

FLITECAM Spectroscopy Pipeline Tutorial

This tutorial is designed to help guide users through the steps of processing FLITECAM spectroscopy data, from raw data files to the final, calibrated data product. The information in this tutorial can also be found in more detail FLITECAM User's Manual.

Retrieve the Data

For this sample reduction, we'll use FLITECAM 2.8 – 3.4 μm observations of the planetary nebula BD +30 3639. These data were obtained as part of FLITECAM Guaranteed Time Observations during a 2016 flight, and the results have been published in [Smith et al. \(2020\)](#). To retrieve the data from the SOFIA Science Archive at IRSA, enter the following criteria in the main SOFIA search page (<https://irsa.ipac.caltech.edu/applications/sofia>):

Spatial Constraints → All-Sky

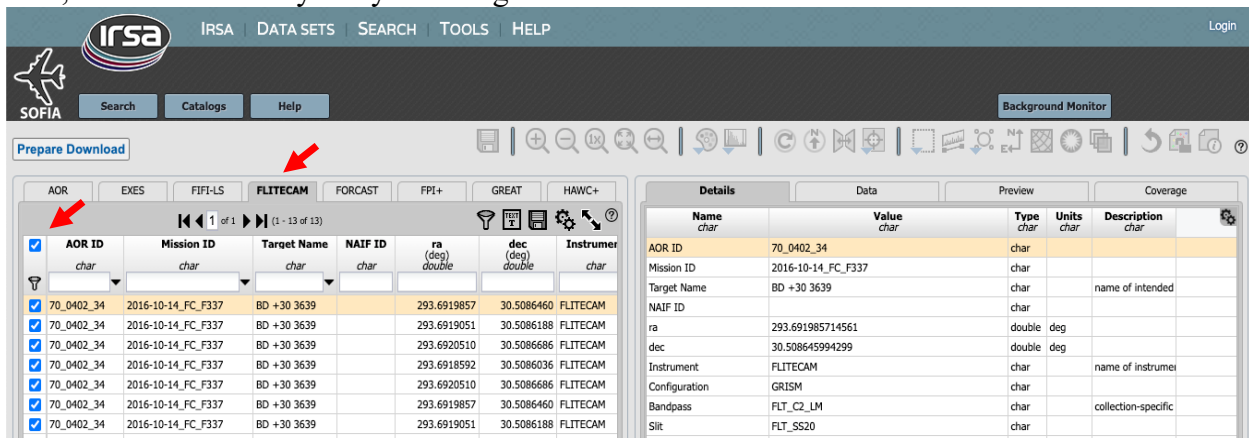
Observation Constraints → AOR ID → 70_0402_34

Data Product Constraints → Select Level 1 only (de-select Level 3 and Level 4)

or follow this link:

https://irsa.ipac.caltech.edu/applications/sofia/?api=search&spatialConstraints=allsky&execute=true&processingLevel=LEVEL_1&aorId=70_0402_34

On the search results page, click on the FLITECAM tab. On the FLITECAM tab, select all 13 data files, either individually or by selecting the box next to the AOR ID column header.



The screenshot shows the IRSA SOFIA search results page. The 'FLITECAM' tab is selected, and 13 data files are checked for download. A red arrow points to the 'Prepare Download' button. The table below shows the details of the selected data files.

Name	Value	Type	Units	Description
AOR ID	70_0402_34	char		
Mission ID	2016-10-14_FC_F337	char		
Target Name	BD +30 3639	char		name of intended
NAIF ID		char		
ra	293.691985714561	double	deg	
dec	30.508645994299	double	deg	
Instrument	FLITECAM	char		name of instrumei
Configuration	GRISM	char		
Bandpass	FLT_C2_LM	char		collection-specific
Slit	FLT_SS20	char		

Click on Prepare Download to open a download dialog box, and then select Prepare Download within the dialog box. After a few moments, you will be asked to save a zip file to disk (It is ~25MB in size). Save this file wherever you wish, unzip it, and navigate the subfolders to locate the 13 FLITECAM FITS files. You may either leave these files in the directory or move them to another location of your choice; the folder containing the 13 FITS files will be referred to as the 'input' directory for the remainder of the tutorial.

Download and Install the Pipeline

Instructions on how to download and install the *sofia_redux* pipeline package can be found at https://github.com/SOFIA-USRA/sofia_redux. If you need assistance, you can contact us through GitHub or the SOFIA Helpdesk (sofia_help@sofia.usra.edu).

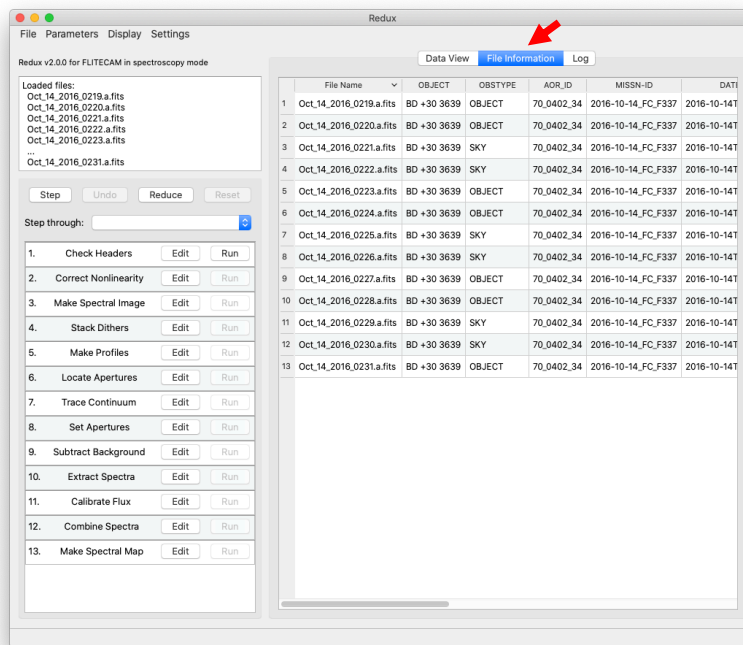
Start the GUI

The pipeline can be executed in either Automatic Mode (on the command line) or in Manual Mode (through a GUI). In this tutorial, we will focus on running the pipeline through the GUI. To begin, launch the GUI by opening a terminal and typing:

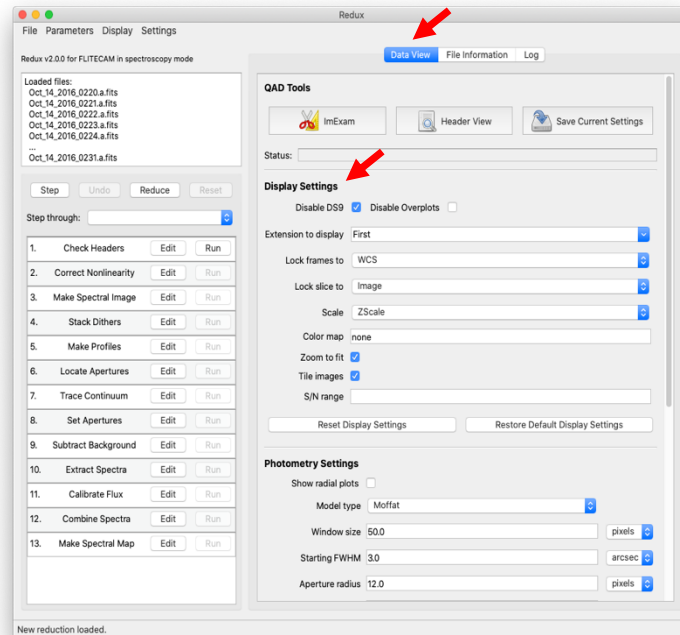
```
> redux
```

In the Redux GUI, load the BD +30 3639 data by selecting File → Open New Reduction, navigate to the input directory where you saved the data, select all 13 FITS files by clicking on the first file and shift-clicking on the last file, and then click Open. After clicking Open, the software reads the FITS headers and extracts relevant information, such as the instrument name for determining which pipeline the software will call (note that ‘Redux v2.0.0 for FLITECAM in spectroscopy mode’ is now displayed above the list of loaded files). Some additional FITS header information is shown on the File Information on the right side of the GUI.

These observations were taken in the nod along slit mode, which is typically carried out in an ABBA pattern. In the ‘File Information’ tab, if you scroll all the way to the right, the nod beam for each file is displayed. The first file, Oct_14_2016_0219a.fits, shows a value of ‘UNKNOWN’; in addition, the integration time (EXPTIME) is only 0.3 seconds compared to 30 seconds for all of the other files. In order to keep the proper ABBA pairing, this file should be removed from the reduction. ** To do this, go to the ‘File’ menu on the top left of the redux GUI and select ‘Remove Files’ from the pull-down menu, which will open a window with the list of files that are part of the current reduction. Select file Oct_14_2016_0219a.fits. Click OK to exclude this file from processing. ***



When the pipeline runs, it is possible to automatically display the intermediate data using SAO DS9 if it is set up properly (see <http://ds9.si.edu/> for download and installation instructions; the ds9 executable must be available in the PATH environment variable for the pyds9 interface to be able to find and control it). Alternatively, the automatic display can be disabled (each pipeline module can optionally produce FITS file output in case a different FITS viewer is preferred). Options for displaying images in DS9 are found under Display Settings on the Data View tab.

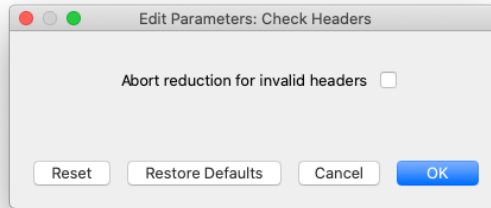


Run the Pipeline

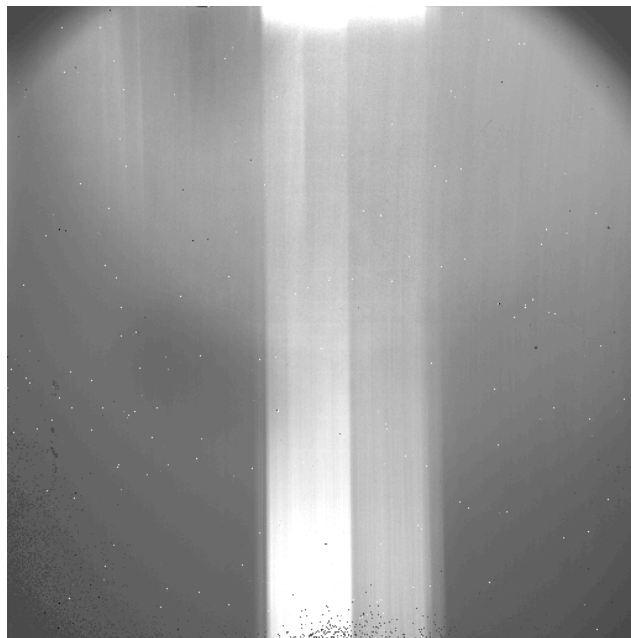
There are 13 modules in the FLITECAM spectroscopy pipeline, shown in the bottom-left panel of the GUI. Each pipeline module can be configured by clicking the 'Edit' button for that module. The entire pipeline can be executed by clicking the 'Reduce' button. Alternatively, the modules can be run individually by clicking on the 'Run' button for that module, or in a small group by selecting an end point in the 'Step Through' dropdown menu, then clicking 'Step.' In this tutorial, we'll run the modules one by one and examine their output.

1. Check Headers: This module examines the fits headers to make sure that they have the keywords required by the pipeline.

Options: Click on the Edit button next to Check Header module. A popup window for Edit Parameters for Check Headers will open up. In the popup window if the 'Abort reduction for invalid headers' option is not selected, the pipeline may fail in unexpected ways (as always: garbage in, garbage out!).



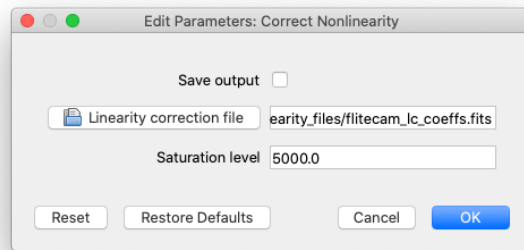
Output: This module creates no output; it allows the data set to pass through to the next modules in the reduction. For comparison with the output of the next module, we show the input file Oct_14_2016_0219a.fits before any pipeline modules have been applied.



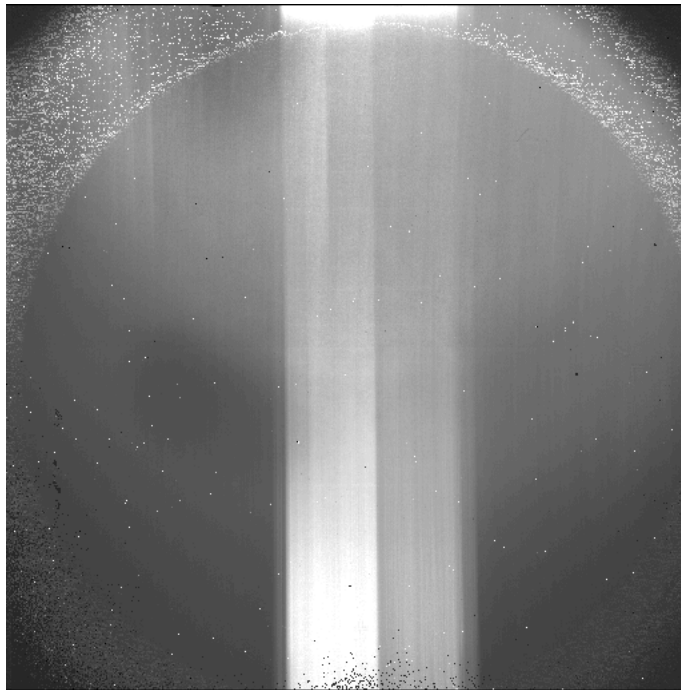
First plane of file Oct_14_2016_0224a.fits.

2. Correct Nonlinearity: This module corrects the data for detector nonlinearity using the method described in [Vacca et al. \(2004\)](#). It also creates a bad pixel mask that is associated with the data, which initially contains the locations of saturated pixels.

Options: You may notice an unusual (and non-local) file name in the ‘Linearity correction file’ field. If you installed the pipeline using pip or conda, the default file used in this step has not yet been installed. It will be automatically downloaded from cloud storage (which requires an internet connection) the first time this module is run and cached locally for future running of the pipeline. You can expect similar behavior for other pipeline modules that use reference data. (Note that if you installed from source, then these reference data files are download during the install) The ‘Saturation level’ value species the threshold used to flag saturated pixels that are then included in the bad pixel mask. If no saturation clipping is desired, no number should be entered in this field. By default, the output FITS file for this step is not saved.



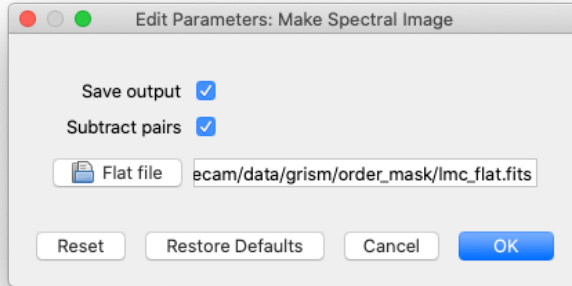
Output: The output from this step is shown below.



First plane of F0337_FC_GRI_70040234_FLTC2LM_LNZ_0224.fits.

3. Make Spectral Image: This module combines the A and B nod data, and also applies a flat correction to the data.

Options: The 'Subtract pairs' option combines A/B nod data in the order they were taken, which is why removing file 219 (see p. 2) was important.



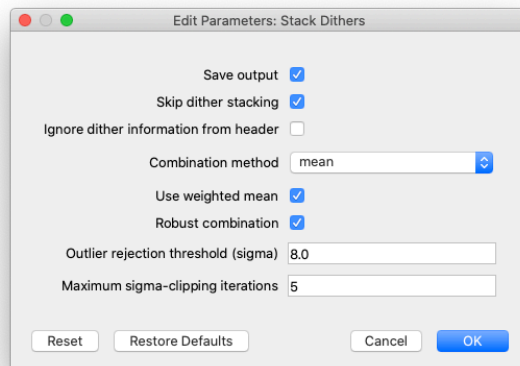
Output: The output from this module shows the positive (white horizontal stripe) and negative (black horizontal stripe) images of the source.



First plane of F0337_FC_GRI_70040234_FLTC2LM_IMG_0224-0225.fits. Wavelength is along the x axis, and slit position is along the y axis.

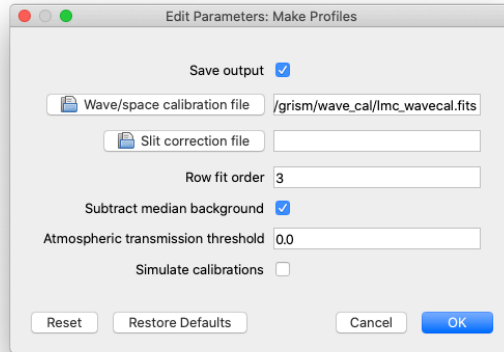
4. Stack Dithers: If the source is very faint, then we can perform a dither stacking module. Because we can see the source in the previous image, this module can be skipped.

Options: The default option is to skip dither stacking. If it is skipped, the other parameters are ignored.

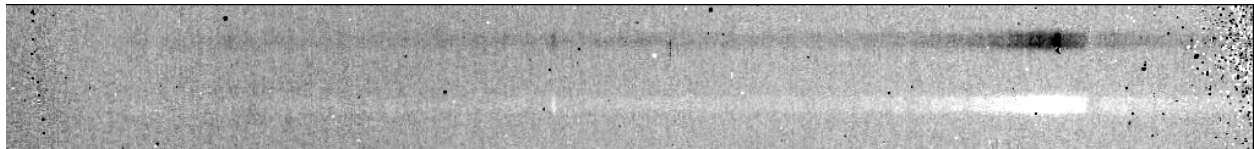


5. Make Profiles: This module creates a rectified image in which the data are resampled onto a regular spatial-spectral grid. It also creates and displays the smoothed spatial profile of the source across the slit.

Options: The relevant wavelength calibration and slit correction files (if they exist) are loaded by default, but can be specified by the user. In this example, no slit correction file is used. The ‘Row fit order’ is used to calculate the spatial profile. Order 3 typically works well, but a higher or lower order may yield better results. The ‘Subtract median background’ will optionally subtract a background from the profile. We will leave this box checked and examine the results.

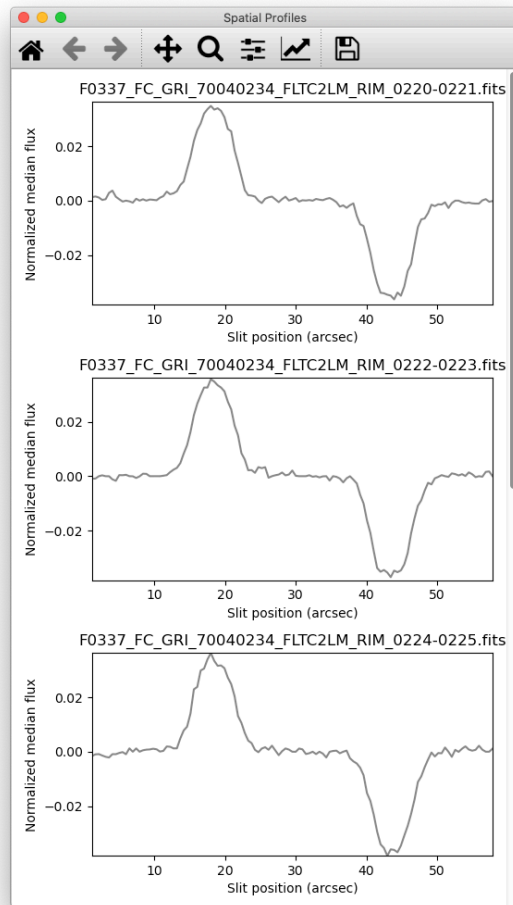


Output: In the image below, the y-axis is along the slit (the spatial direction), and the x-axis is the wavelength axis.



First plane of F0337_FC_GRI_70040234_FLTC2LM_RIM_0224-0225.fits.

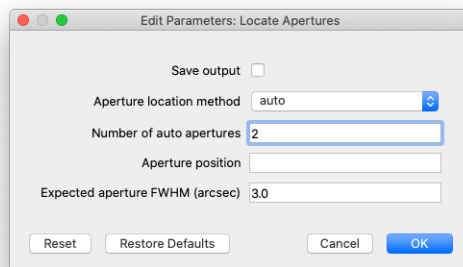
In addition to the FITS file output, this module (and several of the next modules) also displays results in a pop-up spectral viewer. The spectral viewer displays the relevant data (shown in the title) in a single column format and the user can use the scroll bar to view the various data or resize the spectral viewer as shown below:



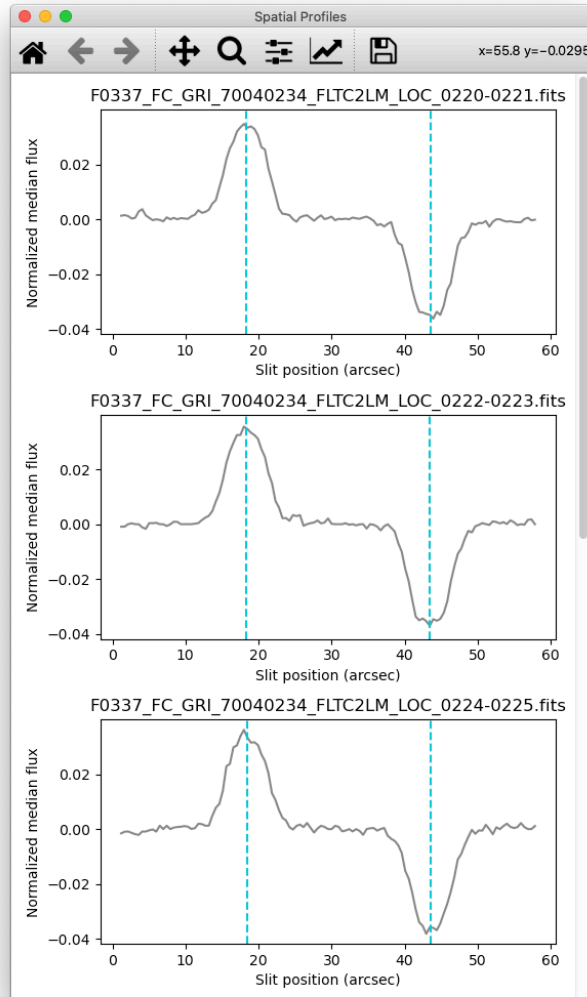
The pop-up window displays the spatial profiles for the 6 AB nod pairs.

6. Locate Apertures: This module identifies the location(s) of the source along the slit.

Options: The default 'auto' option attempts to find the location of the strongest Gaussian peak in the spatial profile. If this does not work for all spectra, users can also specify a specific location along the slit (using 'fix to input') or simply use the central position (using 'fix to center'). It is also possible to fit multiple sources. Since we have one positive and one negative image of our source, we will use two apertures.



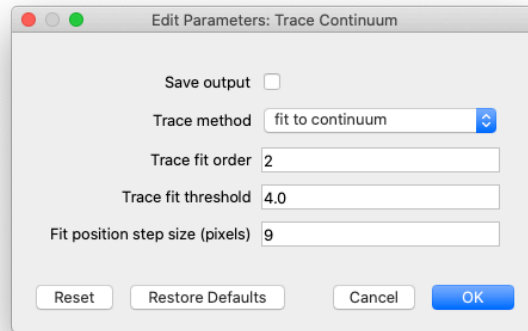
Output: The image below shows the results when the pipeline automatically determines the aperture positions. For each of the 6 nod pairs, the pipeline correctly identifies the positive and negative peaks.



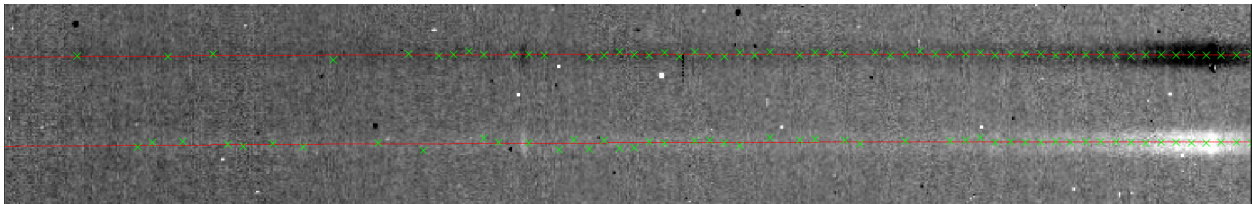
The pop-up window displays the identified aperture centers, overlaid (blue dashed line) on the spatial profiles for the 6 AB nod pairs.

7. Trace Continuum: This module identifies the location of the spectrum across the array, to account for the slit curvature across the array.

Options: The main options are either to have the pipeline determine the location of the spectrum automatically or to fix it to the aperture position. If fixed to the aperture position, a default slit curvature will be used. We will use the 'fit to continuum' method for a more accurate determination of the curvature.



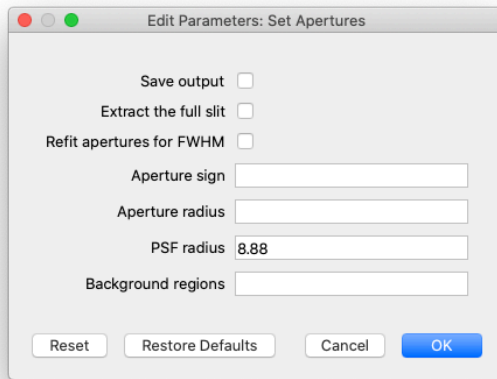
Output: The image below shows the output of this module. The green 'x' positions mark the position of the source at each wavelength, and the red curve is the polynomial fit to the 'x' positions.



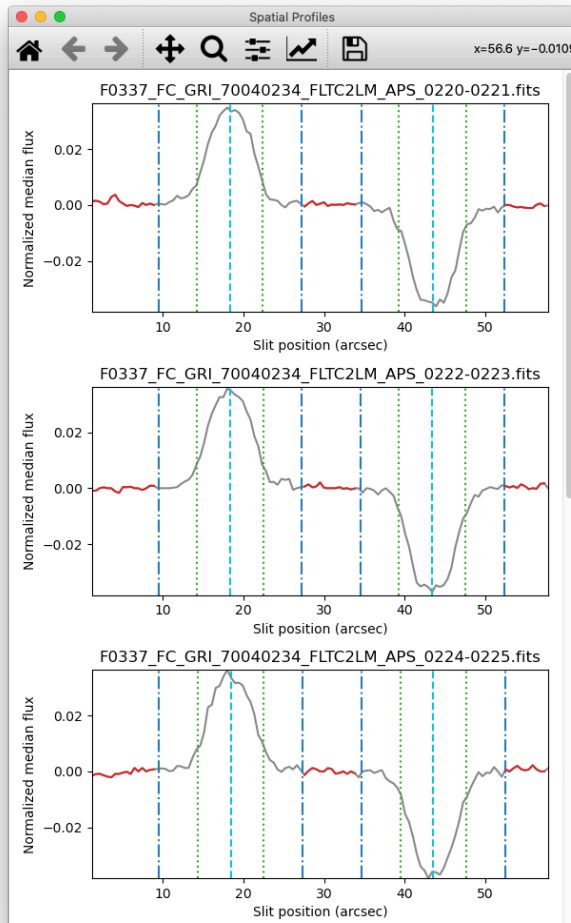
The first plane of F0337_FC_GRI_70040234_FLTC2LM_TRC_0224-0225.fits overlaid with ds9 region file F0337_FC_GRI_70040234_FLTC2LM_TRC_0224-0225.reg

8. Set Apertures: This module identifies the region that will be extracted from each spatial profile to create the final spectrum.

Options: By default, the pipeline automatically determines the aperture and PSF radius to extract by analyzing the spatial profile and the aperture position defined above. If run using these default options, the pipeline returns the error: "The extraction apertures overlap. Please lower the aperture radii." This occurs because the automatically determined PSF radius is too large. As found in the Users' Manual the PSF radius is $2.15 \times \text{FWHM}$. The average FWHM for our data was determined in Step 6, and is 5.92 arcseconds (you can see this by clicking on the 'Log' tab in the GUI and scrolling up). We will instead try a factor of 1.5, or a PSF radius of $1.5 \times 5.92 = 8.88$ arcseconds. We can leave the other fields blank, and they will be automatically determined by the pipeline.

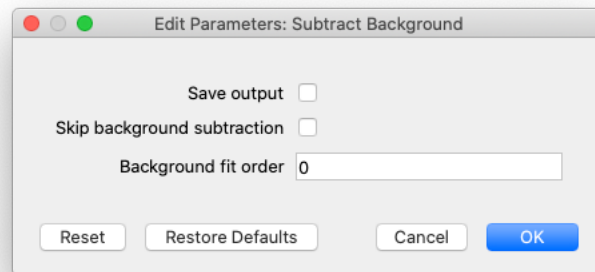


Output: The results of the aperture fitting are shown in the pop-up window, shown below. The cyan line shows the aperture center, the green lines show the edges of the extraction aperture, and the dark blue line shows the region as the flux goes to zero (PSF radius). The red lines indicate the background regions.

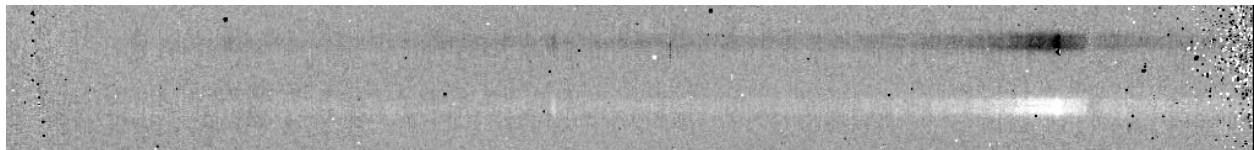


9. Subtract Background: In this module, the residual background is removed using the regions defined in the previous module.

Options: By default, the background is removed, but this module can also be skipped. In our example, the background levels are already close to zero so this module does not make a big difference in the final product. Nevertheless, we will leave the background subtraction on.



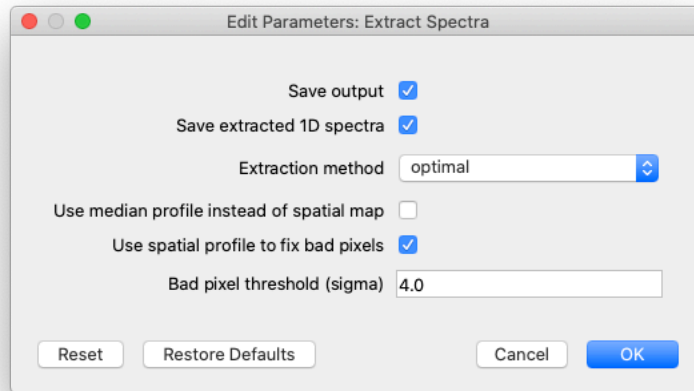
Output: Here is the output from this module, which is the background-subtracted 2-d image. As with the other 2-d images shown, the y-axis is along the slit (the spatial direction), and the x-axis is the wavelength axis.



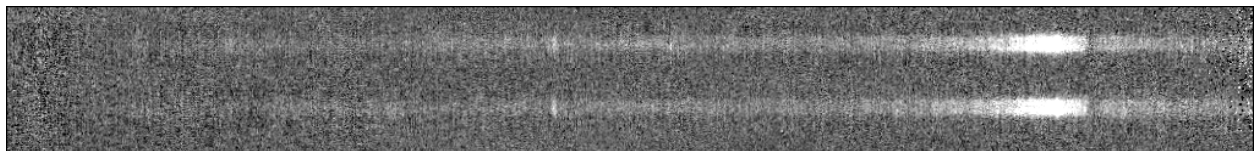
The first plane of F0337_FC_GRI_70040234_FLTC2LM_BGS_0224-0225.fits.

10. Extract Spectra: This module uses the apertures defined in previous modules to extract a 1-d spectrum from each of the input file pairs.

Options: The ‘optimal’ extraction method is the one we will use; it is also the default option unless the observations are of very extended sources, or if the data were taken in a slit scan mode. The pipeline will also attempt to fix bad pixels; if this causes errors to occur (it doesn’t for our example), this option can be turned off.

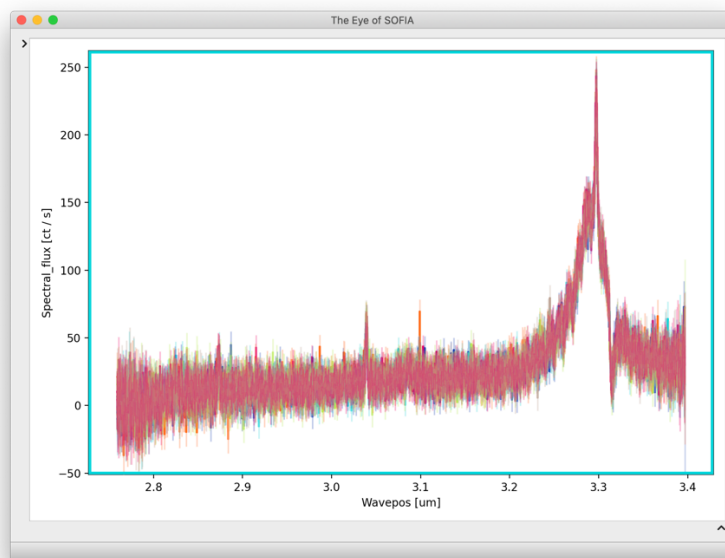


Output: The output image shows that the bad pixels have been repaired, and that the negative spectrum has been multiplied by -1 so that it can be combined with the positive one.



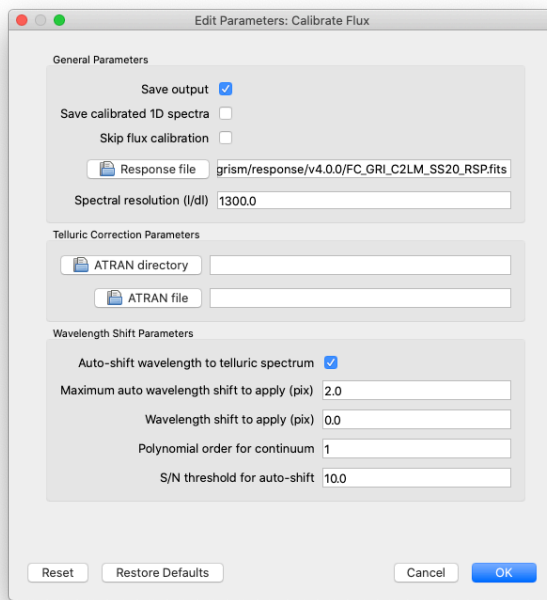
F0432_FO_GRI_05006326_FORG227_SPM_0108.fits

The 12 spectra are now plotted together in the Eye of SOFIA window, an advanced spectral viewer. Note that the y-axis units are still in counts/s since we have not yet flux calibrated the data, which happens in the next module.

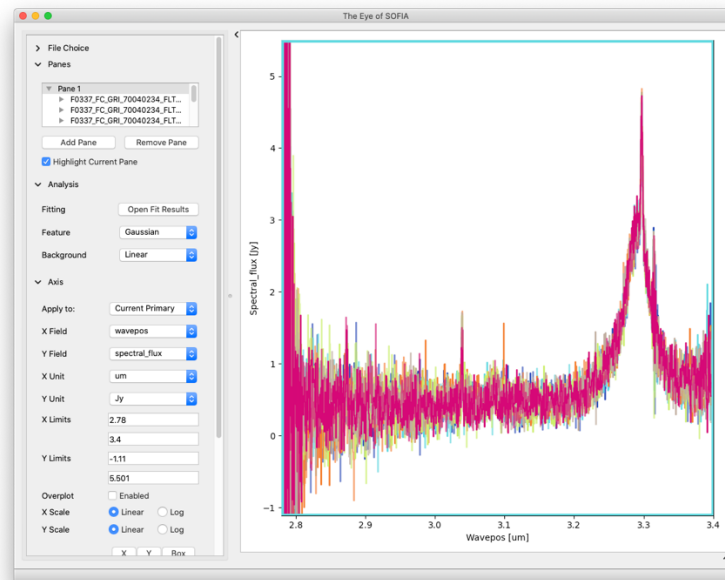


11. Calibrate Flux: In this module, each spectrum is corrected for instrumental response and atmospheric transmission, resulting in a calibrated spectrum in units of Jy per pixel. This module is broken up into three sub-modules as shown below. The telluric correction sub-module corrects for the opacity of the atmosphere using ATRAN models of the atmosphere (courtesy of Steve Lord: <https://atran.arc.nasa.gov/cgi-bin/atran/atran.cgi>). Due to size constraints in the git repository, the default pipeline installation contains only a single atmospheric model. It's very likely that this file will be insufficient to properly correct for the atmosphere, so you will need to download a library of ATRAN files for a range of flight altitude, telescope elevation, and water vapor. This library is available on the <https://www.sofia.usra.edu/science/data/data-pipelines> page. Take the time now to download the models, and note their destination directory (if you have trouble finding or downloading the files, please contact the SOFIA Helpdesk at sofia_help@sofia.usra.edu).

Options: In the 'General Parameters' sub-module, the instrumental response file can be specified. The appropriate file should be loaded by default, but a different file can be used if desired. In the 'Telluric Correction Parameters' sub-module, click on the 'ATRAN directory' button and browse to the directory containing the models you downloaded. This sub-module also provides an option to choose a custom user supplied telluric model using the ATRAN file selection button. If a user provided telluric model is used, then all other options are de-selected. The 'Wavelength Shift Parameters' sub-module provides options to apply a wavelength shift to the data to get the best telluric correction. By default, the pipeline finds the best shift using an optimization routine and tries shift values up to the maximum shift of 2.0 pixels. If the correlation between the transmission and source spectra is not strong, this routine may suggest shifts that are relatively large and not appropriate for the data. Here again the user can use a custom shift using the 'Wavelength shift to apply (pix)' input, which de-selects all the other parameters from this sub-module.

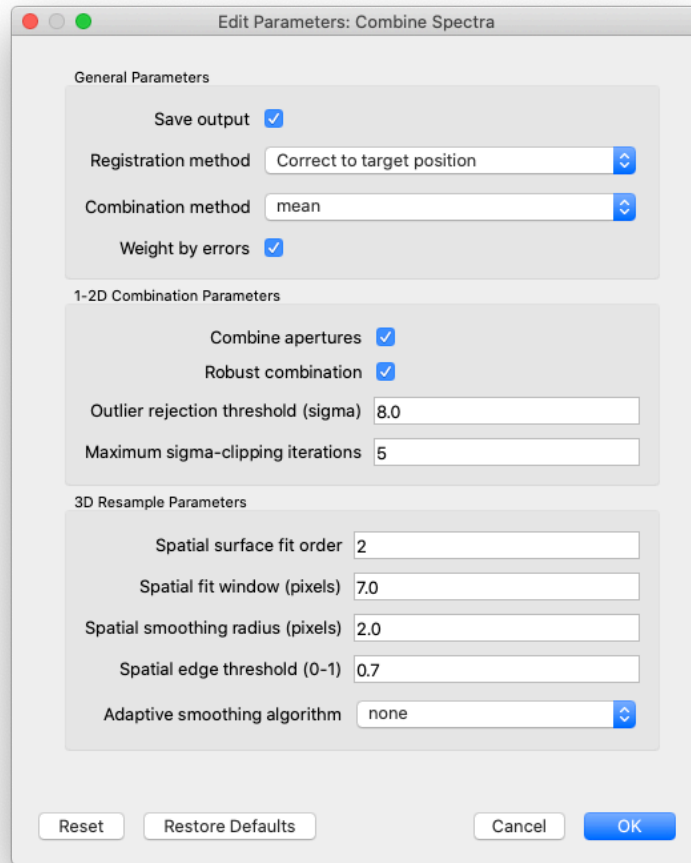


Output: The calibrated spectra, now in Jy, are plotted together in the Eye of SOFIA window.

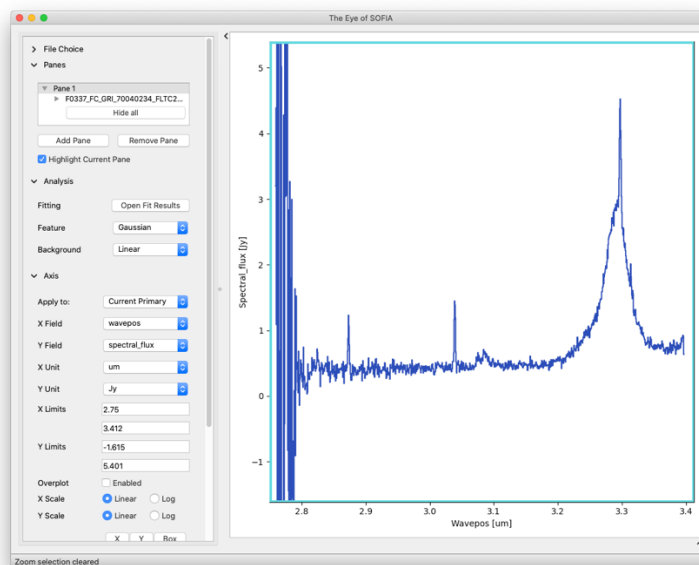


15. Combine Spectra: This module combines the 1-D spectra into a single spectrum and the 2-D images into a single image.

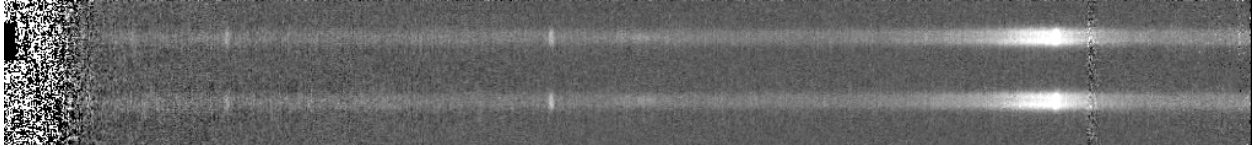
Options: The options in this module are also broken up into three sub-modules. In the 'General Parameters' sub-module, we can select how the images are registered. The default method of 'Correct to target position' will use the target positions from the headers, if they exist, or else will use the WCS as-is. The combination method determines if the mean (optionally weighted by errors) or median is used. The default is to use the error-weighted mean. In the 1-2D Parameters sub-module, the spectra from the two apertures can be combined to increase the signal-to-noise. If the 'Robust combination' option is selected, the data are iteratively sigma-clipped before they are combined using the other two settings. The '3D Resample Parameters' are used for slit-scan data when creating 3D data cubes and are not applicable to this example.



Output: The calibrated, combined spectrum is plotted in the Eye of SOFIA window.



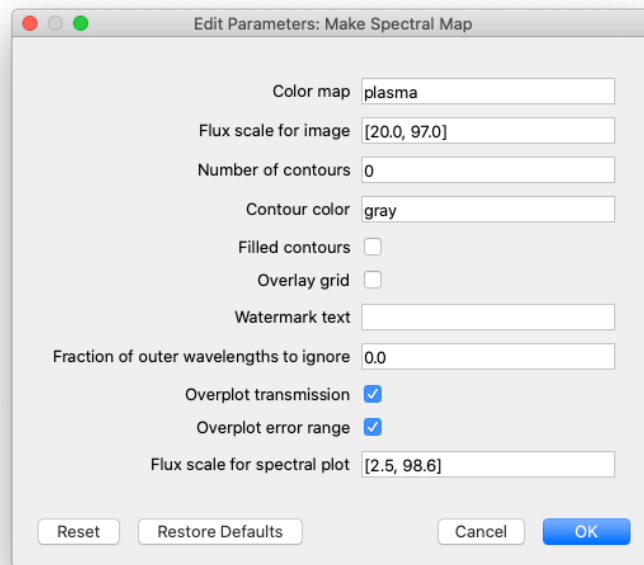
In addition, two final FITS data products are produced, one containing the final 2D image (shown below; the y-axis is the spatial direction, and the x-axis is wavelength) and one containing the final 1D spectrum.



The first plane of F0337_FC_GRI_70040234_FLTC2LM_COA_0220-0231.fits.

16. Make Spectral Map: This last module is used to generate a png file from the final data product.

Options: These options control the look of the final png image. After a few attempts, it appears that setting 'Flux scale for image' to [20.0, 97.0] and 'Flux scale for spectral plot' to [2.5, 98.6] yields a well-scaled final image.



Output: The final png file contains both the spectrum (overlaid with a plot of the atmospheric transmission) and the 2D image.

Object: BD +30 3639, Grism: FLT_C2_LM

