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

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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 CLEAN (Högbom 1974), MEM_GE (Massa et al. 2020) or the forward-fit (fwdfit, Volpara et al. 2022) algorithm. If the fwdfit algorithm is selected, and the configuration of the reconstructed image is not known a priori (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 (independently from the selected algorithm);
- The regularized visibilities are used. Set the keyword `/standard_vis` to use the standard visibilities;
- By default, the script generates maps using all three algorithms: CLEAN, MEM_GE, and fwdfit. This enables cross-checking of the flare configuration in each energy interval and verification of whether the reconstructed images from the different algorithms are plausible. It is also recommended to validate the obtained imaging spectra (in OSPEX, see later) using different algorithms. If the user prefers not to use some of the algorithms, the keywords `/no_mem_ge`, `/no_clean`, and `/no_fwdfit` can be set.
- If fwdfit is chosen and if `configuration_fwdfit` is not specified, the script assumes circular Gaussians. Set the keyword `/ellipse_shape` to use elliptical Gaussians;
- If fwdfit is chosen and if the location of the sources is not specified, then they are fitted. If the keyword `/select_location` is set, then the user can select the location of the fwdfit 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 use fwdfit and fix the location of certain sources (e.g. footpoints) but fit others (e.g. nonthermal coronal sources, as in Krucker & Battaglia 2014), it is possible to 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: September 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.

It is highly recommended to have a look at the **Tips & tricks** section.

User guide

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

- `stx_imaging_spectroscopy`
- `stx_img_spectra_sav2ospex`

There is an additional optional procedure called `stx_plot_imaging_spectra`. This procedure allows you to quickly obtain a postscript file that compares the standard fully integrated and fwdfit spectra. More details are provided below.

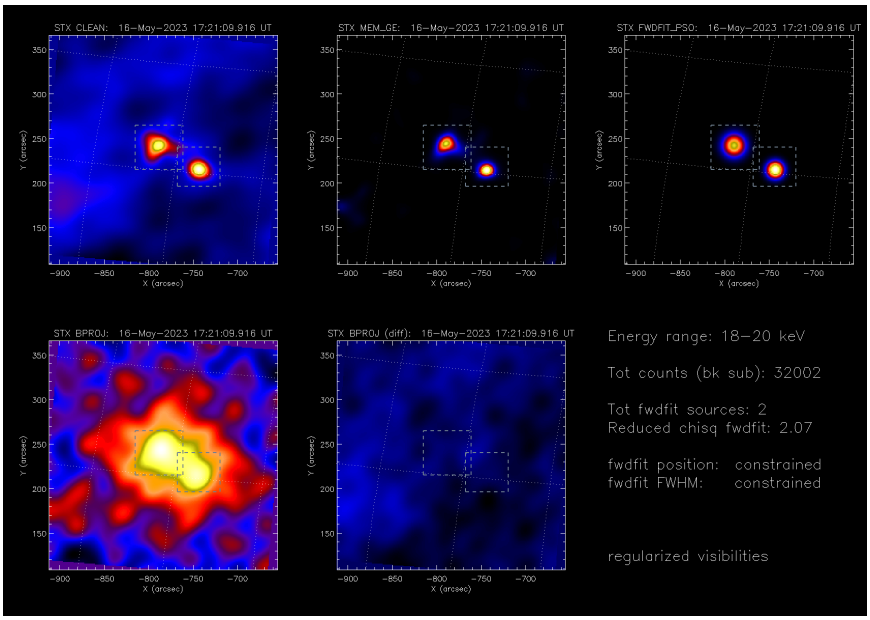
stx_imaging_spectroscopy

The first script to be run is the one that allows us to perform imaging at each selected energy bin. By default, CLEAN, MEM_GE and fwdfit maps are produced. If the user prefers not to use some of the algorithms, the keywords `/no_mem_ge`, `/no_clean`, and `/no_fwdfit` can be set.

If the user only wants to use CLEAN and MEM_GE (without fwdfit), there is no need for any interaction with the software. It will iterate through all selected energy bands to generate and store the maps. The user can provide input to `stx_imaging_spectroscopy` using the standard optional keywords for CLEAN and MEM_GE. By default, if no specific settings are specified for CLEAN, a CLEAN box will be created using the 50% contour of the backprojection. It is possible to adjust the percentage level by setting the `contour_clean_box` parameter.

If the user wants to use fwdfit, then the number of sources present at each selected energy band has to be specified. This information is necessary for the forward-fit algorithm. Alternatively, the user can input the number of sources and configuration externally to enable automatic program execution (rather than semi-automatic). However, it is highly recommended (if fwdfit is selected) to analyze the images at each step to ensure meaningful results at the end.

At each step in energy, an IDL save file is created and stored externally. A summary figure is also generated and saved. This approach enables the user to make changes to a specific energy bin without the need 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. The dashed boxes indicate the locations within which fwdfit has to place sources.

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!**

```
; ********** Example with the 2023 May 16 17:20 flare **********

;;;;; Path where to store the save and png files that will be generated
path_sav_folder = 'path_to_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/
path_data4demo = '/absolute_path_to/data4demo/'
this_path_sci_file = path_data4demo + 'cpd/solo_L1_stix-sci-xray-cpd_20230516T170425-
this_path_bkg_file = path_data4demo + 'bkg/solo_L1_stix-sci-xray-cpd_20230517T061006-
this_aux_fits_file = path_data4demo + 'aux/solo_L2_stix-aux-ephemeris_20230516_V01.fi

;;;;; 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
time_range = ['16-May-2023 17:20:30', '16-May-2023 17:21:50']

;;;;; Energy range
;; By setting this, the script will loop all native energy bins within the specified
```

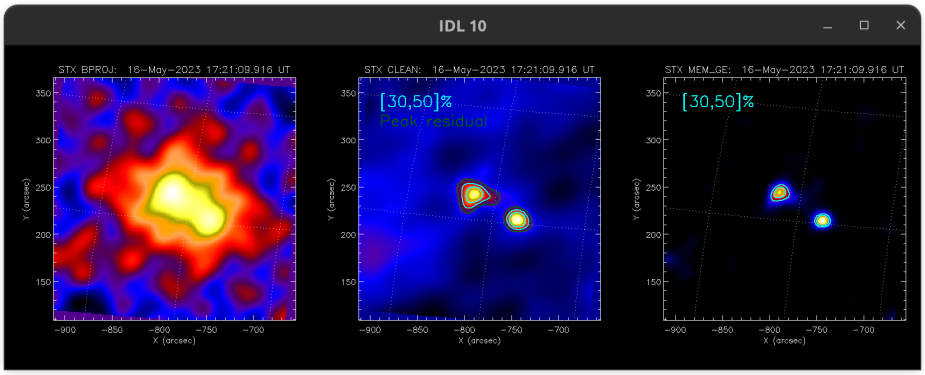
```
energy_range = [18, 50]
;; By setting this, you can bin in energy
;energy_low = [32,40,50]
;energy_high = [40,50,70]

;;;;; Maximum energy to use for the inversion to calculate the regularized visibiliti
energy_max_inversion = 100

;;;;; Suffix to append at the end of the newly created folder
;; This allows to run the imaging spectroscopy software with different settings
;; by creating different folders, instead of overwrite them
suffix_folder = '_demo'

;;;;; 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

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



;; STEP 1: run the imaging spectroscopy tool
stx_imaging_spectroscopy, $
  ;; --- Necessary inputs
  this_path_sci_file, $
  this_path_bkg_file, $
  this_aux_fits_file, $
  time_range, $
  energy_max_inversion, $
  ;; --- Optional inputs and keywords
  ;/select_loc, $
  ;/observed_vis, $
  path_sav_folder = path_sav_folder, $
  ;/stop_here, $
  ;/earth_ut, $
  ;source_fwhm = source_fwhm
  min_fwhm = min_fwhm, $
  max_fwhm = max_fwhm, $
  ;/ellipse_shape, $
  /select_box, $
  ;energy_low = energy_low, $
  ;energy_high = energy_high, $
  ;configuration_fwdfit = configuration_fwdfit, $
  ;source_loc = source_loc, $
```

```
   ;box_location = box_location, $
   uncertainty = uncertainty, $
   energy_range = energy_range, $
   suffix_folder = suffix_folder, $
   ;/no_mem, $
   ;/no_clean, $
   ;/no_fwdfit, $
   ;; --- Output
   path_new_folder = path_new_folder
```

With the demo-code above, we decided to do he following

- Run CLEAN, MEM_GE and fwdfit, as none of the following keywords have been set: `/no_mem_ge`, `/no_clean`, and `/no_fwdfit`;
- For fitting the fwdfit sources, by setting `/select_box`, we decided to select a box around each source to fit (see more details below);
- Since no a priori configuration of the fwdfit sources is assumed (no `configuration_fwdfit` is given), then the number of sources has to be chosen at each step (see more details below);
- The FWHM of the fwdfit sources have to be within 14.6 arcsec and 178.6 arcsec (see `/min_fwhm` and `/max_fwhm`).

After running the code above, the software first produces 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.



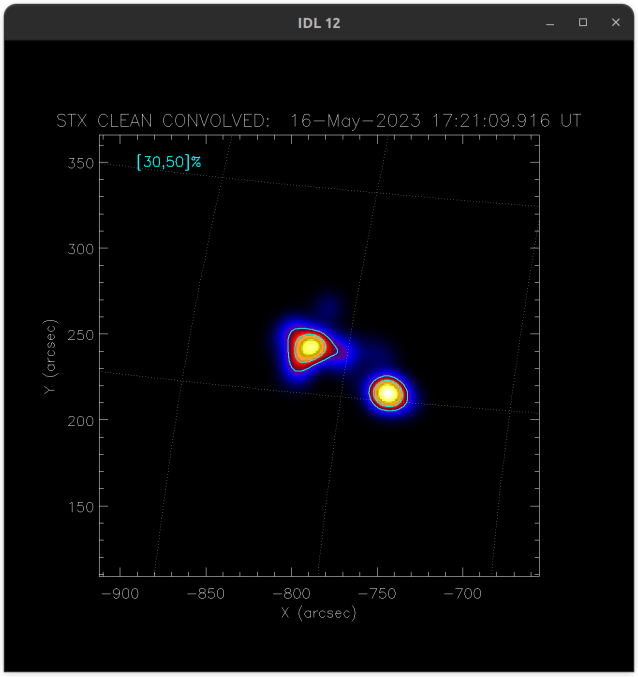
Afterwards, the following message appears in the command line. (Please note that, by default, the procedure will abort automatically if there are less than 1000 counts in the selected bin.)

```
**********************************************************************************
Number of counts in this energy bin (18-20 keV):
      32002.1
**********************************************************************************
```

```
>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
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 2 sources are found, then the user needs to click 2 times to select all centers (**check the command line after each click!**). In such a way, the location is fixed and not fitted by fwdfit. 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, 4 clicks are needed for 2 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.

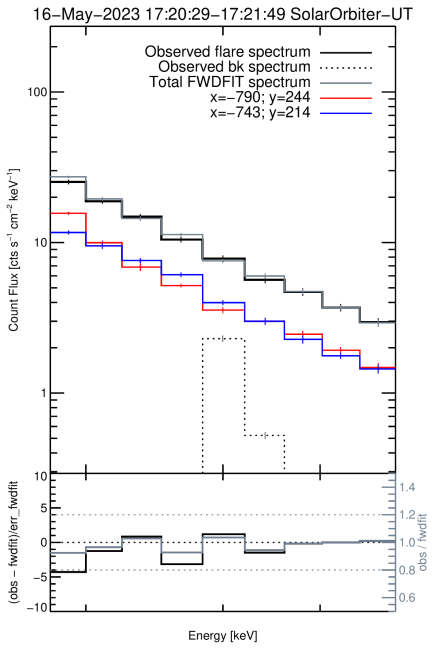
Name	Size	Modified
stix-imaging-spectroscopy_018-020-keV_2023-05-16_172029-172149_SolarOrbiter-UT.png	174.0 kB	08:24
stix-imaging-spectroscopy_018-020-keV_2023-05-16_172029-172149_SolarOrbiter-UT.sav	2.2 MB	08:24
stix-imaging-spectroscopy_020-022-keV_2023-05-16_172029-172149_SolarOrbiter-UT.png	168.0 kB	08:25
stix-imaging-spectroscopy_020-022-keV_2023-05-16_172029-172149_SolarOrbiter-UT.sav	2.2 MB	08:25
stix-imaging-spectroscopy_022-025-keV_2023-05-16_172029-172149_SolarOrbiter-UT.png	168.5 kB	08:26
stix-imaging-spectroscopy_022-025-keV_2023-05-16_172029-172149_SolarOrbiter-UT.sav	2.2 MB	08:26

IMPORTANT REMARK 1: 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.** If you do not plan to use `stx_plot_imaging_spectra`, then the order does not matter

IMPORTANT REMARK 2: Imaging spectroscopy with regularized visibilities works only for energies above 10 keV. This is because the inversion process assumes that the emission is primarily driven by the bremsstrahlung mechanism. This assumption holds above 10 keV, but not below, where other emission mechanisms, such as the iron line complex around 6.7 keV, become significant.

OPTIONAL: stx_plot_imaging_spectra

This procedure allows to performs several tasks. Firstly, it reads all sav files created with the procedure `stx_imaging_spectroscopy` and extracts the fwdfit fluxes for all different energies and sources. Secondly, it extracts the spatially integrated 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 (see example on the right). Currently, this procedure 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 (see Github issue #154).



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

```
;; OPTIONAL STEP: plot the fwdfit and spatially integrated spectra
stx_plot_imaging_spectra, $
  ;; -- Necessary inputs
  path_new_folder, $     ; this is an output of stx_imaging_spectroscopy
  this_path_sci_file, $
  this_path_bkg_file
```

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

stx_img_spectra_sav2ospex

This final procedure allows for importing previously obtained images into OSPEX and performing spectroscopic fitting on single sources. What it does is open all .sav files that were previously generated by `stx_imaging_spectroscopy` and create "image cubes" which are then imported into OSPEX. Running this code is straightforward, as it only requires two inputs:

- `path_new_folder`: path to the folder containing the sav files generated by `stx_imaging_spectroscopy`;
- `algo`: which maps have to be imported in OSPEX. Currently supported are: `'clean'`, `'fwdfit'` and `'memge'`.

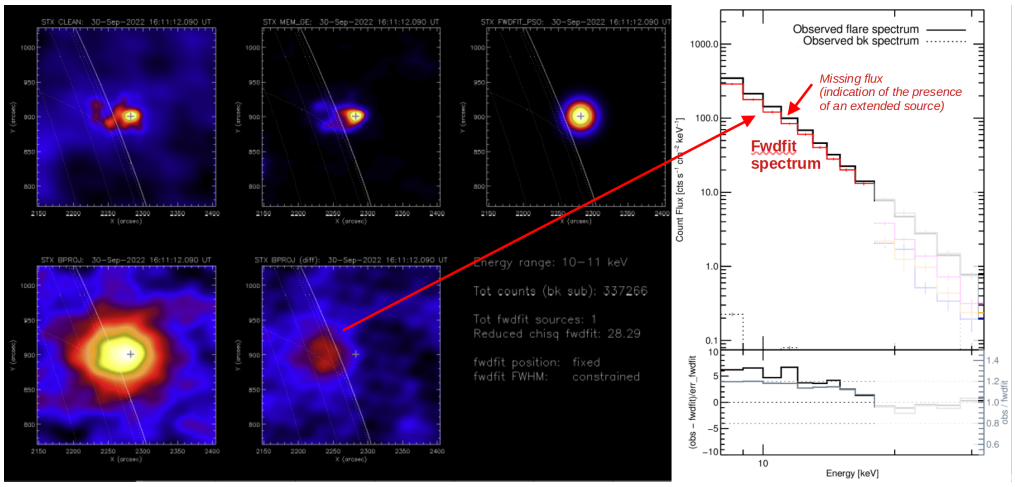
```
;; STEP 2: input the fluxes into OSPEX
algo = 'fwdfit'
stx_img_spectra_sav2ospex, path_new_folder, algo
```

In the end, the standard OSPEX GUI with a preview of the imported images appears. Then, the user can perform imaging spectroscopy as it was done with RHESSI. For more details, please refer to the following documentation: https://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/ospex_imaging_spectroscopy.htm

Enjoy imaging-spectroscopy with STIX observations 🙂

Tips & tricks

1. It is highly recommended to include fwdfit in the imaging spectroscopy analysis as it allows, in the current implementation, for the identification of any missing flux. In the example below, a fwdfit source was fixed. However, from the second panel of the second row, which shows the difference between the backprojection obtained with the predicted fwdfit visibilities and the observed backprojection, it is clear that there is still some missing flux. By comparing the spatially integrated spectra with the fwdfit spectra, it becomes evident that the fwdfit flux is nearly 20% lower, indicating that some flux has been missed. This is a useful way to test our understanding of the flare's geometry. In this example, the missing flux is likely associated with a source that extends towards the limb, at lower altitudes, as it can be observed from CLEAN and MEM_GE.



The left panel has been produced with `stx_imaging_spectroscopy`, whereas the right one with `stx_plot_imaging_spectra`.

2. If you are not happy with the reconstructed images of a specific energy band, there is no need to start everything from the beginning. For instance, if you are not happy with the images reconstructed between 22 and 25 keV, simply run the same code with the `energy_range = [22, 25]`. Alternatively, you can define a non-native binning by specifying `energy_low` and `energy_high`.
3. It is possible to run automatically also the fwdfit algorithm. In this case, the user needs to define `configuration_fwdfit` and one of the following two parameters: `source_loc` or `box_location`. By setting `source_loc`, the sources will be fixed (and not fitted!), whereas with `box_location`, the sources will be fitted within the boundaries provided by the boxes. By doing so, the fwdfit will be fully automatic. This can only be done **if and only if**:
   a. the flare geometry is known a priori AND
   b. the flare geometry does not change within the considered energy range!

Important remarks

⚠ **IMPORTANT REMARK 1**: There is currently a mismatch (of a factor of 3 to 4) between the full-disk integrated spectrum and the spatially integrated ones with imaging fluxes. The reason is because of a bug in the OSPEX software for STIX when exporting the spectrum. Luckily, this only affects the exported spectra and not the spectral parameters, as the fit is done with the correct spectrum. This only appears when exporting spectra from OSPEX. This can be seen when running `stx_plot_imaging_spectra`, as the “Observed flare spectrum” is multiplied by a factor of 3.5.

⚠ **IMPORTANT REMARK 2**: The current version of `stx_img_spectra_sav2ospex` does not work with non-native 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 implemented**. So, please use only native energy bins in the selection of the energy edges.

👉 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!