6543 on 10 September 1996 using three different formats of the camera: 512z x 1024, 512 x 1024, and 256 x 1024. Along with these observations, we took internal flat-field images in each format, so that we could correct the camera distortions by rectifying the respective reseau grids. Table 1 lists the datasets used in the calibration and their characteristics. Figure 1 presents an example of a raw calibration image.

**Table 1.** Wavelength Calibration Observations

| Dataset   | Target   | Format             | Exp. Time |
|-----------|----------|--------------------|-----------|
| x3bd0101t | NGC 6543 | 512z x 1024 - SLIT | 657 sec   |
| x3bd0102t | NGC 6543 | 512 x 1024 - SLIT  | 682 sec   |
| x3bd0103t | NGC 6543 | 256 x 1024 - SLIT  | 717 sec   |
| x3bd0104t | INTFLAT  | 512z x 1024        | 600 sec   |
| x3bd0105t | INTFLAT  | 512 x 1024         | 500 sec   |
| x3bd0106t | INTFLAT  | 256 x 1024         | 500 sec   |



**Figure 1:** Raw 512z x 1024 FOC  $f/48$  spectrum of NGC6543. [O III]  $\lambda 5007$  is the bright line at the bottom, and [O II]  $\lambda 3727$  is the last line at the top. To the left of the slit is a dispersed image of NGC 6543, in which the [O III]+H $\beta$  and H $\gamma$  regions are most prominent.

### 3. Correcting Camera Distortion

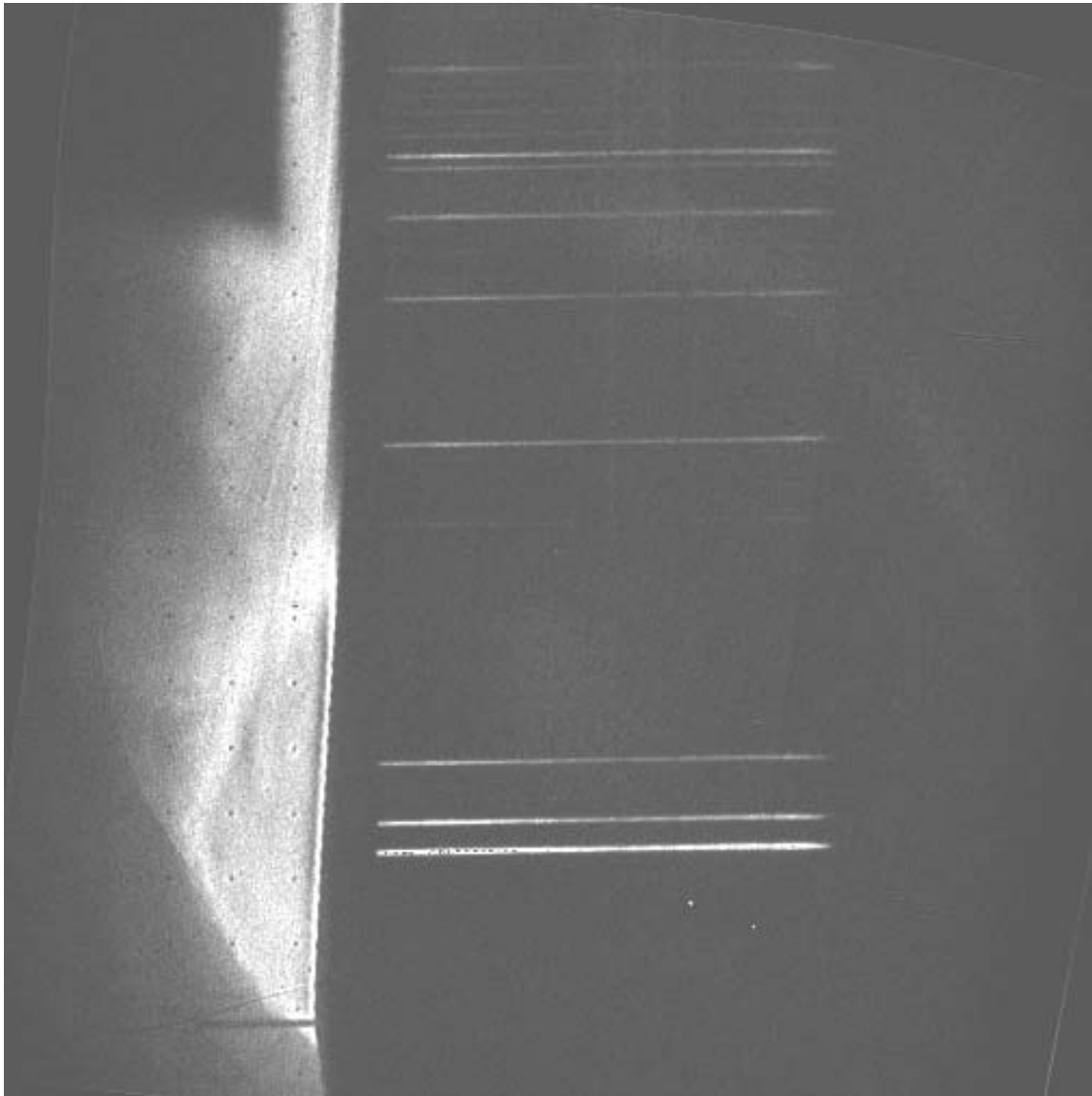
The imaging cameras of the FOC are subject to significant geometrical distortions. One way to correct these distortions is to find the 2-D transformation that maps the distorted reseau grid in a raw internal flatfield image (INTFLAT) onto a standard rectilinear set of reseau positions. Applying this transformation to the raw spectral images then yields images showing how the spectrum actually falls onto the image tube. Because the dispersion direction of the spectrograph aligns roughly with the reseau grid, this correction also rotates the spectral image close to its orientation in a fully calibrated image. What follows is a step-by-step description of how we correct the camera distortion of each format.

***Dezoom, if necessary.*** Before zoomed images can be rectified, they must first be dezoomed using the `dezoomx` task in the `focphot` package of STSDAS.

***Find reseau positions.*** The `rfindx` task in the `focgeom` package (all the following tasks can be found in `focgeom` unless otherwise stated) will find the reseau marks in an FOC image. However, the task requires as input an adequate set of reference reseau positions to initiate its search. Because the reseau positions in raw FOC images shift with time, it is sometimes necessary to shift the reference set appropriately. Reseau finding is thus best done iteratively. The first run of `rfindx` typically locates some, but not all, of the reseau marks in the image. We then use `rfitx` to determine the 2-D polynomial transformation between the found reseau positions and the reference grid. Using the task `revalfitx`, with the parameter `direction = forwards`, we apply this transformation to the reference grid, generating a new reference grid whose reseau positions are closer to those in the INTFLAT. A second run of `rfitx` with these new reference positions generally finds many more reseau marks.

***Map reseau positions to rectilinear grid.*** Once we have determined the reseau positions in an INTFLAT image, we need to find a transformation that maps them onto a rectilinear grid. The task `rgenx` generates grids of FOC reseau positions, and we use it to produce a 17 x 17 reseau grid, spaced 60 pixels apart in both dimensions, running from pixel 160 to pixel 1120 in both the  $x$  and  $y$  directions. We then use the task `rfitx` to find the polynomial transformation taking the observed reseau positions to these rectified positions. Typically, fifth-order polynomials are needed to push the residuals down below the 0.2 pixel level.

***Transform spectral images.*** The polynomial transformation that corrects the reseau grid of a given INTFLAT contains the information needed to remove the camera-based geometric distortion from a spectral image taken in the same format. To construct an appropriate geometric correction file from this polynomial, we used the task `p2geo` with `smmmodes = inbeam`. Applying this correction to the spectral images using the `newgeom` task produced corrected images ready for wavelength calibration. Figure 2 shows a spectral image following the removal of camera-based distortion.



**Figure 2:** Geometrically corrected 512z x 1024 FOC f/48 spectral image of NGC 6543. Some slight tilt and distortion of the spectral lines is still evident.

#### **4. Calibrating the Wavelength Scale**

Once camera distortion has been removed, the wavelength calibration proceeds in two steps. The first step, in which spectral lines are identified, rectified, and calibrated, is fairly standard and relies on the `noao.twodspec` package in IRAF. The second step, in which we determine the transformation that takes a raw image to a wavelength-calibrated image, is quite peculiar, because we must work within the limitations of the existing FOC calibration software.

## *Identification and Calibration*

**Initial line identification.** To identify the spectral lines in our calibration image, we used the `identify` task in IRAF. Table 2 gives our list of reference wavelengths. We avoided using the 397.007 nm H $\epsilon$  line for wavelength calibration because of its proximity to [Ne III] at 396.75 nm. The [O II] line, a density-sensitive blend, is not particularly reliable either, but we use it anyway for lack of any other information at that end of the spectrum.

**Table 2.** Calibration Line List

| Line       | $\lambda$ (nm) |
|------------|----------------|
| [O III]    | 500.68         |
| [O III]    | 495.89         |
| H $\beta$  | 486.132        |
| H $\gamma$ | 434.046        |
| H $\delta$ | 410.173        |
| H $\zeta$  | 388.905        |
| [Ne II]    | 386.88         |
| [O II]     | 372.6          |

### *Line identification in the spatial dimension.*

Once the task `identify` has been run, the task `reidentify` can be used to find the pixel positions of the identified lines at each point along the slit. In this case, we chose to measure the locations of the lines at 10 pixel intervals perpendicular to the dispersion direction. Automatic identification of the majority of the calibration lines was successful between columns 480 and 890 in the 512z x 1024 format, columns 180 and 570<sup>1</sup> in the 512 x 1024 format, and columns 180 and 350<sup>1</sup> in the 256 x 1024 format.

### *Rectification.*

The preceding tasks generate a file containing the pixel positions of each calibration line at 10-pixel intervals along the slit. We then feed this information to the IRAF task `fitcoords`, which finds a 2-D polynomial transformation mapping these pixel positions onto a grid having the wavelength scale as its vertical coordinate and the spatial position along the slit as its horizontal coordinate. As we will discuss in Section 5, our calibration accuracy depends on the width of the spatial region we choose to calibrate.

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1. In order to accommodate rotations, the pixel grid of a geometrically corrected image must be somewhat larger than the format of the original raw image.

## *Calibration of Raw Images*

Our calibration procedure provides us with two 2-D polynomial transformations, one that removes the camera distortion, taking the raw image to a geometrically corrected image, and one that removes the optical distortion and calibrates wavelength scale of the spectrograph. From these two transformations we need to construct a single FOC geometric correction file that takes a raw image directly to a wavelength-calibrated image. Two separate correction files would require two separate rebinning steps, unnecessarily degrading the quality of the calibrated image.

The time dependence of the camera distortion complicates matters. Significant changes in FOC reseau positions can arise within even a single visit. Calibration files for  $f/48$  long-slit spectrograph images are therefore most reliable when they are custom made from INTFLATs taken virtually simultaneously. A wise FOC observer would include as many INTFLATs as possible to ensure proper calibration of his or her images.

To generate a custom calibration file, we do the following:

1. Follow the procedure outlined in Section 3 to find the polynomial transformation taking the reseau positions in the contemporaneous INTFLAT to the standard rectilinear reseau grid. We will refer to this transformation as  $T_{\text{geo}}$ .
2. Let  $T_{\lambda}$  be the transformation that rectifies and calibrates a geometrically corrected spectrum taken in the desired format, as described earlier in Section 4. We do not expect these transformation to vary significantly with time, so the transformations  $T_{\lambda}$  derived here for each format ought to be adequate for calibrating all images taken with that format.
3. Generate a pseudo-reseau grid using the routine `rgenx`. The reseau positions in the  $x$ -direction should span the spatial interval of interest, and those in the  $y$ -direction should span the wavelength interval. In this program we used a  $20 \times 40$  pseudo-reseau grid, with  $y_{\text{min}} = 5300$  and  $y_{\text{max}} = 3600$ , so the blue end of the spectrum lies at the top of the calibrated image, just as in an uncalibrated image. We will call this grid the `wavegrid`.
4. Using `rtransformx` or `rgenx`, create another pseudo-reseau grid spanning the same range in  $x$  but with a  $y$ -range in pixel coordinates. In this program we used `rgenx` with  $y_{\text{min}} = 100$  and  $y_{\text{max}} = 1100$ . These choices ultimately map the wavelengths  $5300 \text{ \AA}$  and  $3600 \text{ \AA}$  nto  $y$ -pixel positions 100 and 1100, so this step sets the dispersion of the calibrated images:

$$(5300 \text{ \AA} - 3600 \text{ \AA}) / (100 - 1100) = -1.7 \text{ \AA/pixel.}$$

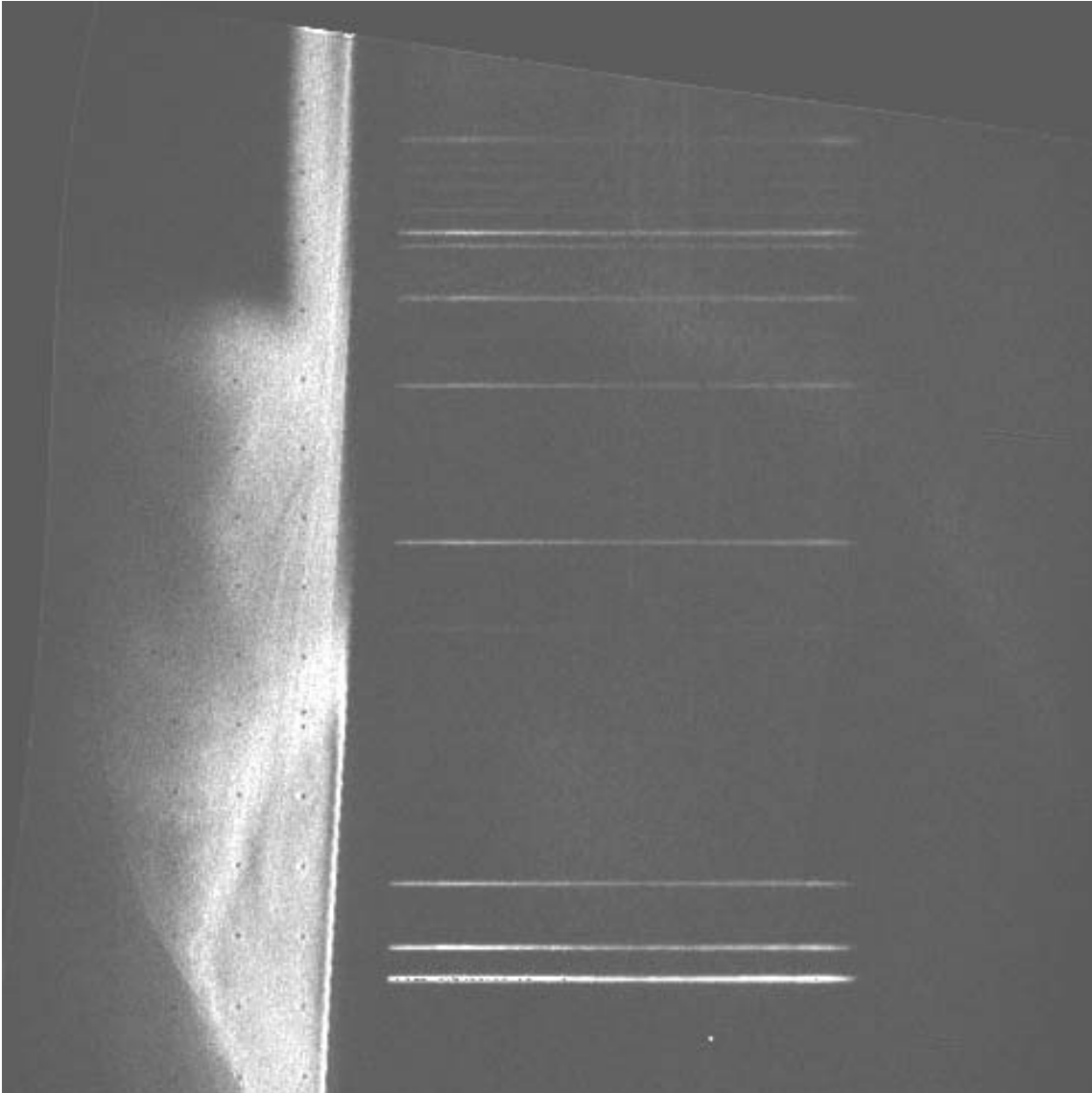
5. Run `revalfitx`, applying  $T_{\lambda}$  to `wavegrid`, with the parameter `direction = backwards`, thereby generating a new pseudo-reseau grid we will call `camgrid`.

6. Pixel numbers in FOC formats smaller than  $512z \times 1024$  are shifted relative to the full format by an amount depending on the parameter SAMPOFF. As of this writing, SAMPOFF = 192 in the  $512 \times 1024$  long-slit format, and SAMPOFF = 320 in the  $256 \times 1024$  long-slit format. Because of these shifts, pixel numbers in the  $x$  dimension are offset from the reference positions used in the software by  $1024 - 192 - 512 = 320$  pixels in the  $512 \times 1024$  format and  $1024 - 320 - 256 = 488$  pixels in the  $256 \times 1024$  format. To correct for these offsets, use `rtransformx` to shift the `camgrid` for the  $512 \times 1024$  ( $256 \times 1024$ ) format by 320 (488) pixels in the positive  $x$  direction. The  $512z \times 1024$  format requires no shifting.
7. Run `revalfitx`, applying  $T_{\text{geo}}$  to `camgrid`, with the parameter `direction = forwards`, thereby generating a another new pseudo-reseau grid we will call `rawgrid`.
8. Use `rfitx` to find the 2-D polynomial transformation taking `rawgrid` to `fingrid`. This final transformation is the one that will transform the raw image directly into a fully corrected, wavelength-calibrated image. We will call this transformation  $T_{\text{full}}$ .
9. Use the task `p2geo` to generate an FOC geometric correction file from  $T_{\text{full}}$ .
10. Correct the FOC image as usual, using `newgeom`.

The calibration files generated through the program described here are available for calibrating all post-COSTAR  $f/48$  spectrograph data. They can be used if no contemporaneous INTFLATs are available, or if a speedy calibration is preferred to an accurate one. However, observers who desire the most accurate possible calibration should generate a custom calibration file as detailed above. Figure 3 shows a fully calibrated version of the image pictured in Figures 1 and 2.

## 5. Calibration Accuracy

To test the accuracy of this calibration procedure, we analyzed how much the spectral lines in calibrated images deviate from their lab values. We binned the NGC6543 data into 10 pixel bins along the slit direction and measured the line centroids in each bin. By and large, the variances of the residuals remained within 0.2 pixels. In a few cases the residuals were larger for reasons having to do with the quality of the original image rather than the accuracy of the calibration. For instance, in the full-format image some of the pixels along the [O III]  $\lambda 5007$  line suffer from 8-bit wraparound, shifting the measured line centroid away from its true position. The calibration files created here thus correct the  $f/48$  spectroscopic wavelength scale to better than  $0.5 \text{ \AA}$ .



**Figure 3:** Fully calibrated 512z x 1024 FOC f/48 spectral image of NGC 6543.