The Data Reduction Pipeline for FIFI-LS, the MIR Integral Field Spectrograph for SOFIA

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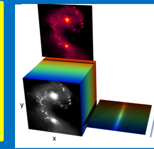

Introduction:

The Far-Infrared Field Imagine Line Spectrometer (FIFI-LS) is a mid-infrared integral field spectrometer used on the Stratospheric Observatory For Infrared Astronomy (SOFIA). [1,2] It consists of two separate grating spectrometers (channels) that share a common set of foreoptics. A dichroic splits the light into a “blue” channel covering 51-125 µm and a “red” channel covering 115-203 µm. Each spectrometer contains an image slicer, a grating, and a Ge:Ga detector with 400 (16 x 25) pixels. Within each spectrometer, the image slicer reconfigures the 5 x 5 spatial pixels (‘spaxels’) that comprise the field of view into a one-dimensional long slit array of 25 pixels. (The spaxels are 6” on the blue side and 12” on the red, giving fields of view of 30” and 60”, respectively, approximately co-aligned.) The 1-D array of 25 spaxels is then dispersed by the grating and projected onto the detector. The detectors comprise 16 spectral pixels (‘spexels’) for each of the 25 (5x5) spaxels. See Fig. 1.

The SOFIA pipeline to reduce FIFI-LS data and generate 3-D data cubes is written in Python and runs within the SOFIA Redux environment that allows both fully automatic and manual processing. Manual processing is carried out via the Redux graphical interface [3].

Observations and Data Files:

As is typical for MIR instruments, observations with FIFI-LS are usually obtained by chopping and nodding:

- At a given position (A) the secondary is chopped at 4 Hz between the source and an off-source/sky position.
- After ~30 sec, the telescope is nodded to a second position (B), and the chop cycle is repeated. Subtracting the chops and then combining the nods removes the sky and telescope background.
- To expand the wavelength coverage beyond the instantaneous range provided by the 16 spectral pixels, the grating angle is usually stepped through a number of values every 10 sec at each nod position.
- Each pixel is read out at 256 Hz, and is re-set after 32 reads. The source flux is proportional to the slope of the pixel values during a read-out sequence (‘up-the-ramp’ sampling). See Fig. 2
- A map of a source is generated by dithering several observations

A single FIFI-LS data file contains a table of all the readout values for each pixel, for the two chop positions and all the grating positions, at a given nod position.

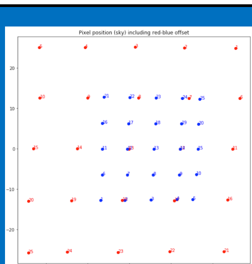

Fig. 4.: Spaxel positions in arcseconds on the sky relative to the center of the red detector. Red dots refer to the red spaxels; blue dots are for the blue spaxels. The numbers refer to the internal numbering scheme of the spaxels.

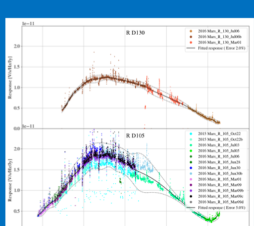

Fig. 5.: Instrumental response curves for the red detector for two different dichroics. The responses are derived from observations of the calibrators divided by model fluxes.

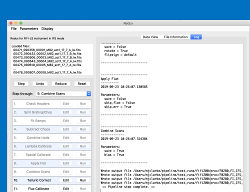

Fig. 6.: The Python Redux interface for running the FIFI-LS pipeline manually. The files loaded for reduction are shown in the top panel. The reduction steps are shown below. The reduction steps can be performed individually by clicking on Run. Parameters adopted in the reductions can be modified via the Edit button. A log of the reduction procedure is shown in the panel to the right.

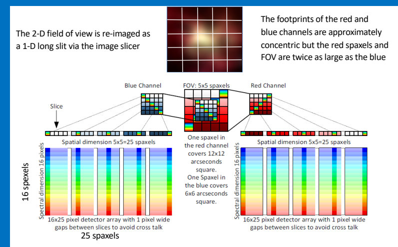

Fig. 1.: Basic design of FIFI-LS; the fields of view (FOVs) on the blue and red sides are divided into 25 spatial pixels (spaxels), which are re-imaged into a long-slit configuration by the image slicers. These are then dispersed onto 16 spectral pixels (spexels) by the gratings. Adapted from [1].

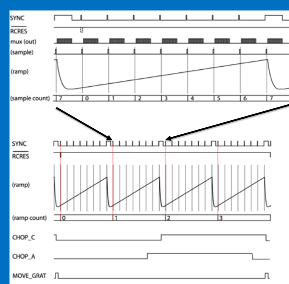

Fig. 2.: Readout sequence of a FIFI-LS pixel. The upper diagram shows 8 readouts per ramp. The lower diagram shows that there are two ramps per chop position, and the grating is moved after the chop cycle is completed.

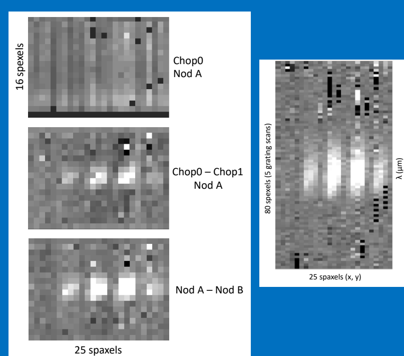

Fig. 3.: Left: (Top) Detector array after an observation in chop position 0 in nod position A. (Middle) After subtracting the array values obtained at the two chop positions. (Bottom) After combining the array values obtained at the nod positions. Right: After combining 5 grating scans. The wavelengths are irregularly sampled, even though they appear to be on a grid.

Resampling onto a regular grid:

The combined data set for an observation consists of a cloud of data points, irregularly sampled in both space and wavelength. For display and analysis, this data cloud must be re-sampled onto a regular 3-D grid in both space and wavelength. The previous version of the pipeline carried out this resampling in two steps: first in λ and then in (x, y). The current version performs the resampling in one step, by fitting a smooth polynomial to the fluxes within a volume as a function of (x, y, λ) simultaneously. (Fig. 7)

- Determine absolute $(x, y, \lambda)_{min}$ and $(x, y, \lambda)_{max}$ from all the data.
- Determine sampling Δ = FWHM/n_{samp} where n_{samp} is the number of sample points per FWHM (both spatial and spectral); n_{samp} = 8 for spectral points and 5 for spatial points.
- Construct a regular grid spanning the entire volume in (x, y, λ).
- At each point in the grid, find all *n* pixel values within an ellipsoidal volume f x FWHM (f = 0.5 in wavelength and 3 in space).
- Robustly fit an N-order (N ~ 2) polynomial surface to the *n* data points within the volume, weighted by errors and a Gaussian function of the distances δ from the grid point; flux and error at the grid point are determined from the fit.

The data have a spatial sampling of 1” in the blue and 2” in the red; the spectral sampling is set by the spectral FWHM. The data are now on a regular 3-D grid (x, y, λ) and the 3-D data cube can be visualized in RA and Dec (with N up, E left) at each λ or as a spectrum at a given pixel (Fig. 8).

Output Files:

The output of the pipeline is a single FITS file with a number of extensions for: telluric-corrected flux and error, uncorrected flux and error, λ, offsets in x and y, atmospheric transmission curve, instrumental response curve, and exposure map (number of observations at each point). The fluxes (in Jy), errors, and exposure maps are 3-D cubes (n_x x n_y x n_λ), with axes of RA, Dec, and λ (µm). Comparisons with Herschel/PACS observations of the same source indicate the FIFI-LS pipeline fluxes are accurate to within 10%.

Pipeline Steps:

1. **Read the input file and re-format the data**:
   - Separate the values for the chop positions and the grating positions.
   - Perform a robust linear fit to the data values to derive count rates from the ramp slopes.
   - Combine the count rates at a given chop position with a weighted mean to derive instrumental fluxes and errors.
2. **Demodulate the data**:
   - Subtract the count rates for the two chop positions.
   - Combine the values for the two nod positions. (Fig. 3, left)
3. **Apply instrumental calibrations**:
   - Wavelengths are assigned to each pixel. Each of the 25 spaxels has its own wavelength calibration for its 16 spexels derived from lab measurements; each spexel has a different spectral width $\Delta\nu$ as well. The instrumental flux density at each λ is computed by dividing by the spectral width.
   - The relative sky position of each pixel is computed and recorded, including the offset between the blue and red arrays. Due to misalignments in the optics, the spaxels are not oriented on a rectilinear, regular grid on the sky (Fig. 4).
   - Apply spectral and spatial flat fields, derived from sky observations (‘sky dips’) and lab measurements.
4. **Combine data from the various grating positions**:
   - Subtract bias offsets between values obtained for different grating positions.
   - Sort by wavelength; because of the different λ calibrations for the spaxels, the data are irregularly sampled in λ (Fig 3, right).
5. **Apply telluric and flux calibration curves**:
   - Telluric corrections are derived from ATRAN [4] models for the Altitude and ZA of the observations.
   - Telluric spectrum is smoothed to instrumental resolution, binned, resampled and then applied to the observed data.
   - Values where the transmission is below a set value (60% by default) are set to NaNs.
   - Instrumental response curves to convert ADU/s/Hz to Jy, derived from observations of standards (primarily Mars) and theoretical models [5], are then applied (Fig. 5).
6. **Resample onto a regular grid in both wavelength and space**

While the pipeline can be run completely automatically with predefined parameter values, it can also be run manually, one step at a time. The Redux interface allows the parameters of each step to be modified, and the steps to be run sequentially. The output of each step can be inspected and a step can be re-run if desired. (See Fig. 6.) The data viewer adopted by Redux is SAOImage DS9.

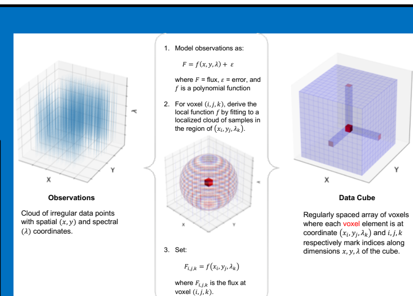

Fig. 7.: Overview of the resampling method adopted in the FIFI-LS pipeline. The cloud of data values, irregularly sampled in both space and wavelength, is resampled onto a regular grid by fitting a low order polynomial to the values within a local region/window.

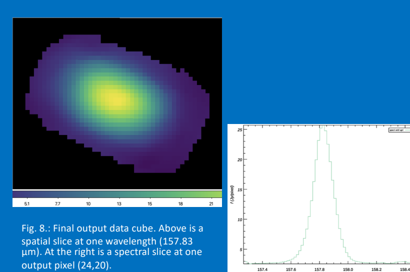

Fig. 8.: Final output data cube. Above is a spatial slice at one wavelength (157.83 µm). At the right is a spectral slice at one output pixel (24,20).

References:

[1] Fischer, C., et al. 2018, J. of Astr. Instr., vol. 7, no. 4, 1840003
[2] Colditz, S., et al. 2018, J. of Astr. Instr., vol. 7, no. 4, 1840004
[3] Clarke, M., Vacca, W. D., & Shuping, R. Y. 2015 in ADASS Conf. Ser. 24, ADASS, ed. A. R. Taylor & J. M. Stil, (San Francisco, CA: ASP)
[4] Lord, S.D. 1992, NASA Technical Memorandum 103957
[5] Amri, H. & Lellouch, E. 2006: http://www.lesia.obspm.fr/perso/emmanuel-lellouch/mars/index.php