Super-resolution of EUV images using small-scale offpoints

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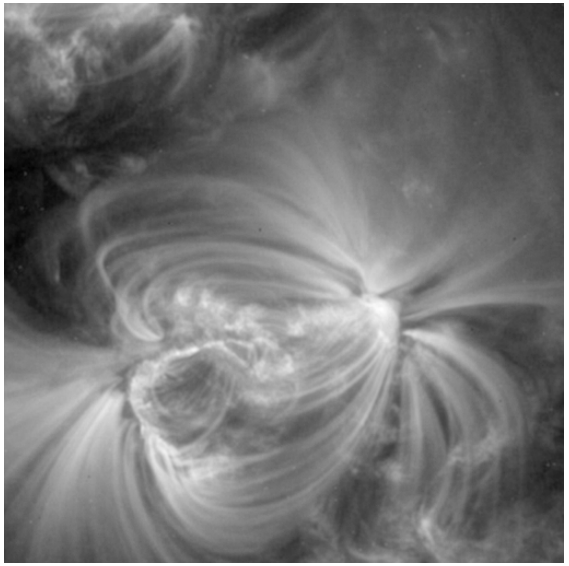
Motivation for existing missions

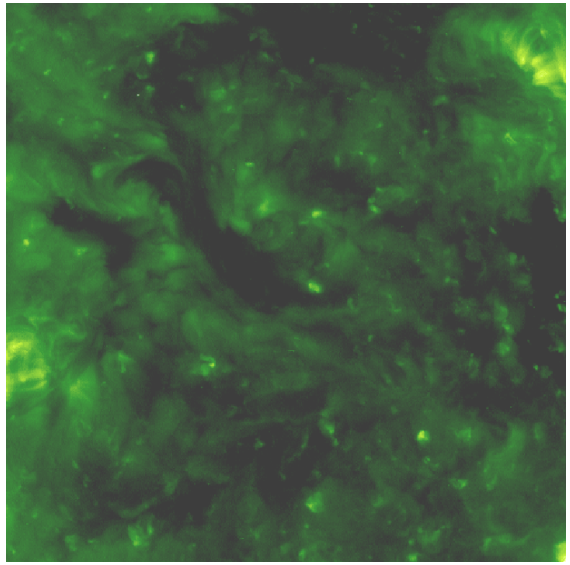
Super-resolution (SR) = post-processing that allows e.g. to :

- Better resolve coronal loops
  - Feature extraction easier
- Resolve small explosive events (nanoflares)
  - More precise account of heating events, and hence of energetic balance for coronal heating (Krucker & Benz, 1998)

Implementation: combine a set of images translated at sub-pixel level :
Take into account the solar rotation !

TRACE
14 July 1998





EIT 195 Å
1997

Motivation for future missions: EUI onboard Solar Orbiter

Super-resolution on **Full Sun Imager (FSI):**

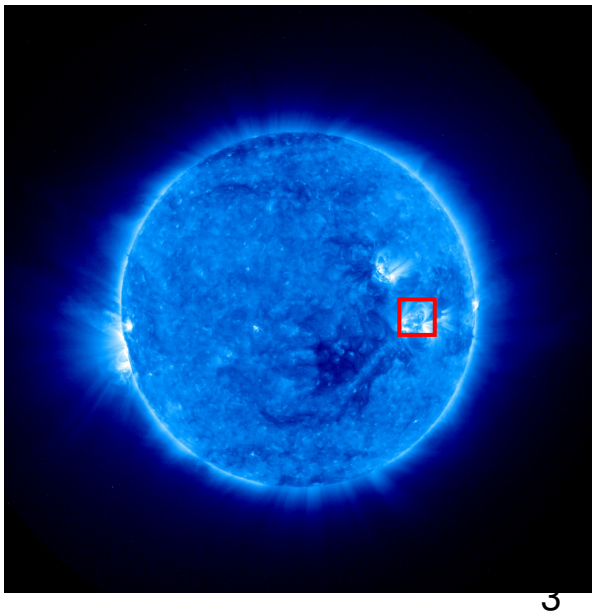
- Will provide medium resolution capabilities, i.e.
- bridge the resolution gap between High Resolution & Full Sun Imagers

Super-resolution on
High resolution Imager (HRI):

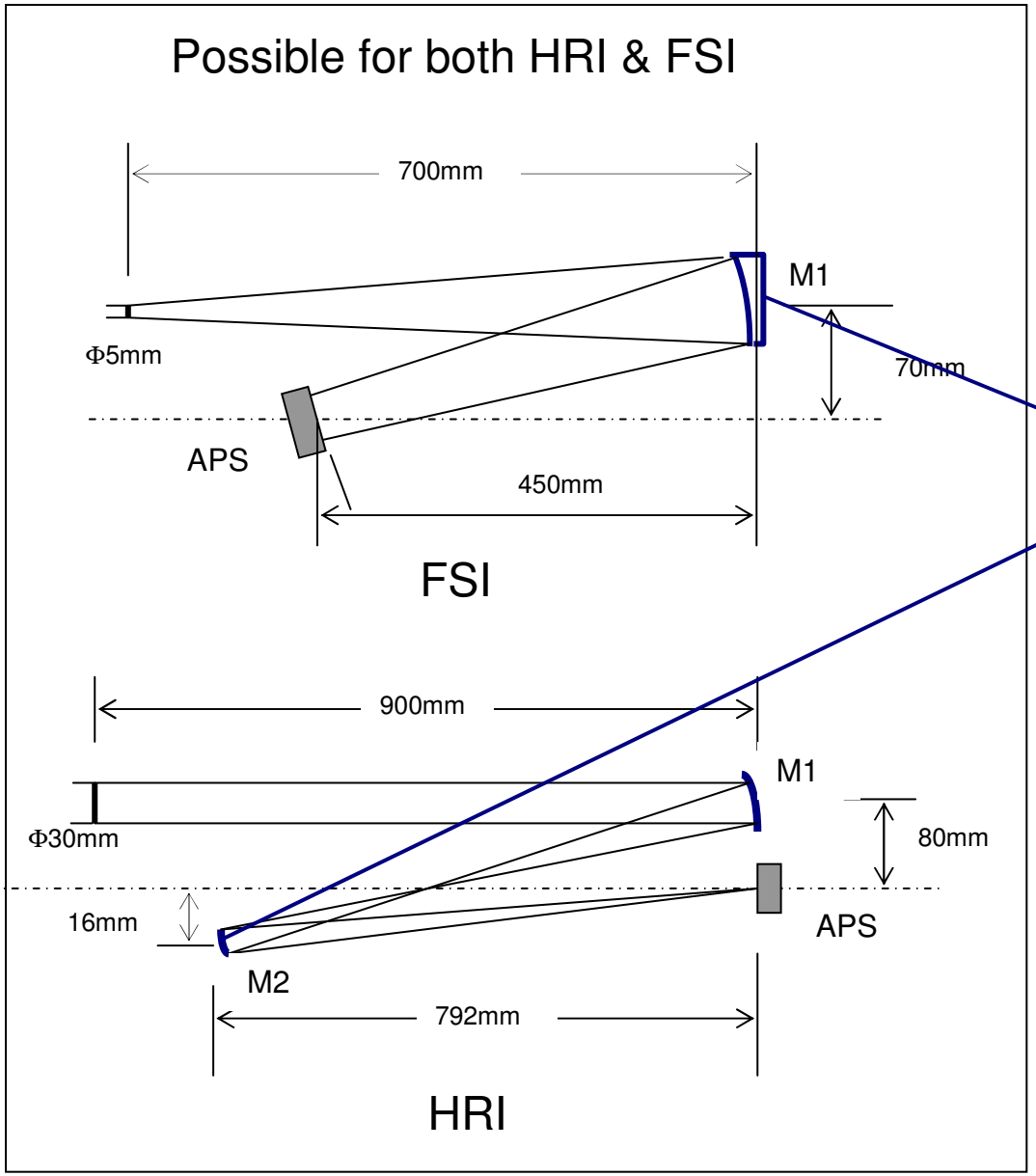
- gain an extra resolution step toward fundamental physical scales:
  resolution of 0.5 arcsec = 80 km
  at perihelion (reached a few days/orbit)

- is 80 km the fundamental scale ?
- pixel pitch > 100 km most of the time

Implementation: use hardware possibilities



Hardware implementation for producing translated images



Need to move the image by a fraction of a pixel

Move either:

- The detector (or CCD clocks)
- One mirror

Piezos on mirror can provide

- super resolution
- image stabilization
- flat fielding

Cheap, robust mechanisms

Offpoint used in STEREO/EUVI for flat-fielding

- Set of ~10 shifted images: from a few arcseconds (small-scale offpoints) to several arcmins (large scale offpoints)
- Successfully used on SOHO (EIT, MDI) using maneuvers (complex, risky) and now on STEREO with active secondary mirror (much easier)

21 Feb 2007: small scales offpoints on EUVI – A, 171Å

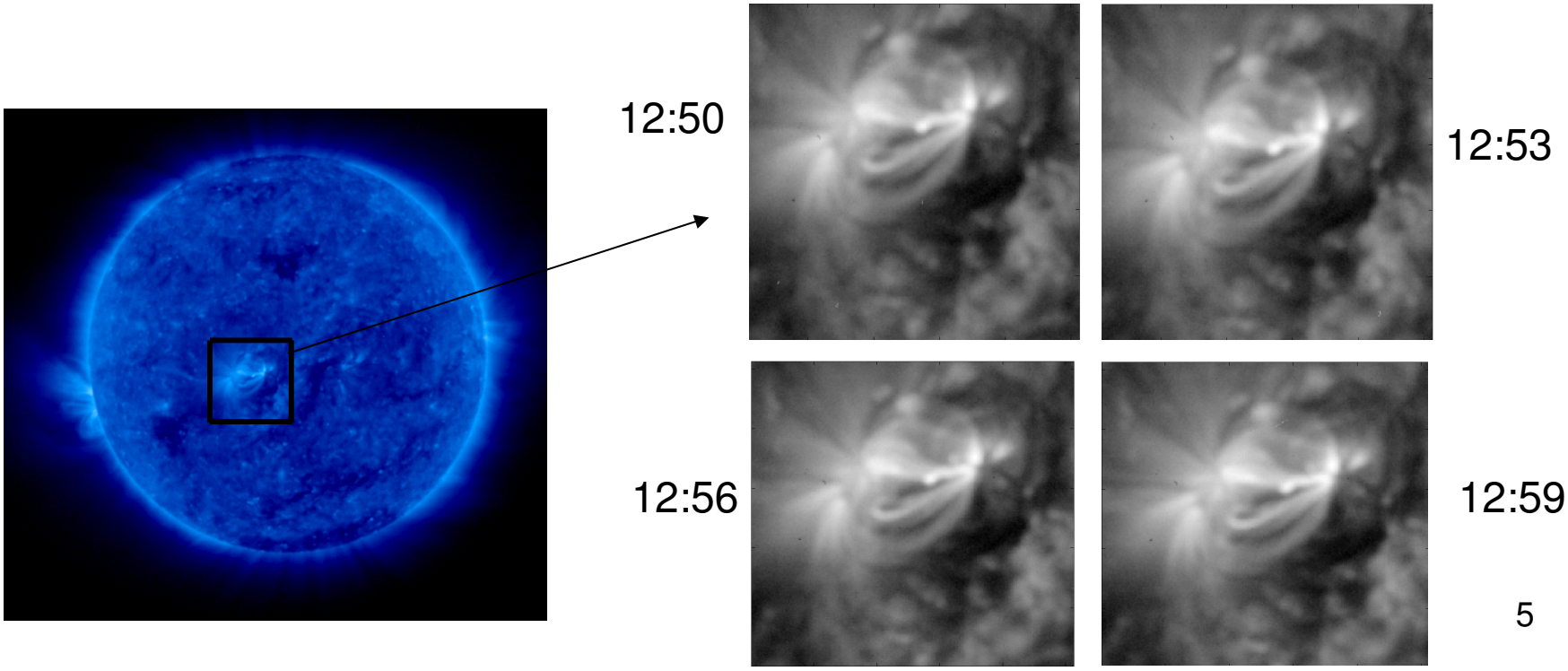


Image model

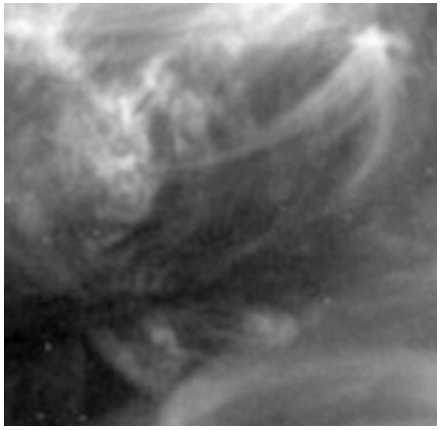
Gaussian errors

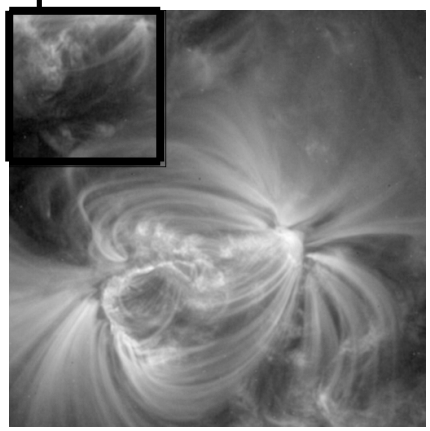
$$x_k = D \cdot B \cdot S_k \cdot f + \epsilon$$

$$x_k = K f + \epsilon$$

Aim: recover *f* from a set of $\{x_k\}_k$

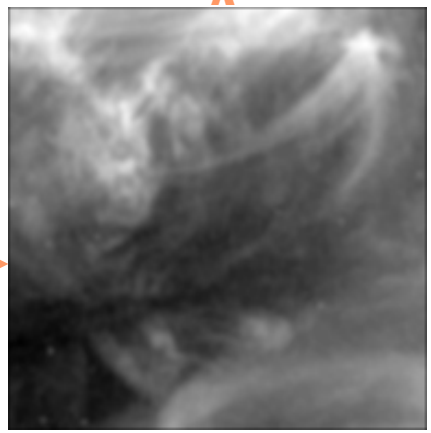
High resolution image *f*



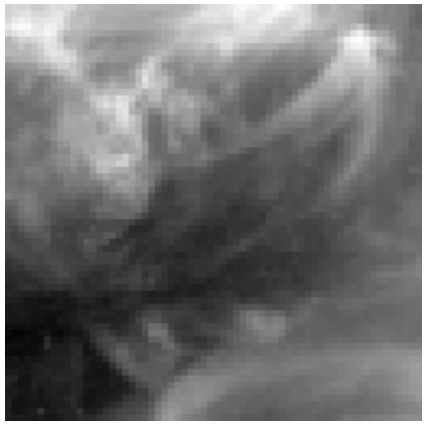


TRACE, 14 July 1998

Shift S_k blur *B*



Downsampling *D*



Low resolution, noisy observation x_k

Solve inverse problem : regularization with non-quadratic (L_1) constraints that promote sparsity

Daubechies et al ('04),
Figueiredo et al ('03)
Willett et al ('03)

- If no penalization term, iteration becomes

$$f^n = f^{n-1} + K^*(x - Kf^{n-1}) \quad ; \qquad K^* = \text{adjoint of } K$$

Landweber ('51) iteration, also known as Iterative Back-Propagation (IBP) in tomographic reconstruction

- With a L1-penalization term and an orthonormal basis (ONB) φ_γ, iteration becomes

1. Compute $f^+ := f^{n-1} + K^*(x - Kf^{n-1})$ as above
2. Compute $f_\gamma^+ := \langle f^+, \varphi_\gamma \rangle$, i.e. compute f^+ in the ONB φ_γ
3. Denoise by soft-thresholding f_γ^+: $f_\gamma^n = S_{w,1}(f_\gamma^+)$

Reconstruction methods

Choose a reference image

Register low-resolution (LR) images to reference image (find displacement)

L1-regularization

Initialization SR image

Correction of SR image using registration

Denoising of SR image

'Multiple interpolation'

Interpolate LR images on high resolution grid

Register each image onto one another using estimated translation

Sum registered images

Simplified version of Takeda et al '06

Registration of EUV solar images

- Data = projection on a 2D plane of a 3D object that is subject to differential rotation, and to a dynamics of its components

→ **shifts are not uniform** over the whole image

→Need a local method !

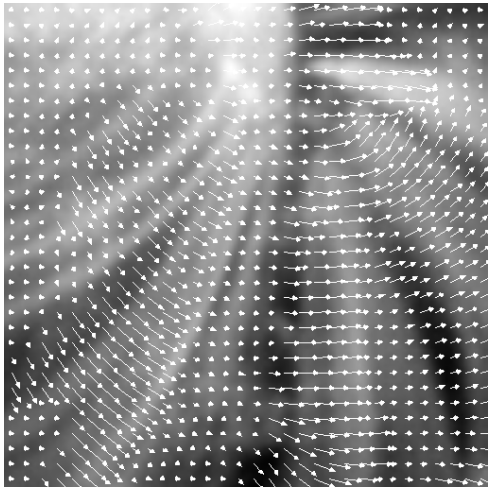
1. Use theoretical formula for differential rotation (when there is no offpoints)

2. Use optical flow estimation
Gissot et al '06, Corpetti et al '02

w(Φ) = angular speed

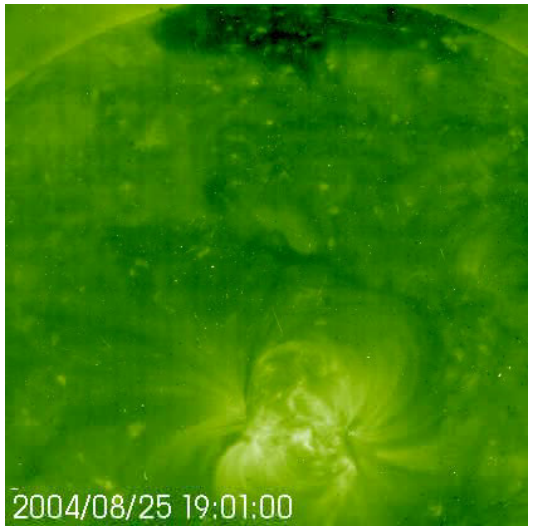
$$w(\phi) = a + b\sin^2(\phi) + c\sin^4(\phi)$$
$$\phi : \text{latitude}$$

a,b,c : instrument-dependent

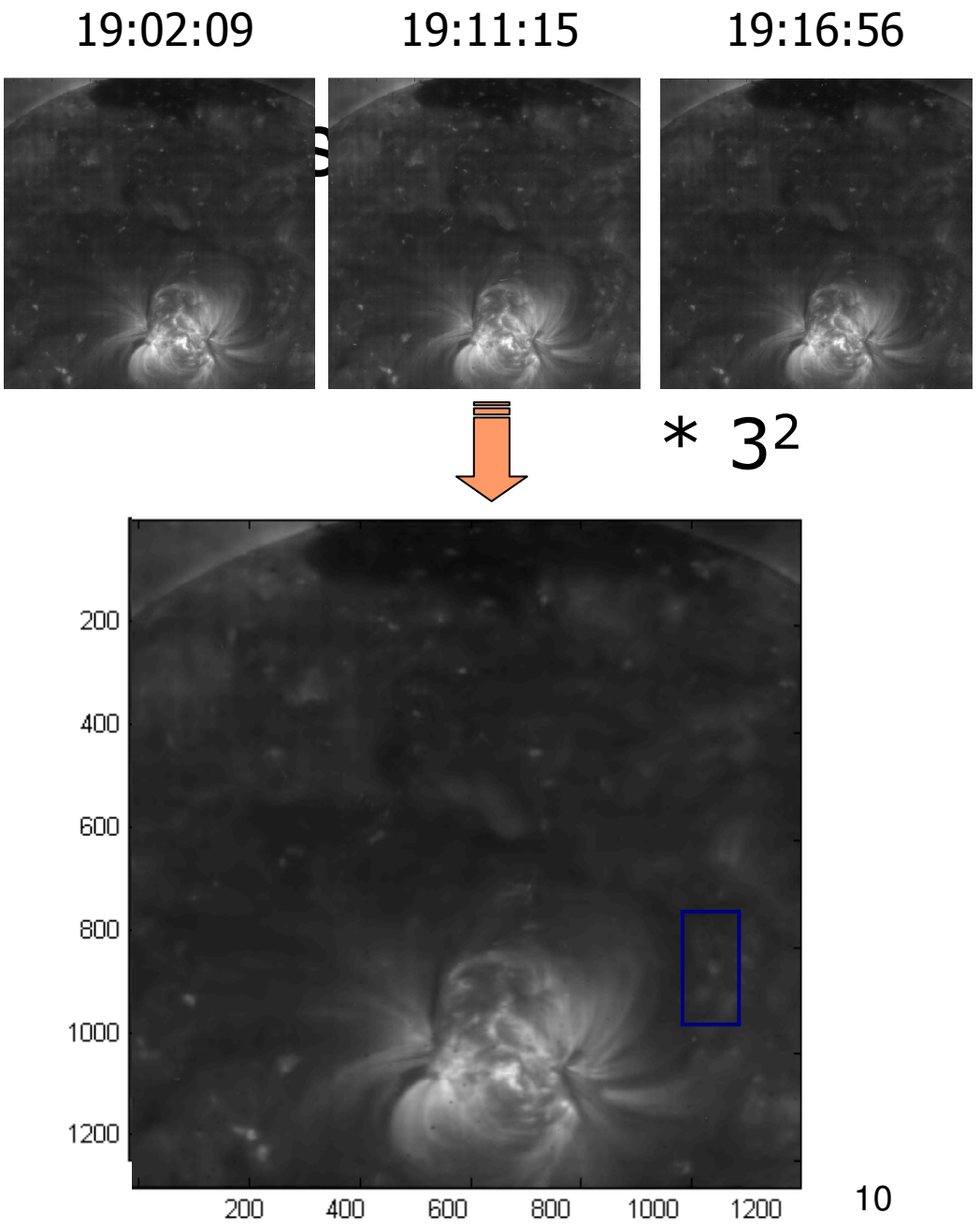


Results EIT

Analytical formula of *solar rotation* used to find displacement on EIT 195Å shutterless sequence

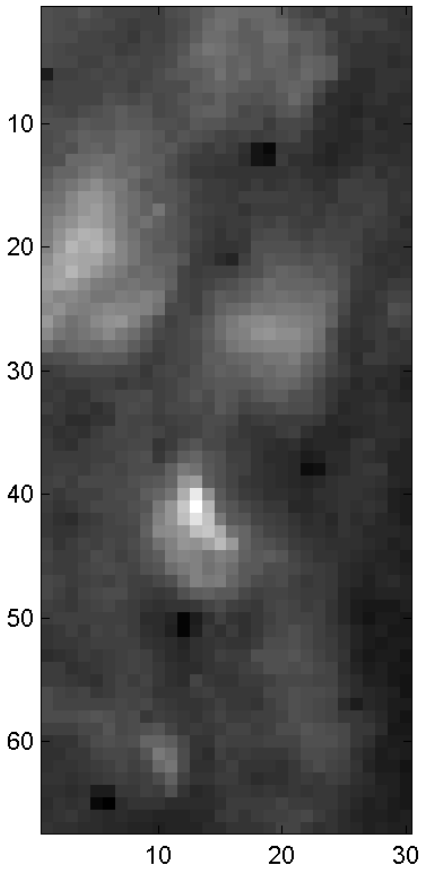


- ✓Gaussian errors
- ✓Mean filter to model blurring and down-sampling

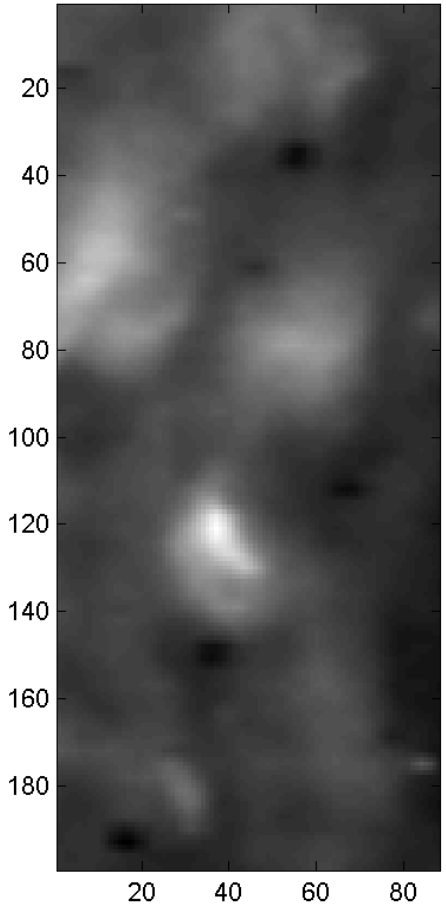


Multiple Interpolation vs regularized linear inverse problem

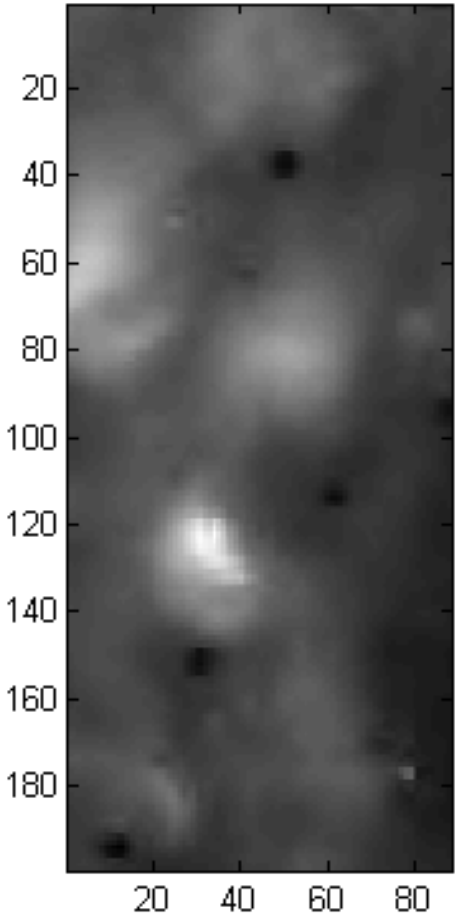
Original image



Sum interpol. images



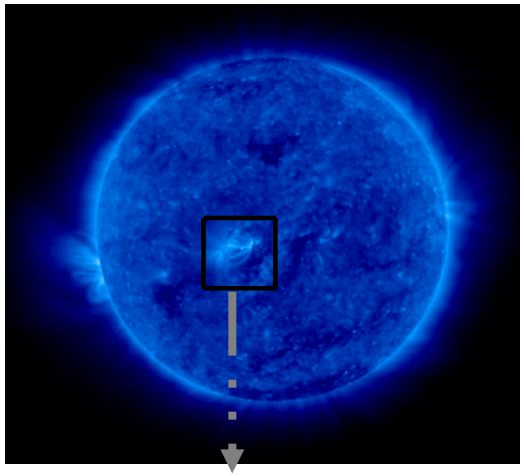
L1-regularization inverse pb



Interpolation & Inverse pb: smooth results (denoising effect)
Inverse problem : peaks seem better preserved

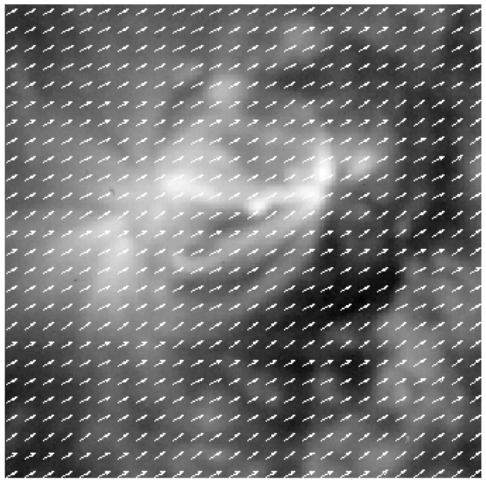
Results SECCHI, small scale offpoints

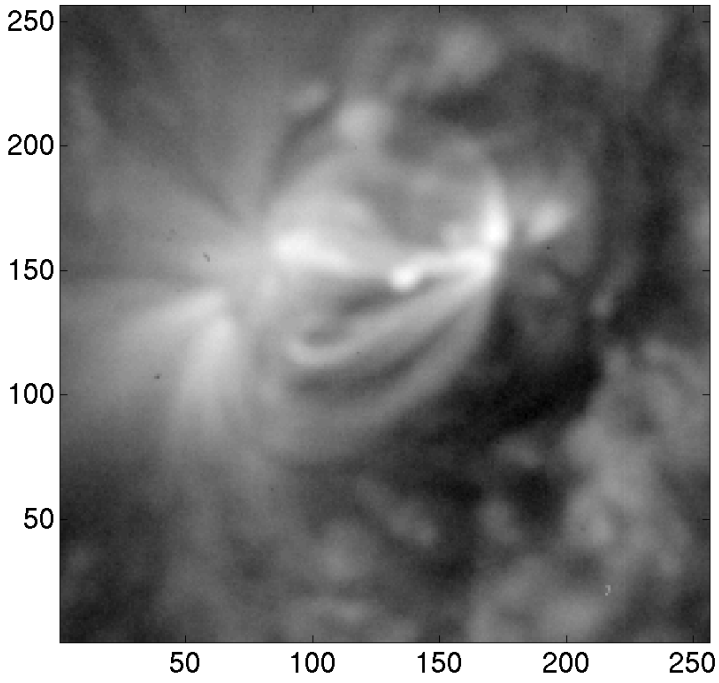
EUVI Ahead, 21 Feb 2007, 12h50



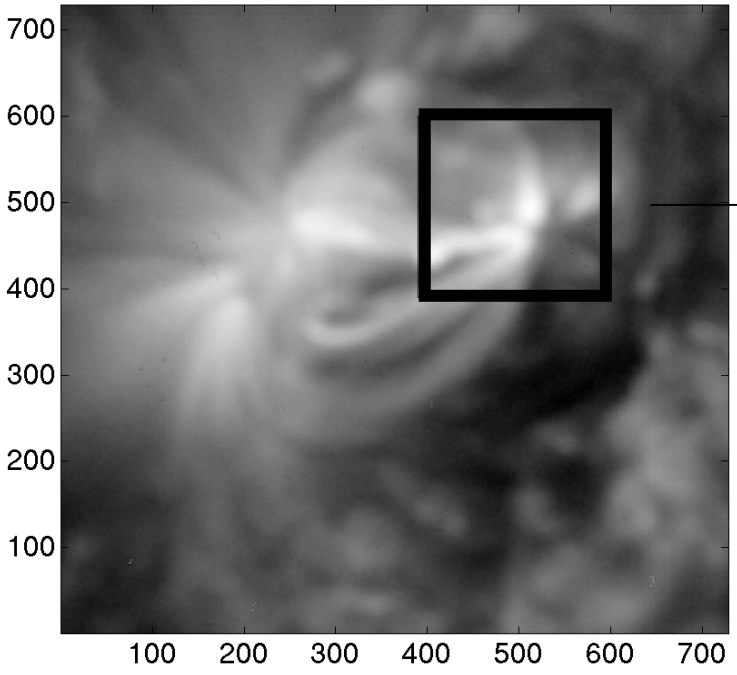
✓Images compressed using ICER7 (20x more than EIT)

✓Optical flow algorithm (Corpetti '02) for registration





$* 3^2$



Zoom

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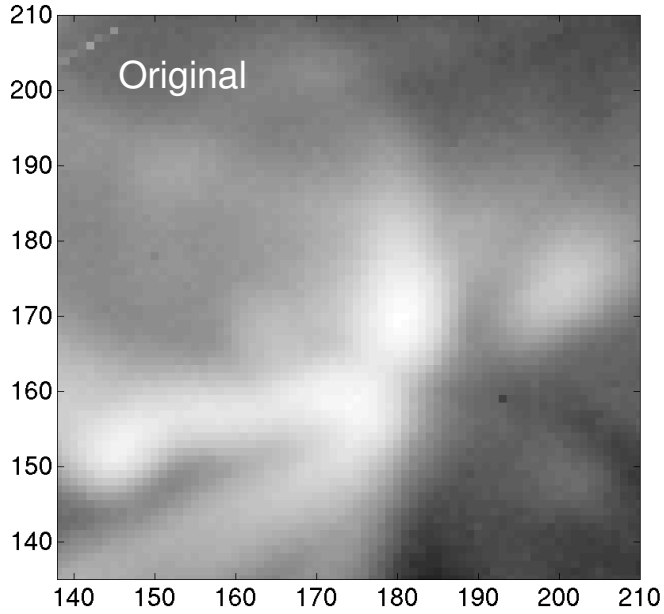
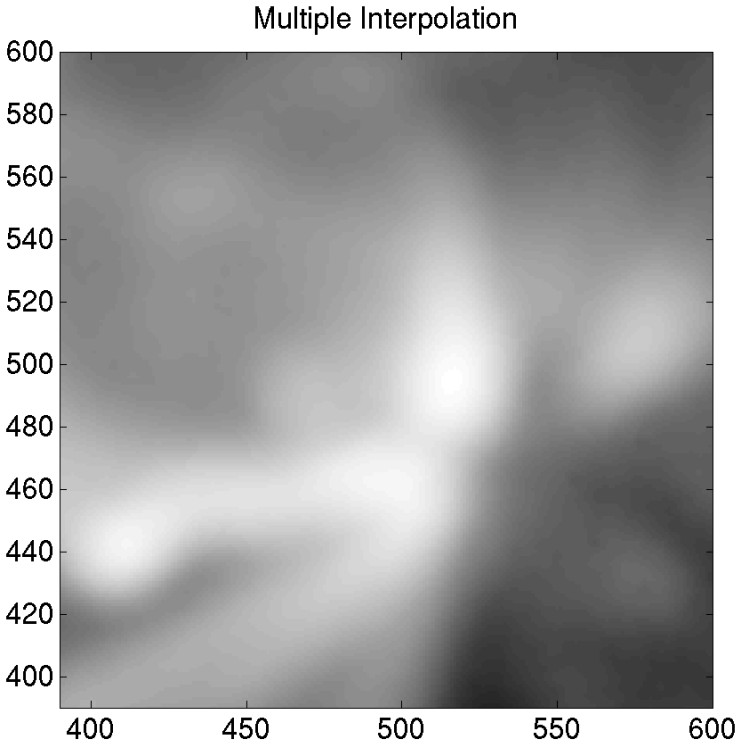
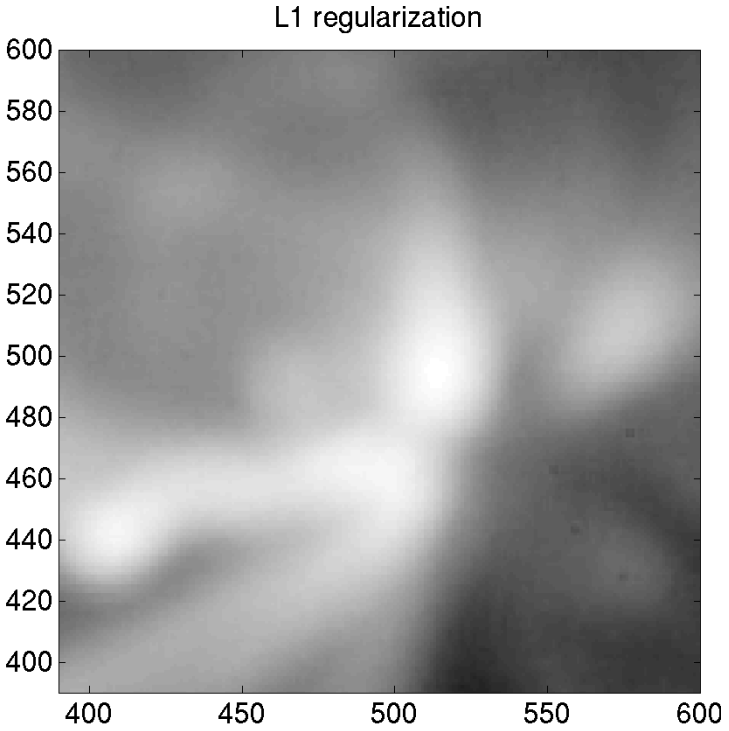
Multiple Interpolation vs regularized linear inverse problem

Smooth image: multiple interpolations and linear inverse problem give similar results







Conclusion

- Super-resolution possible for EUV images using sub-pixel displacements due to
  - solar rotation (need fast enough cadence)
  - small-scale offpoints (need hardware-manipulation, e.g. movement of the mirrors in the telescope)
- Registration must find local displacements, not a global one
- Limits of super-resolution
  - Effective magnification factor for least-square-based method
    - Theory: 5.7
    - If the denoising or registration part is not good enough: 1.6
  - M^2 images are sufficient for a magnification factor M

(Ref: Z. Lin, H-Y. Shum, IEEE Trans. PAMI, 2004)