

First Hard X-Ray Imaging Results by Solar Orbiter STIX

Original

First Hard X-Ray Imaging Results by Solar Orbiter STIX / Massa, P., Battaglia, A.F., Volpara, A., Collier, H., Hurford, G.J., Kuhar, M., Perracchione, E., Garbarino, S., Massone, A.M., Benvenuto, F., Schuller, F., Warmuth, A., Dickson, E.C.M., Xiao, H., Maloney, S.A., Ryan, D.F., Piana, M., Krucker, S.. - In: SOLAR PHYSICS. - ISSN 0038-0938. - 297:7(2022), pp. 1-18. [10.1007/s11207-022-02029-x]

Availability:

This version is available at: 11583/2973111 since: 2023-06-04T10:48:31Z

Publisher:

Springer

Published

DOI:10.1007/s11207-022-02029-x

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)



First Hard X-Ray Imaging Results by Solar Orbiter STIX

Paolo Massa¹ · Andrea F. Battaglia^{2,3} · Anna Volpara¹ · Hannah Collier^{2,3} · Gordon J. Hurford² · Matej Kuhar² · Emma Perracchione⁴ · Sara Garbarino¹ · Anna Maria Massone^{1,5} · Federico Benvenuto¹ · Frederic Schuller⁶ · Alexander Warmuth⁶ · Ewan C.M. Dickson⁷ · Hualin Xiao² · Shane A. Maloney^{8,9} · Daniel F. Ryan² · Michele Piana^{1,5} · Säm Krucker^{2,10}

Received: 7 March 2022 / Accepted: 16 June 2022 / Published online: 22 July 2022
© The Author(s) 2022

Abstract

The Spectrometer/Telescope for Imaging X-rays (STIX) is one of six remote sensing instruments on-board Solar Orbiter. The telescope applies an indirect imaging technique that uses the measurement of 30 visibilities, i.e., angular Fourier components of the solar flare X-ray source. Hence, the imaging problem for STIX consists of the Fourier inversion of the data measured by the instrument. In this work, we show that the visibility amplitude and phase calibration of 24 out of 30 STIX sub-collimators has reached a satisfactory level for scientific data exploitation and that a set of imaging methods is able to provide the first hard X-ray images of solar flares from Solar Orbiter. Four visibility-based image reconstruction methods and one count-based are applied to calibrated STIX observations of six events with GOES class between C4 and M4 that occurred in May 2021. The resulting reconstructions are compared to those provided by an optimization algorithm used for fitting the amplitudes of STIX visibilities. We show that the five imaging methods produce results morphologically consistent with the ones provided by the Atmospheric Imaging Assembly on board the Solar Dynamic Observatory (SDO/AIA) in UV wavelengths. The χ^2 values and the parameters of the reconstructed sources are comparable between methods, thus confirming their robustness.

Keywords Instrumentation and data management · Spectrum, X-ray · Integrated Sun observations

1. Introduction

The Spectrometer/Telescope for Imaging X-rays (STIX) on Solar Orbiter studies solar flares in hard X-rays (Krucker et al., 2020). STIX imaging is not based on focusing optics; instead, it exploits an imaging technique realized by means of 30 pairs of Tungsten grids (Hurford, 2013) placed in front of coarsely pixelated CdTe detectors (Meuris et al., 2015). As a consequence, STIX is a Fourier-based imager that provides 30 angular Fourier components of the X-ray source termed *visibilities*, and STIX images at different photon energies can be reconstructed utilizing algorithms for the inversion of the Fourier transform from limited

Extended author information available on the last page of the article

data (Piana et al., 2022; Perracchione, Massone, and Piana, 2021). A first version of the calibration of STIX visibility amplitudes became available in spring 2021, and a demonstration of STIX imaging capabilities using these semi-calibrated visibilities has been obtained by parametric approaches (Massa et al., 2021). Since then, the calibration of both amplitude and phase of STIX visibilities has been carried out for the 24 coarsest sub-collimators labeled from 3a through 10c, where the number refers to the detector resolution and the letter a, b, or c refers to the orientation of the grids (see Table 2 in Krucker et al., 2020). Sub-collimators 1 and 2 have the finest angular resolution and were fabricated differently than the coarsest ones. The complete calibration for these is in progress.

The objective of this paper is two-fold. First, this paper demonstrates that the complete calibration of 24 out of 30 STIX visibilities has reached a satisfactory level for accurate image reconstruction; second, this work demonstrates that several image reconstruction methods can produce comparable, robust, and reliable results. Compared to phase calibration in radio astronomy, where calibration changes in time with changing atmospheric conditions, STIX phase calibration depends only on the mechanical properties of the grids associated with the detectors, and the calibration should therefore be rather stable in time. This enormously simplifies the calibration task for STIX, as a single calibration should be good for all flares. However, a possible variation in the phase calibration may be due to Sun heating when the spacecraft is close to the star since heat may slightly modify the shape of the grids and their relative position with respect to the detectors. The effect of Sun heating on the visibility calibration will be investigated in detail once data recorded during the first closest approach of the Solar Orbiter to the Sun is available.

Our analysis is focused on a set of flaring events that occurred in May 2021. These flares range from GOES C4 to M4 class, and all of them have good counting statistics in the STIX observations. Further, the May 7 event can be considered paradigmatic of the standard flare model with two non-thermal footpoints connected by a flare loop (Tandberg-Hanssen and Emslie, 1988). This event is, therefore, particularly significant for the validation of the calibration process and of the imaging algorithms' performances.

As there is currently no other solar-dedicated hard X-ray imaging telescope observing the Sun, we have no means of comparing STIX observations with other hard X-ray images. For assessing the reliability of the reconstructed flare morphology, the STIX images are compared to ultraviolet (UV) maps of the same events provided by the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory (SDO/AIA) (Lemen et al., 2012). To account for the different vantage points of the SDO and Solar Orbiter, the AIA UV images are rotated to the STIX reference frame under the assumption that the emission comes from the solar surface. Such a rotation is accurate enough for our purpose (i.e., a few arcsec) as most of the UV emission originates from the chromosphere (e.g., Fletcher, Pollock, and Potts, 2004).

The plan of the paper is as follows: Section 2 details the STIX observations utilized for the experiments and provides a brief overview of the imaging methods. Section 3 contains the results of this study. Our conclusions are offered in Section 4.

2. STIX Images of May 2021 Events

2.1. Data Overview

In May 2021, two active regions (ARs) generated a series of C and M class flares observed on disk by Solar Orbiter STIX as well as by GOES and SDO/AIA. The GOES and STIX

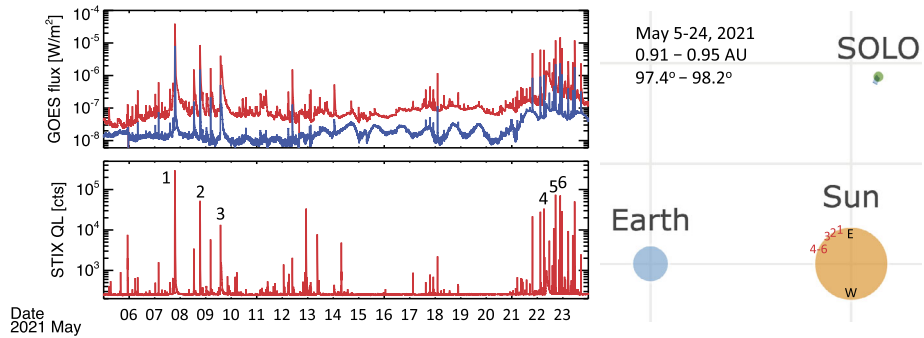


Figure 1 GOES Soft X-ray profiles (*top*: low energy channel in red, high energy channel in blue) and STIX 4–10 keV quicklook lightcurve (*bottom*) during the time period considered in the paper. The six flares selected for the STIX imaging studies are marked by numbers. On the right part of the figure, the relative position of the Solar Orbiter, Earth, and Sun are shown for the same period, as well as the locations of the six flares on the Sun.

lightcurves of all events from May 5 to May 24 are given in the top and bottom left panels of Figure 1. To demonstrate the imaging capability of STIX, we focused on imaging during the impulsive phase of six flares. We reported in Table 1 the relevant parameters of the considered events. We point out that the visibility data associated with these events have been calibrated using parameters and procedures as of February 2022. It is important to highlight that second-order corrections to the calibrations are still in progress and promise to improve the imaging quality in the future.

2.2. Spectroscopy

The spectroscopic analysis of the six events considered in this paper is done using the OSPEX¹ SSWIDL software (release from September 2021) and is presented in Figure 2. The spectral fitting analysis performed in this paper is intended just for finding appropriate energy ranges to use for imaging of the thermal and the non-thermal emission. Therefore, for simplicity and consistency with previous works (see, e.g., Battaglia et al., 2021), all STIX spectra are fitted with a standard isothermal function ‘*vt h*’ in the lower energy range and with a broken power-law ‘*bpow*’ in the higher energy end, where we fixed the value of the power-law index below the break to 1.5. Similarly, we did not include the albedo component as it has a negligible effect on the identification of thermal and non-thermal energy ranges. While the selection of the thermal energy range is rather straightforward (i.e., around the peak in the count spectrum at 6–7 keV), it is desirable to extend the non-thermal range to as low energies as possible to enhance statistics in the derived visibilities, but care should be taken to avoid any contribution of thermal emissions. To include thermal emissions would make the image morphology more complex. For example, in the standard flare model, three sources would exist in this case instead of just two footpoints, which would significantly increase the difficulties of image reconstruction with our limited sample of visibilities.

The spectral plots in Figure 2 are scaled in the same way in terms of energy and rate, making it straightforward to compare the different events (for information on STIX spectral fitting, we refer to Battaglia et al., 2021). As the time intervals are selected at the peak

¹<http://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/>.

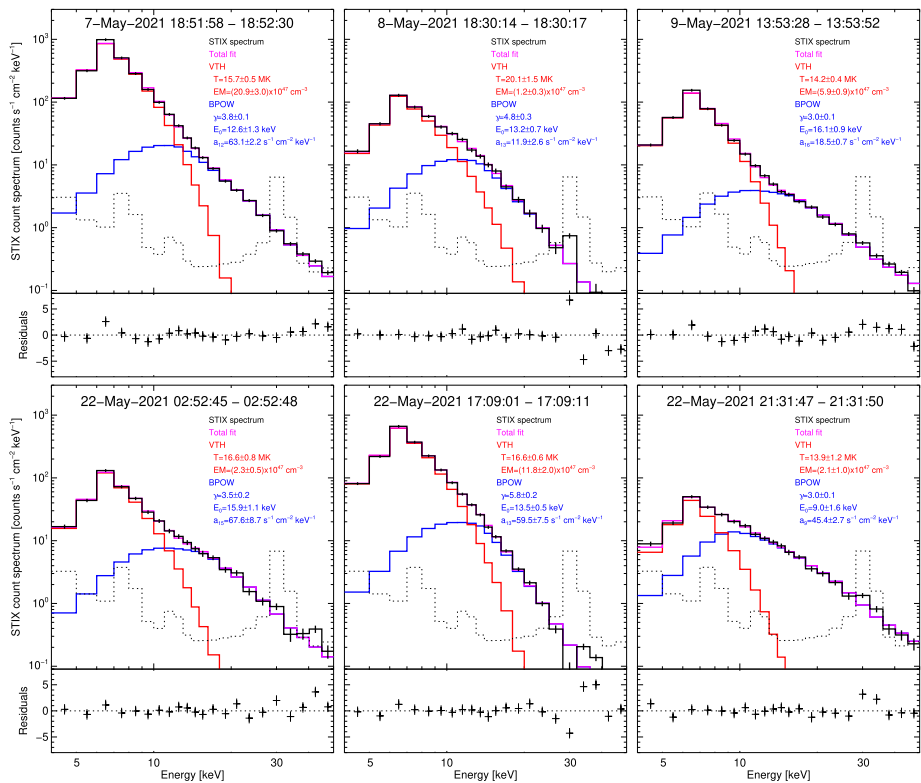


Figure 2 Spectroscopic results of the six events considered in this paper. For each event, the background subtracted count spectrum, given in black, is obtained by integrating the STIX temporal profiles around the non-thermal peak time. The STIX background spectrum used for the subtraction is shown in dotted black. The colored curves represent the fitted components: single thermal ‘vth’ in red and non-thermal broken power-law ‘bpow’ in blue, while the magenta curve denotes their sum. The bottom panel of each spectrum shows the residuals, i.e., the difference between the observed STIX count spectrum and the total fit normalized by the errors derived from counting statistics.

time of the non-thermal emission, which is generally earlier than the GOES peak time, we cannot compare directly the STIX thermal fits with GOES class of these events. The non-thermal emission, however, can be directly compared, revealing a significant spread between events, typical for solar flares (e.g., Battaglia, Grigis, and Benz, 2005). The power law indices of the photon spectra show rather hard spectra for four flares with values below $\gamma = 4$, while the event on May 22 around 17 UT has a very soft spectrum with a γ around 6, a rather high value considering that it is an M1 class flare. As most often is the case in X-ray spectral analysis of solar flares, the fitted energy break is driven by the existence of thermal emission at lower energies, and it does not necessarily indicate the existence of turnover in the distribution of the accelerated electrons below the fitted break energy. However, we used these values to make sure that the energy range for imaging the non-thermal footpoints starts at a higher value than the fitted break energy.

For all of these medium-large flares, the calibration line of the Ba133 source outshines the flare counts at the energy bin that contains the 31 keV line. As the calibration source is essentially stable in time during a flare, background subtraction often works well, even

when the flare signal is ~ 10 times lower than the background. For energy bins above the calibration line, the flare is roughly at the same level as the background emission, at least for the events shown here. Due to a strong calibration line in the 28–32 keV energy bin, image reconstruction, including this energy bin, can be challenging. Indeed, for flares that are not strong enough, the error on the background emission can be larger than the flaring signal itself. In this case, background subtraction can remove any information on the flaring source contained in the count measurements (and, hence, in the visibilities). We are currently further investigating this point. As a current best practice, we recommend to avoid making an image with an energy range starting at 28 keV, as in such a case, the background likely dominates the signal. Similarly, it does not make much sense to include the 28–32 keV channel as the last energy bin in an imaging energy range, as the proportional increase in the background is most often larger than the increase in signal. Hence, for all but one flare in this paper, the highest energy bin included for imaging is 28 keV. To include the 28–32 keV bin as an intermediate bin in the selected imaging energy range made no significant difference for at least the May 7 event presented here (the image presented for the flare of May 7 has the 28–32 keV bin included in the range from 22 to 50 keV). In any case, the effect of enhanced background emission due to the calibration line at 31 keV can be investigated when an image that includes the 28–32 keV energy bin is compared with the corresponding image excluding that energy bin.

2.3. STIX and AIA

For validating the morphology of the reconstructed hard X-ray sources, we performed a comparison with the 1600 Å images provided by SDO/AIA for all six events. To do so, we needed to account for the relative position of STIX and AIA (Earth) with respect to the location of the events on the Sun (Figure 1, right panel). The AIA images have been rotated to the Solar Orbiter vantage point by means of the *reproject*² Python package, where the Solar Orbiter ephemeris have been obtained from the Operational Solar Orbiter SPICE Kernel Dataset,³ following the procedure used in Battaglia et al. (2021). A potentially significant source of error in the location of the flare emissions in the rotated AIA maps is given by the projection effects. Indeed, coronal structures that extend higher up in the atmosphere will be distorted due to projection effects once the rotation of the map is performed. In order to minimize such uncertainty, one has to apply this method only to maps in which the observed emission originates roughly from the same altitudes and is ideally close to the solar surface. This can be the case for the emission that is observed in flare ribbons in the AIA 1600 and 1700 Å maps. In this paper, we compare the STIX reconstructed images with the rotated AIA 1600 Å maps as they would be seen from the Solar Orbiter vantage point. However, a word of caution is required here. The routine for rotating the AIA maps assumes all the emission is coming from the solar surface, i.e., from the bottom of the photosphere. That is not exactly what the AIA 1600 Å shows, since, according to the standard flare scenario, the emission mostly comes from the chromosphere. This may eventually result in a systematic offset in the location of flare ribbons as seen from the Solar Orbiter vantage point, which also depends on the location of Solar Orbiter relative to the Earth and its distance from the Sun. In the case of the flares considered in this paper, we estimated this uncertainty to be roughly 0.9 arcsec for the May 7, May 8, and May 9 events and 1.4 arcsec for the May 22 events, which is much smaller than the angular resolution of the finest sub-collimators used at 14.6 arcsec. We, therefore, neglected this second-order effect.

²<https://reproject.readthedocs.io/en/stable/>.

³DOI.

Table 1 Parameters of the events reconstructed in Figures 3 and 4. From left to right: selected time interval, active region number, GOES class associated with the event, and shift applied to the x and y coordinates of the center of the STIX reconstruction to make it overlap with the flare ribbons in the corresponding AIA map. The x and y shifts are defined in the heliocentric coordinate system and increase towards solar west and solar north, respectively.

Time interval (UT)	Active region	GOES class	Δx (arcsec)	Δy (arcsec)
May 7, 2021 18:51:00 – 18:53:40	AR2822	M3.9	44	54
May 8, 2021 18:29:00 – 18:32:00	AR2822	C8.6	45	57
May 9, 2021 13:53:00 – 13:55:00	AR2822	C4.0	47.5	53
May 22, 2021 02:52:00 – 02:55:00	AR2824	C6.1	47	55
May 22, 2021 17:08:00 – 17:11:00	AR2824	M1.1	47	50
May 22, 2021 21:30:30 – 21:34:00	AR2824	M1.4	50	50

2.4. Location of the STIX Reconstructions

The STIX reconstructions are performed in an instrument reference frame. In order to plot them in the helioprojective coordinate system, we need to perform a roto-translation that takes into account the spacecraft roll-angle and the angular offset between the instrument optical axis and the spacecraft reference axis. The roll-angle value used for the rotation is provided by the SPICE as-flown attitude kernel². As for the offset issue, for the events considered in this study, the Solar Orbiter was too far (outside 0.75 AU) from the Sun for the STIX Aspect System to be able to provide absolute pointing information (Warmuth et al., 2020). In order to superimpose the reconstructed hard X-ray sources on the UV ribbons, we therefore performed a manual shift of the reconstructed and rotated STIX maps. The shift, however, should not be arbitrarily large. For times when the aspect solution is available, and the spacecraft is pointing at the solar center (except for campaigns, the Solar Orbiter is most of the time pointing at solar center), the absolute pointing of the STIX images without applying the aspect correction should be less than 100'' offset from the actual value. Furthermore, the shift should not be drastically different for individual flares. The values we used for the six flares presented here are given in Table 1, and they indicate that the applied shifts are reasonable.

We point out that the image placement accuracy issue will not represent a problem during the Solar Orbiter mission science phase, which started at the end of November 2021. During the official science window, the Solar Orbiter will be close enough to the Sun to allow precise measurements of STIX pointing by means of the Aspect System. We expect the error in the location of STIX reconstructions to be better than 4 arcsec (Warmuth et al., 2020) once the corrections based on these measurements are implemented.

2.5. Imaging Methods

A set of image reconstruction methods is already implemented in the STIX data analysis software available in SolarSoftWare.⁴ Specifically, here we considered:

- The Maximum Entropy Method MEM_GE (Massa et al., 2020), which realizes the χ^2 minimization with respect to the observed visibilities, under three constraints: maximum entropy, positivity of the reconstructed signal, and a flux constraint. Specifically, the latter

⁴<https://www.lmsal.com/solarsoft/>.

forces the sum of the image pixels to be equal to an a priori estimate of the total imageable flux. This estimate is obtained from the visibility values; hence, the flux constraint does not add any further information on the solution. However, this constraint is needed for simplifying the optimization problem. MEM_GE represents a computational upgrade of the MEM_NJIT algorithm implemented for the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) (Bong et al., 2006; Schmahl et al., 2007), since it involves a mathematically sound optimization problem and a robust optimization technique.

- Back projection (see, e.g., Hurford et al., 2002), which realizes the discrete Fourier transform inversion of STIX visibilities and is equivalent to the *dirty map* in radio interferometry. This Fourier integration can be computed using different quadrature formulae. Although arbitrary weights can be used, the two main choices utilize the same weighting for all visibilities (*natural weighting*) or utilize a weighting that accounts for the distribution of visibilities in the frequency plane (*uniform weighting*). The former weighting has been applied in this paper.
- Clean (see, e.g., Högbom, 1974), which provides a set of point sources (named Clean Components) by iteratively deconvolving the instrumental point spread function (PSF) from a dirty map, which is provided by Back Projection with natural weighting in this case. While the Clean Components are the actual result, the Clean process is extended by two standard steps for visualization purposes: the convolution of the Clean Components with an idealized PSF and the addition of the residual map.
- VIS_FWDFIT (see, e.g., Hurford et al., 2002), which minimizes the difference between the measured visibilities and those predicted by assumed sources (single and double Gaussian circular source, Gaussian elliptical source, loop). The algorithm utilizes the AMOEBA function to perform minimization (Press, 2007). An estimate of the retrieved parameter uncertainty is obtained by perturbing 20 times the data with Gaussian noise, by forward-fitting the perturbed data and computing the standard deviation of the set of optimized parameters.
- EM (Massa et al., 2019), which is the Expectation Maximization algorithm, also known as the Richardson-Lucy algorithm when applied to image deconvolution problems (Richardson, 1972; Lucy, 1974). EM takes as input the measured STIX counts instead of the corresponding visibilities. The calibration of the counts follows the count formation model described in Massa et al. (2019) and exploits the same correction factors introduced for the visibility calibration. Following a maximum-likelihood approach, EM starts from a constant image and uses an iterative scheme based on the discrepancy between the observed counts and those predicted from the current iterate through the forward count formation model. The algorithm finds the image, which maximizes the probability that the observed counts are a realization of the Poisson random variable whose mean value is the array of the predicted counts. A positivity constraint is also imposed on the solution.

The results provided by these five approaches have been compared with the ones provided by a visibility amplitude fitting method based on Particle Swarm Optimization (PSO). Amplitude fitting, which has been validated in a previously published paper by Massa et al. (2021), was an intermediate approach to extract imaging information from STIX observations before the phase calibration reached a satisfactory level. With the phase calibration now available, this method is essentially obsolete. Nevertheless, it is worth to compare this algorithm with the imaging methods presented in this paper. Amplitude fitting realizes forward-fit by means of an optimization scheme simulating social behavior, specifically swarm intelligence (Clerc, 2006). The method also provides an estimate of the uncertainty on the retrieved parameters in a way analogous to VIS_FWDFIT. Table 2 summarizes the

Table 2 Parameters and input data of the algorithms used for solving the STIX image reconstruction problem. For each parameter, the value set for obtaining the reconstructions presented in the paper is reported between brackets.

Method	Input data	Parameters (value used in the paper)		
Back Projection	Visibilities	Weighting (natural)		
Clean	Visibilities	Weighting Back Projection (natural)	Beam width – FWHM (16.5 arcsec)	Clean boxes (50% contour level)
MEM_GE	Visibilities	Regularization parameter (0.005 for thermal, 0.02 for non-thermal)	Total flux estimate (max visib. amplitudes)	
EM	Counts	Stopping rule tolerance (10^{-4})		
VIS_FWDFIT	Visibilities	Source shape (Gaussian elliptical source for thermal, double Gaussian circular source for non-thermal)		
Amplitude fitting PSO	Visibility amplitudes	Source shape (Gaussian elliptical source for thermal, double Gaussian circular source for non-thermal)	Parameter uncertainty (on)	

main parameters of the algorithms and reports the values we set for performing the reconstructions. The STIX data (visibilities, counts, or visibility amplitudes) taken as input by each method are also indicated.

3. Results

Figure 3, top row, contains the UV maps of the May 7, 8, and 9 events provided by AIA at 1600 Å. In the bottom row of the same figure, the UV maps have been rotated in order to account for the Solar Orbiter vantage point and contour levels of the MEM_GE reconstructions have been superimposed. The same procedure has been followed in Figure 4, in the case of the May 22 events. In order to give an idea of possible flare loop geometry, a schematic vertical semi-circle connecting the ribbons is plotted in each panel of Figures 3 and 4.

Figure 5 compares the reconstructed images for the six methods in the case of the May 7, 2021 event. The STIX reconstructions have been superimposed on the rotated AIA 1600 Å map. As for the reconstructions of the non-thermal component, we report the uncertainty on the location of the reconstructed sources just for VIS_FWDFIT and the amplitude fitting method. Indeed, these are the only two methods that provide this information since they rely on a parametric formulation of the image reconstruction problem. In Figures 6 and 7, we compared the amplitude and phases of the experimental visibilities with the ones predicted from the Clean, MEM_GE, EM and VIS_FWDFIT reconstructions of the thermal

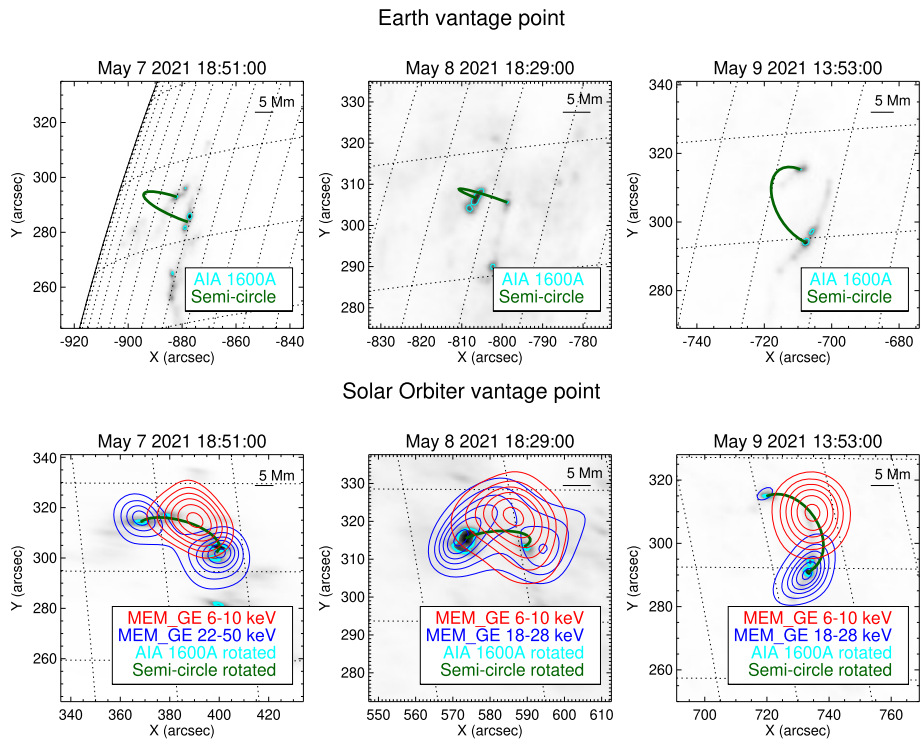


Figure 3 Top row, from left to right: AIA 1600 Å images of the May 7, 2021, May 8, 2021, and May 9, 2021 events, respectively. Bottom row: MEM_GE reconstructions overlaid on the rotated AIA maps of the same events. The 50% contour levels of the AIA images are plotted in cyan, while the 20, 35, 50, 65, 80, and 95% contour levels of the reconstructed thermal and non-thermal X-ray emissions are plotted in red and blue, respectively. The energy intervals considered are 6–10 keV for the thermal components, 22–50 keV for the non-thermal component of the May 7 event, and 18–28 keV for the non-thermal component of the remaining events. As a reference, a semi-circle connecting the flare ribbons is plotted in dark green as seen from the Earth and as seen from Solar Orbiter in the top-row and in the bottom-row panels, respectively. A horizontal bar indicating a length of 5 Mm on the plane of the sky is reported in the top-right corner of each plot.

and non-thermal components. In each panel, the data are ordered with respect to the corresponding detector label, whose number is reported in the abscissa. Detectors with the same resolution are ordered from left to right according to the label letter a, b, or c. As expected, the observed amplitude values shown in the plots are decreasing with respect to the detector resolution. For instance, if we assume that the source has a Gaussian shape, then its bidimensional Fourier transform is still a Gaussian function. Hence, the visibility amplitudes decay at a rate that is inversely proportional to the resolution of the sampling frequencies. We also note that the observed visibility phases are close to zero for the coarsest sub-collimators, as is expected when the map center in the visibility calculation is selected to be at the flare location. Below each plot, we reported the residuals, i.e., the difference between the measured data and the ones predicted from the reconstruction normalized by the errors. The reduced χ^2 values of the reconstructions provided by the same algorithms are shown in Table 3. Since the reconstructions of the thermal and the non-thermal emission of each event under examination have been performed separately, from data integrated over two different energy ranges, the associated reduced χ^2 values have been computed as the squared dif-

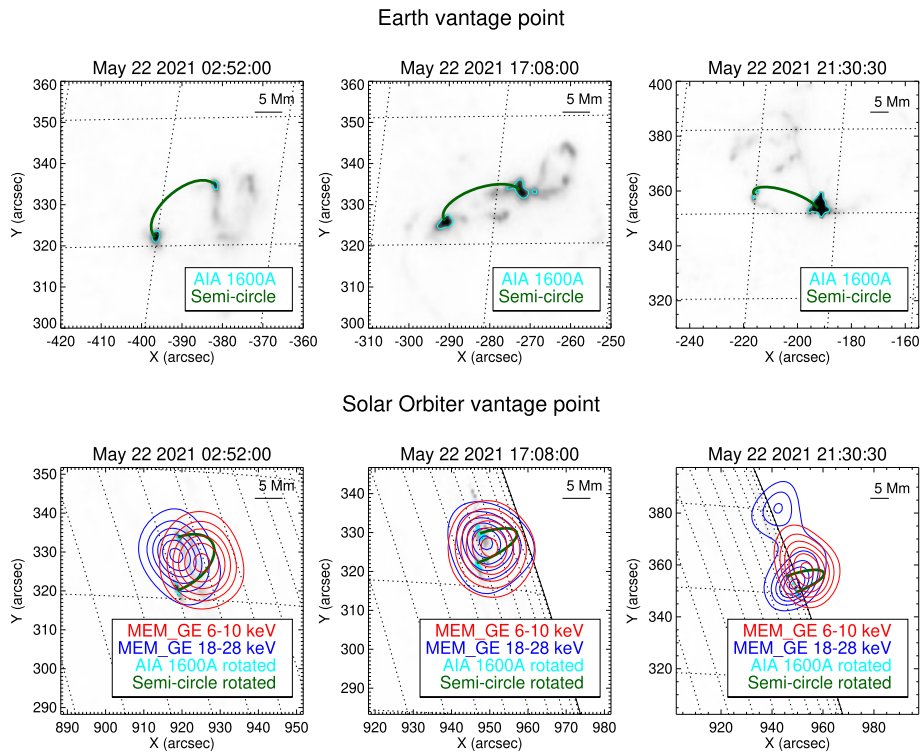


Figure 4 Same as Figure 3 for the May 22 events recorded at 02:52:00 UT, 17:08:00 UT, and 21:30:30 UT. The energy intervals considered are 6–10 keV for the thermal components and 18–28 keV for the non-thermal components.

Table 3 Reduced χ^2 values for the reconstructions of the thermal and the non-thermal emission provided by Clean, MEM_GE, EM, and VIS_FWDFIT on the May 7, 2021 event. The χ^2 values are computed with respect to the observed visibilities. We note that the value of the χ^2 is of limited statistical relevance due to the not-yet finalized error estimates. Hence, they should only be compared between the different methods.

Method	χ^2 thermal	χ^2 non-thermal
Clean	2.05	1.13
MEM_GE	0.93	0.65
EM	2.76	0.91
VIS_FWDFIT	4.24	1.41

ference between the visibilities predicted from each reconstruction and the corresponding observed ones (normalized by the squared uncertainty). We note that, for Clean, the predicted visibility amplitudes and phases and the reduced χ^2 values are computed using the derived Clean Components (in this analysis, we did not include the fits and the reduced χ^2 corresponding to the amplitude fitting method, because it does not consider visibility phases, and the ones corresponding to Back Projection, because it is a direct inversion without any regularization). We also point out that the interpretation of these reduced χ^2 values in terms of probability strongly depends on the estimate of the errors associated with the visibility

Table 4 Ratio between the flux of the first and second source of the May 7, 2021 event reconstructed by Clean, MEM_GE, EM, VIS_FWDFIT, and by the amplitude fitting method.

Method	Ratio fluxes
Clean	0.57
MEM_GE	0.56
EM	0.53
VIS_FWDFIT	0.56
Amplitude fitting	0.45

measurements. In fact, while the error component associated with photon counting is fully understood, the systematic component is largely unknown at this stage. For example, in the case of the Clean reconstruction of the May 7 event thermal component, with a systematic error of 5%, the reduced χ^2 value is 2.05, and the associated probability is 2.8×10^{-5} , which is a clearly unreliable number. On the other hand, with a systematic error of 8%, the reduced χ^2 value is 0.94, and the associated probability is 0.59, which is a reasonable value. Therefore, we used these reduced χ^2 values just for relative comparison of the methods' reliability, without giving them a probabilistic significance.

For a quantitative comparison of the results of the different methods, we reported in Table 4 the flux ratio of the non-thermal footpoints reconstructed by the different methods. The top-left footpoint is referred to as *first source*, while the bottom-right footpoint is referred to as *second source*. As for the Clean algorithm, we used the Clean Components map for this analysis in order not to bias the results with the choice of the beam width used in the final convolution.

Finally, we show in Table 5 the values of the parameters related to the dimension, orientation, and intensity of the sources reconstructed by the two forward-fitting algorithms, i.e., VIS_FWDFIT and the amplitude fitting method. We do not report the absolute location of the sources since it is not possible to retrieve this information from the visibility amplitudes only. Indeed, the amplitude fitting method uses source configurations whose center is fixed at the origin of the coordinate system.

3.1. Discussion of Results

The X-ray emissions reconstructed from STIX data are consistent with the ribbons shown in the AIA maps in terms of separation, shape, and orientation (see Figures 3 and 4). In particular, the reconstructions of the May 7, 2021, May 8, 2021, and May 9, 2021 events are compatible with a standard flaring configuration with two chromospheric footpoints and a coronal loop-top source. For these events, the relative position between the thermal and the non-thermal emission agrees with the height and direction of the semi-circles connecting the ribbons, at least in projection.

The reconstruction of the first two flares on May 22 reveals a rather compact source size, and the non-thermal sources appear unresolved. Once fully calibrated, the finest sub-collimators should be used to potentially separate the flare ribbons in the non-thermal image. While the first May 22 flare clearly shows a separation of the thermal and non-thermal emission, the event around 17 UT shows both emissions originating from close to the same location. Co-spatial thermal and non-thermal sources are occasionally observed in so-called thick target coronal sources (Veronig and Brown, 2004). Coronal thick target sources tend to have soft (steep) non-thermal spectra, which is similar to what is observed in this flare (see Figure 2). In the case that this event would indeed be a coronal thick target, the X-ray

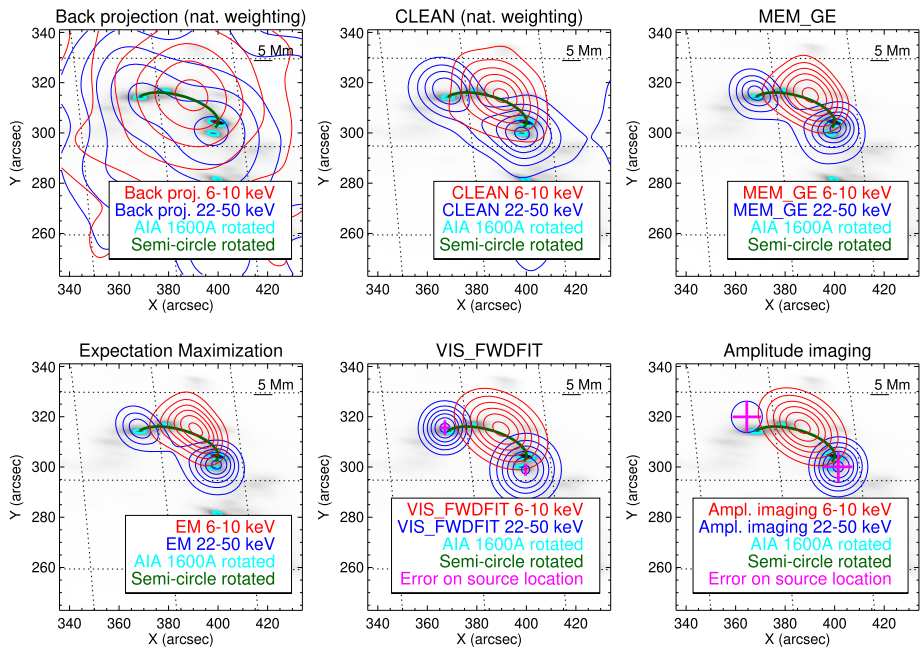


Figure 5 From top to bottom, left to right: reconstructions of the May 7, 2021 event provided by Back Projection, Clean, MEM_GE, EM, VIS_FWDFIT, and the amplitude fitting method. The STIX reconstructions are overlaid on the rotated AIA 1600 Å map of the same event. Energy intervals, contour levels, semi-circles, and bars, indicating the 5 Mm length on the plane of the sky, are the same as in Figure 3. In the VIS_FWDFIT and amplitude fitting panels, the magenta crosses indicate the estimated error in each source location.

sources would come from the corona, and our alignment by eye would need to be adapted accordingly. Further analysis is in progress investigating this flare.

For the May 22 flare around 21 UT, the brighter of the two non-thermal sources appears to be a superposition of the two main sources from the two flare ribbons seen in the projection. The weaker non-thermal source to the north (Figure 4, bottom right) might be a secondary non-thermal source on the extension of the eastern flare ribbon towards the north. This clearly shows the value of combining observations of different look directions to fully understand the flare geometry.

The five imaging methods from calibrated visibilities provide consistent results for the May 7, 2021 event, particularly with respect to the location of the reconstructed sources and the ratio between the footpoint fluxes (see Figure 5 and Table 4). The MEM_GE, EM, and VIS_FWDFIT reconstructions of the thermal emission present very similar dimension and orientation, and those of the non-thermal emission show two footpoints with comparable size, orientation, and separation. The Back Projection reconstructions, as expected, present sidelobes due to the limited number of Fourier components sampled by STIX and the fact that this algorithm directly inverts the data without applying any regularization (Hurford et al., 2002). Clean provides reconstructions with much-reduced noise levels with respect to Back Projection; however, the dimensions of the retrieved sources can be larger when compared to the results of MEM_GE, EM, and VIS_FWDFIT. This behavior is intrinsic to the Clean algorithm because the derived point source model (the Clean Components) is convolved with an idealized PSF (the Clean beam). There are various choices for the selection of the beam size. The most conservative case is to approximate the core of the PSF

Table 5 Parameter values retrieved by the amplitude fitting method and by VIS_FWDFIT on the May 7, 2021 event. Top: parameters values of a fitted elliptical Gaussian shape. Bottom: parameters values of a fitted double circular Gaussian shape.

May 7, 2021 – Thermal component				
	Amplitude fitting		VIS_FWDFIT	
Flux (counts s ⁻¹ keV ⁻¹ cm ⁻²)	515 ± 7		516 ± 8	
FWHM max (arcsec)	25.8 ± 0.3		27.1 ± 0.5	
FWHM min (arcsec)	17.2 ± 0.3		18.1 ± 0.3	
Orientation angle (degrees)	146 ± 2		149 ± 2	
May 7, 2021 – Non-thermal component				
	Amplitude fitting		VIS_FWDFIT	
	First source	Second source	First source	Second source
Flux (counts s ⁻¹ keV ⁻¹ cm ⁻²)	0.14 ± 0.07	0.3 ± 0.1	0.15 ± 0.03	0.27 ± 0.03
FWHM (arcsec)	21 ± 20	16 ± 7	14 ± 6	19 ± 4

of input image (dirty map) with a Gaussian function. This choice gives a beam size of 31.3'' FWHM, which would smear out the Clean maps significantly. On the other extreme, the resolution provided by the finest sub-collimators used in the image reconstruction could be used to approximate the clean beam size. For the Clean images presented here, this would give a beam size of 14.6'' FWHM. For such compact beam sizes, Clean boxes around the potential solar sources should be used to avoid having noise peaks wrongly identified as solar sources. If, by mistake, a noise peak is cleaned and convolved with such a narrow beam, noise features can be significantly enhanced compared to Back Projection map, making the resulting clean image look questionable. For this paper, we used a beam size of 16.5'' FWHM applying Clean boxes derived from the 50% contours. The use of a smaller Clean beam could result in a better match of the Clean source size compared to the other imaging algorithms. Alternatively, the beam size can be estimated by considering the distribution of the Clean components with respect to the source center (Dennis and Pernak, 2009). While the output of Clean (i.e., the list of Clean Components) is independent of the selected beam size, the visualization of the Clean result (i.e., the Clean image) is affected by choice of the clean beam. The selection of the Clean beam width should be adopted depending on the size of the sources within the image. For compact footpoint sources, a small beam size is a good option, while for extended sources, a small beam size can artificially break up the source, and it is better to use a larger beam size.

From the data fitting shown in Figures 6 and 7 and from the low χ^2 values shown in Table 3, we deduce that the algorithms from calibrated data are able to fit the experimental visibilities with high accuracy. MEM_GE systematically outperforms the other methods in terms of data-fidelity (see Table 3). The good performance of this algorithm is also due to an ad hoc choice of the regularization parameter, whose values are shown in Table 2. Changing parameters in the other algorithms, such as the selection of Clean boxes, can be used to optimize the image quality. Clean and EM provide reconstructions of the non-thermal emission with a comparable χ^2 value, while the visibility-based method has a slightly better performance with respect to the count-based one in the reconstruction of the thermal emission. Finally, the χ^2 values associated with the VIS_FWDFIT reconstructions are consistently the highest ones. This is most likely due to the fact that the shapes used for fitting do not always represent the true morphology accurately.

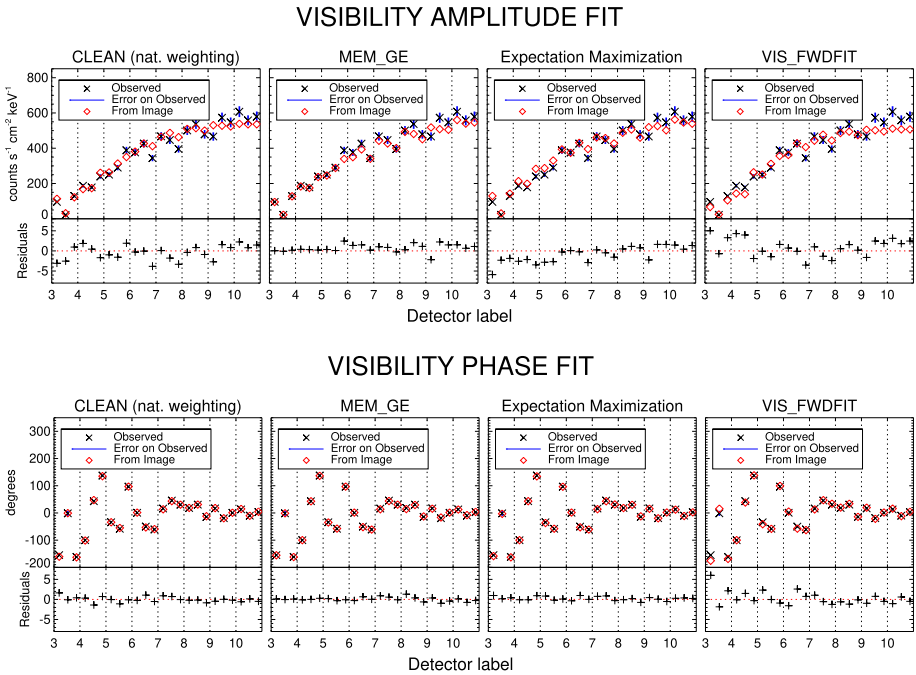


Figure 6 Visibility amplitude fit (top panels) and visibility phase fit (bottom panels) of the thermal component reconstructions of the May 7, 2021 event provided by Clean, MEM_GE, EM, and VIS_FWDFIT (from left to right, respectively). The black crosses indicate the measured data, the blue bars represent the experimental uncertainty, and the red diamonds denote the data predicted from each reconstruction. The fit residuals are reported below each panel.

Finally, as far as the comparison between the two forward-fitting algorithms (the amplitude fitting method and VIS_FWDFIT) is concerned, Table 5 shows that the parameters retrieved by the two methods are very similar in the case of the thermal emission. However, the source reconstructed by VIS_FWDFIT is slightly larger and tilted with respect to the one reconstructed by the amplitude fitting method. Instead, the non-thermal footpoints reconstructed by the two methods have comparable fluxes but different FWHM; nevertheless, the discrepancy between the retrieved FWHM values is compatible with the associated uncertainty, which is particularly large in the case of the first source for the amplitude fitting method. This large uncertainty is possibly due to the fact that amplitude fitting utilizes half of the data with respect to VIS_FWDFIT consisting of just the visibility amplitudes; consequently, it suffers from a more pronounced numerical instability.

4. Conclusions

We presented the first results of STIX imaging using the best current calibration and imaging software implementation as of February 2022. Specifically, we showed that the visibility phases of the 24 coarsest detectors are well-calibrated since images reconstructed from STIX visibilities are reliable in terms of morphology, dimension, and orientation when compared to the flare ribbons seen in the AIA 1600 Å maps of the same events. Further, we compared the performances of several algorithms implemented for the solution of the STIX imaging

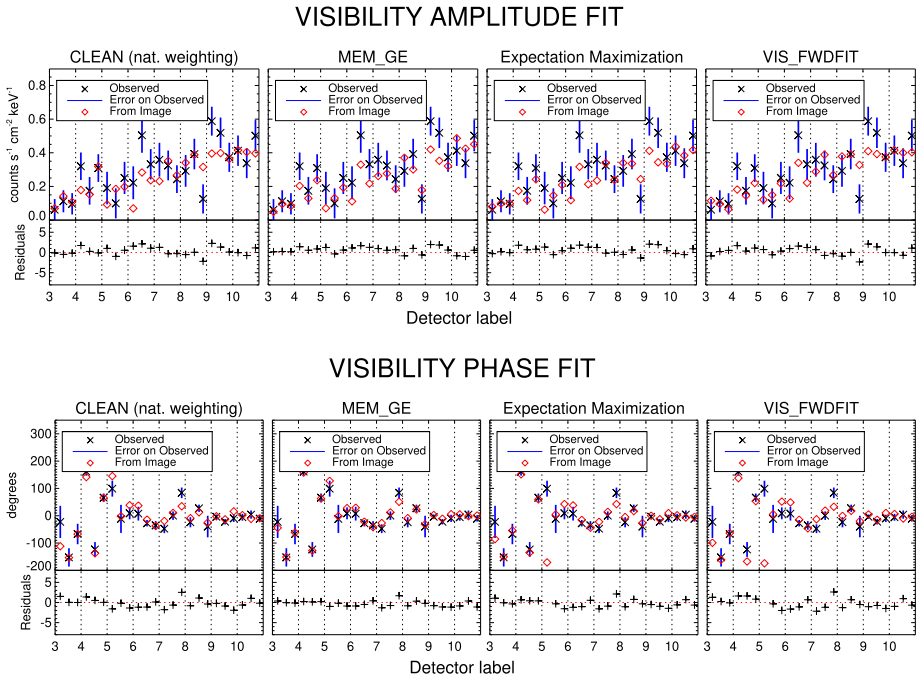


Figure 7 Same as Figure 6 for the non-thermal component of the May 7, 2021 event.

problem from calibrated data, showing consistent results and good accuracy in reproducing the experimental visibilities. We strongly recommend to compare the reconstructions obtained by means of the five imaging methods from calibrated data every time a flaring event is analyzed. The STIX imaging problem has no unique solution, and each algorithm produces different, although consistent, results. Based on previous experience with RHESSI imaging (Piana et al., 2022), we expect no method to systematically outperform the others. Hence, for thorough validation of the imaging results, it is necessary to compare the reconstructions provided by as many different techniques as possible. In view of this, we point out that the implementation of other reconstruction methods is under construction and will involve a Sequential Monte Carlo scheme (Sciacchitano et al., 2018; Sciacchitano, Lugaro, and Sorrentino, 2019), compressed-sensing methods (Duval-Poo, Piana, and Massone, 2018; Felix, Bolzern, and Battaglia, 2017), and another EM-like approach for counts (Siarkowski et al., 2020). Finally, we provided validation of the phase calibration by showing good agreement between the reconstructions obtained from visibility amplitudes and those obtained from calibrated data. Future work will be devoted to further improve the existing calibration, as well as a first calibration of the data recorded by the finest six sub-collimators at 7 and 10 arcsec resolution.

Acknowledgments *Solar Orbiter* is a space mission of international collaboration between ESA and NASA, operated by ESA. The STIX instrument is an international collaboration between Switzerland, Poland, France, Czech Republic, Germany, Austria, Ireland, and Italy. AFB, HC, GH, MK, HX, DFR and SK are supported by the Swiss National Science Foundation Grant 200021L_189180 and the grant ‘Activit es Nationales Compl ementaires dans le domaine spatial’ REF-1131-61001 for STIX. PM, EP, FB and MP acknowledge the financial contribution from the agreement ASI-INAF n.2018-16-HH.0. SG acknowledges the financial support from the ‘‘Accordo ASI/INAF Solar Orbiter: Supporto scientifico per la realizzazione degli strumenti Metis, SWA/DPU e STIX nelle Fasi D-E’’. ECMD acknowledges the Austrian Science Fund (FWF): I4555-N.

Funding Note Open access funding provided by Università degli Studi di Genova within the CRUI-CARE Agreement.

Data Availability The STIX data analyzed in the current study are available at <https://pub023.cs.technik.fhnw.ch/view/list/bsd>.

Declarations

Conflict of Interest The authors declare that they have no conflicts of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.


References

- Battaglia, M., Grigis, P.C., Benz, A.O.: 2005, Size dependence of solar X-ray flare properties. *Astron. Astrophys.* **439**, 737. DOI.
- Battaglia, A.F., Saqri, J., Massa, P., Perracchione, E., Dickson, E.C.M., Xiao, H., Veronig, A.M., Warmuth, A., Battaglia, M., Hurford, G.J., Meuris, A., Limousin, O., Etesi, L., Maloney, S.A., Schwartz, R.A., Kuhar, M., Schuller, F., Senthamizh Pavai, V., Musset, S., Ryan, D.F., Kleint, L., Piana, M., Massone, A.M., Benvenuto, F., Sylwester, J., Litwicka, M., Steŝlicki, M., Mrozek, T., Vilmer, N., Fárník, F., Kašparová, J., Mann, G., Gallagher, P.T., Dennis, B.R., Csillaghy, A., Benz, A.O., Krucker, S.: 2021, STIX X-ray microflare observations during the Solar Orbiter commissioning phase. *Astron. Astrophys.* **656**, A4. DOI.
- Bong, S.-C., Lee, J., Gary, D.E., Yun, H.S.: 2006, Spatio-spectral maximum entropy method. I. Formulation and test. *Astrophys. J.* **636**, 1159. DOI.
- Clerc, M.: 2006, *Particle Swarm Optimization*, ISTE, London Newport Beach. ISBN 978-1-905-20904-0.
- Dennis, B.R., Pernak, R.L.: 2009, Hard X-ray flare source sizes measured with the Ramaty High Energy Solar Spectroscopic Imager. *Astrophys. J.* **698**, 2131. DOI. ADS.
- Duval-Poo, M.A., Piana, M., Massone, A.M.: 2018, Solar hard X-ray imaging by means of compressed sensing and finite isotropic wavelet transform. *Astron. Astrophys.* **615**, A59.
- Felix, S., Bolzern, R., Battaglia, M.: 2017, A compressed sensing-based image reconstruction algorithm for solar flare x-ray observations. *Astrophys. J.* **849**, 10.
- Fletcher, L., Pollock, J.A., Potts, H.E.: 2004, Tracking of TRACE ultraviolet flare footpoints. *Solar Phys.* **222**, 279. DOI.
- Högbom, J.A.: 1974, Aperture synthesis with a non-regular distribution of interferometer baselines. *Astron. Astrophys. Suppl.* **15**, 417.
- Hurford, G.J.: 2013, In: Huber, M.C.E., Pauluhn, A., Culhane, J.L., Timothy, J.G., Wilhelm, K., Zehnder, A. (eds.) *X-Ray Imaging with Collimators, Masks and Grids*, Springer, New York, 243. 978-1-4614-7804-1. DOI.
- Hurford, G., Schmahl, E., Schwartz, R., Conway, A., Aschwanden, M., Csillaghy, A., Dennis, B., Johns-Krull, C., Krucker, S., Lin, R., McTiernan, J., Metcalf, T., Sato, J., Smith, D.: 2002, The RHESSI imaging concept. *Solar Phys.* **210**, 61. DOI.
- Krucker, S., Hurford, G.J., Grimm, O., Kögl, S., Gröbelbauer, H.-P., Etesi, L., Casadei, D., Csillaghy, A., Benz, A.O., Arnold, N.G., Molendini, F., Orleanski, P., Schori, D., Xiao, H., Kuhar, M., Hochmuth, N., Felix, S., Schramka, F., Marcin, S., Kobler, S., Iseli, L., Dreier, M., Wiehl, H.J., Kleint, L., Battaglia, M., Lastufka, E., Sathiapal, H., Lapadula, K., Bednarzik, M., Birrer, G., Stutz, S., Wild, C., Marone, F., Skup, K.R., Cichocki, A., Ber, K., Rutkowski, K., Bujwan, W., Juchnikowski, G., Winkler, M., Darmetko, M., Michalska, M., Seweryn, K., Białek, A., Osica, P., Sylwester, J., Kowalinski, M., Ścisłowski, D., Siarkowski, M., Steŝlicki, M., Mrozek, T., Podgórski, P., Meuris, A., Limousin, O., Gevin, O., Le Mer, I., Brun, S., Strugarek, A., Vilmer, N., Musset, S., Maksimović, M., Fárník, F., Kozáček, Z., Kašparová, J., Mann, G., Önel, H., Warmuth, A., Rendtel, J., Anderson, J., Bauer, S., Dionies, F., Paschke, J.,

- Plüschke, D., Woche, M., Schuller, F., Veronig, A.M., Dickson, E.C.M., Gallagher, P.T., Maloney, S.A., Bloomfield, D.S., Piana, M., Massone, A.M., Benvenuto, F., Massa, P., Schwartz, R.A., Dennis, B.R., van Beek, H.F., Rodríguez-Pacheco, J., Lin, R.P.: 2020, The spectrometer/telescope for imaging X-rays (STIX). *Astron. Astrophys.* **642**, A15. DOI.
- Lemen, J.R., Title, A.M., Akin, D.J., Boerner, P.F., Chou, C., Drake, J.F., Duncan, D.W., Edwards, C.G., Friedlaender, F.M., Heyman, G.F., Hurlburt, N.E., Katz, N.L., Kushner, G.D., Levay, M., Lindgren, R.W., Mathur, D.P., McFeaters, E.L., Mitchell, S., Rehse, R.A., Schrijver, C.J., Springer, L.A., Stern, R.A., Tarbell, T.D., Wuelser, J.-P., Wolfson, C.J., Yanari, C., Bookbinder, J.A., Cheimets, P.N., Caldwell, D., Deluca, E.E., Gates, R., Golub, L., Park, S., Podgorski, W.A., Bush, R.I., Scherrer, P.H., Gummin, M.A., Smith, P., Auker, G., Jerram, P., Pool, P., Soufli, R., Windt, D.L., Beardsley, S., Clapp, M., Lang, J., Waltham, N.: 2012, The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). *Solar Phys.* **275**, 17. DOI.
- Lucy, L.B.: 1974, An iterative technique for the rectification of observed distributions. *Astron. J.* **79**, 745.
- Massa, P., Piana, M., Massone, A.M., Benvenuto, F.: 2019, Count-based imaging model for the spectrometer/telescope for imaging X-rays (STIX) in Solar Orbiter. *Astron. Astrophys.* **624**, A130. DOI.
- Massa, P., Schwartz, R., Tolbert, A.K., Massone, A.M., Dennis, B.R., Piana, M., Benvenuto, F.: 2020, MEM_GE: a new maximum entropy method for image reconstruction from solar X-ray visibilities. *Astrophys. J.* **894**, 46.
- Massa, P., Perracchione, E., Garbarino, S., Battaglia, A.F., Benvenuto, F., Piana, M., Hurford, G., Krucker, S.: 2021, Imaging from STIX visibility amplitudes. *Astron. Astrophys.* **656**, A25.
- Meuris, A., Limousin, O., Gevin, O., Blondel, C., Martignac, J., Vassal, M.-C., Soufflet, F., Fiant, N., Bednarzik, M., Stutz, S., Grimm, O., Commichau, V.: 2015, Caliste-SO, a CdTe based spectrometer for bright solar event observations in hard X-rays. *Nucl. Instrum. Methods Phys. Res., Sect. A* **787**, 72. DOI.
- Perracchione, E., Massone, A.M., Piana, M.: 2021, Feature augmentation for the inversion of the Fourier transform with limited data. *Inverse Probl.* **37**, 105001. DOI.
- Piana, M., Emslie, A.G., Massone, A.M., Dennis, B.R.: 2022, *Hard X-Ray Imaging of Solar Flares*, Springer, Berlin.
- Press, W.: 2007, *Numerical Recipes: The Art of Scientific Computing*, Cambridge University Press, Cambridge. ISBN 978-0-521-70685-8.
- Richardson, W.H.: 1972, Bayesian-based iterative method of image restoration. *J. Opt. Soc. Am. A* **62**, 55.
- Schmahl, E.J., Pernak, R.L., Hurford, G.J., Lee, J., Bong, S.: 2007, Analysis of RHESSI flares using a radio astronomical technique. *Solar Phys.* **240**, 241. DOI.
- Sciacchitano, F., Lugaro, S., Sorrentino, A.: 2019, Sparse Bayesian imaging of solar flares. *SIAM J. Imaging Sci.* **12**, 319.
- Sciacchitano, F., Sorrentino, A., Emslie, A.G., Massone, A.M., Piana, M.: 2018, Identification of multiple hard X-ray sources in solar flares: a Bayesian analysis of the 2002 February 20 event. *Astrophys. J.* **862**, 68.
- Siarkowski, M., Mrozek, T., Sylwester, J., Litwicka, M., Dąbek, M.: 2020, The non-Fourier image reconstruction method for the STIX instrument. *Open Astron.* **29**, 220. DOI.
- Tandberg-Hanssen, E., Emslie, A.G.: 1988, *The Physics of Solar Flares, Cambridge Astrophysics*, Cambridge University Press, Cambridge. ISBN 9780521308045.
- Veronig, A.M., Brown, J.C.: 2004, A coronal thick-target interpretation of two hard X-ray loop events. *Astrophys. J.* **603**, L117. DOI.
- Warmuth, A., Önel, H., Mann, G., Rendtel, J., Strassmeier, K.G., Denker, C., Hurford, G., Krucker, S., Anderson, J., Bauer, S.-M., et al.: 2020, The STIX aspect system (SAS): the optical aspect system of the spectrometer/telescope for imaging X-rays (STIX) on Solar Orbiter. *Solar Phys.* **295**, 90. DOI.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Paolo Massa¹  · Andrea F. Battaglia^{2,3} · Anna Volpara¹ · Hannah Collier^{2,3} · Gordon J. Hurford² · Matej Kuhar² · Emma Perracchione⁴ · Sara Garbarino¹ · Anna Maria Massone^{1,5} · Federico Benvenuto¹ · Frederic Schuller⁶ · Alexander Warmuth⁶ · Ewan C.M. Dickson⁷ · Hualin Xiao² · Shane A. Maloney^{8,9} · Daniel F. Ryan² · Michele Piana^{1,5} · Säm Krucker^{2,10}

✉ P. Massa
massa.p@dima.unige.it

- 1 MIDA, Dipartimento di Matematica, Università di Genova, via Dodecaneso 35, 16146 Genova, Italy
- 2 University of Applied Sciences and Arts Northwestern Switzerland, Bahnhofstrasse 6, 5210 Windisch, Switzerland
- 3 ETH Zürich, Rämistrasse 101, 8092 Zürich, Switzerland
- 4 Dipartimento di Scienze Matematiche “Giuseppe Luigi Lagrange”, Politecnico di Torino, Torino, Italy
- 5 CNR - SPIN Genova, via Dodecaneso 33 16146 Genova, Italy
- 6 Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
- 7 Institute of Physics, University of Graz, 8010 Graz, Austria
- 8 Astrophysics Research Group, School of Physics, Trinity College Dublin, Dublin 2, Ireland
- 9 School of Cosmic Physics, Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin, D02 XF86, Ireland
- 10 Space Sciences Laboratory, University of California, 7 Gauss Way, 94720 Berkeley, USA