Measurement and Interpretation of X-ray Visibilities with RHESSI

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INTRODUCTION

- RHESSI uses 9 rotating modulation collimators (RMCs) to image solar flares at x-ray and gamma-ray energies.
- Each RMC consists of a pair of widely separated grids with equal, parallel slits in front of a detector.
- As the spacecraft rotates, imaging information is encoded as rapid time-variations of the detected flux.
- This poster describes two new approaches to converting the modulated time profiles to images.

SUMMARY

- Stacking data using spacecraft roll angle and 'aspect phase' makes long data sets equivalent to a single rotation.
- Stacking has significant advantages for imaging, and enables the calculation of visibilities.
- Visibilities are direct, calibrated measurements of specific Fourier components of the source spatial structure.
- They provide a powerful intermediate data product and a alternative starting point for image reconstruction.

DATA STACKING

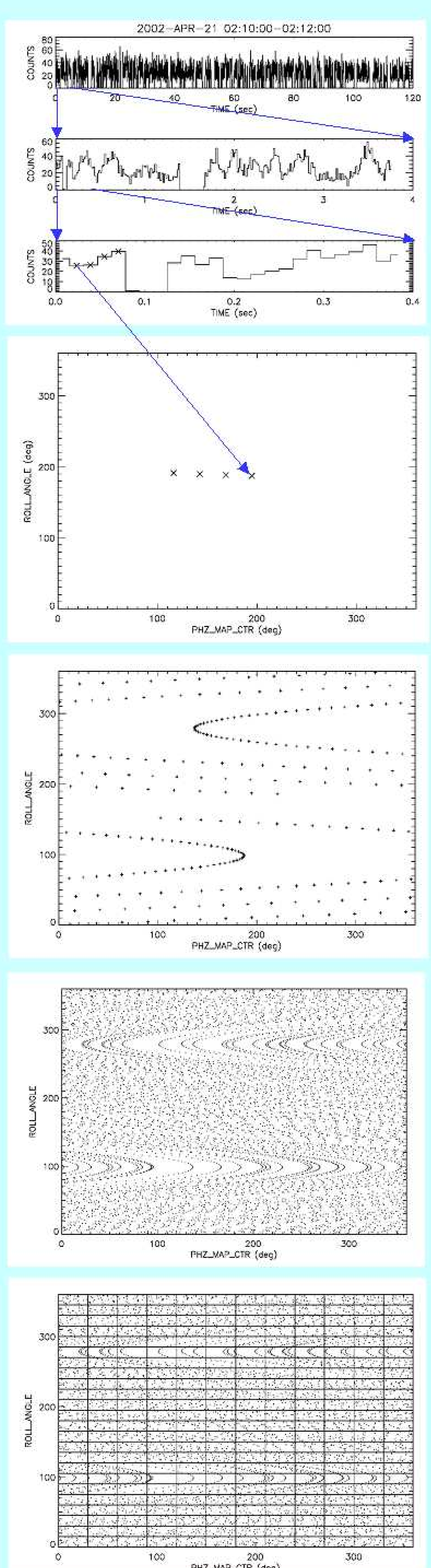
WHAT IS IT ?

- **Data stacking is an adaptation of superimposed epoch analysis that makes RHESSI data from multiple rotations equivalent to that from a single rotation.**
- Since spacecraft pointing variations makes the modulated light curves different in each 4 second rotation, simply averaging count rates from subsequent rotations does not usually work.
- Instead of superimposing data on the basis of *time*, data are combined on the basis of spacecraft *roll angle* and '*aspect phase*' (the component of pointing direction orthogonal to the grid slits).

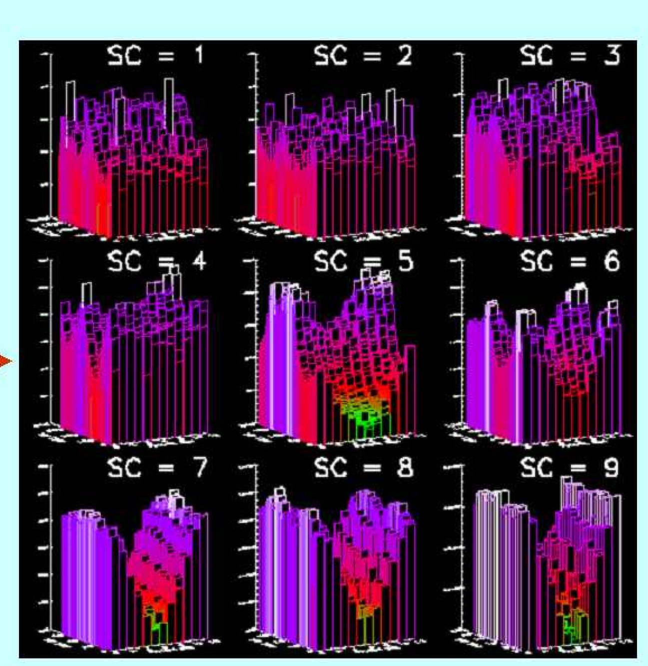
ADVANTAGES

- Improves image quality by eliminating statistical issues associated with large numbers (>>10^5) of sparsely populated time bins.
- Helps with background and flare-variability issues
- Improves imaging speed
- Makes long integrations possible (10's of minutes to days)
- Opens the way to using visibilities…..

Mapping time bins to roll/phase bins



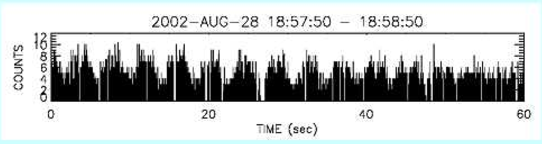
- RHESSI counts are binned into a large number of very short time bins.
- Top panel shows typical observed counts for a single RMC binned into 16 ms time bins and shown for 2 minute, 4 second and 0.4 second intervals.
- Each time bin is associated with the roll angle and 'aspect phase' which is shown in the 2nd panel as a point in a roll/phase diagram.
- The sequence of roll/phase points for a single rotation is shown in the 3rd panel. In some cases, the roll/phase plane is thinly sampled.
- Inclusion of many rotations provides a much more complete set of roll/phase points (4th panel). This is due to random variations in spacecraft pointing.
- Roll-phase points are grouped into 32x12 roll/phase bins in the 5th panel.
- The live time and observed counts in the original time bins are accumulated in these roll/phase bins.



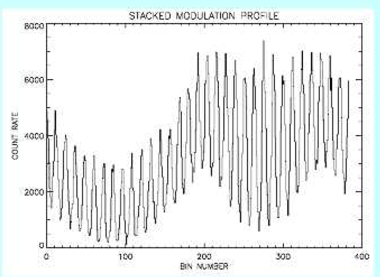
Typical plot of count rates as a function of roll/phase bin for all 9 subcollimators.

Stacking converts

One minute of data for subcollimator 3 accumulated in 60000 sparsely-populated 1 ms time bins.



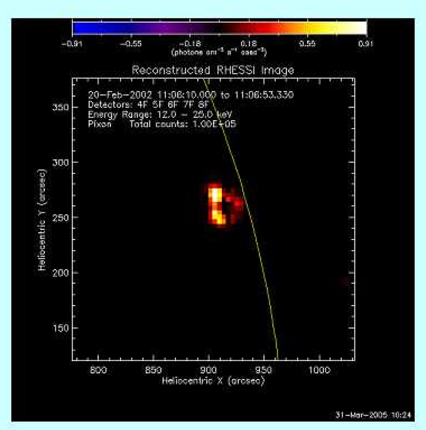
to

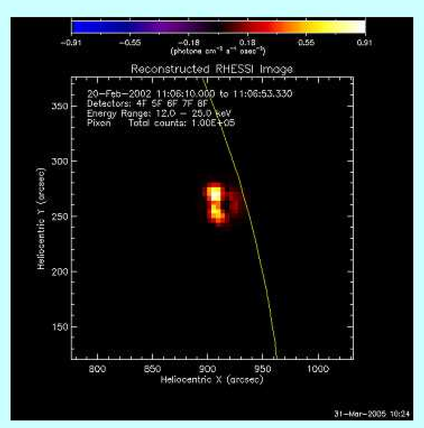


The same data summed into 288 roll/phase bins, shown as a linear raster in aspect phase, then roll angle.

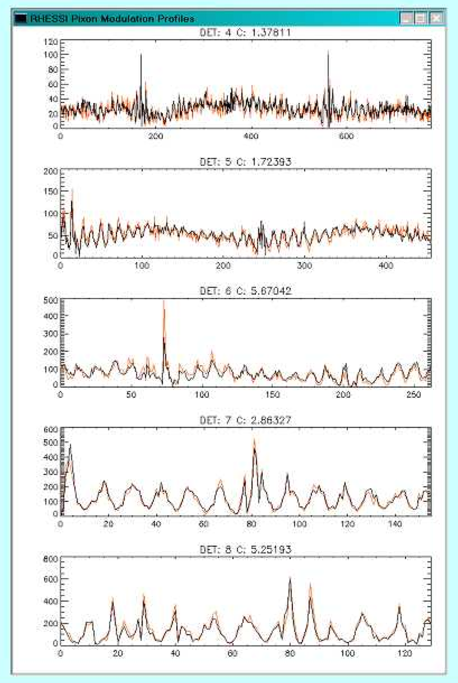
with no loss of imaging information

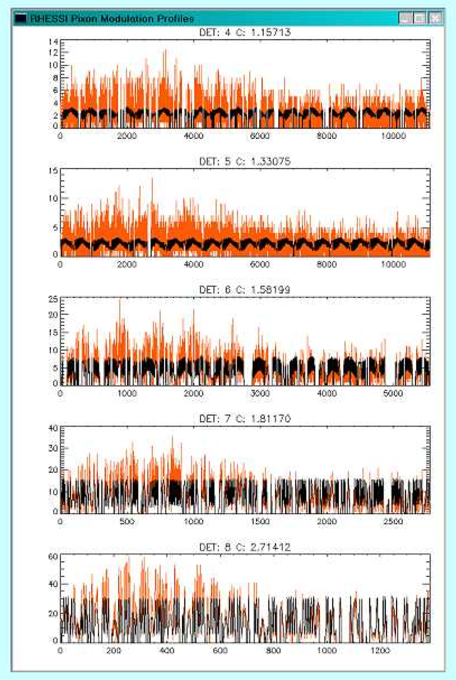
Imaging with stacked data





- A pixon image made from stacked counts (left) is seen to be equivalent to the corresponding image made from time-binned data (right).
- The figures below show how well the count rate predictions (black) from the reconstructed image fit the observed counts (red). The stacked data (left) enable the user to better understand the quality of the fit.





VISIBILITIES

WHAT ARE THEY ?

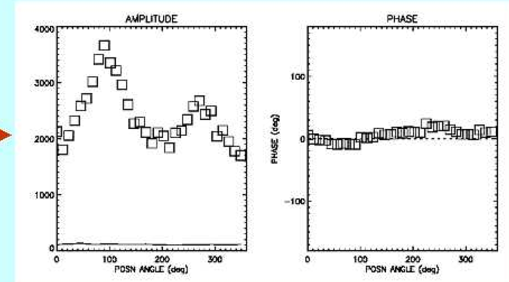
Visibilities are calibrated measurements of Fourier components of the source distribution.

- They are measured at specific spatial frequencies, whose magnitude is 1 / (the angular resolution of the collimator) and whose direction is perpendicular to the grid slits.
- Visibilities represent a compact, noise-free transformation of the input imaging data, containing all the information required for image reconstruction.
- Visibilities are complex numbers with amplitude and phase.
- **Visibilities are also the fundamental input to imaging with radio interferometry, where they are measured by correlating signals from widely separated antennas.**

PROPERTIES

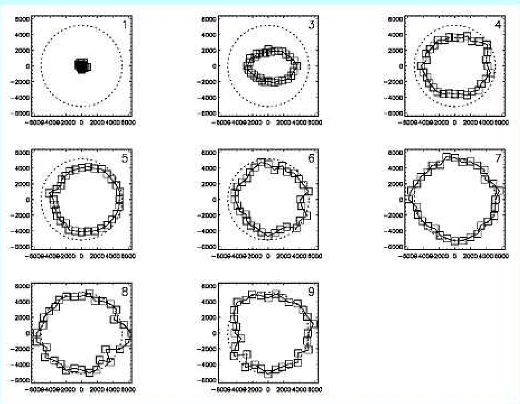
- **Visibilities depend *linearly* on the source and measured data.**
  - ➔ The visibility of a multicomponent source = vector sum of the corresponding visibilities of its components
  - ➔ Can add or subtract visibilities at different energy bands
  - ➔ Can add or subtract visibilities as a function of time
  - ➔ Can weight data in energy and/or time
- **RHESSI visibilities provide redundant information, independent of source morphology.**
  - Correctly calibrated visibilities measured at opposite position angles *must* have equal amplitudes and opposite phases.
  - Visibilities measured by the 3rd harmonic of grid n must equal the visibility measured by the fundamental of grid n-2.

How are they measured by RHESSI ?

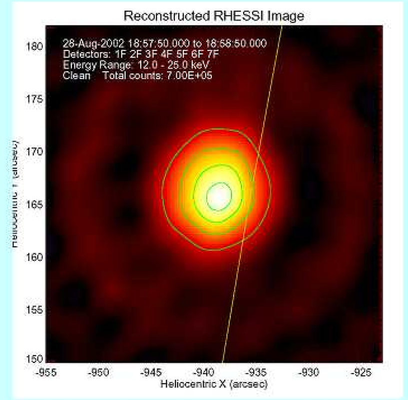


Measured visibility amplitude and phase for subcollimator 3 as a function of heliographic position angle. (The statistical error in amplitude is shown as the light line at the bottom.)

- Starting from stacked events, count rates in each roll bin are fit with a sinusoid plus offset.
- The calibrated visibility is the amplitude & phase of the sinusoidal fit, after normalization for grid transmission, modulation and detector efficiency.



Visibility amplitude as a function of grid position angle, shown as polar plots for subcollimators with FWHM resolutions ranging from 2.3 to 183 arcsec.

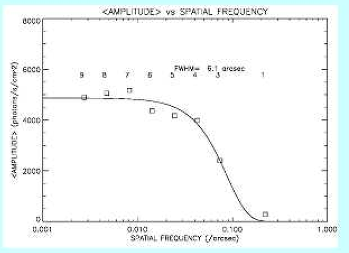


Source map corresponding to the data shown at left, below and at right. (30,50,70,90% contours)

APPLICATIONS

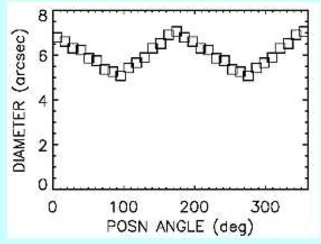
- By combining visibilities as a function of energy
  - Enables mapping in the 7 keV iron line (suppresses continuum)
  - Enables mapping of the sum of nuclear lines
  - Enables mapping in terms of photon energy, not detected energy.
  - Enables separate mapping of nuclear and electron components of the gamma ray continuum.
  - Enables improved pileup corrections for hard x-ray images.
- By combining visibilities as a function of time and/or energy
  - Enhances statistical sensitivity by enabling data weighting
- Provides a compact starting point for imaging algorithms
  - Useful for iterative processing
  - Enables use of highly developed image reconstruction packages developed for radio interferometry
  - Improves χ^2 sensitivity in mapping algorithms.
- Can accurately determine source parameters (e.g. diameter, ellipticity, source separation) without algorithm-dependent mapping.
- Redundancies provide a sensitive tool for self calibration of grid parameters

Source size and shape example



For a circularly symmetric source, the amplitude as a function of spatial frequency depends on the source diameter.

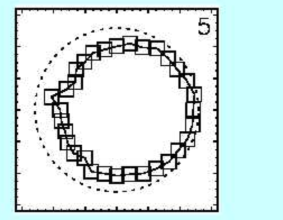
In this case, a gaussian fit yields an average diameter of 6.1 arcseconds.



Visibilities enable the FWHM diameter to be determined independently at each position angle.

The ellipticity of the source, only weakly suggested by the image, is well determined by the visibility analysis.

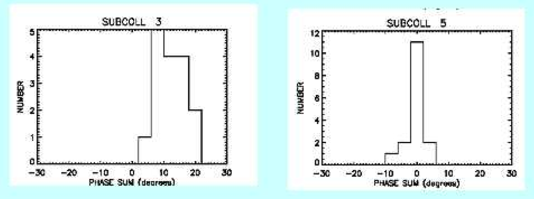
Self calibration examples



Polar plot of amplitudes for subcollimator 5.

Independent of source morphology, the amplitudes should be identical at opposite position angles.

The obvious offset is an indicator of a small (~arcminutes) error in the current grid tilt calibration.



Histograms of phase sums for opposite position angles for grids 3 and 5. Independent of source morphology, the phases should have opposite signs at opposite position angles. This is true for grid 5 (right) but for grid 3 (left), the 12.5+-1.2 degree offset corresponds to a 1.8 +- 0.2 micron error in grid phase calibration (=0.24 arcsec).