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Compressed sensing and Sequential Monte Carlo for solar hard X-ray imaging

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Summary. — We describe two inversion methods for the reconstruction of hard X-ray solar images. The methods are tested against experimental visibilities recorded by the *Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)* and synthetic visibilities based on the design of the *Spectrometer/Telescope for Imaging X-rays (STIX)*.

1. – Introduction

The NASA *Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)* [1] and the ESA *Spectrometer/Telescope for Imaging X-rays (STIX)* [2] are two space telescopes for imaging hard X-rays that rely on rather similar imaging technologies. *RHESSI* has been decommissioned on August 16 2018 after more than 16 years of successful operations, while *STIX* is going to fly in the next two years. Both hardwares allow the modulation of the X-ray flux coming from the Sun, providing as a result sparse samples of its Fourier transform, named visibilities, picked up at specific (u, v) points of the Fourier plane. Therefore, for both *RHESSI* and *STIX*, image reconstruction is needed to determine the actual spatial photon flux distribution from the few Fourier components acquired by the hard X-ray collimators [3-8]. In Section 2 of this paper we briefly overview a reconstruction method based on compressed sensing [9]. In Sec. 3 we provide more insights on a Monte Carlo method for the Bayesian estimation of several imaging parameters [10, 11]. Our conclusions are offered in Sec. 4.

2. – Compressed sensing for hard X-ray image reconstruction

Figure 1 shows how *RHESSI* and *STIX* grids sample the (u, v) frequency domain. From this design, it follows that the mathematical model for data formation in the

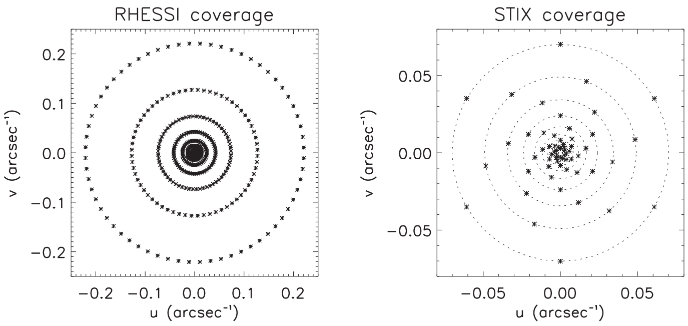

Fig. 1. – Sampling of the visibility (u, v) plane performed by *RHESSI* (left panel) and *STIX* (right panel), respectively.

framework of these two instruments is, in a matrix form:

$$HFx = V \ , \tag{1}$$

where x is the photon flux image to reconstruct, V are the experimental visibilities, F is the discretized Fourier transform, H is a mask that realizes the sampling in the (u, v) plane. The reconstruction of x from V is an ill-posed problem and therefore regularization is required to mitigate the numerical instabilities induced by the observation noise. A possible approach is to apply an l_1 penalty term in some transformation domain. This can be realized by solving the minimum problem [9]

$$\hat{x} = \min_x \{ \|HFx - V\|_2^2 + \lambda \|Wx\|_1 \} \ , \tag{2}$$

where the regularization term $\|Wx\|_1$ is designed to penalize reconstructions that would not exhibit the sparsity property with respect to the Finite Isotropic Wavelet Transform [9]. Figure 2 compares the reconstructions provided by this compressed sensing algorithm to the ones obtained by using other four visibility-based imaging methods currently implemented in the *RHESSI* pipeline [5-7].

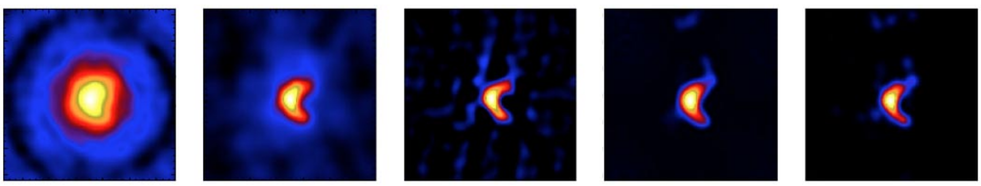

Fig. 2. – Image reconstructions from *RHESSI* visibilities provided, from left to right, by a Back-Projection algorithm, CLEAN, an interpolation/extrapolation method, a compressed sensing method based on exploiting an image catalogue, and by our wavelet-based compressed sensing method. The reconstructions refer to the May 13, 2013 event in the time interval 02:04:16-02:04:48 UT and energy range 6-12 keV. *RHESSI* visibilities recorded by detectors from 3 to 9 have been used in all cases.

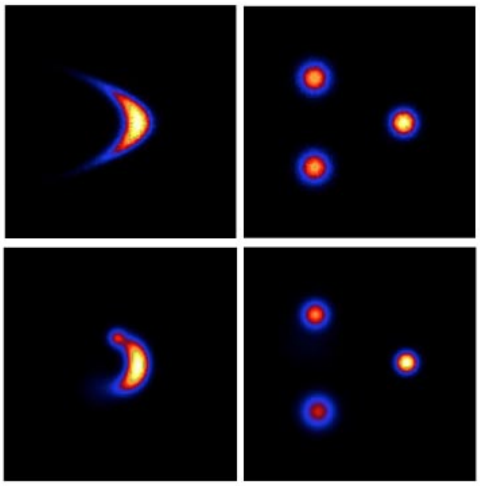

Fig. 3. – Reconstructions of two simulated configurations estimated by the SMC algorithm using synthetic *STIX* visibilities corresponding to a realistic signal-to-noise ratio. Top row: ground truth; bottom row: SMC reconstructions.

3. – Sequential Monte Carlo for hard X-ray image reconstruction

Sequential Monte Carlo (SMC) samplers are computational methods aiming at sampling target distributions of interest, and are often applied to sample the posterior distribution $p(x|y)$ as given by Bayes' theorem

$$p(x|y) = \frac{p(y|x)p(x)}{p(y)} \ , \tag{3}$$

where x is the unknown, y is the observation, $p(x)$ is the prior probability encoding all *a priori* information, $p(y|x)$ is the likelihood encoding the image formation model (1) and the noise model, and the marginal likelihood $p(y)$ is a normalization factor. In the case of *RHESSI* and *STIX* imaging, x is the image to reconstruct and y denotes the set of recorded visibilities. We modeled x as $x(N, T_{1:N}, \Theta_{1:N})$ where N is the number of sources in the image, $T_{1:N} = (T_1, \ldots, N)$ represents the source types (Gaussian, elliptical, loop-like) and $\Theta_{1:N} = (\theta_1, \ldots, \theta_N)$ contains the parameters characterizing each source. We chose a prior distribution factorized as the product of a Poisson distribution for N, uniform distributions for the source types and uniform distributions for the source parameters [10, 11]. Sequential Monte Carlo [12] computes the posterior distribution iteratively, by constructing a sequence of converging approximate distributions. Once the posterior is determined, it can be used to compute the solution image and all image parameters. Figures 3 and 4 show results provided by this approach using simulated *STIX* visibilities and experimental *RHESSI* visibilities, respectively.

4. – Conclusions

This paper shows the performances of two image reconstruction methods formulated for hard X-ray solar visibilities. The implementation of the corresponding tools within *Solar SoftWare (SSW)* is under construction.

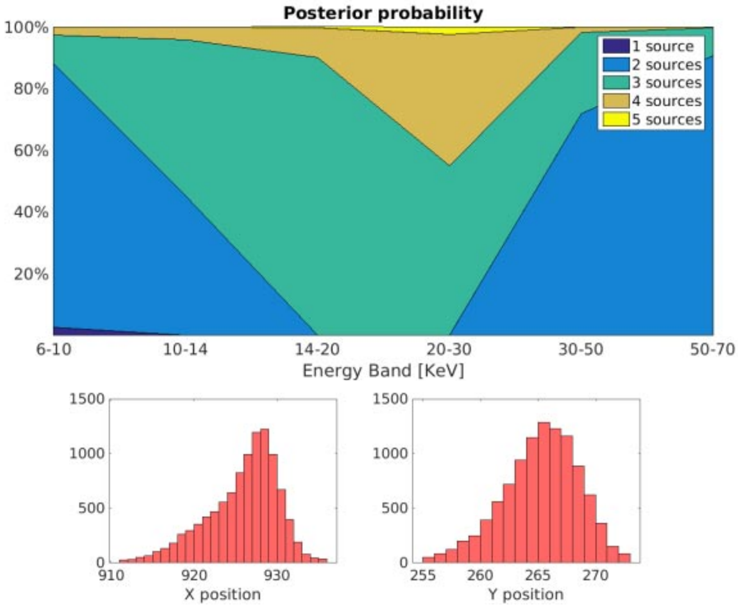

Fig. 4. – Parameters estimation provided by SMC in the case of the February 20, 2002 *RHESSI* visibilities. Top panel: posterior probabilities for the number of sources at different energy channels. Bottom panel: histograms of the x and y position of the loop-top source detected with high probability at the $20-30$ keV channel.

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