numerical approximation for image reconstruction in the ’Spectrometer/Telescope for Imaging X-rays (STIX)’ mission on-board ’Solar Orbiter’

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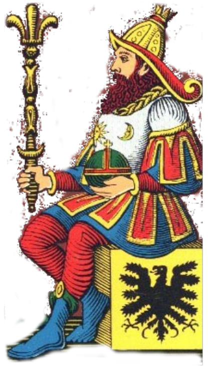
6th IM-workshop on applied approximation, signals, and images

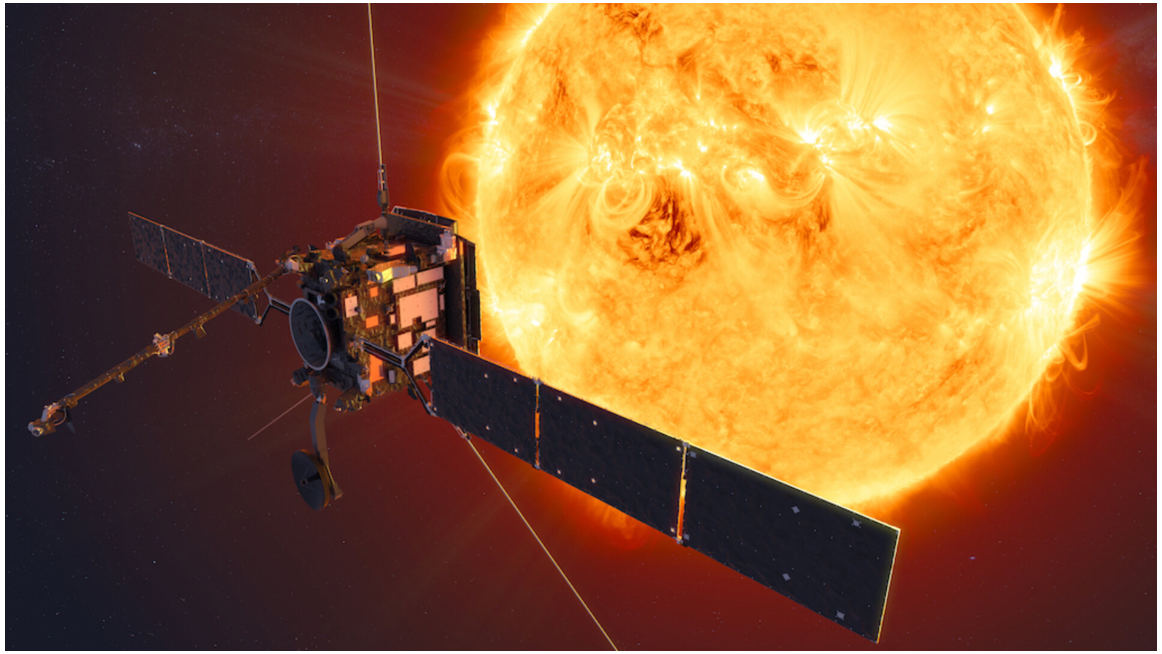
bernried, february 20–24 2023



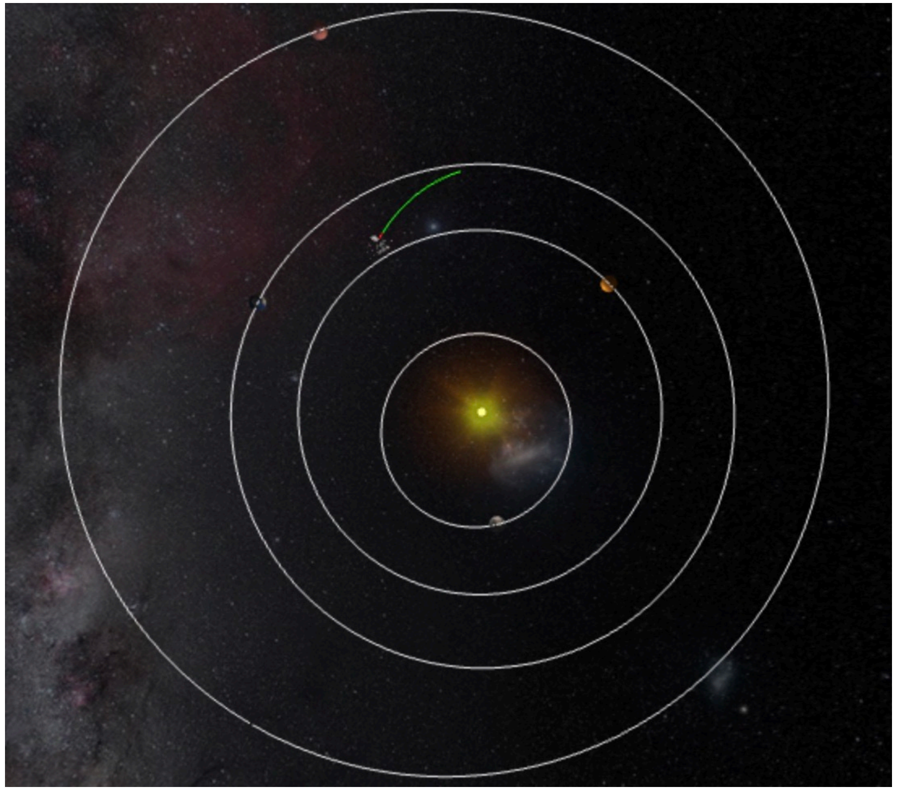
STIX in solar orbiter

solar orbiter: ESA mission launched on February 10, 2020

STIX: one of the four remote sensing instruments on-board solar orbiter

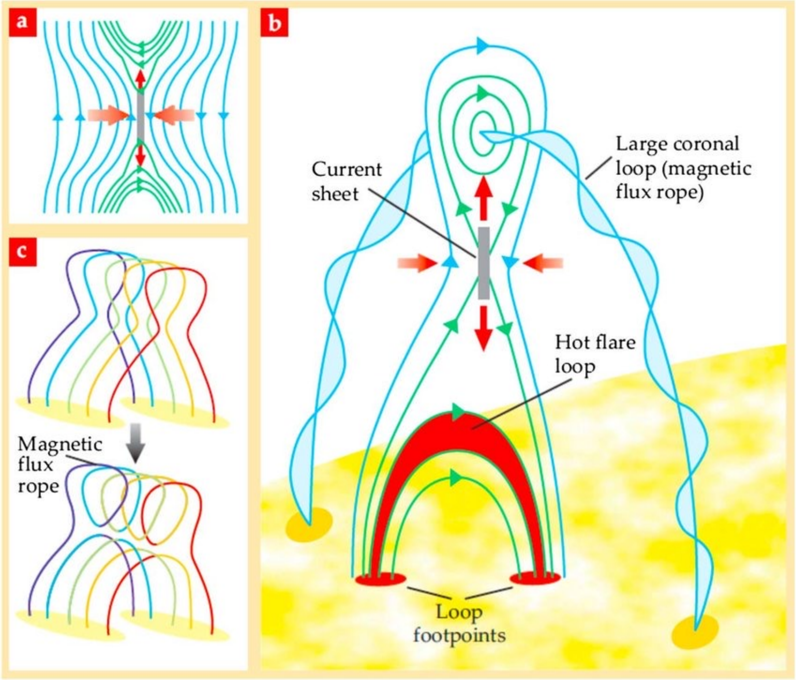


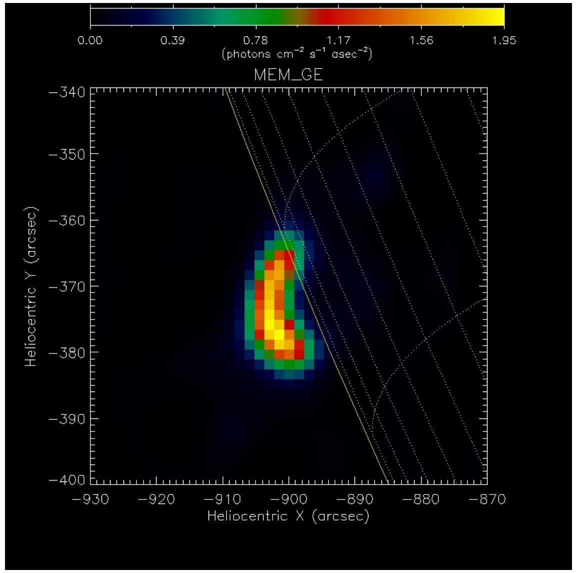
(credits: ESA website)

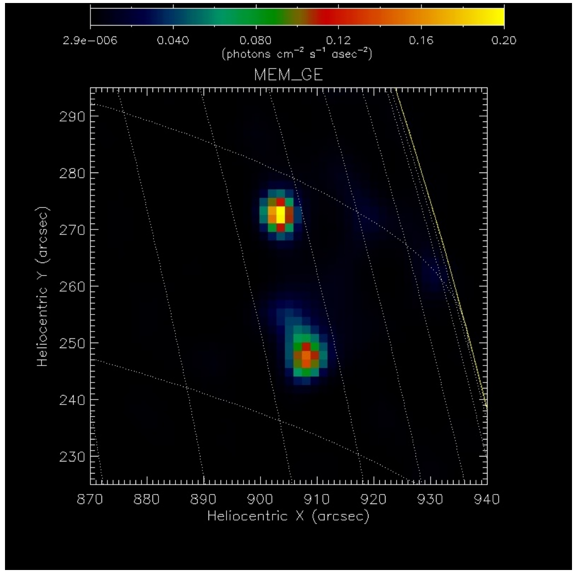


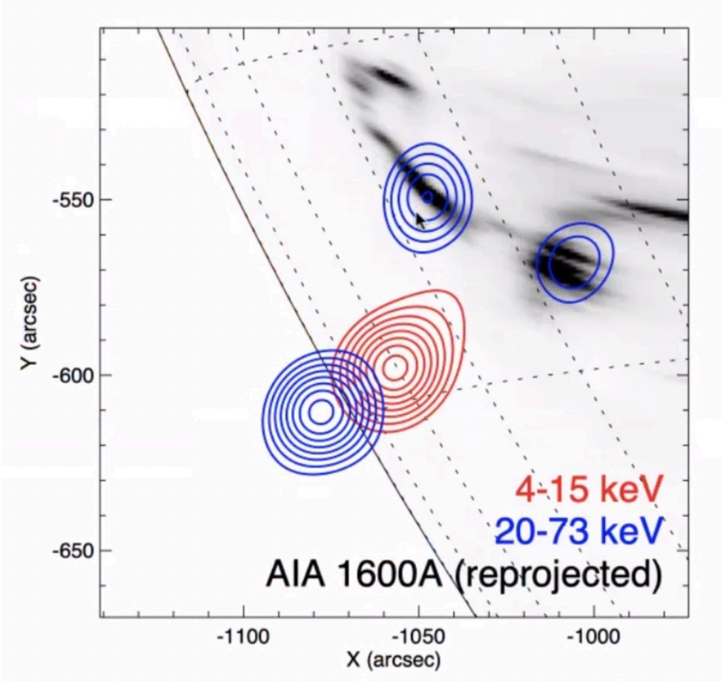
(https://solarorbiter.esac.esa.int/where/)

STIX scientific objective: how about solar flares at high energy?









the STIX instrument

A&A 642, A15 (2020)
https://doi.org/10.1051/0004-6361/201937362

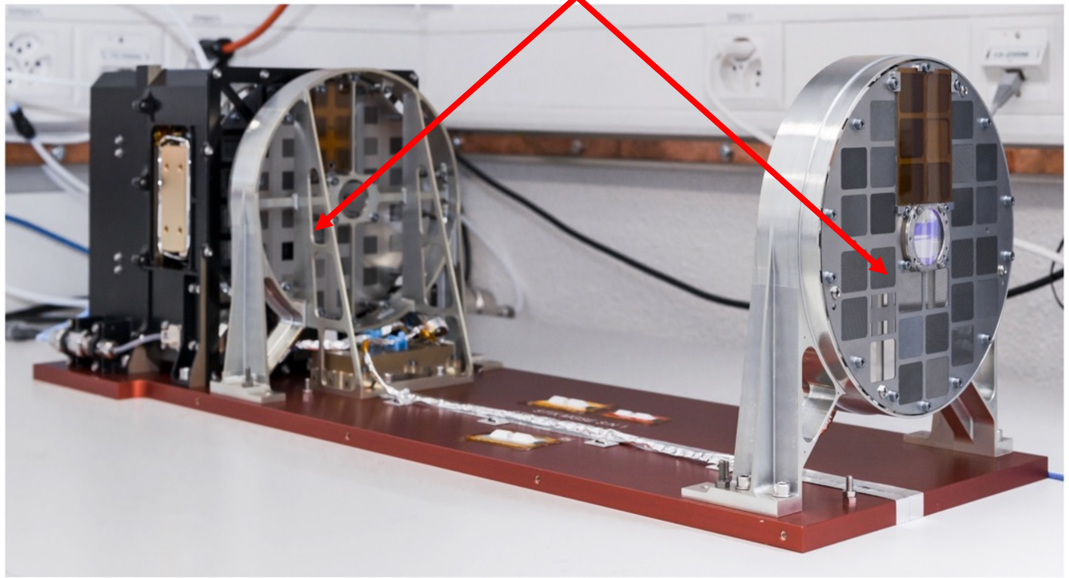
The Solar Orbiter mission

Astronomy & Astrophysics
Special issue

The Spectrometer/Telescope for Imaging X-rays (STIX)

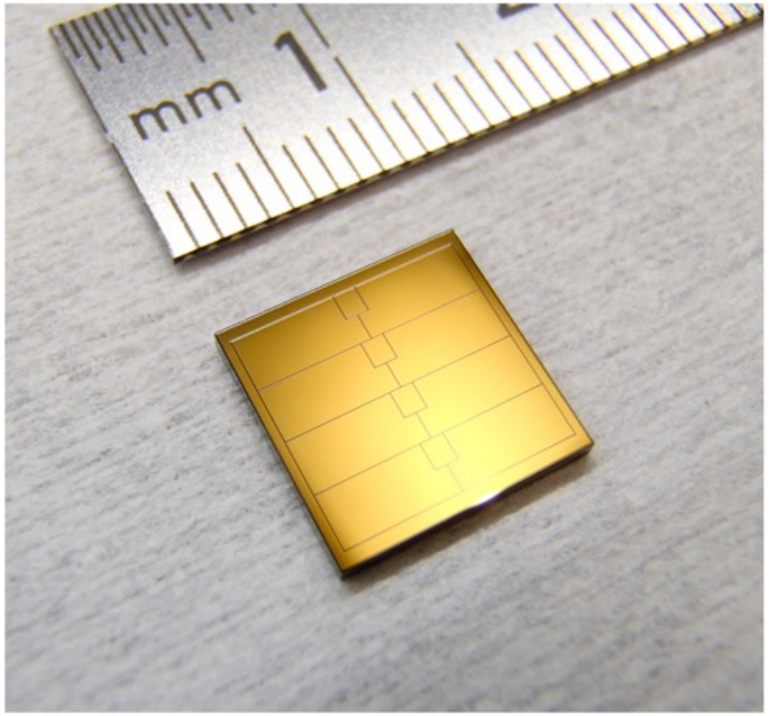
Säm Krucker[1,2], G. J. Hurford[1,2], O. Grimm[1,3], S. Kögl[1], H.-P Gröbelbauer[1], L. Etesi[1], D. Casadei[1], A. Csillaghy[1], A. O. Benz[1], N. G. Arnold[1], F. Molendini[1], P. Orleanski[1], D. Schori[1], H. Xiao[1], M. Kuhar[1], N. Hochmuth[1], S. Felix[1], F. Schramka[1], S. Marcin[1], S. Kobler[1], L. Iseli[1], M. Dreier[1], H. J. Wiehl[1], L. Kleint[1], M. Battaglia[1], E. Lastufka[1,3], H. Sathiapal[1], K. Lapadula[1], M. Bednarzik[4], G. Birrer[4], St. Stutz[4], Ch. Wild[4], F. Marone[4], K. R. Skup[5], A. Cichocki[5], K. Ber[5], K. Rutkowski[5], W. Bujwan[5], G. Juchnikowski[5], M. Winkler[5], M. Darmetko[5], M. Michalska[5], K. Seweryn[5], A. Białek[5], P. Osica[5], J. Sylwester[5], M. Kowalinski[5], D. Ścisłowski[5], M. Siarkowski[5], M. Stęślicki[5], T. Mrozek[6,5], P. Podgórski[5], A. Meuris[7], O. Limousin[7], O. Gevin[8], I. Le Mer[7], S. Brun[7], A. Strugarek[7], N. Vilmer[9], S. Musset[9,10], M. Maksimović[9], F. Fárník[11], Z. Kozáček[11], J. Kašparová[11], G. Mann[12], H. Önel[12], A. Warmuth[12], J. Rendtel[12], J. Anderson[12], S. Bauer[12], F. Dionies[12], J. Paschke[12], D. Plüschke[12], M. Woche[12], F. Schuller[12], A. M. Veronig[13], E. C. M. Dickson[13], P. T. Gallagher[14,15], S. A. Maloney[15,14], D. S. Bloomfield[14,16], M. Piana[17], A. M. Massone[17], F. Benvenuto[17], P. Massa[17], R. A. Schwartz[13,14,18], B. R. Dennis[19], H. F. van Beek[20], J. Rodríguez-Pacheco[21], and R. P. Lin[2]

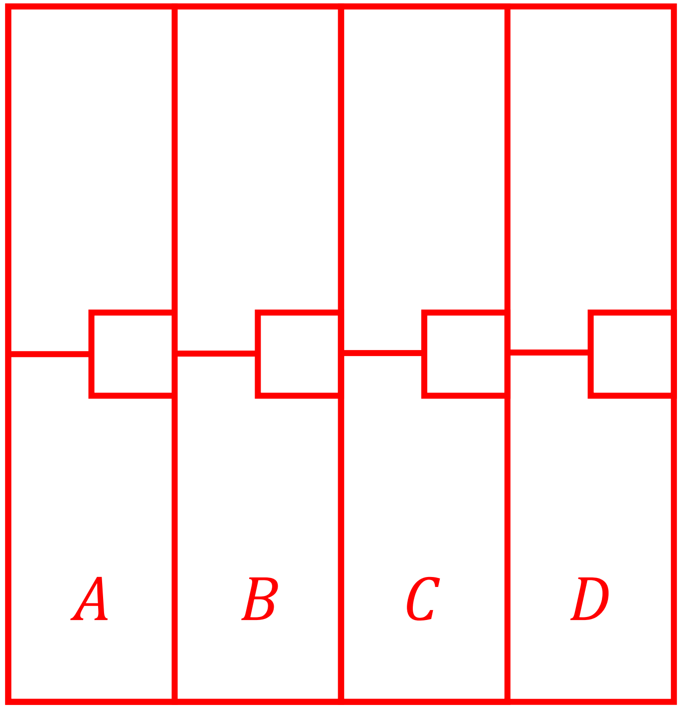
sub-collimator = front grid + rear grid + detector



- bi-grid imaging system
- STIX consists of 32 subcollimators:
  - 30 are used for imaging
  - coarse Flare Locator
  - background monitor

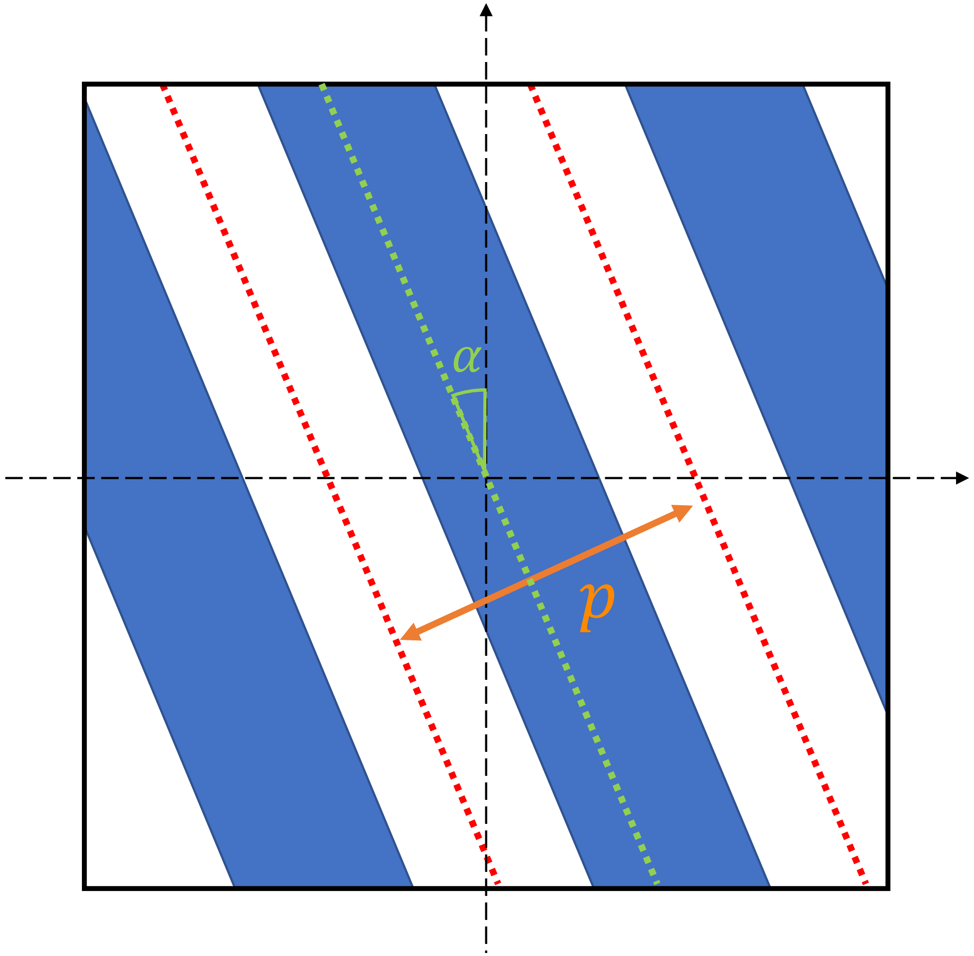
the STIX detectors





A, B, C and D: number of counts recorded by the detector pixels

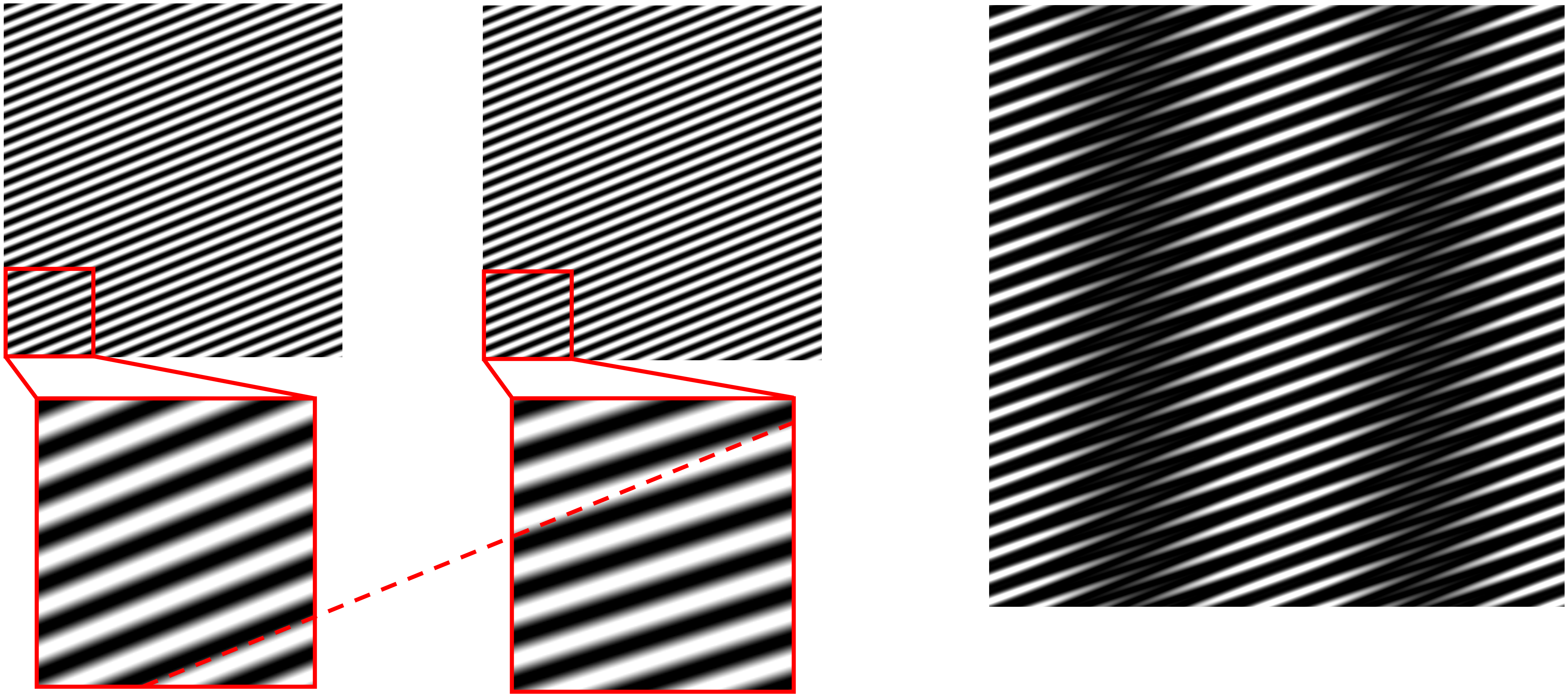
the STIX grid parameters



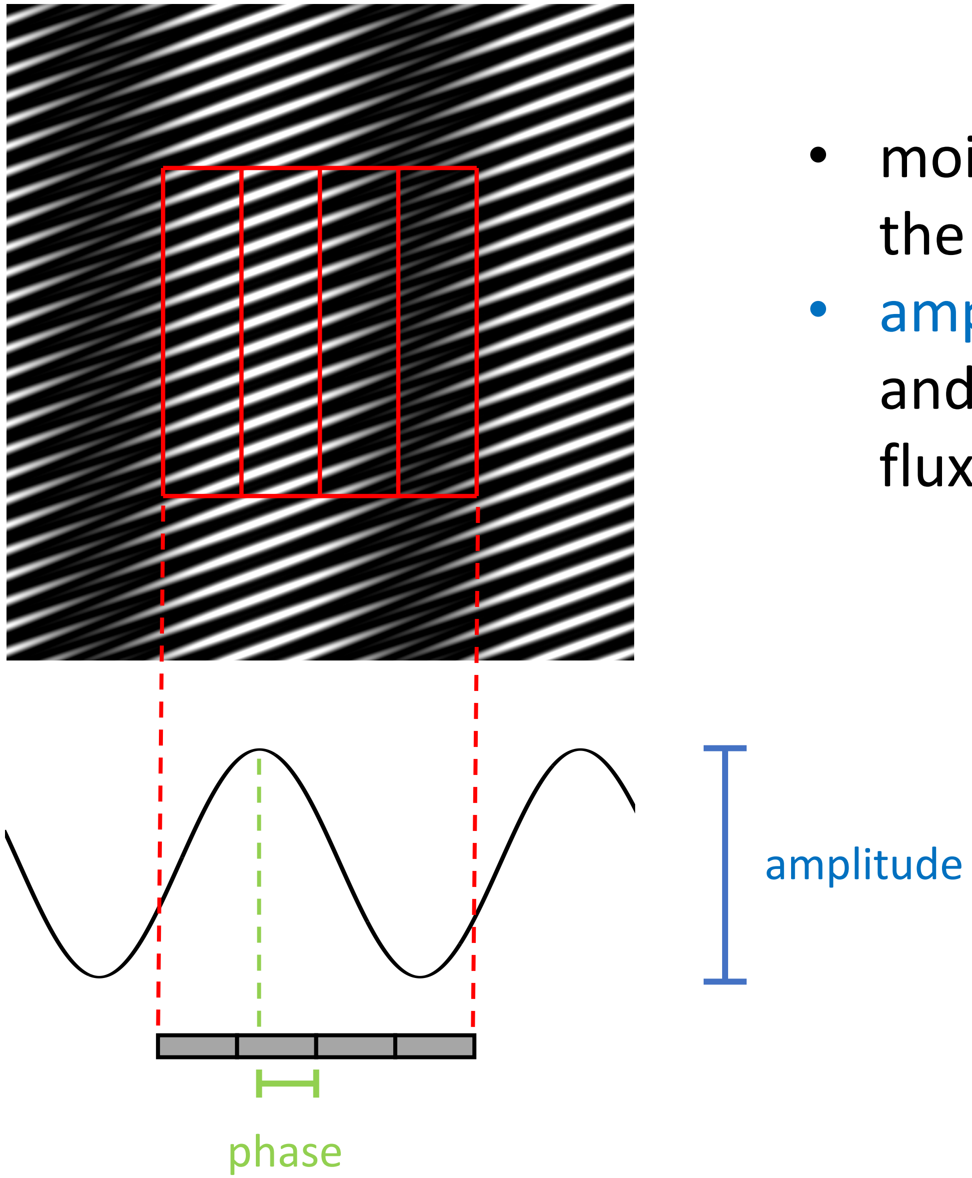
- α: orientation angle
- p: pitch = distance between two consecutive slit centers

the STIX imaging concept

front grid | rear grid | moiré pattern



moiré pattern - 1

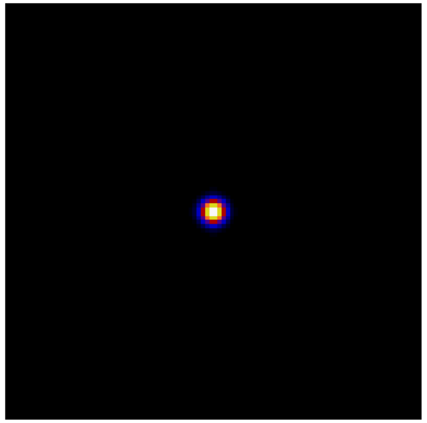


- moiré pattern: sinusoidal wave with period equal to the detector width
- amplitude and phase of the pattern → amplitude and phase of a Fourier component of the photon flux (***visibility***)

moiré pattern - 2

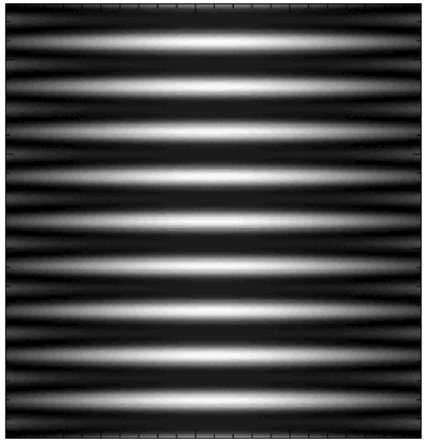
the amplitude of a moiré pattern is sensitive to the source size and shape

X-ray source

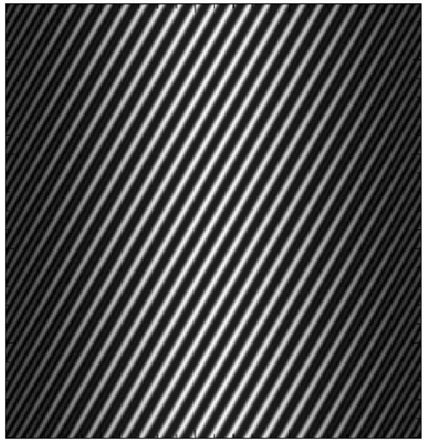


FWHM from 12 to 120 arcsec

Resolution: 178.6 arcsec



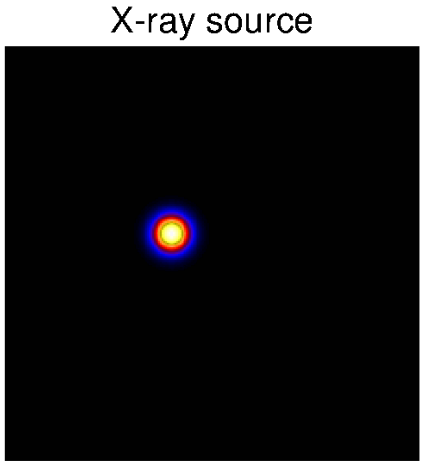
Resolution: 61.0 arcsec

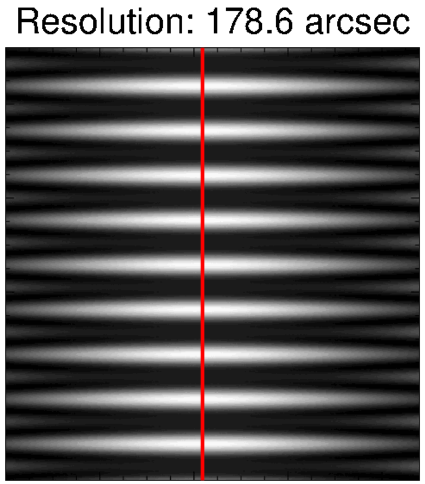


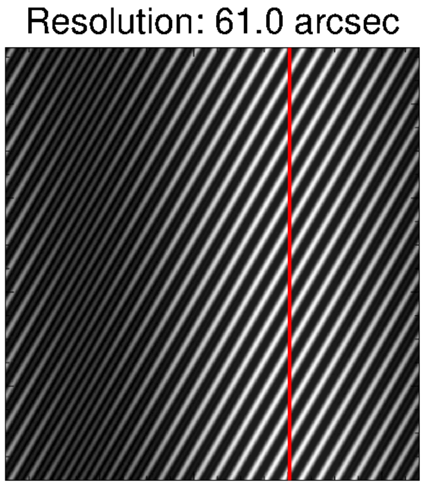
Resolution: 20.9 arcsec

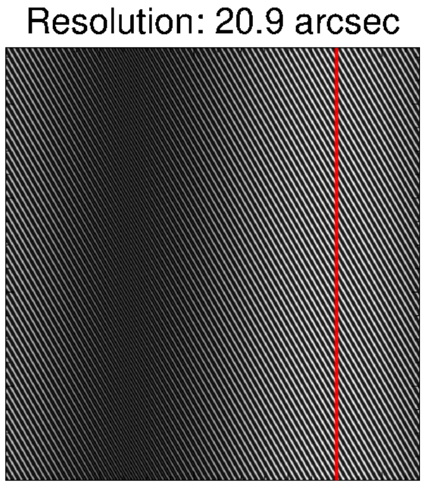
moiré pattern - 3

the phase of a moiré pattern is sensitive to the source location









visibilities

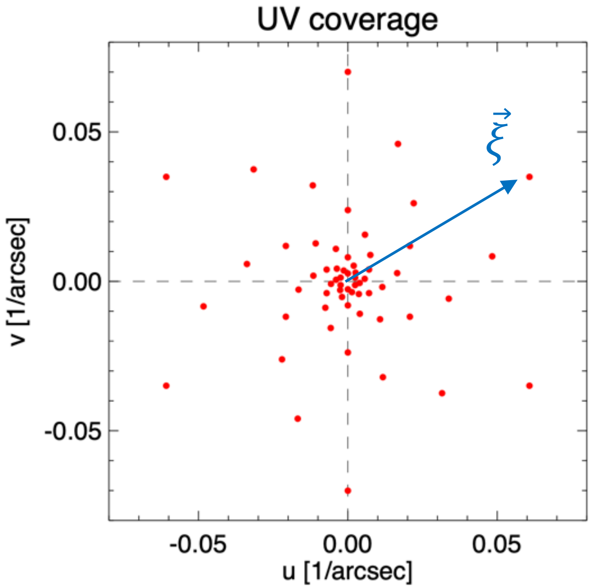
each sub-collimator measures a visibility value, i.e. a fourier sample

visibilities

each sub-collimator measures a visibility value

grid pitch and orientation

norm and orientation of the sampling frequency $\vec{\xi}$



(Krucker et al., 2020)

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

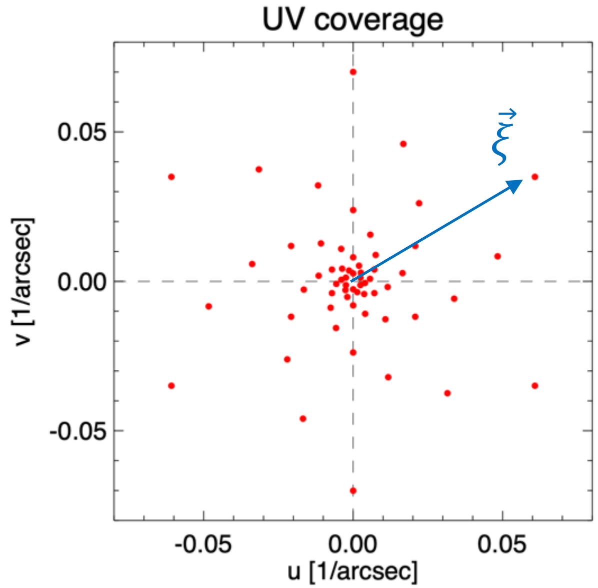
visibilities

each sub-collimator measures a visibility value

grid pitch and orientation

↓

norm and orientation of the sampling frequency $\vec{\xi}$



(Krucker et al., 2020)

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

count measurements A, B, C, D

↓

amplitude and phase of the visibility:

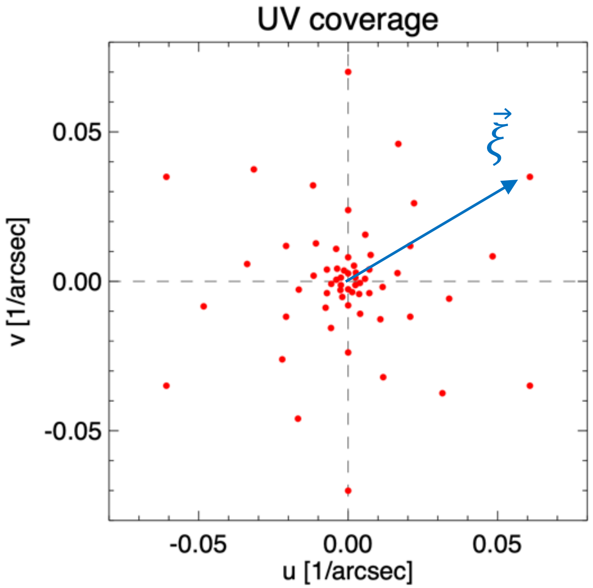
- $|V| \propto \sqrt{(C-A)^2 + (D-B)^2}$
- $\phi = \text{atan}\left(\frac{D-B}{C-A}\right) + 45° + \phi_{calib}$

visibilities

each sub-collimator measures a visibility value

grid pitch and orientation

norm and orientation of the sampling frequency $\vec{\xi}$



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- $|V| \propto \sqrt{(C-A)^2 + (D-B)^2}$
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the data measured by STIX are 30 visibilities

STIX image reconstruction problem

image reconstruction problem for STIX:

$$F\phi = \boldsymbol{V}$$

where:

- ϕ is the image to reconstruct
- F is the fourier transform sampled at STIX frequencies
- $\boldsymbol{V}$ is the complex array of observed visibilities

the STIX image reconstruction problem is an inverse fourier transform problem with limited data

imaging methods

state-of-the-art

The Astrophysical Journal, 894:46 (11pp), 2020 May 1
https://doi.org/10.3847/1538-4357/ab8637

CrossMark

MEM_GE: A New Maximum Entropy Method for Image Reconstruction from Solar X-Ray Visibilities

Paolo Massa[1], Richard Schwartz[2], A Kim Tolbert[2], Anna Maria Massone[1,3], Brian R. Dennis[2], Michele Piana[1,3], and

A&A 656, A25 (2021)
https://doi.org/10.1051/0004-6361/202140946

Astronomy & Astrophysics

Solar Orbiter First Results (Cruise Phase)

Special issue

Imaging from STIX visibility amplitudes

A&A 668, A145 (2022)
https://doi.org/10.1051/0004-6361/202243907

Astronomy & Astrophysics

Forward fitting STIX visibilities

Anna Volpara[1], Paolo Massa[2], Emma Perracchione[3], Andrea Francesco Battaglia[5,6], Sara Garbarino[1], Federico Benvenuto[1], Säm Krucker[5,7], Michele Piana[1,8], and Anna Maria Massone[1,4]

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5 University of Applied Sciences and Arts Northwestern Switzerland, Bahnhofstrasse 6, 5210 Windisch, Switzerland
6 ETH Zürich, Rämistrasse 101, 8092 Zürich, Switzerland
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Received 29 April 2022 / Accepted 17 October 2022

under construction:

- multi-scale CLEAN
- neural network
- pixon
- **uv_smooth**

MEM_GE

solves the maximum-entropy regularized problem

$$\arg\min_{\phi \geq 0} \chi^2(\phi) - \lambda H(\phi)$$

$$\text{with} \sum_j \phi_j = f$$

where

$$\chi^2(\phi) = \sum_i \frac{|(\mathcal{F}\phi)_i - V_i|^2}{\sigma_i^2} \qquad H(\phi) = -\sum_j \phi_j \log\left(\frac{\phi_j}{me}\right)$$

MEM_GE

solves the maximum-entropy regularized problem

$$\arg\min_{\phi \geq 0} \chi^2(\phi) - \lambda H(\phi)$$

$$\text{with} \sum_j \phi_j = f$$

where

$$\boxed{\chi^2(\phi) = \sum_i \frac{|(\mathcal{F}\phi)_i - V_i|^2}{\sigma_i^2}}$$

data fitting

$$H(\phi) = -\sum_j \phi_j \log\left(\frac{\phi_j}{me}\right)$$

MEM_GE

Solves the maximum-entropy regularized problem

$$\arg\min_{\phi \geq 0} \chi^2(\phi) - \lambda H(\phi)$$

$$\text{with} \sum_j \phi_j = f$$

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$$\boxed{H(\phi) = -\sum_j \phi_j \log\left(\frac{\phi_j}{me}\right)}$$

regularization

MEM_GE

solves the maximum-entropy regularized problem

$$\arg\min_{\phi \geq 0} \chi^2(\phi) - \lambda H(\phi)$$

regularization parameter

$$\text{with} \sum_j \phi_j = f$$

where

$$\chi^2(\phi) = \sum_i \frac{|(\mathcal{F}\phi)_i - V_i|^2}{\sigma_i^2} \qquad H(\phi) = -\sum_j \phi_j \log\left(\frac{\phi_j}{me}\right)$$

MEM_GE

solves the maximum-entropy regularized problem

$$\underset{\boxed{\phi \geq 0}}{\arg\min}\, \chi^2(\phi) - \lambda H(\phi)$$

positivity constraint

$$\text{with} \sum_j \phi_j = f$$

where

$$\chi^2(\phi) = \sum_i \frac{|(\mathcal{F}\phi)_i - V_i|^2}{\sigma_i^2} \qquad H(\phi) = -\sum_j \phi_j \log\left(\frac{\phi_j}{me}\right)$$

MEM_GE

solves the maximum-entropy regularized problem

$$\arg\min_{\phi \geq 0} \chi^2(\phi) - \lambda H(\phi)$$

$$\boxed{\text{with} \sum_j \phi_j = f}$$

flux constraint

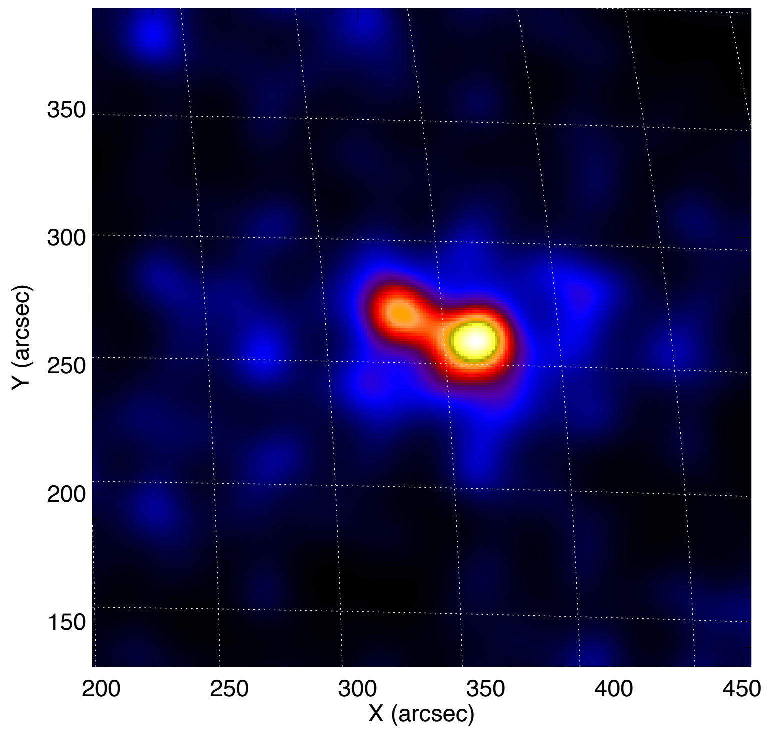
where

$$\chi^2(\phi) = \sum_i \frac{|(\mathcal{F}\phi)_i - V_i|^2}{\sigma_i^2} \qquad H(\phi) = -\sum_j \phi_j \log\left(\frac{\phi_j}{me}\right)$$

MEM_GE

λ: finds a tradeoff between data fitting and regularization

large λ



MEM_GE

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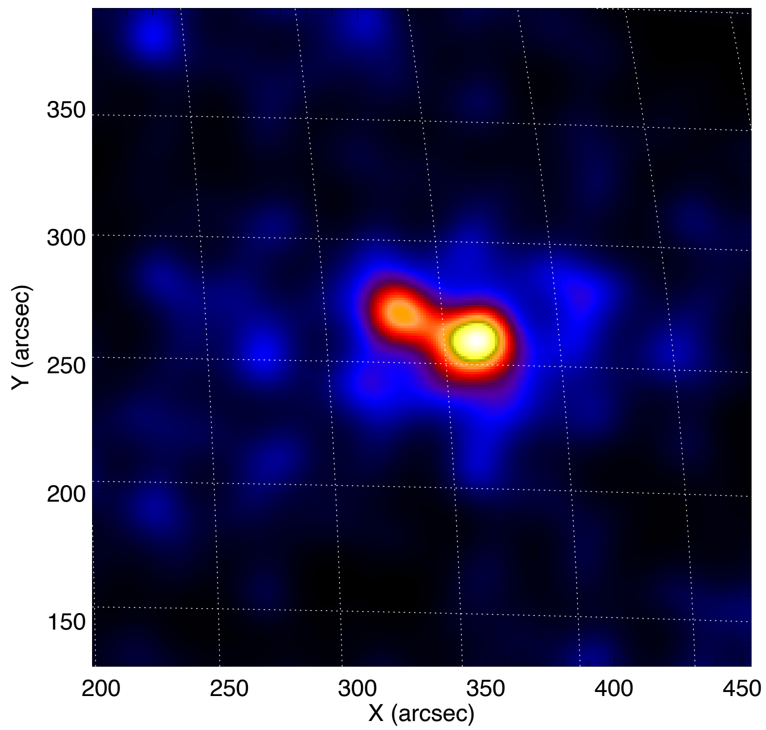
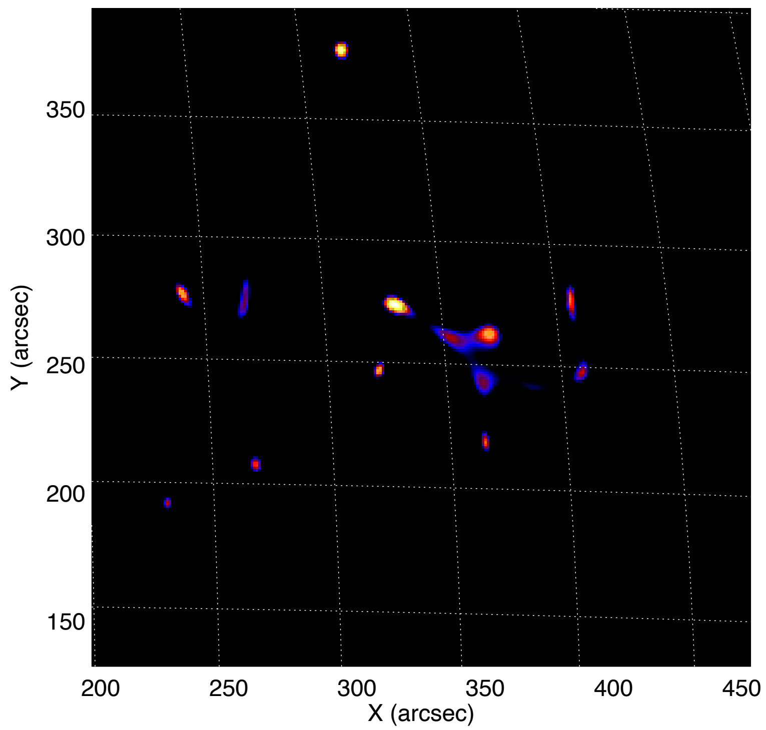


low λ



MEM_GE

λ: finds a tradeoff between data fitting and regularization

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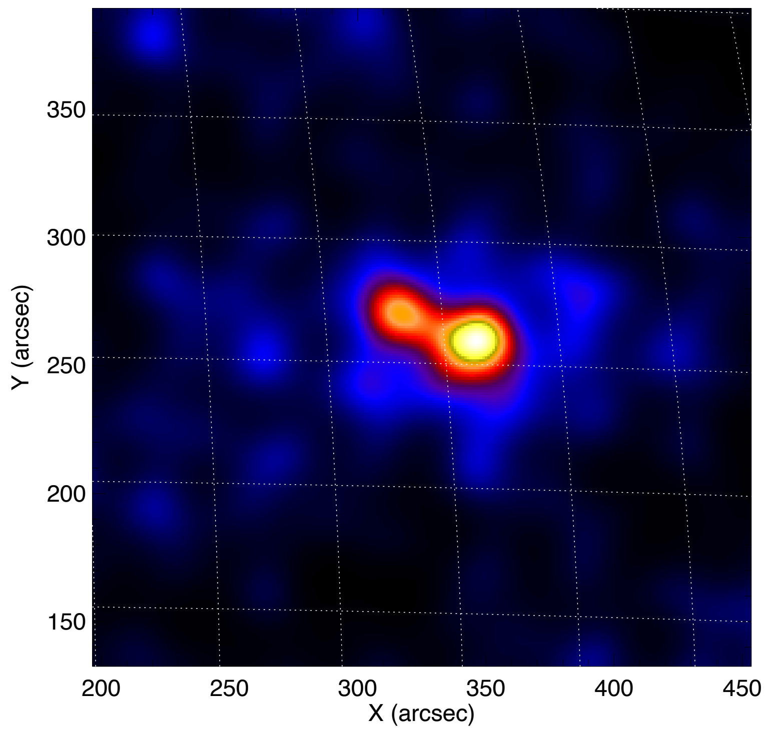
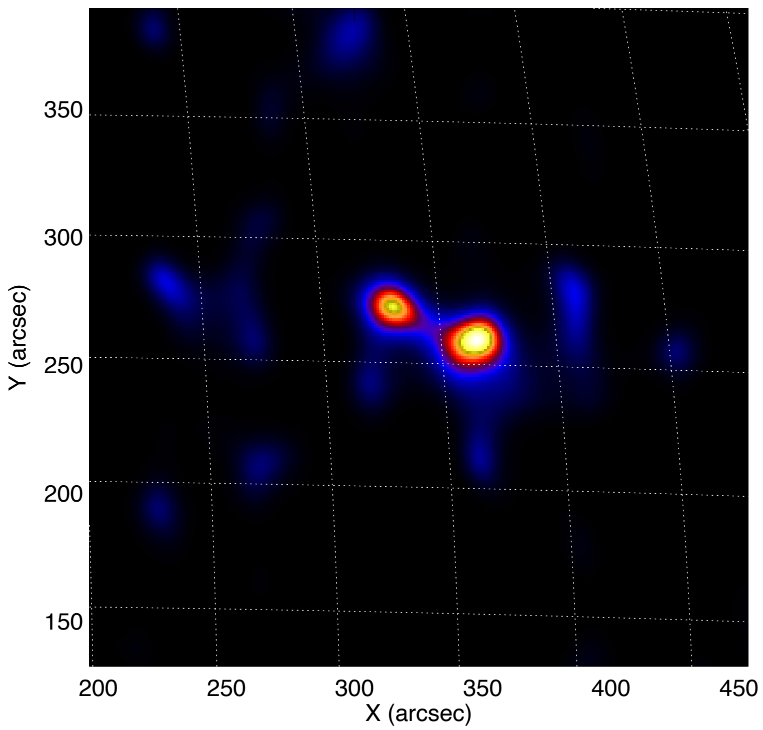
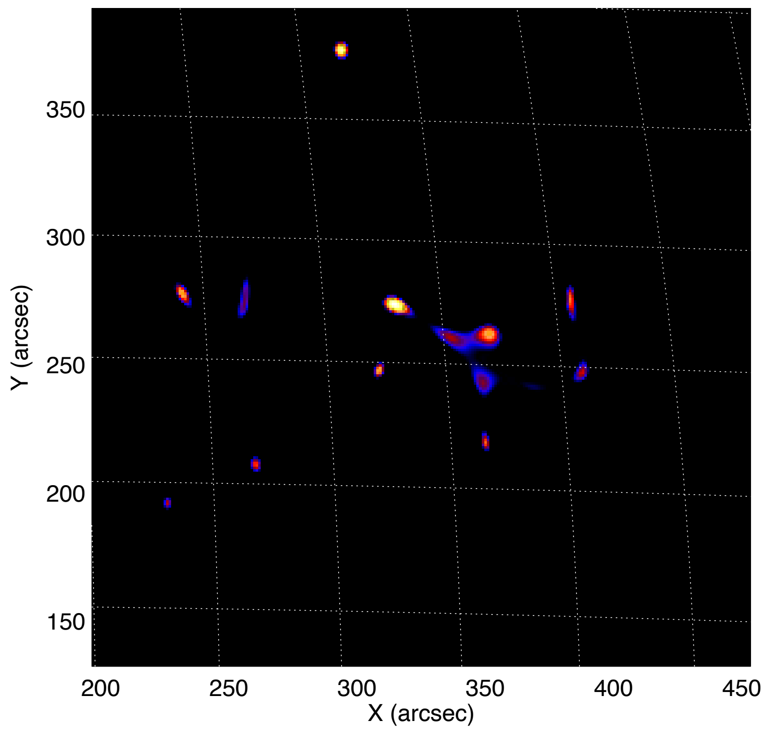


tradeoff



low λ



may 2021 events

angle relative to Earth-Sun (in may 2021): $97.4° – 98.2°$

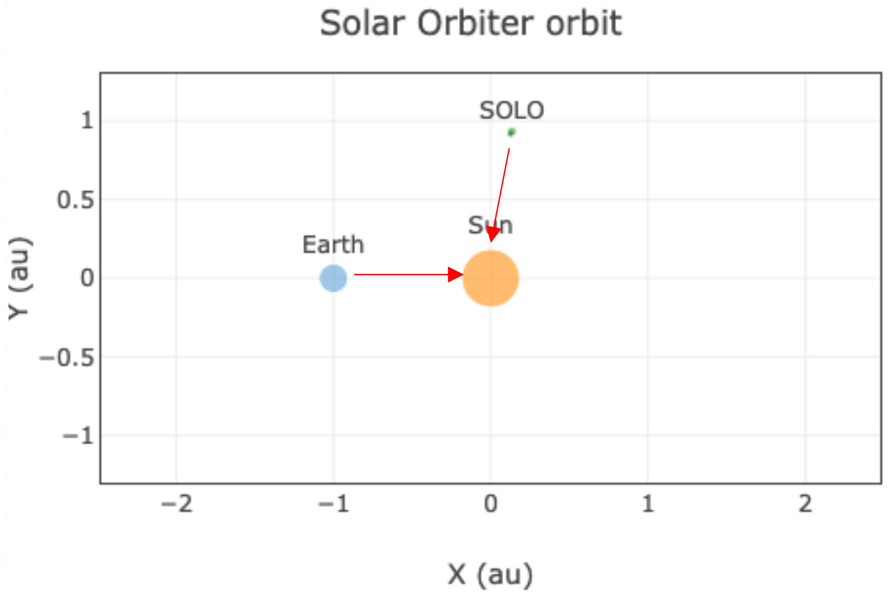
Solar Physics (2022) 297:93
https://doi.org/10.1007/s11207-022-02029-x

Check for updates

First Hard X-Ray Imaging Results by Solar Orbiter STIX

Paolo Massa[1] · Andrea F. Battaglia[2,3] · Anna Volpara[1] · Hannah Collier[2,3] · Gordon J. Hurford[2] · Matej Kuhar[2] · Emma Perracchione[4] · Sara Garbarino[1] · Anna Maria Massone[1,5] · Federico Benvenuto[1] · Frederic Schuller[6] · Alexander Warmuth[6] · Ewan C.M. Dickson[7] · Hualin Xiao[2] · Shane A. Maloney[8,9] · Daniel F. Ryan[2] · Michele Piana[1,5] · Säm Krucker[2,10]

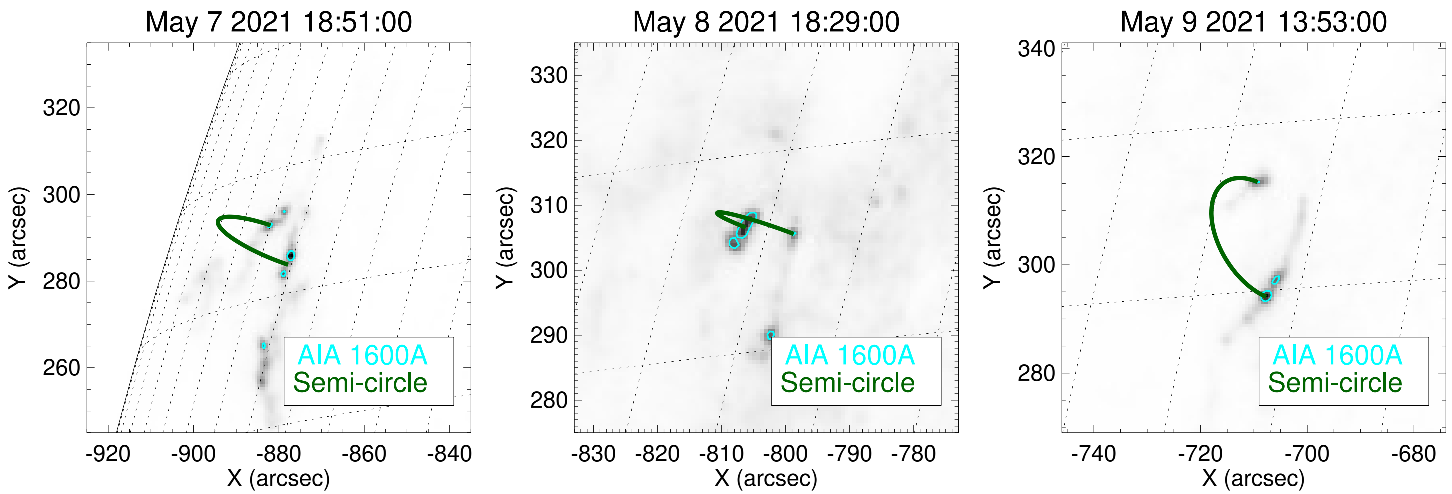
Received: 7 March 2022 / Accepted: 16 June 2022 / Published online: 22 July 2022



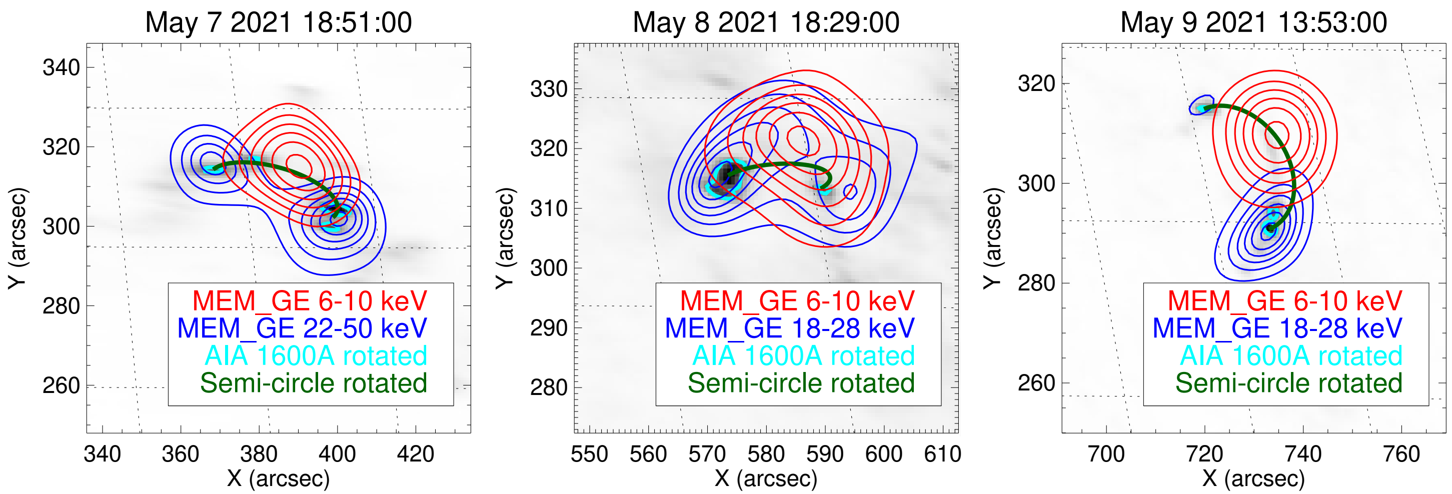
AIA images rotated by means of the *reproject* Python package (see battaglia et al., 2021)

may 2021 events

Earth vantage point



Solar Orbiter vantage point



active region AR2822

- may 7: GOES M3.9
- may 8: GOES C8.6
- may 9: GOES C4.0

manual shift STIX reconstructions

event	Δx (arcsec)	Δy (arcsec)
may 7	44	54
may 8	45	57
may 9	47.5	53

STIX and numerical approximation

interpolation/extrapolation: general scheme

1. interpolation of the scattered observations of the fourier transform to generate a uniform sampling in the spatial frequency domain

$$P(\boldsymbol{u}_i) = \boldsymbol{V}_i, \quad i = 1,\ldots,n.$$

$$P(\boldsymbol{u}) = \sum_{k=1}^{n} a_k b_k(\boldsymbol{u}) \ ,$$

2. extrapolation/inversion of the generated interpolants (possibly via FFT) to perform (super-resolved) image reconstruction

$$\bar{I}(\boldsymbol{x}) = \left(\mathcal{F}^{-1} P_V^D\right)(\boldsymbol{x}),$$

+ some constraint to regularize while realizing out-of-band extrapolation and beat the shannon theorem

uv_smooth: first release

The Astrophysical Journal, 703:2004–2016, 2009 October 1 doi:10.1088/0004-637X/703/2/2004

HARD X-RAY IMAGING OF SOLAR FLARES USING INTERPOLATED VISIBILITIES

Anna Maria Massone[1], A. Gordon Emslie[2], G. J. Hurford[3], Marco Prato[1,4], Eduard P. Kontar[5], and Michele Piana[1,6]
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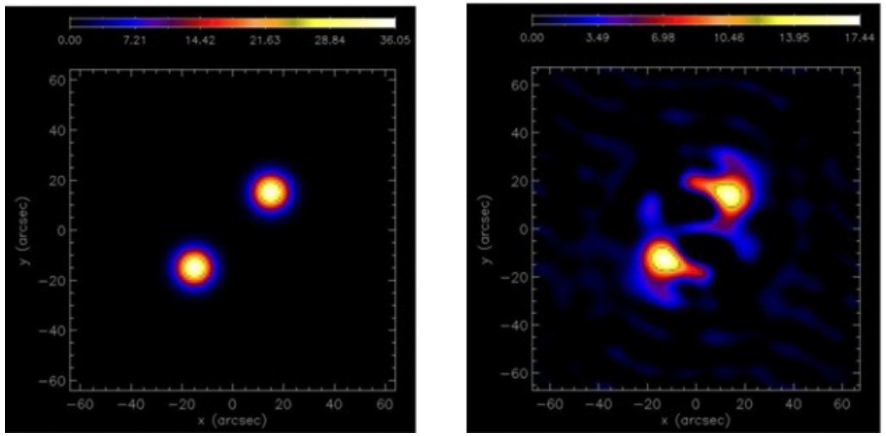
Received 2009 April 29; accepted 2009 August 20; published 2009 September 15

interpolation:
thin-plate spline

extrapolation:

$$\mathcal{F}(I^{(k+1)}) = \tau\mathcal{F}(\bar{I}) + (1 - \tau\chi_D)\mathcal{F}(I^{(k)}), \quad k = 1, 2, \ldots,$$

$$I^{(k+1)} = \mathcal{P}_+ I^{(k+1)}, \quad \left(\mathcal{P}_+ I^{(k+1)}\right)(\boldsymbol{x}) = \begin{cases} 0 & I^{(k+1)}(\boldsymbol{x}) < 0, \\ I^{(k+1)}(\boldsymbol{x}) & \text{otherwise.} \end{cases}$$



augmented uv_smooth: theory

IOP Publishing Inverse Problems

Inverse Problems **37** (2021) 105001 (21pp) https://doi.org/10.1088/1361-6420/ac1ad7

Feature augmentation for the inversion of the Fourier transform with limited data

Emma Perracchione[1,2], **Anna Maria Massone**[1,2] **and Michele Piana**[1,2,*]

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CrossMark

$$P(\boldsymbol{u}_i) = V_i, \quad i = 1,\ldots,n.$$

$$P(\boldsymbol{u}) = \sum_{k=1}^{n} a_k b_k(\boldsymbol{u}) \,,$$

$$b_k(\boldsymbol{u}) = \phi(\|(\boldsymbol{u},\, \psi(\boldsymbol{u})) - (\boldsymbol{u}_k,\, \psi(\boldsymbol{u}_k))\|), \quad k = 1,\ldots,n \,,$$

$$K\boldsymbol{a} = \boldsymbol{V}$$

technical results:

$$\phi(||\boldsymbol{u}||) = \mathrm{e}^{-\varepsilon||\boldsymbol{u}||},$$

$$K_\varepsilon(\boldsymbol{w},\boldsymbol{z}) = \varphi_\varepsilon(\|\boldsymbol{w}-\boldsymbol{z}\|_2),$$

$$K_\varepsilon^\Psi(\boldsymbol{w},\boldsymbol{z}) := K_\varepsilon((\boldsymbol{w},\, \Psi(\boldsymbol{w})), (\boldsymbol{z},\, \Psi(\boldsymbol{z}))),$$

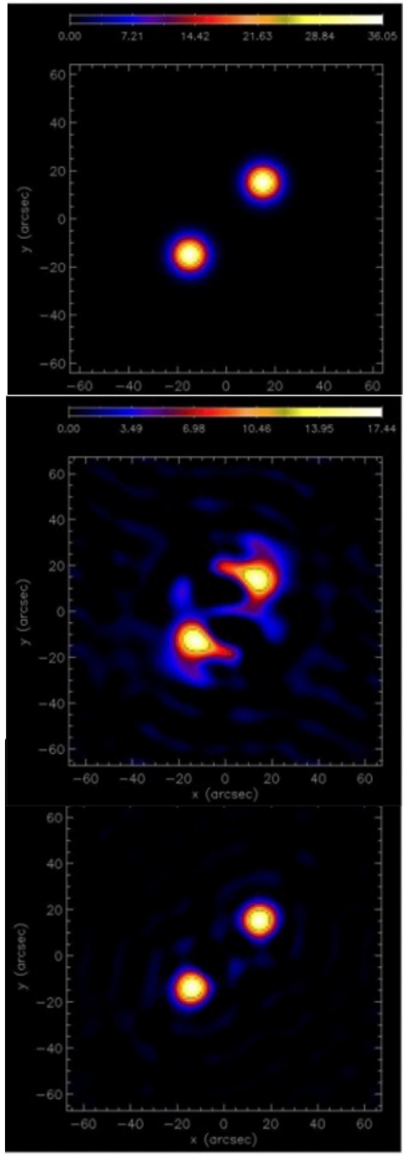
$$\Downarrow$$

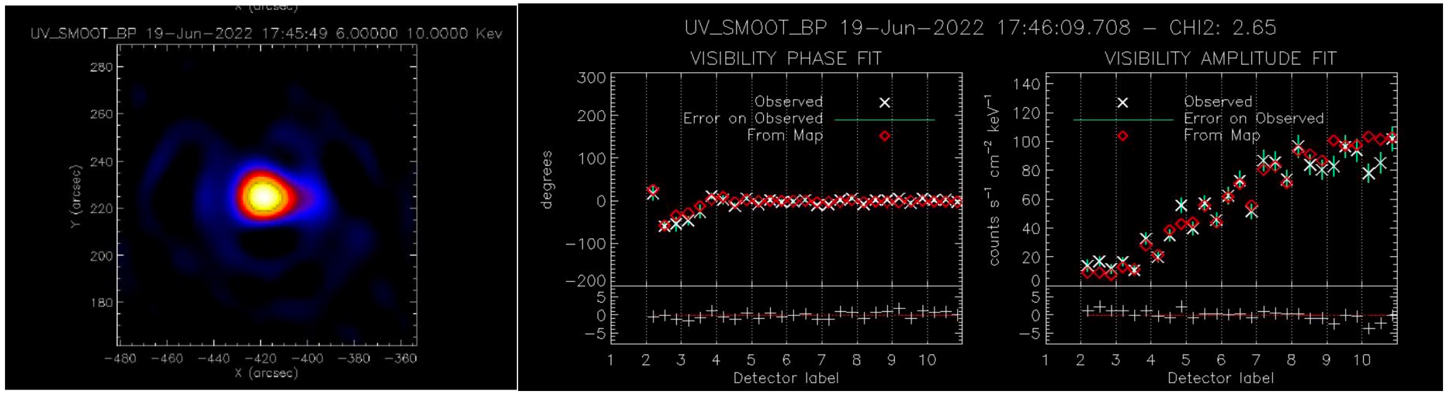
$$S(\mathsf{K}) = \frac{n}{\|\mathsf{K}\|_{\mathsf{F}}} \leqslant \frac{n}{\|\mathsf{K}^\Psi\|_{\mathsf{F}}} = S(\mathsf{K}^\Psi).$$

$$\mathrm{cond}(\mathsf{K}^\Psi) \leqslant \mathrm{cond}(\mathsf{K}).$$

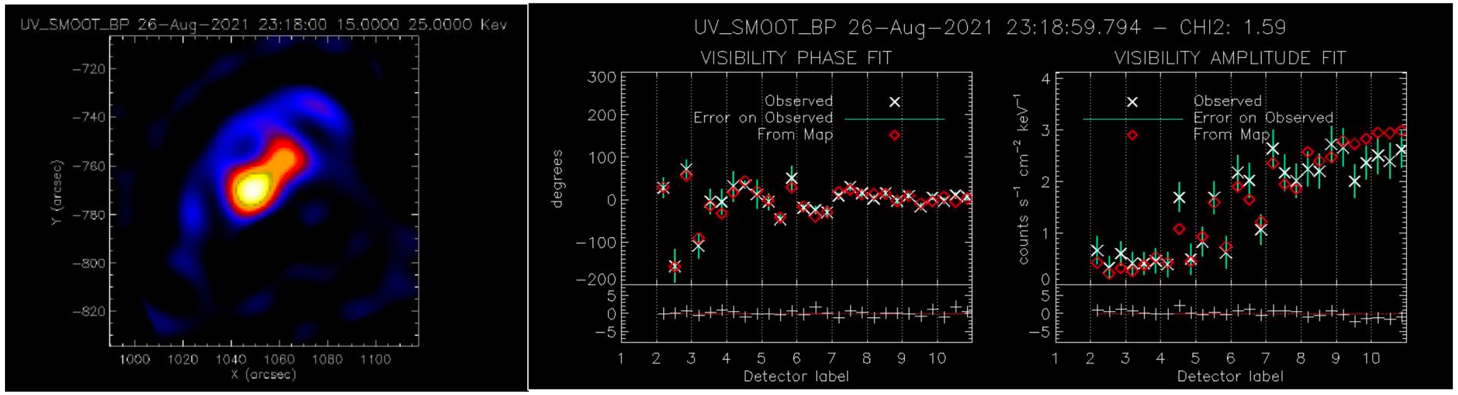
augmented uv_smooth: results

synthetic
visibilities





june 19 2022



august 26 2021

credits

from MIDA:

- paolo massa
- anna volpara
- emma perracchione
- sara garbarino
- anna maria massone

from the rest of the STIX crew:

- sam krucker
- gordon hurford
- andrea battaglia
- ewan dickson
- hualin xiao

references

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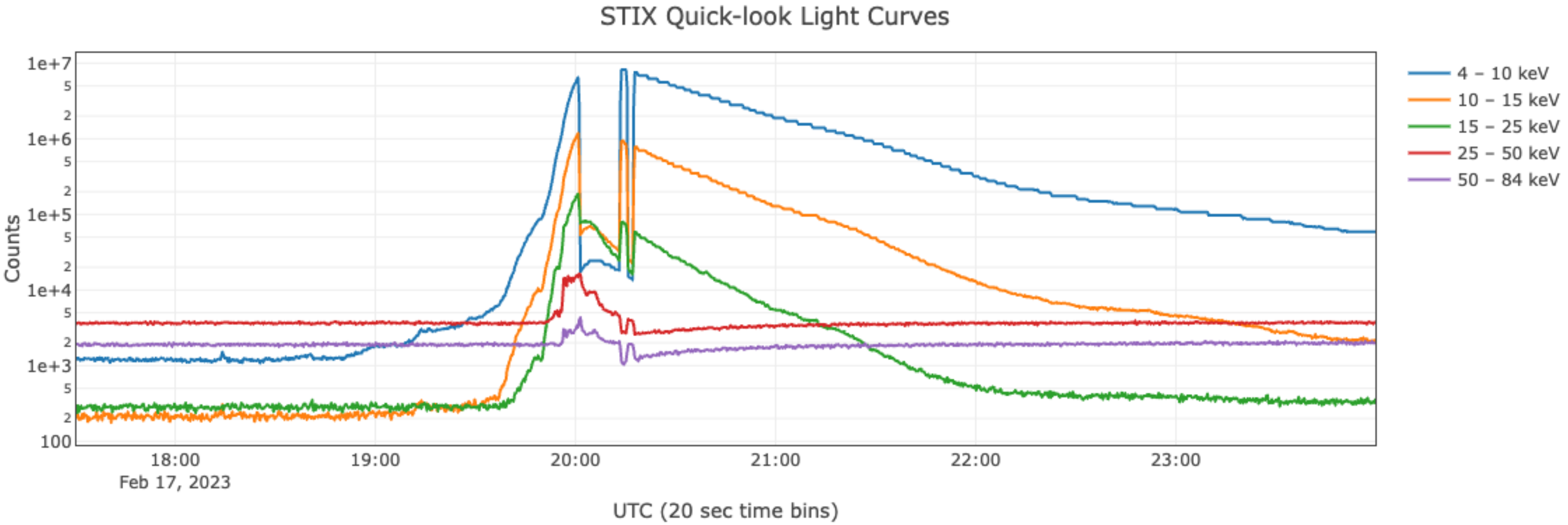
- massone et al, astrophysical journal, 703, 2, 2004

we are hiring people at MIDA

- junior position: two-year position within the solar orbiter contract (STIX imaging)

- senior position: two-year position within the horizon europe project ARCAFF (flare forecasting)

thank you for the attention



Visibility calibration

Amplitude calibration:

- background subtraction
- grid transmission (including the flare location)
- ELUT
- livetime

Phase calibration: keeps into account the grid geometry

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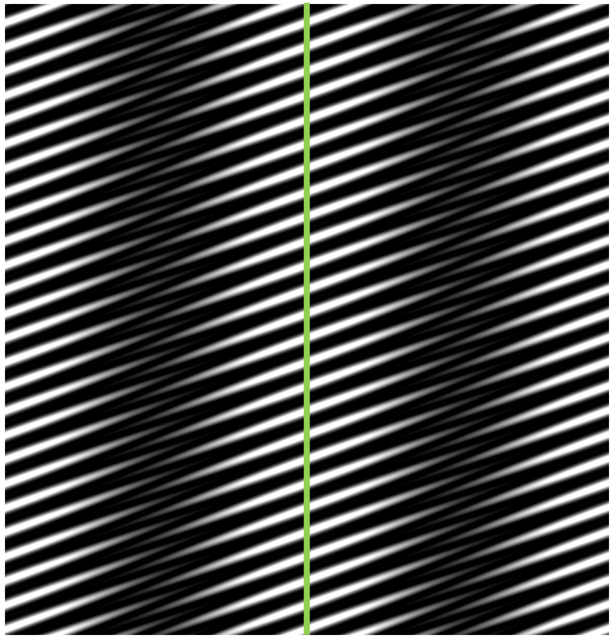

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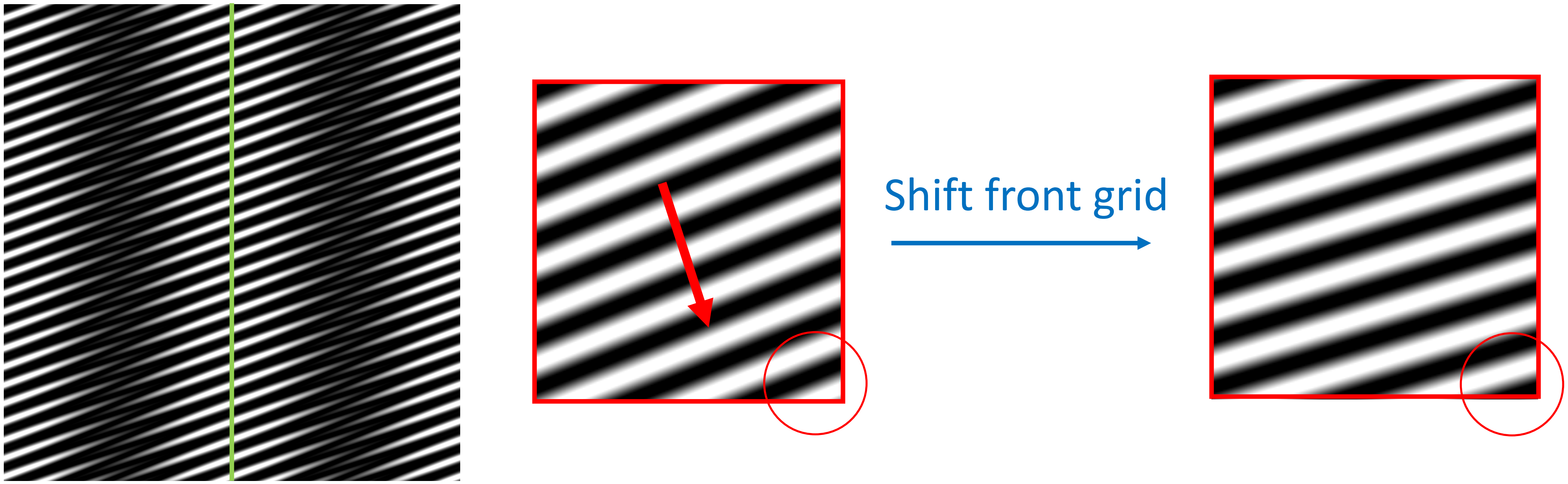

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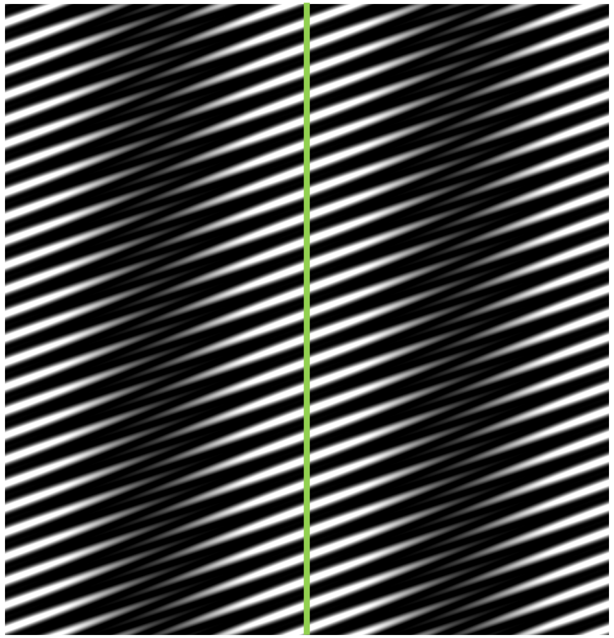
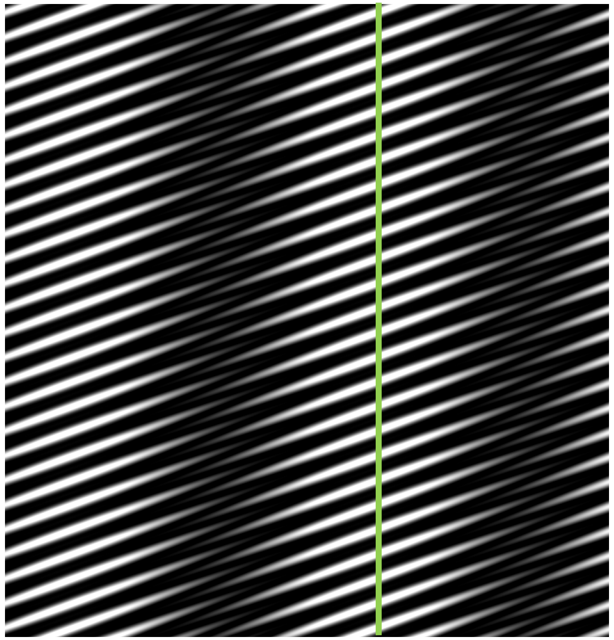
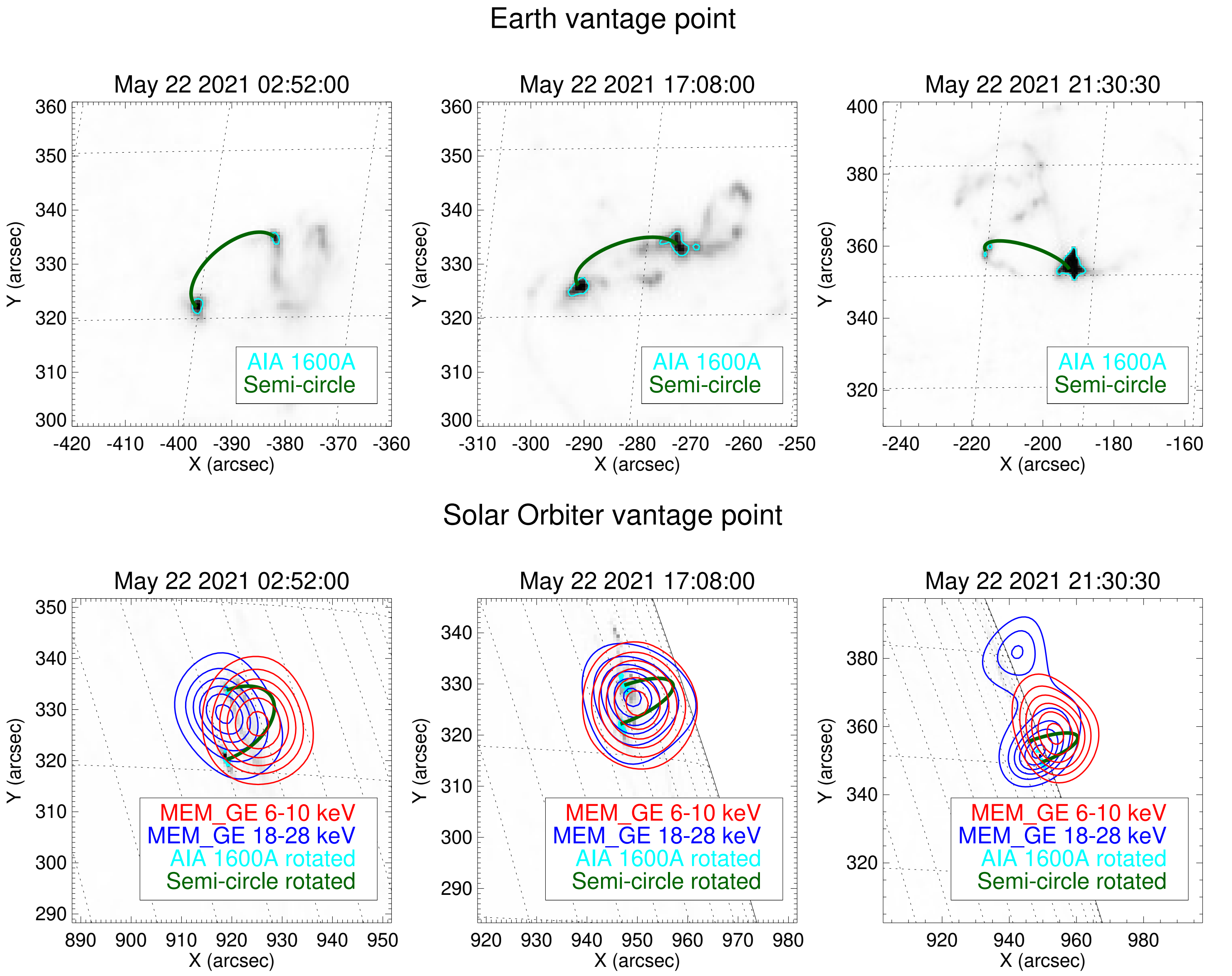


Shift front grid



May 2021 events (Massa et al., 2022, in preparation)



Active region AR2824

May 22:

- 02:52:00 UT: GOES C6.1
- 17:08:00 UT: GOES M1.1
- 21:30:30 UT: GOES M1.4

Manual shift STIX reconstructions

Event	Δx (arcsec)	Δy (arcsec)
02:52	47	55
17:08	47	50
21:30	50	50