SIRENA: software for Athena X-IFU event reconstruction

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Abstract. SIRENA is a software prototype package currently in development for the reconstruction of the energy of the X-ray events detected by the X-IFU instrument of the Athena observatory. During this development phase it is integrated in a larger project for Athena end-to-end simulations (SIXTE), where X-IFU data can be simulated, initially triggered and finally, energy reconstructed, thus helping in the assesment of different instrument configurations.

SIRENA implements different analysis and triggering algorithms with the aim of testing their performance in terms of energy resolution and computing resources. The best performance algorithms, optimized for in-flight use, will be finally implemented on board in the X-IFU Digital Readout Electronics (DRE) unit.

1. The X-IFU instrument on board Athena observatory

Athena (Nandra et al. 2013) is an X-ray astronomical observatory selected by the European Space Agency in 2014 as the second large mission of its Cosmic Vision Programme. It will consist of an X-ray telescope and two focal plane instruments, the X-IFU (Barret et al. 2016) and the WFI (Meidinger et al. 2016).

The X-IFU is a cryogenic microcalorimeter array based on Transition Edge Sensor technology aimed at providing spatially resolved high-resolution spectroscopy. The signal of each channel in which the focal plane array is read using a *FDM* technique, is processed by the two Digital Readout Electronics (Ravera et al., 2014) sub-units: the DRE-DEMUX demultiplexer and the event processor DRE-EP.

The continuous high-rate raw data stream pre-processed by the demultiplexer has to be processed on board to reduce the output data rate required by the telemetry constraints of the mission. This processing is done in the DRE-EP sub-unit in two stages: an initial on-the-fly event triggering done over hardware, and a subsequent (deferred in time) X-ray event characterization done in software using the SIRENA functionality.

2. SIRENA package

SIRENA is the software package currently in development as an anticipated contribution of IFCA/Spain to the X-IFU international consortium, through the DRE unit, in particular to perform the event characterization task of the Event Processor Subsystem. It will provide a reduced output with the physical relevant parameters of the input X-ray photons, including their energy, spatial position, quality (grade) and arrival time.

During this phase, SIRENA is part of the publicly available end-to-end Athena simulator SIXTE [1]. Inside this environment, the SIXTE tool `tessim` (Wilms et al. 2016) implements the microphysics of the Transition Edge Sensor in the X-IFU instrument, thus making possible the simulation of X-IFU data streams under different conditions. These data streams can be ingested in the SIRENA tools for detailed event triggering and reconstruction, following different techniques and levels of precision.

At the current stage of development, three main building blocks compose this package: event detection, event grading and event energy determination. Initially, the `tessim` pre-triggered data stream is searched for possible multiple events in the record. These detected events are then analyzed by the grading block to establish their quality (high, mid or low resolution), according to the proximity of the previous and following events. In the last block, different algorithms can be applied to determine the energy content of the input X-ray photons. A detailed description of these blocks and several examples can be found in the documentation of the SIRENA site at *Read The Docs*. [2]

2.1. Input/Output files

Running SIRENA requires the use of an input data file with the events stream split into RECORDS (operation that can be performed with `tessim` tool), and two auxiliary files: a noise spectra and a library file. The noise spectra can be obtained from a simulated stream (with or without events) using an auxiliary SIRENA task call `gennoisespec` and is used to weight the optimization problem in the Optimal Filtering reconstruction techniques. The library file can also be created by SIRENA and contains (for the different calibration energies) pulse templates, pre-calculated optimal filters (both in time and in frequency domain) at different lengths to be used (if requested) in the Optimal Filtering techniques, covariance matrices of the noise and some pre-calculated values to shorten forthcoming calculations.

The final output is a typical FITS event list with an HDU named *EVENTS*, containing the arrival time of the photons detected, their energy content and both the length of the filter used and the distance to the preceding pulse as a measure of their grade.

2.2. Detection

The detection of the events in the input data is performed through a threshold algorithm, by which a trigger is raised when the derivative signal at a given sample exceeds a tunable number of times the standard deviation of that signal. Once a pulse is detected (and its energy initially estimated according to its height), a template is selected from the library and subtracted from the signal, so that new secondary pulses can be found.

[1] `http://www.sternwarte.uni-erlangen.de/research/sixte/`

[2] `http://sirena.readthedocs.io`

If the input signal is very noisy, the detection stage can include a previous filtering process of the data signal. As a baseline, SIRENA implements a low pass filtering where the length of the box-car filter can be selected by an input parameter. In addition, there is also currently under development a new filtering technique based on wavelet functions, where a noiseless version of the signal can be recovered inverting the wavelet transform after the removal of some coefficients of the discrete wavelet.

2.3. Reconstruction algorithms

In addition to the broadly used Optimal Filtering technique implemented as a baseline, SIRENA includes other reconstruction techniques with the aim of comparing their performance for the SIXTE X-IFU simulated data, in terms of final energy resolution and usage of computational resources (an overview of these techniques and their comparison is given in (Peille et al. 2016)). Basically:

Optimal Filtering (Szymkowiak et al., 1993; Boyce et al., 1999): It relies on two main assumptions: the detector response is linear (the pulse shapes are identical regardless of their energy and thus, the pulse amplitude is the scaling factor from one pulse to another) and the noise is stationary, i.e. it does not vary with time. The amplitude of each pulse can then be estimated by minimizing (weighted least-squares sense) the difference between the noisy data and the model pulse shape. In the time domain, the amplitude is the best weighted (optimally filtered) sum of the values in the pulse.

Resistance Space (Bandler et al., 2004): An initial transformation of the input signal (before reconstruction) producing a more linear scaling of the signal with the energy and a more stationary noise can help to deal with the intrinsic non-linearities of the above method. For this purpose several transformations to, what has been called, a “resistance space” are currently implemented in SIRENA, following different approaches and simplifications.

The Optimal Filtering method above (in current space or after signal transformation), can be run with two different levels of simplifications: fixed or *on-the-fly* filters. If the option of fixed filters is used, a pre-calculated optimal filter will be selected from the library file according to the length of the pulse being analysed. Otherwise, an ad-hoc filter will be created for each pulse during the reconstruction stage, with the maximum pulse length available. This selection of fixed filters have an impact on the final energy resolution of the reconstructed events that can be assessed comparing both results.

Covariance matrices (Fixsen et al., 2004): A different approach is required both in the presence of non-stationary noise along the signal event, and when the constant shape of the signal is not a good approximation. In this method, a family of pulse templates can be constructed at different calibration energies, where the linear assumption can be locally assumed. In addition, instead of using the noise power as in the optimization performed in the Optimal Filtering technique, the noise covariance matrix is adopted, which constitutes a better representation of the noise.

Principal Component Analysis (Busch et al., 2016; Yan et al., 2016): This is a non-parametric approach that does not require an initial knowledge of the datasets, and thus can be applied when there is a large shape variation of the pulses or in the presence of low frequency variations of different TES parameters that can affect the above reconstruction methods in a different manner. The most representative eigenvectors and eigenvalues of the covariance matrix of the signal (or that of the noise) are taken and the data are projected in the relevant components. The events energy can thus be correlated to a linear combination of these components. Although in a very preliminary phase, SIRENA also implements a PCA reconstruction method for the analysis of narrow band spectra (currently only two input monochromatic energies are possible).

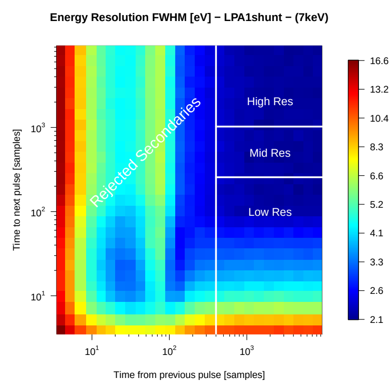

Figure 1. SIRENA reconstructed energy resolution of *tessim* simulated photons for different separations from their preceding and following photons in the stream.

3. Summary and Outlook

SIRENA software inside the SIXTE simulation environment is a publicly available, perfectly suited tool to study the performance of different triggering and reconstruction algorithms as well as the effect of different instrument configurations on the energy resolution of the events in the detector. As an example, Figure 1 shows a grading study of the photons detected by the baseline configuration of X-IFU. Being a package in active continuum development, SIRENA will be incorporating to the analysis all those future simulation effects in *tessim* that will have an impact in the reconstruction process, such as the subsample simulation of the incoming photons or the saturation effects linked to the non linearity of the transition.

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References

Bandler, S. R., et al. 2004, Nuclear Instruments and Methods in Physics Research A, 520, 285
Barret, D., et al. 2016, in SPIE 2016: Ultraviolet to Gamma Ray, vol. 9905 of SPIE Conf. Ser,
Boyce, K. R., et al. 1999, in EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy X, edited by O. H. Siegmund, & K. A. Flanagan, vol. 3765 of SPIE Conf. Series, 741
Busch, S. E., et al. 2016, Journal of Low Temperature Physics, 184, 382
Fixsen, D. J., et al. 2004, Nuclear Instruments and Methods in Physics Research A, 520, 555
Meidinger, N., et al. 2016, in SPIE 2016: Ultrav. to Gamma Ray, vol. 9905 of SPIE Conf. Ser.
Nandra, K., et al. 2013, ArXiv e-prints. 1306.2307
Peille, P., et al. 2016, in SPIE 2016: Ultraviolet to Gamma Ray, vol. 9905 of SPIE Conf. Series
Ravera, L., et al. 2014, in SPIE 2014: Ultrav. to Gamma Ray, vol. 9144 of SPIE Conf. Series
Szymkowiak, A. E., Kelley, R. L., Moseley, S. H., & Stahle, C. K. 1993, J. L. T. Phys., 93, 281
Wilms, J., et al. 2016, in SPIE 2016: Ultraviolet to Gamma Ray, vol. 9905 of SPIE Conf. Series
Yan, D., et al. 2016, Journal of Low Temperature Physics, 184, 397