



The SVOM/ECLAIRs Scientific Analysis Pipeline

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Abstract

This paper reports on the scientific pipeline for the analysis of the ECLAIRs data of the Space-based multi-band Variable Objects Monitor mission. We describe the overall procedure, the different steps and the main algorithms of the data analysis for this hard X-ray coded mask instrument. The pipeline runs in automatic mode at the science center generating standard products but can also be used offline with specific choices of parameters. Generated data products and preliminary performances are illustrated along with perspectives for future improvements.

Key words: X-rays: general – techniques: image processing – methods: data analysis

1. Introduction

The ECLAIRs instrument (Godet et al. 2026) on the Space-based multi-band Variable Objects Monitor (SVOM) space mission (Cordier et al. 2026) is an X-ray/hard X-ray (4–150 keV) telescope based on the coded-mask imaging technique (Goldwurm & Gros 2022). A position-sensitive detector of 80×80 square CdTe semiconductor pixels records the shadows of a mask projected by the sources in the field of view (FoV). A sky image is reconstructed by correlating the detector image to the mask pattern and by applying cleaning algorithms to reduce the systematic effects. A dedicated “ECLAIRs pipeline” (ECPI) to perform such an analysis has been developed in the frame of the SVOM French Science Center (FSC) (Louvin et al. 2026).

As the set of X-band telemetry (TM) data, received on ground during a mission download period (pass), is pre-processed at the FSC, ECPI runs automatically in quick look analysis (QLA) mode, feeding the SVOM science database (SDB) with the generated science data products (SDP) to be distributed to the scientists. The pipeline can also be used offline for a specific analysis on selected data and with user-chosen parameters (energy bands, time intervals, etc.), allowing also the combination of the derived products (stacking, mosaics). The generated SDP are stored in FITS files, compatible with most of the standard astronomical tools (e.g., FTOOLS, DS9, XSPEC) and including all needed metadata (energy bands, exposure times, etc.) in keywords (KW).

We describe here the main steps and algorithms of the analysis, mentioning the acronyms of the pipeline components and of the SDP files. The analysis principles are explained in

Goldwurm & Gros (2022) and the treatment is similar to the one applied to INTEGRAL/IBIS data (Goldwurm et al. 2003) as the instruments are similar. Notable differences are that the ECLAIRs FoV is much larger ($\approx 90^\circ \times 90^\circ$), the Earth often obscures part of it, due to the mission observation strategy, the angular resolution ($\approx 1.5^\circ$ FWHM) and location accuracy ($< 12'$) are lower, and the background is highly variable, due to the low orbit and frequent passages of the satellite in the energetic particle zones of the South Atlantic Anomaly (SAA).

2. Overview of the Pipeline

The scheme of the pipeline is sketched in Figure 1. It has as inputs the SVOM preprocessed TM data stored in the SDB and the set of correction, calibration and response files, prepared by the ECLAIRs Instrument Center and stored in the calibration database (CalDB). ECPI is composed of six large components that run in sequence, with some loops described below. Each component generates SDP, stored in the SDB, which are used by the following components and/or directly by the scientists.

The first two of them prepare the data and the correction parameters (data preparation and correction component, DPCO) and calibrate and flag the events (calibration component, CALI). They can be run only once, and in the most general case, the user can start the analysis from the following component (Binning, non-Uniformity, Background, with Earth occultation, correction: BUBE), using the SDP stored in the SDB by the automatic processing, since no choice of scientific parameters is made before this level.

In the BUBE component, based on the input user parameters, the events are selected and binned in detector images, which then are corrected for non-uniformity and background modulation,

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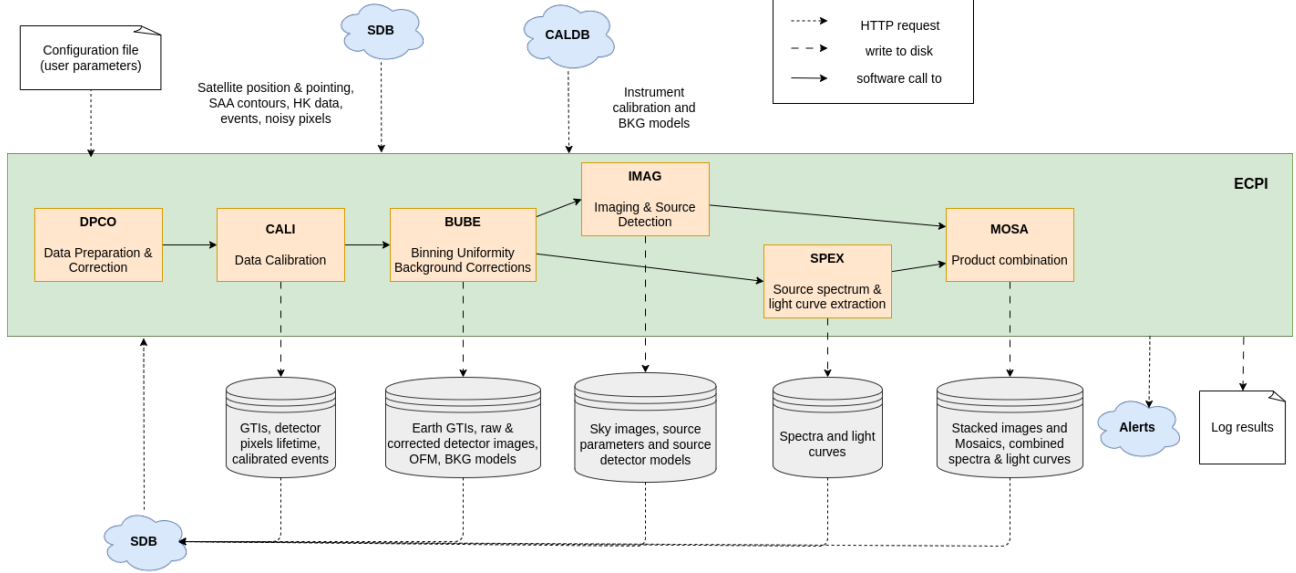


Figure 1. Scheme of the ECLAIRS scientific analysis pipeline. Processing components are shown as rectangles in a sequence from left to right. Input preprocessed TM data are read from the SDB, and the auxiliary data (calibration, response and model) from the CalDB. SDP generated by the different components (shown as cylinders in the bottom) are stored in the SDB and may be given as input to the following components. The MOSA component is run on SDP produced by the previous components for different passes or observations.

considering the Earth obscuration. Sky images are then reconstructed and sources are detected, positioned, identified with a catalog source and their ghosts cleaned, in the so called IMAG (imaging) component.

To obtain products of specific sources, the BUBE component can be run again to bin detector images properly (small energy bins or time intervals), and then the source product extraction component (SPEX) generates source products, spectra or light curves (LC). The different sets of SDP (for passes or observations) can be combined by stacking detector images and running the analysis components on them, by making sky image mosaics (component MOSA) and combining source spectra, LCs and event lists.

The ECPI pipeline is implemented in Python and is deployed as a Docker image within the FSC. In online mode, it interacts through an API interface with the other services (databases, pipelines, orchestration). On top of the scientific modules depicted in Figure 1, there are other software layers that deal with data forwarding between scientific components, scientific data product generation and dynamic handling of the ECLAIRS calibration. These layers will be described elsewhere.

3. Data Correction and Calibration

The preprocessed ECLAIRS science data, as input to the DPCO, are in the form of event lists (EVT-CNV files), giving for each recorded single event (multiple are neglected): the time (in UTC), the position Y - Z in the detection plane and the energy channel. Other input TM data are the satellite attitude and orbit, the pixels identified as noisy by the on-board

software with the time they were set off/on, and the instrument House-Keeping (HK) data (temperatures, tensions, etc.). ECPI also uses the pre-calculated times of entry and exit of the SAA, both for the core and extended zones.

3.1. Good Time Intervals and Dead/Noisy Pixels

DPCO defines the good time intervals (GTIs) to be used in the analysis, and establishes the effective lifetime of the pixels (PIX-LIF) during the period of the input data. The GTIs are for periods out of SAA passages, with stable attitude (versus unstable or slewing intervals), with no or partial Earth occultation, during no TM gaps and good instrument functioning. Pixel lifetime is computed from TM information on the noisy pixels and HK status, and using the CalDB tables of dead pixels (set off permanently). The process also analyzes the science data in order to identify residual dead or noisy pixels, not detected by the on-board software, and to optimize the contours of the SAA based on the recorded count rate. All extracted information is coded in the GTI and PIX-LIF files.

3.2. Event Energy Calibration and Flagging

The CALI performs the energy calibration of the events by applying a pixel gain and offset, tabulated in a dedicated calibration file, to the recorded channel (Pulse Height Amplitude, PHA) so that an invariant channel (Pulse Invariant, PI), with direct correspondence to an energy interval in keV, can be attributed to each event. The component also flags the events that are not valid either because they are out of the valid energy thresholds or because they are detected by pixels in

periods of noisy status or with an out-of-limit value of an HK parameter. The calibrated and flagged events are stored (EVT-CAL) along with their GTI and PIX-LIF files.

4. Image Binning and Background and Non-uniformity corrections

The first component of the proper scientific analysis (BUBE) bins the events in detector images for the requested time periods and energy channels and corrects them for the camera non-uniformity and non-flat background.

4.1. Detector Image Binning and Efficiency Computation

The procedure selects the “good” (flag = 0) events that belong to the user-requested GTIs, typically in periods out of SAA, with stable attitude, no TM gaps and when the FoV is not obscured by the Earth (NEO). Partial (PEO) and total (TEO) Earth occultation GTIs can also be used, as well as other specific intervals, like the active periods of a transient source or even slew periods, which must be entered by the user. Events are binned into detector images generating, for each requested energy band, three 80×80 -element arrays (DET-IMA): one containing the counts per pixel, one the associated variance and one the efficiency. The normalized efficiency of each pixel is inferred from the PIX-LIF information and the ground-calibrated pixel low and high energy thresholds. The user can also neglect, in the analysis, other parts of the detector that show malfunctions (noisy pixels/sectors, column effect, etc.) by setting the corresponding pixel efficiency to 0.

4.2. Non-uniformity and Background Correction with Earth Modulation

While a coded mask system is not sensitive to temporal variations of the background or of the detector efficiency, any spatial modulation that is not produced by the mask hampers the proper reconstruction of the source fluxes and positions (Goldwurm & Gros 2022). It is therefore necessary to correct the non-uniformity of the detector plane response (Xie et al. 2024) and the spatially modulated background, before decoding the sky with the mask pattern. The correction of the detector image D affected by a non-uniformity U and a non-flat background B can be performed by computing the corrected image as $D^C = \frac{D}{E \cdot U} - b \cdot B$ where dot or division means element-by-element matrix multiplication or division, E is the efficiency and the scalar b a normalization factor, presently computed from the exposure time, but in the future possibly fitted to the data. The variance is computed accordingly. The efficiency image associated with D^C is now the global efficiency $E^g = E \cdot U$. The main contribution to the background is the isotropic Cosmic X-ray Background (CXB) and its model is calculated from the solid angle that

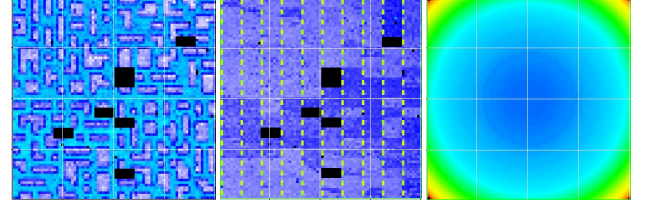


Figure 2. Left: A corrected intensity detector image during a Crab on-axis observation. Center: the corresponding global efficiency image. Right: The background model detector image, dominated by the CXB, not modified by the Earth occultation (NEO period).

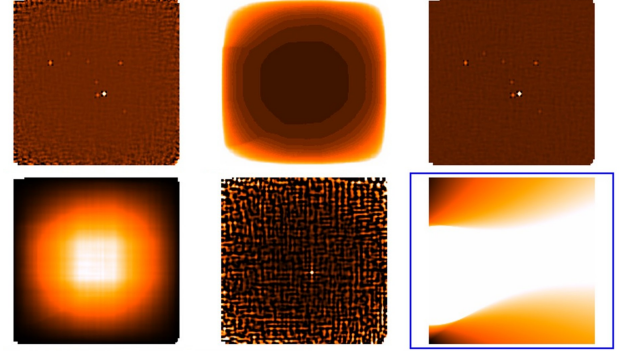


Figure 3. IMAG sky image reconstruction products. From top-left to top-right: Intensity, variance and SNR images; bottom-left and bottom-center: effective exposure time and sum of deconvolved source models. The bottom-right image is the Earth open FoV map computed by BUBE.

each pixel of the camera subtends to the sky considering the ECLAIRS geometry and the CXB spectrum (Moretti et al. 2009). When the FoV is obscured by the Earth, the induced modulation on the CXB shape during the PEO GTI is taken into account. The corrected detector images (DET-UBC) and the background detector models used for the correction (DET-BKG) (Figure 2) are saved in output, along with the computed time-averaged FoV non-obscured by the Earth (EAR-OFM) (Figure 3, bottom-right).

5. Image Reconstruction and Source Localization

Reconstruction of sky images (IMAG component) is performed by deconvolving the corrected detector images, iteratively searching and localizing sources, modeling and subtracting their secondary lobes, then correcting for Earth occultation and off-axis effects, before sky map normalization and unit transformation (Figures 3–4).

5.1. Sky Image Deconvolution

A sky image is derived from the detector image D , its variance D_V and efficiency E , by decoding it with the mask pattern following the prescriptions of Goldwurm & Gros (2022). The mask of 46×46 quasi-random transparent and opaque elements plus a central opaque cross (Lachaud et al.

2026) (represented by 0.0 value when opaque and 1.0 when transparent) is re-binned over an array of pixels with the same area as the detector pixels (linear ratio mask-element/detector-pixel = 2.53). From the re-binned mask array M of 120×120 pixels with values between 0.0 and 1.0, we define the decoding array $G = \frac{1}{a} \cdot M - \mathbf{1}$ where $\mathbf{1}$ is an arrays of 1s and the scalar a is the aperture of the mask (= 0.4).

Using $G^+ = \begin{cases} G & \text{for } G \geq 0 \\ 0 & \text{elsewhere} \end{cases}$ and $G^- = \begin{cases} G & \text{for } G \leq 0 \\ 0 & \text{elsewhere} \end{cases}$ the sky image S is given by

$$S = \frac{G^+ \star (D \cdot W) - \text{Bal} \cdot (G^- \star (D \cdot W))}{A},$$

where $\star$ means correlation operator. The weighing array can be taken as $W = E$, neglecting in this way the pixels that are off and giving low weight to those with low efficiency, but can also integrate other corrections, for example to neglect detector parts contaminated by bright sources or high background. The balance array $\text{Bal} = \frac{G^+ \star W}{G^- \star W}$ gives the open to closed mask element ratios and ensures a flat image with a mean of 0 in absence of sources. The normalization array $A = (G^+ \cdot M) \star W - \text{Bal} \cdot ((G^- \cdot M) \star W)$ takes into account the partial modulation. With this normalization, the sky image S with dimensions 199×199 pixels gives at the source peak the mean recorded source counts within one totally illuminated detector pixel. The associated sky variance V is (where $X^2 = X \cdot X$)

$$V = \frac{(G^+)^2 \star (D_V \cdot W^2) + \text{Bal}^2 \cdot ((G^-)^2 \star (D_V \cdot W^2))}{A^2}.$$

Finally the signal-to-noise image is $\text{SNR} = S / \sqrt{V}$.

5.2. Source Localization, Identification, Modeling and Iterative Cleaning, and Sky Image Normalization

The decoded sky image is searched for point sources, i.e., SNR excesses larger than a user-defined threshold of ≈ 6 –10. The source peak, of size (FWHM) equal to about the projected mask element, is fitted with a 2D-Gaussian, approximation of the spatial response, the so-called System Point-Spread Function (SPSF) (Lachaud et al. 2026), in order to estimate the source fine position. The image coordinates are transformed to celestial ones and the source is identified using a catalog of known X-ray objects. Estimated source parameters (fine positions, fluxes, SNR, identified objects, etc.) are provided in output (SOP-IMA).

Due to the quasi-random ECLAIRs mask pattern (Lachaud et al. 2026), the main source peak is surrounded by a “coding noise” composed of numerous smaller secondary positive and negative lobes. This noise is distributed all over the FoV, depends on the source location and intensity (see bottom-center of Figure 3), and can hamper the search for weaker objects. It is therefore necessary to implement an iterative cleaning procedure in order to subtract the secondary lobes of

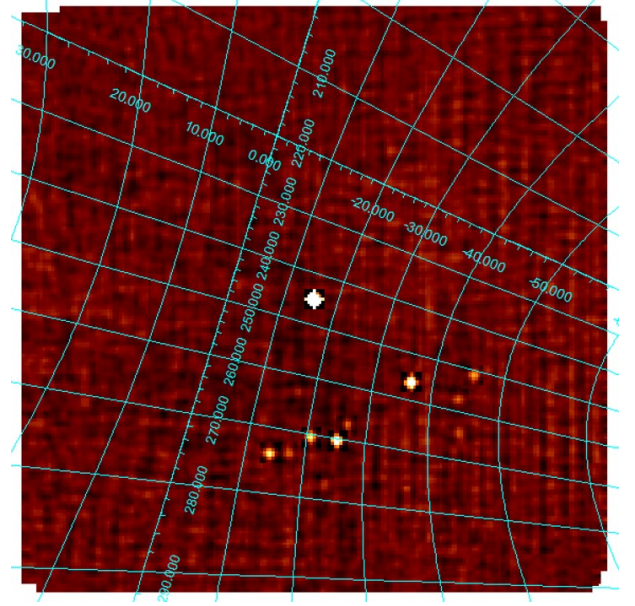


Figure 4. Reconstructed SNR sky image of the Sco X-1 field, shown in logarithmic scale with equatorial coordinates: several sources from the Galactic plane are visible below the bright central target.

a source before searching for a weaker one. Each detected source is modeled at the fitted position, and the detector image model (DET-MOD) is decoded, normalized and subtracted from the initial sky image, reducing the coding noise contamination before searching and deriving parameters for a weaker source.

At the end of the loop, source main peaks are reintroduced in the cleaned image, which is then normalized for the effect of the Earth occultation and off-axis effects and converted to units that give at each point the source count rate detected on the whole camera, as for an on-axis location. The proper world coordinate system KWs (J2000 equinox equatorial coordinates in tangential projection), computed from the GTI-average attitude, are associated with the image FITS files of the cleaned and normalized sky images (SKY-IMA). Examples of in-flight data IMAG products are shown in Figure 3 and a cleaned SNR sky map of the Sco X-1 field in Figure 4.

5.3. Preliminary Estimation of Imaging Biases and Point Source Location Error

Using results of the imaging analysis on ECLAIRs data of the first year observations of known bright point-like sources, namely the offsets between the SPSF fitted centroids and the known source positions, we have studied the Point Source Location Error (PSLE) of the system, determined some of the imaging biases and then the parameters of the function PSLE versus the SNR, which characterizes the location accuracy for a source of given SNR (see Gros et al. 2003; Goldwurm & Gros 2022). We have derived a more precise “effective

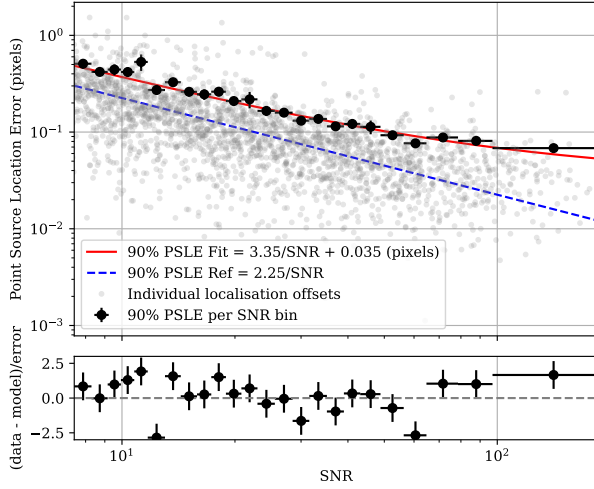


Figure 5. Estimated ECLAIRS PSLE from 1 yr of in-flight data of known-sources: measured localization offsets in pixel unit versus source SNRs (gray points), their 90th percentiles in the SNR bins that contain 100 points each (black points), and the best fit function of the PSLE at 90% c.l. versus the SNR (red line), compared to the theoretical PSLE for a perfect system (blue broken line). Fit residuals are shown at the bottom.

distance” between the mask and the detector plane, which results in +0.11 cm with respect to the ECLAIRS geometry, and a marginally significant misalignment with respect to the platform attitude along the image axes (Y , Z) and in rotation of ≈ 0.7 , 0.9 , and 0.3 .

The preliminary calibrated PSLE, at 90% confidence level (c.l.), versus the SNR is illustrated in Figure 5, once the estimated biases are corrected, and it is compared to the expected trend in case of a perfect system with the same geometry as ECLAIRS. The PSLE was estimated by measuring the offsets of Crab, Cyg X-1, Cyg X-2, and Cyg X-3. After a selection of images containing no artifacts, the resulting 2475 data points were binned by SNR with 100 points per bin. Then, to obtain a robust 90th percentile and the associated error bar in each bin, a bootstrapping procedure was applied: in each bin, 100 points were drawn with replacement a large number of times (Foisseau 2025). The mean 90th percentile and its standard deviation in all samples are used as data points and errors in the fit of the 90% c.l. PSLE function. We find (Figure 5) that the trend of the error, in units of sky pixels, versus the SNR is given by

$$\text{PSLE}_{90\%}(\text{SNR}) = \frac{(3.35 \pm 0.03)}{\text{SNR}} + (3.5 \pm 0.5) \times 10^{-2} \text{ pix.}$$

Since, on-axis, a sky pixel corresponds to $\approx 34'$, the error at the image center varies between $12.5'$ and $2.3'$ for SNRs between 10 and 100. Note that due to the tangential projection, the off-axis pixel angular sizes reduce along the direction from the center, to reach, at the edges of the FoV, about half the size the on-axis value. The fact that a plateau (1.2 on-axis) is reached at high SNR indicates that some systematic effect is still present,

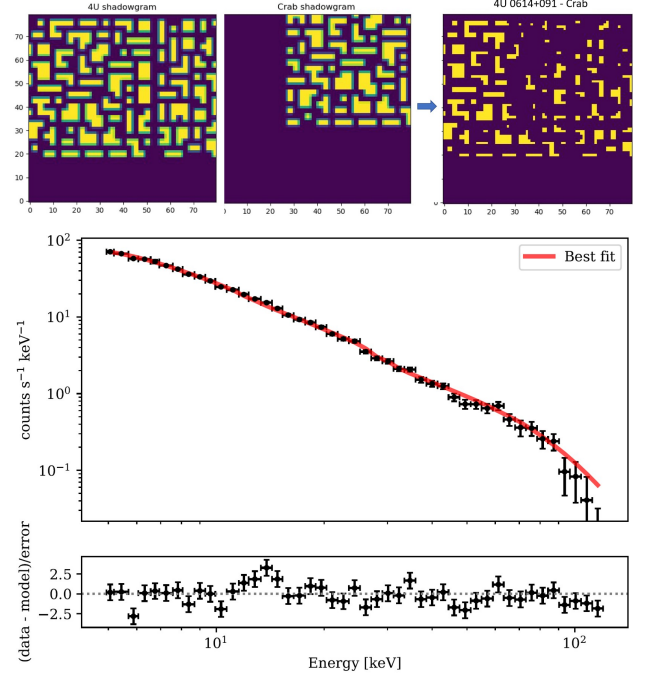


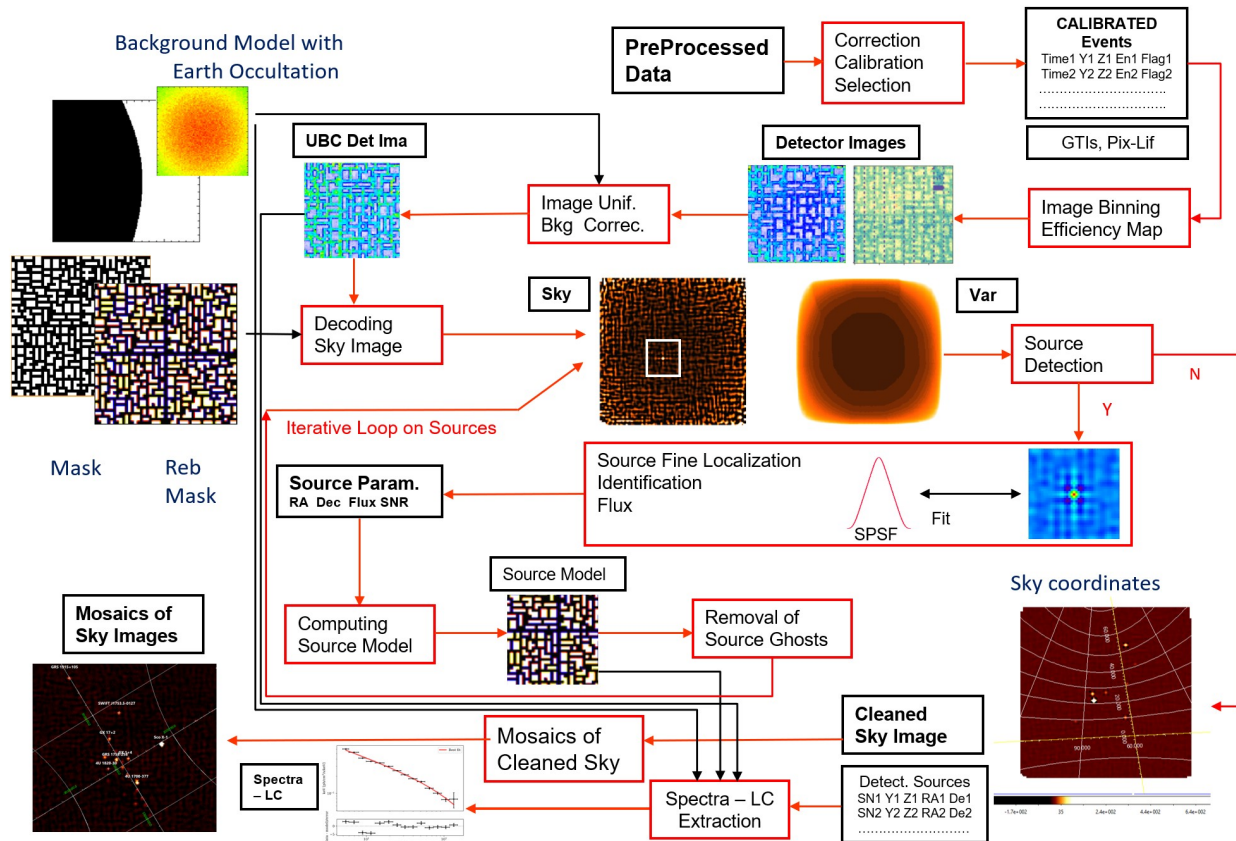
Figure 6. Top: source DET-MODs for two sources and combination for event selection of the 1st one. Bottom: ECLAIRS count spectrum of the Crab with its best fit power-law model (red line) and residuals, for an on-axis NEO observation of ≈ 800 s.

while the error at low SNR may be dominated by noise in the images, as indicated by the outlying points. Future improvements of the pipeline for the reduction of noise and the correction of residual imaging biases may reduce this localization uncertainty.

6. Source spectra and light curve Extraction

Once the positions of the active sources in the FoV are defined, either by the imaging process or by a choice of the user, the extraction of source products (SPEX) can be performed.

Data are reprocessed with BUBE to bin and correct detector images in the desired energy or time bins (in automatic QLA mode at FSC, the same binning of 5 energy bands for imaging is used and SPEX in spectral mode is called directly after IMAG without running BUBE again). They are used to fit a global model that contains the computed shadow-grams (Figure 6 top) of the chosen sources (at their fixed positions) and, possibly, a background model. The fit can be performed by least-squares (default) or maximum likelihood (adapted to very short exposures) methods, and determines simultaneously the fluxes of all sources and of the background. The normalized to on-axis count rate spectra (SPS-SOE) or LCs (LCS-SOE) contain fluxes and errors for all fitted sources and, if included, the background. The spectra (Figure 6, bottom), after some manipulations, can be compared, using standard



tools like XSPEC, to spectral models convolved with the instrument energy response (ENE-RSP), described by an ARF and RMF matrices and the PI-channel to energy relation. Note that the background spectrum is already subtracted by the procedure from the source spectra, and it shall not be subtracted again with XSPEC or other tools.

The user has the choice to fit the DET-UBC images, already corrected for background, in which case a background spectrum is not generated in the output, or to fit as well a background model to uncorrected images (DET-IMA). Such a model is, by default, a 2D polynomial function, whose parameters are adjusted to the image simultaneously with the amplitude of the sources. Other models (e.g., from empty field data or including Earth albedo and reflection) will be possibly implemented in the future.

The final component (MOSA) (Figure 1) and other tools, some provided as a separate software set from ECPI (Coleiro et al. 2026), are, or will be soon, available, to combine, handle and analyze the SDP.

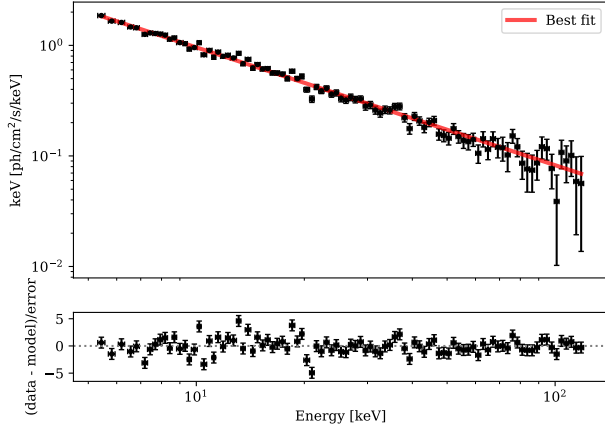


Figure 8. ECLAIRs photon spectrum of the Crab Nebula and its best fit power-law model (red line) from a ≈ 970 s observation with the target off-axis ($\approx 30^\circ$), with residuals at the bottom.

Stacking of detector images, before decoding and analysis, for periods of constant attitude, is already operational for NEO and PEO data, producing routinely the combined NPO products, while stacking data of different passes of the same observation will be available soon and will generate stacked products (STK files). Production of mosaics of sky images of different attitudes will also be soon implemented.

A simplified, logical scheme of the ECLAIRs scientific data analysis, that summarizes the described procedures, including the iterative loop to search and fit the sources and clean their coding noise, is illustrated in Figure 7.

8. Pipeline Performance and Perspectives

ECPI has run automatically at FSC since the SVOM launch (2024 June) and feeds the SDB with SDP that are available to scientists, with standard choices of parameters (e.g., five energy bands, standard GTIs). Revised sets of SDP will be regularly produced by the FSC with improved software and auxiliary files. The ECPI is documented and can be installed in individual computers to run specific analyses.

The preliminary evaluations of the ECPI performance show that, overall, it works well. A set of scientific results has been obtained with it, for both core and observatory science programs (see Coleiro et al. 2026), and for the performance of ECLAIRs (Godet et al. 2026). Even if more work is needed to better clean images from the background (the correction with a 2D polynomial function fitted to the data, as for spectral extraction, is in progress), the source localization approaches the expected theoretical performance and is within the requirements, provided that the images are not too affected by noise. The reconstructed spectra (Figures 6 and 8) and light curves (Figure 9) of the Crab Nebula, the standard candle in X-ray astronomy, show that expected spectral parameters and stable behavior are obtained when the background is well corrected, even for highly off-axis targets. ECLAIRs and MXT

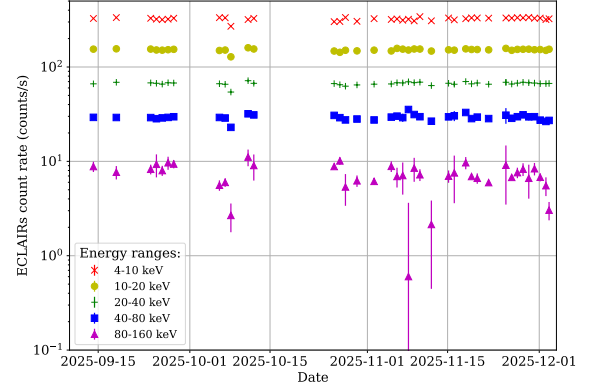


Figure 9. ECLAIRs count rate light curves of the Crab Nebula in the fall of 2025 in different energy bands.

(the SVOM X-ray telescope) spectra combine very well (Coleiro et al. 2026) and comparison with results from other observatories also shows consistent trends. The ECLAIRs scientific performance, from in-flight data analyzed with ECPI and other software, is presented in Godet et al. (2026).

The work to complete ECPI functionalities (stacking, short-bin LC, mosaics, slew data), to improve instrument and background modeling and complete the software tools to handle and analyze the products, is in progress.

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