[IMAGING-SPECTROSCOPY] User Guide to STIX Imaging-Spectroscopy in IDL

Andrea Francesco Battaglia (andrea.battaglia@fhnw.ch)
Last modification of the document: 2023-07-04

Fachhochschule Nordwestschweiz

TABLE OF CONTENTS

Introduction

This document contains information on how to run the imaging-spectroscopy software written in IDL. To run it, a working SSWIDL is needed, including the STIX-GSW package.

The current version of the software allows you to extract the flux of different sources using the forward-fit (fwdfit, Volpara et al. 2022) algorithm. This algorithm was chosen because the normalization of the flux is done automatically by the algorithm and is not an input of the user. If necessary, fluxes obtained from other algorithms (e.g., CLEAN, MEM_GE, ...) can be implemented. In such cases, however, the user must input the contour level over which to integrate, which may not be an easy decision beforehand.

Idea of the current version of the software. If you do not know a priori the configuration of the reconstructed image (in the considered energy range), then at each energy bin you have to specify the number of sources. If you know it, by specifying `configuration_fwdfit`, you do not have to select the sources each time. By default:

- if we have less than 1000 counts in a given energy range, the procedure stops iterating;
- the regularized visibilities are used. Set the keyword `/standard_vis` to use the standard visibilities;
- if `configuration_fwdfit` is not specified, the script assumes circular Gaussians. Set the keyword `/ellipse_shape` to use elliptical Gaussians;
- if the location of the sources is not specified, then they are fitted with the fwdfit algorithm. If the keyword `/select_location` is set, then the user can select the location of the sources on the screen (for each energy bin) using the cursor. If the keyword `/select_box_location` is set, then the user can select boxes on the screen to constrain the location of the sources for the fwdfit algorithm.

If the user wants to fix the location of certain sources (e.g. footpoints) but fit others (e.g. nonthermal coronal sources, as in Krucker & Battaglia 2014), they can set the `/select_box_location` keyword. The location can then be fixed by double-clicking on the same location. This allows the user to fix the location of known sources (e.g. footpoints) and fit the location of unknown sources (e.g. nonthermal loop-top sources) with boxes.

Note that in the current version of the software (status: July 2023), if the `/select_box_location` keyword is set and the user manually fixes the location (by double-clicking on the same location), the shape will automatically change to circular Gaussian.

User guide

The current STIX imaging-spectroscopy version of the software is based on three different procedures:

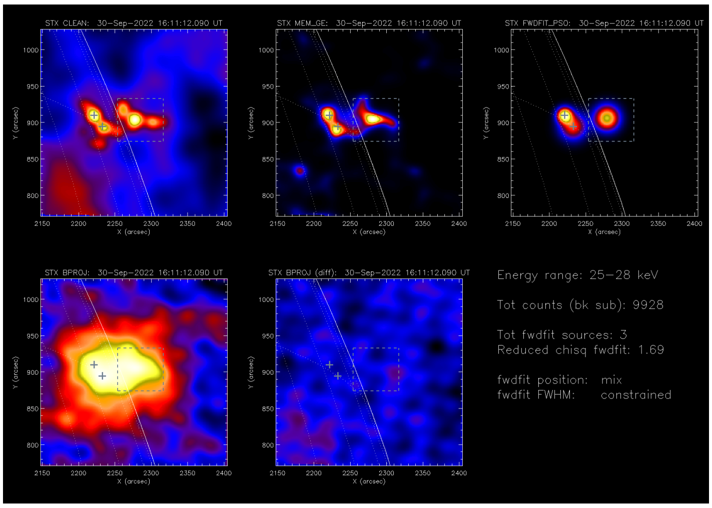
- `stx_imaging_spectroscopy`
- `stx_plot_imaging_spectra`
- `stx_flux2ospex`

The current version of the imaging-spectroscopy software has three separate procedures. However, in the near future, we could think to merge them together. In the following sections, we will briefly explain each of these procedures.

stx_imaging_spectroscopy

The first script to be run is the one that allows us to perform imaging at each selected energy bin. By default, backprojection, CLEAN, and MEM_GE maps are produced for context. Indeed, at each energy bin, the user needs to indicate how many sources are present so that this information can be passed to the forward-fit algorithm. There is also the option to input the number of sources and configuration externally, so that the program runs automatically (and not semi-automatically). However, it is highly recommended to analyze the images at each step in order to obtain meaningful results in the end.

At each step in energy, an IDL save file, together with a summary figure, is stored externally. This allows the user to make changes to a specific energy bin without having to rerun the program for all energy bins. Here is an example of the summary figure that is stored with the save file:



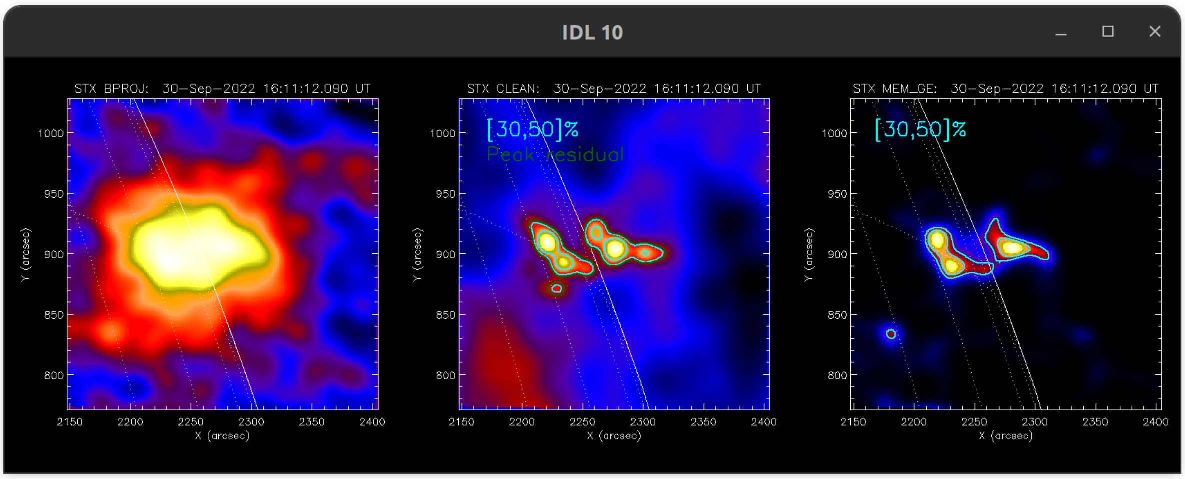
Summary figure that is stored in the same folder as the IDL save files. CLEAN, MEM_GE, forward-fit, and backprojection maps are shown. The panel in the bottom-center displays the difference between the backprojection map and the backprojection map obtained from the forward-fit predicted visibilities. The two maps in the bottom row share the same color-table.

Below is an example script for running the code. It lists all required inputs, as well as some relevant optional keywords. (Please note that some keywords have already been activated for demo purposes. Please review all of them to meet your needs.) **Please note that the program will crash if we do not provide the absolute path for the science, bkg and aux files!**

```
; ********** INPUT PARAMETERS **********

;;;;; Path where to store the save and png files that will be generated
path_sav_folder = '../../'

;;;;; Path to the science, bkg and auxiliary files
;; It only works by giving the ABSOLUTE PATH!!!
;; You can find the data in the following folder:
;;          imaging-spectroscopy_temporary-folder/data4demo/
this_path_sci_file = '/absolute_path/data4demo/cpd_4s/solo_L1_stix-sci-xray-cpd_20220930T160153-20220930T162949_V01_2209303250-64438.fits'
this_path_bkg_file = '/absolute_path/data4demo/bkg/solo_L1_stix-sci-xray-cpd_20221002T092421-20221002T101741_V01_2210022580-50759.fits'
this_aux_fits_file = '/absolute_path/data4demo/aux/solo_L2_stix-aux-ephemeris_20220930_V01.fits'

;;;;; Time range
; It can be given in Solar Orbiter UT or Earth UT
; If you want to use Earth UT times, then you MUST set the keyword earth_ut
this_time_range_so = ['30-Sep-2022 16:15:35', '30-Sep-2022 16:16:59']

;;;;; Energy range
;; By setting this, the script will loop all native energy bins within the specified range
energy_range = [9, 32] ; [8, 32]
;; By setting this, you can bin in energy
;energy_low = [32,40,50]
;energy_high = [40,50,70]

;;;;; maximum energy to use for the inversion to calculate the regularized visibilities
energy_max_inversion = 63

;;;;; Suffix to append at the end of the newly created folder
;suffix_folder = '_test-new-software_std-visibilities'
suffix_folder = '_test-new-software_reg-visibilities'

;;;;; Set the minimum/maximum size of the source FWHM
min_fwhm = 14.6  ; corresponding to the resolution of sc3
max_fwhm = 178.6  ; corresponding to the resolution of sc10

;;;;; If to calculate the uncertainty on the fwdfit parameters
```

```
;; Default: uncertainty = 1 (i.e., calculate the uncertainties)
uncertainty = 1

; **************************************

; *********** SCRIPT TO RUN ************
stx_imaging_spectroscopy, $
  ;; --- Necessary inputs
  path_sci_file, $         ; path to the science file
  path_bkg_file, $         ; path to the background file
  aux_fits_file, $         ; path to the auxiliary file
  time_range, $            ; time range for imaging
  energy_max_inversion, $  ; maximum energy to use for the inversion
  ;; --- Optional keywords
  ;/select_loc, $     ; set this if you want to select the location of the sources on the screen and FIX their location
  ;/standard_vis, $   ; set to use standard visibilities
  /select_box, $      ; set this OR /select_loc. If this is set, the location is not fixed but fitted within the "selected box"
  path_sav_folder = path_sav_folder, $   ; path where to store the folder that will be created by the procedure. Default: working directory
  ;/stop_here, $      ; feature for debugging
  /earth_ut, $        ; if the user wants to input the time in Earth time, it MUST set this keyword. Default: Solar Orbiter time
  ;source_fwhm = source_fwhm    ; If the FWHM of the sources has to be fixed
  min_fwhm = min_fwhm, $        ; If the minimum of the FWHM of the sources has to be constrained
  ;max_fwhm = max_fwhm, $       ; The same with the maximum
  ;/ellipse_shape, $            ; Set this keyword if elliptical gaussians have to be used. Default: circular Gaussians
  ;energy_low = energy_low, $    ; If a different binning is needed. This defines the low-energy edges. In this case, energy_high is needed!
  ;energy_high = energy_high, $   ; High-energy edges. Same as energy_low but for high-energy
  energy_range = energy_range, $  ; Energy range for the imaging. Default: consider native binning from 4 to 28 keV. You can say [5, 10]
  suffix_folder = suffix_folder, $   ; If you want to add additional text at the name of the folder. This for avoiding to overwrite different runs
  ;; --- Optional output
  path_new_folder = path_new_folder    ; path to the newly created folder. This will then be given to stx_plot_imaging_spectra
; **************************************
```

After running the code above, the first step is to produce backprojection, CLEAN, and MEM_GE maps (as shown in the screenshot below). These maps provide context to determine the number of sources present in the images.

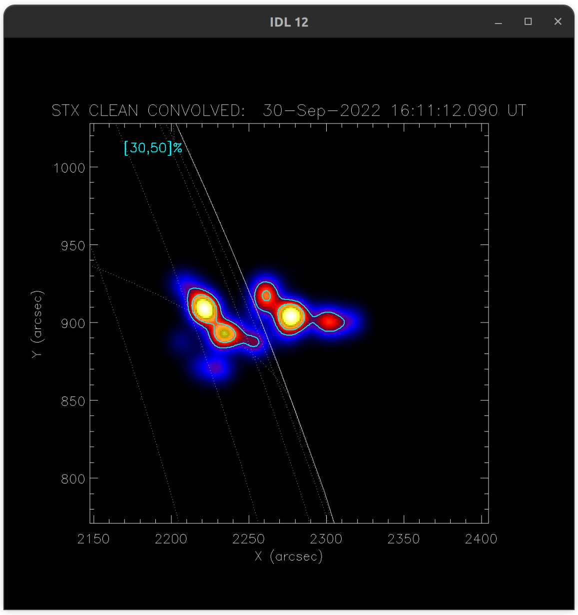


Afterwards, the following message appears in the command line. (Please note that, by default, the procedure will abort automatically if there are less than 1000 counts in the selected bin.)

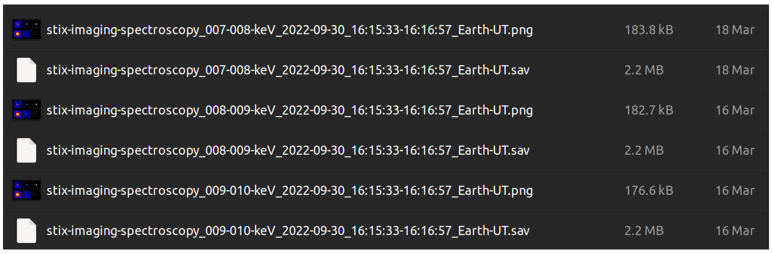
```
********************************************************************************
Number of counts in this energy bin (25-28 keV):
      9928.13
********************************************************************************

>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
Enter number of sources and press ENTER (0: abort):
```

Here you have to input the number of sources you think there are in the images. Select 0 to abort the algorithm. Then, press `Enter`.

Afterwards, another window will appear (see screenshot below). If either the keyword `/select_loc` or `/select_box` is set, then the user will need to interact with the window. **Please follow the instructions in the command line when interacting with the IDL 12 window!** If `/select_loc` is set, the user needs to select the center of each source by clicking on the corresponding location in the image. For example, if 3 sources are found, then the user needs to click 3 times to select all centers (**check the command line after each click!**). If `/select_box` is set, the user needs to select the bottom-left and top-right corners of the box in which to fit each source. Therefore, 6 clicks are needed for 3 sources (**again, check the command line after each click!**). An additional feature to note: if `/select_box` is set, but the location of some of the sources is already known (such as the flare footpoints), it is possible to fix the location of a source by double-clicking on the same location. In this case, the source will be fixed and a circular Gaussian will be assumed. For example, if we find 3 sources and only want to fit the location of one of them, we can double-click on the same location for two of the sources (which will be set as circular Gaussians) and select the bottom-left and top-right corners for the remaining one (which can be a circular or elliptical Gaussian).



This process will be repeated for all energy bins given as input. In the end, all images and fluxes will be stored in the `path_sav_folder` (or in the working directory). Below an example screenshot of the content of the newly created folder.



stix-imaging-spectroscopy_007-008-keV_2022-09-30_16:15:33-16:16:57_Earth-UT.png	183.8 kB	18 Mar
stix-imaging-spectroscopy_007-008-keV_2022-09-30_16:15:33-16:16:57_Earth-UT.sav	2.2 MB	18 Mar
stix-imaging-spectroscopy_008-009-keV_2022-09-30_16:15:33-16:16:57_Earth-UT.png	182.7 kB	16 Mar
stix-imaging-spectroscopy_008-009-keV_2022-09-30_16:15:33-16:16:57_Earth-UT.sav	2.2 MB	16 Mar
stix-imaging-spectroscopy_009-010-keV_2022-09-30_16:15:33-16:16:57_Earth-UT.png	176.6 kB	16 Mar
stix-imaging-spectroscopy_009-010-keV_2022-09-30_16:15:33-16:16:57_Earth-UT.sav	2.2 MB	16 Mar

IMPORTANT REMARK: When selecting multiple sources, please use the same order for subsequent energy bins, otherwise, in the `stx_plot_imaging_spectra` (see later), wrong fluxes will be grouped together. For example, if you have two sources, one towards the East and the other towards the West, and the Eastern source is selected first (and the Western source second), the same order MUST be kept for all subsequent energy ranges. If a new source appears, make sure it is the third one! **A useful way to remember the selection order is to select the sources in ascending x-coordinate order.**

stx_plot_imaging_spectra

This procedure performs several tasks. Firstly, it reads all sav files created with the procedure `stx_imaging_spectroscopy` and extracts the fluxes obtained from imaging for all different energies and sources. Secondly, it extracts the observed total flux from the L1 file using the procedures implemented to use OSPEX with STIX data (`stx_convert_pixel_data` and all procedures therein). Finally, it automatically generates a plot comparing the imaging and OSPEX fluxes. Optionally, an output structure can be returned, which can be used later in `stx_flux2ospex` .

At the time of writing, there are some limitations to this procedure:

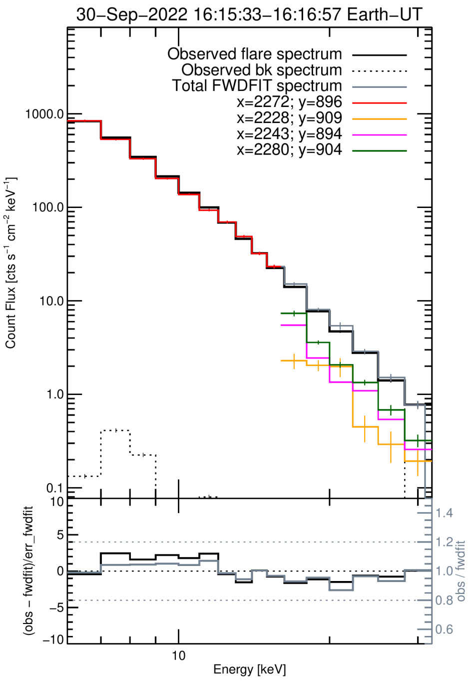
- It does not work if there is only one source for all energy bins. At least one energy bin with two (or more) sources is needed.
- Currently, it only works if `stx_convert_pixel_data` and the procedures therein (`stx_convert_science_data2ospex` and `stx_fsw_sd_spectrogram2ospex`) have the keyword `/sav_srm` , which was created ad-hoc for imaging-spectroscopy. Please note that this will not be integrated into STIX-GSW, and will be deleted soon once a reliable replacement is in place.

Below is an example script for running the code. It lists all required inputs, as well as an optional output.

```
stx_plot_imaging_spectra, $
  ;; --- Necessary inputs
  path_new_folder, $    ; Path to the folder created with stx_imaging_spectroscopy (output of stx_imaging_spectroscopy)
  path_sci_file, $      ; Path to the science file used for imaging
```

```
  path_bkg_file, $      ; Path to the related bkg file
  ;; --- Optional output
  flux_str = flux_str   ; Flux structure that will be used in stx_flux2ospex for spectral fitting
```

This procedure automatically generates the following plot, where red, yellow, magenta and green solid lines represent the different selected sources.



stx_flux2ospex

The final procedure, `stx_flux2ospex`, allows for importing imaging fluxes into OSPEX and performing spectroscopic fitting on previously defined sources. This procedure takes `ind_sources` as an argument, which determines which sources should be summed up before passing the fluxes to OSPEX. If `ind_sources` is not specified, the procedure sums up all sources by default. However, if, for example, `ind_sources = [1,2]` then only sources 1 and 2 will be summed up. The numbering refers to the colored curves in the plot generated by `stx_plot_imaging_spectra`, where, in this example, source 1 is represented by the solid orange curve and source 2 by the magenta one. The remaining two sources, 0 (red) and 3 (green) are not considered if `ind_sources = [1,2]` is set.

Below is an example script for running this code.

```
ind_sources = [1, 2]

stx_flux2ospex, $
  ;; --- Necessary input
  flux_str, $                  ; This is the output structure of stx_plot_imaging_spectra
  ;; --- Optional input
  ind_sources = ind_sources, $ ; Which sources to consider for spectral fitting
  ;; -- Optional output
  ospex_obj = ospex_obj        ; OSPEX object containing the imaging spectra
```

IMPORTANT REMARK: As of now (04-07-2023), the current script does not work with re-binned energy bins. This will likely result in odd spectra, since the SRM is not binned in the same way. **This functionality still needs to be included**.

After running the code above, the standard OSPEX GUI (SPEX Main Window) will appear. To fit the imaging spectra, follow these steps:

- Click 'File' on the top-left corner of the window.
- Cllick 'Select fit options and do fit.'
- The usual OSPEX window for spectral fitting will appear.
- You can now fit imaging spectra in the same way as it is always done with spatially integrated spectra. Enjoy! 🙂

Final remark

> 👉 Please note that this software and documentation are currently under construction. 🚧 Any feedback or input from the user is welcome, regarding either the software or the documentation. Do not hesitate to contact the author of this document for support and updates to the software or documentation. Your input is highly appreciated!