Early results on STIX imaging

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Spectrometer/Telescope for Imaging X-rays (STIX)

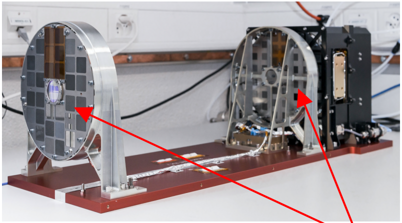

(Credits: ESA website)

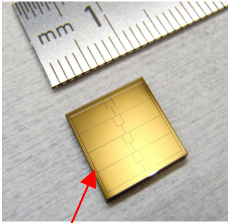
- Hard X-ray imaging spectrometer on Solar Orbiter
- goal: provide information on flare-accelerated nonthermal electrons by measuring the corresponding X-ray bremsstrahlung emission

The STIX imager

32 subcollimators:

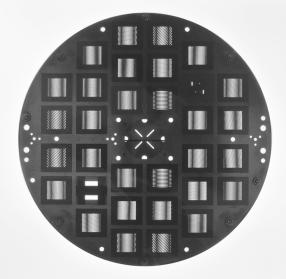
- 30 for imaging
- coarse flare locator
- background monitor





subcollimator = grids + detector

(Krucker, S., et al. (2020))

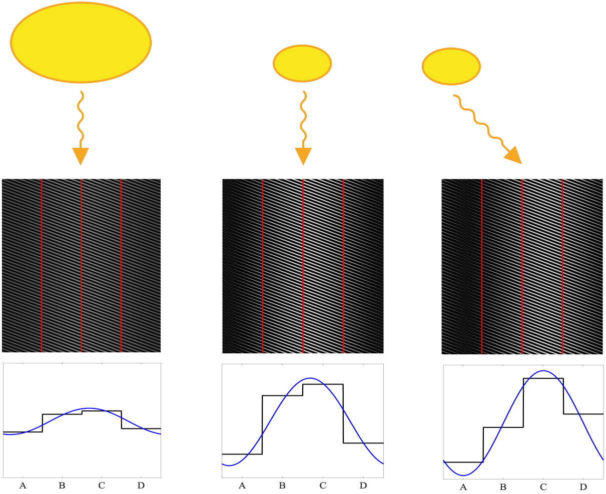


(Krucker, S., et al. (2020))

- The front and the rear grid have slightly different orientation and pitch (i.e. slit + slat dimensions)
- The superimposition of the grids produces a **Moiré pattern** on the detector

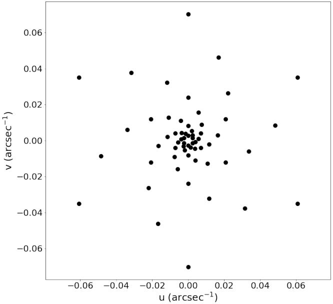
The STIX imager

Moiré patterns are sensitive to location and morphology of the source



STIX data

- Phase and amplitude of the Moiré pattern → phase and amplitude of a Fourier component of the angular distribution of the source (**visibility**)
- Number of photon counts recorded in each detector pixel → value of the visibility phase and amplitude[1]
- The data recorded by STIX is $V = (v_1, \ldots, v_{30})$, where v_i is the complex visibility measured by the i-th subcollimator



10 different angular resolutions between 7.1 and 179 arcsec (logarithmically spaced in steps of 1.43)

[1] Giordano, S., et al. (2015)

STIX imaging problem

Image reconstruction problem from calibrated data

$$\mathcal{F}\varphi = V \ ,$$

where

- $\mathcal{F}$ is the Fourier transform
- φ is the photon flux to reconstruct
- V is the array of visibilities

The visibility amplitudes only are calibrated and available for imaging (calibrated phases are coming soon)

STIX imaging problem (Massa, P., et al. (2021))

Image reconstruction problem semi-calibrated data

$$|\mathcal{F}\varphi| = A \ ,$$

where $A = |V|$.

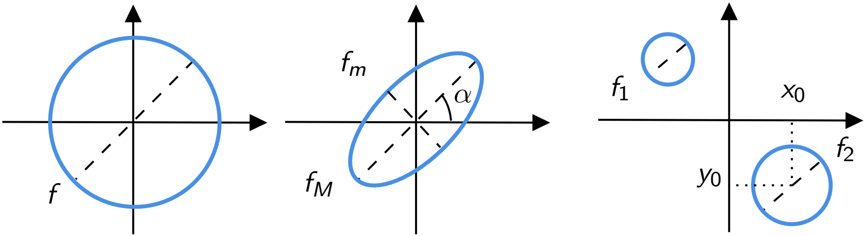
Problems:

- non-linear
- non-unique solution: the position of the source can not be recovered from amplitudes only

Approach:

- parametrized source shapes
- forward–fitting methods for retrieving the parameters

Parametric shapes (Massa, P., et al. (2021))



$\theta = (\phi, f)$ $\qquad$ $\theta = (\phi, f_M, f_m, \alpha)$ $\qquad$ $\theta = (x_0, y_0, \phi_1, f_1, \phi_2, f_2)$

Forward-fitting methods (Massa, P., et al. (2021))

Particle Swarm Optimization (PSO)

- Stochastic optimization method for solving

$$\arg\min_{\theta \in \mathcal{D}} \quad \chi^2(\theta)$$

- Uncertainty estimation: confidence strip approach
- Fast ($\sim$5 sec without uncertainty estimation)

Sequential Monte Carlo (SMC)[2]

- Finds an approximation of

$$p(\theta|A) \propto p(A|\theta)p(\theta) \ ,$$

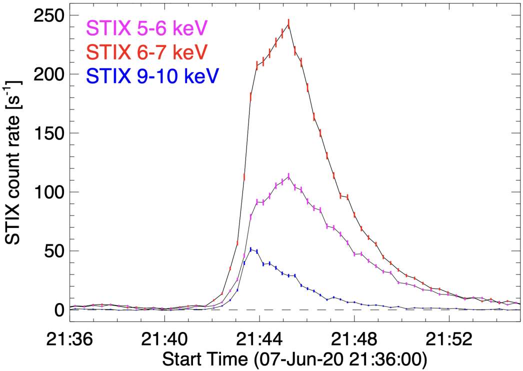
where $p(\theta)$ is the prior on the parameters and $p(A|\theta)$ is the likelihood

- Uncertainty estimation: standard deviation of $p(\theta|A)$
- Slow ($\sim$5 mins)

[2] Sciacchitano, F., et al. (2018)

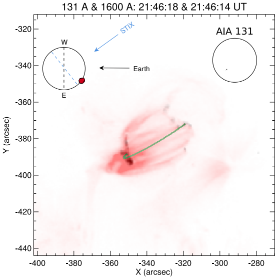
June 7, 2020 event (Battaglia, A. F., et al. (2021))

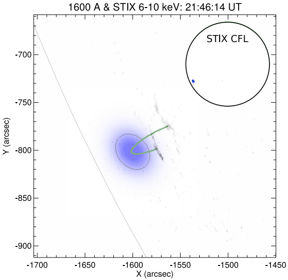
Time interval: 21:45:44 - 21:46:44
Energy range: 6-10 keV
GOES class: B6

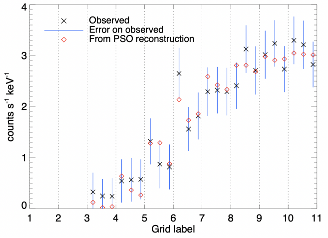


June 7, 2020 event (Battaglia, A. F., et al. (2021))

PSO reconstruction: Gaussian elliptical source



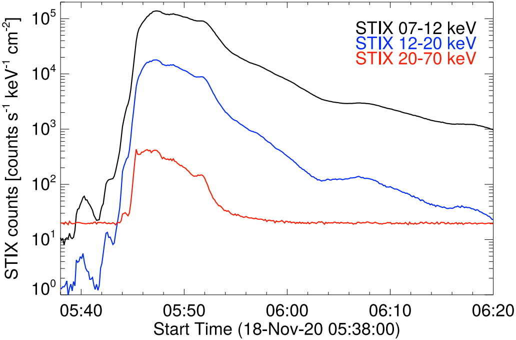




Flux (counts s^{-1} keV^{-1})	3.1 ± 0.2
FWHM max (arcsec)	35.5 ± 5.9
FWHM min (arcsec)	27.5 ± 4.1
Orientation (degrees)	131 ± 38
χ^2	0.35

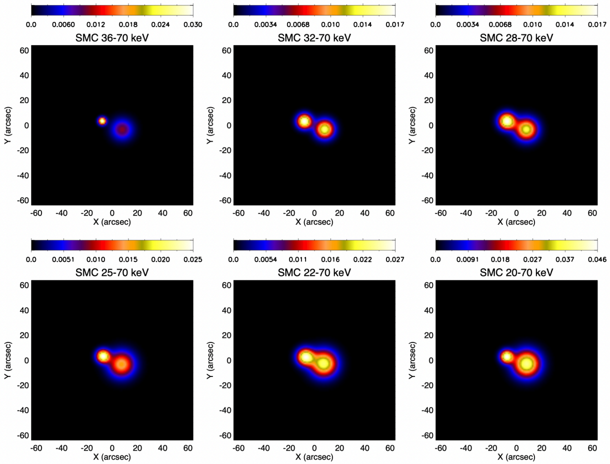
November 18, 2020 event - 1 (Massa, P., et al., (2021))

Time interval: 05:45:30 - 05:46:15
Energy ranges: 36-70 keV, 32-70 keV, 28-70 keV, 25-70 keV, 22-70 keV, 20-70 keV
GOES class: estimate from STIX as > M9



November 18, 2020 event - 1 (Massa, P., et al., (2021))

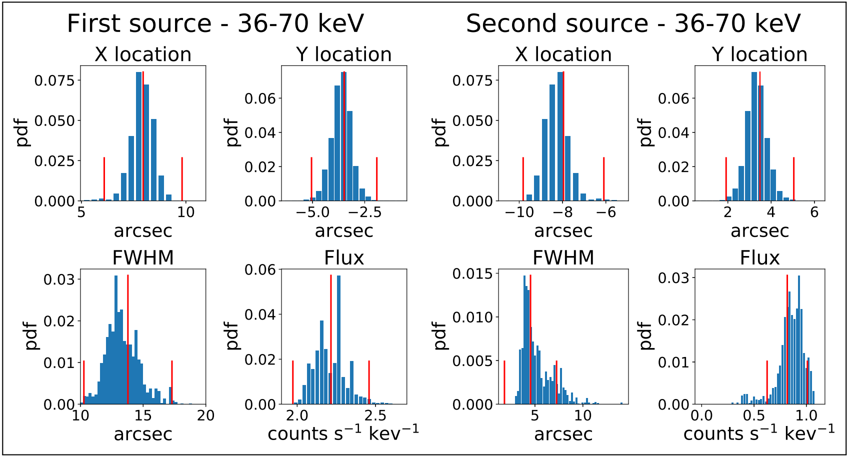
SMC reconstructions: double Gaussian circular source



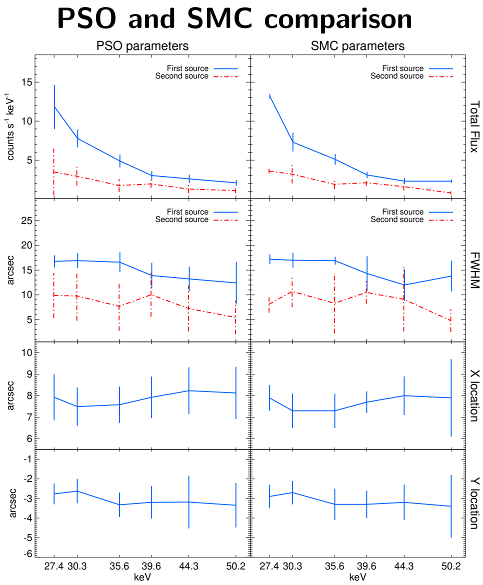
Possible interpretation: nonthermal bremsstrahlung emission (left source), thermal emission with a nonthermal tail (right source)

November 18, 2020 event - 1 (Massa, P., et al., (2021))

SMC posterior distributions



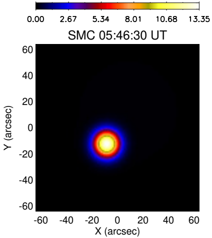
November 18, 2020 event - 1 (Massa, P., et al., (2021))

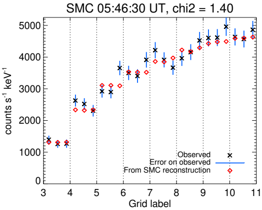


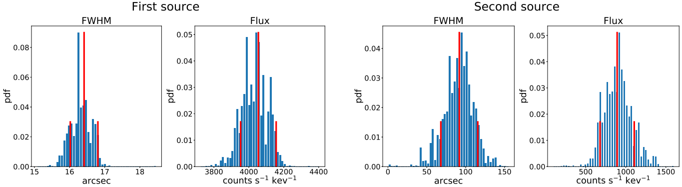
November 18, 2020 event - 2 (Massa, P., et al., (2021))

Time interval: from 05:46:30 to 05:46:31 (1 sec)
Energy range: 7–12 keV

SMC reconstruction: double Gaussian circular source







compact source + faint halo

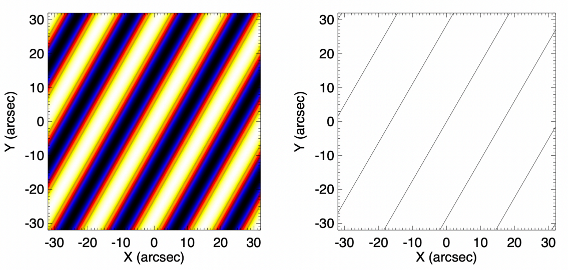
Visibility phase calibration

The backprojection of a single visibility is a sinusoidal wave

$$\varphi(x, y) = A\cos(2\pi(xu + yv) - \Phi) \ ,$$

where

- A is the visibility amplitude
- Φ is the visibility phase
- (u, v) is the frequency sampled by the subcollimator

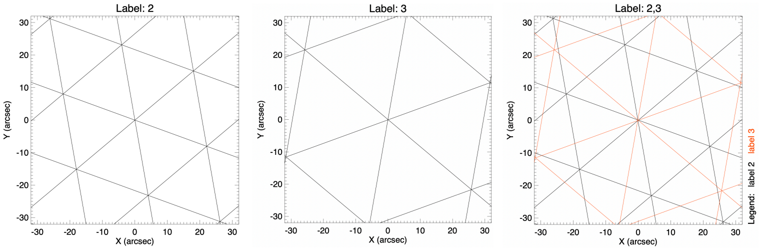


Visibility phase calibration

Assumptions:

- the source is unresolved (point source)
- the phases are well calibrated

The lines corresponding to subcollimators with the same angular resolution form triangles



Simulated point source in $(0, 0)$

Visibility phase calibration

Goal: correct systematic error in the visibility phases due to a modification of STIX hardware parameters:

- relative orientation of rear grid and detectors
- relative orientation of front and rear grids
- relative shift of the rear grid and detectors

Approach: optimize the *closure phases* (signed sum of three phases equal to $2\pi k$, $k = \dots, -1, 0, 1, \dots$)

Check: use the imaging method for monitoring the phase calibration status

Still work in progress!

Conclusions

- We have developed two parametric imaging methods (PSO and SMC) for image reconstruction from STIX visibility amplitudes
- PSO is faster but has a less robust parameter uncertainty estimation
- SMC is slower but provides a full probabilistic description of the sought parameters
- We have shown that it is possible to reconstruct images from data with 1 sec of integration time (for large flares)
- We have given insights about the visibility phase calibration (still in progress)

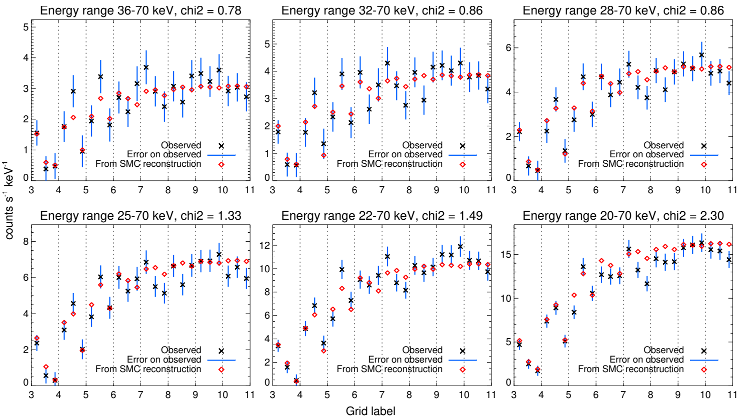
References

- Krucker, S., et al., *The Spectrometer/Telescope for Imaging X-rays (STIX)*, Astronomy & Astrophysics, 642 (2020)
- Giordano, S., et al., *The Process of Data Formation for the Spectrometer/Telescope for Imaging X-rays (STIX) in Solar Orbiter*, SIAM Journal on Imaging Sciences, 8.2 (2015)
- Massa, P., et al., *Imaging from STIX visibility amplitudes*, submitted to Astronomy & Astrophysics (2021)
- Sciacchitano, F., et al., *Identification of multiple hard X-ray sources in solar flares: A Bayesian analysis of the 2002 February 20 event*, The Astrophysical Journal, 862 (2018)
- Battaglia, A. F. et al., *STIX X-ray microflare observations during the Solar Orbiter commissioning phase*, to appear on Astronomy & Astrophysics (2021)

Thank you for the attention!

November 18, 2020 event - 1 (Massa, P., et al., (2021))

SMC reconstructions: double Gaussian circular source



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SMC posterior distributions