Computing challenges in Coded Mask Imaging

Gerry Skinner

The Coded Mask Technique

is the worst possible way of making a telescope

Except when you can’t do anything better!

• Wide fields of view
• Energies too high for focusing, or too low for Compton/Tracking detector techniques
• Very good angular resolution

1) The simplist’s approach to weighing 3 objects

A

B

C

wa ±δ

wb ±δ

wc ±δ

2) Weighing of 3 objects by a member of the Club of the Difficult Approach

A

B

C

A = (wa + wc - wb)/2 ± 0.85 δ

B = (wb + wc - wa)/2 ± 0.85 δ

C = (-wa + wb + wc)/2 ± 0.85 δ
### Position sensitive detectors for coded mask telescopes

<table>
<thead>
<tr>
<th>Detector Technology</th>
<th>Energy Range (keV)</th>
<th>Example</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>JEM-X</td>
<td>5-100</td>
<td>HETE-2</td>
<td></td>
</tr>
<tr>
<td>IBIS</td>
<td>15-10000</td>
<td>770 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>dia</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>thick</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>tungsten</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resolution: 2.5 arc min</td>
<td></td>
</tr>
</tbody>
</table>

**The Coded Masks for Integral**

### The Point Source Response Function

Blurring can always be removed by image processing, but:

1. Deblurring is always done at the expense of noise.
2. For a coded mask telescope, every point in the image is affected by the noise from the whole detector plane.
How to recover an image

Basic method:

Correlation with the Mask Pattern

Recorded pattern is convolution of source distribution and the mask pattern, plus some background \( B \)

\[ D = S \otimes M + B \]

Suppose we form an image as

\[ I = M \otimes D = M \otimes (S \otimes M + MB) = M \otimes M \otimes S + MB \]

where ACF indicated the autocorrelation function.

If ACF(M) were a Delta function and if \( MB \) were zero

we would have recovered \( S \).

'Optimum coded' designs or 'URAs' (Uniformly Redundant Arrays)

Certain patterns have the properties:

i) Their DISCRETE, CYCLIC autocorrelation function is indeed a Delta function, PLUS A FLAT LEVEL.

ii) For uniform background, \( M \otimes B \) is not zero, but it is at least FLAT.

If you can:

- Arrange that coding is cyclic
- Use binned (discrete) arrays
- Be prepared to subtract a DC level

Then this is just what is needed

Some aspects of real systems

- Non cyclic
- Mask Closed element absorption
- Mask Open element transparency
- Mask Element Thickness
- Obstructions in Mask Plane
- Detector finite pixel resolution
- Detector efficiency non-uniformities
- Detector response dependent on off-axis angle
- Detector background non-uniform
- Gaps in the detector plane
- Dead/inactive pixels in the detector plane
- Shielding (collimation) imperfect
- Obstructions between detector and mask
- Leaks onto detector from far outside the fov

Imaginary

(More) real
**Correlation with the Mask Pattern used with Real (Imperfect) Coded Mask Telescopes**

Correlation methods are often used even for real, imperfect, non-optimum, systems based.

- It is can be fast, taking advantage of Fast Fourier Transforms
- It always gives some sort of an image, even for non-ideal systems
- For a single point source it yields the best possible sensitivity (smallest uncertainty on the intensity estimate)

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**The realities lead to**

- Ghosts/Sidelobes
  - (simple approach to reconstruction)
- Additional noise
- Interpixel correlations

Fortunately coded mask telescopes are not very sensitive!

- 100% detection, 5% ghosts - important
- 5% detection, 10% ghosts - who cares?

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**Patching-up the Correlation approach**

Handle non-cyclic systems by extending arrays
Substitute estimates based on means for missing data
Correct for background variations
Correct for sensitivity variations
etc, etc

Iterative removal of sources (IRSOs)

- Assume all sources are pointlike
- Identify the brightest one using a correlation map
- Fit the source position and subtract the data predicted for that source taking into account all the effects in the REAL system
- Form a correlation map from the residuals
Coded Mask Telescopes - Matrix Approach

One wants to obtain the intensity of the sky in each of \(M\) 'pixels':

\[ S_p, S_1, S_2, \ldots, S_{M-1}, \]

One measures \(N\) linear combinations of the \(S_p\):

\[ D_i = \sum_{j=0}^{N-1} h_{ij} S_j \quad (i = 0, N-1) \]

Objective - given the \(D_i\), deduce the \(S_j\).

If \(M=N\), in principle, it's easy. Using matrices we can write:

\[
\begin{bmatrix}
D_0 \\
D_1 \\
\vdots \\
D_{N-1}
\end{bmatrix} =
\begin{bmatrix}
h_{00} & h_{01} & \cdots & h_{0M-1} \\
h_{10} & h_{11} & \cdots & h_{1M-1} \\
\vdots & \vdots & \ddots & \vdots \\
h_{N-1,0} & h_{N-1,1} & \cdots & h_{N-1,M-1}
\end{bmatrix}
\begin{bmatrix}
S_0 \\
S_1 \\
\vdots \\
S_{M-1}
\end{bmatrix}
\]

\[ [D] = [H][S] \]

Matrix approach - the case of \(M>N\)

\(i.e.\) fewer measurements than Sky pixels

This is the usual situation if you make a simple staring observation

(More sky pixels than independent detector positions = unknowns associated with detector background)

An under-determined problem

Solution - fit different masks and make an observation through each

or (more practicable) make more observations with offset pointing directions

\(\Rightarrow\) OVER determined problem \(\Rightarrow\) Use Moore-Penrose Generalised Inverse

Minimising Noise Amplification

* In good signal-to-noise data a (generalised) inverse matrix approach allows for all instrumental effects and removes ghosts
  - but it adds noise

* In low signal-to-noise cases, a matrix method equivalent to the correlation approach minimises the effects of noise
  - but it adds noise

* Minimum Error Matrix Methods
  - provide the optimum compromise between the two

Other approaches to image reconstruction

* Maximum Entropy
  - Allows all instrumental effects to be taken into account and finds image which is consistent with the data which has no information which is not 'required' by the data
  - Iterative - each iteration uses a correlation to find how image should be modified

* Back Projection
  - If all exposure and coding efficiency effects are taken into account Equivalent to correlation methods
  - Fast for few photons (bursts)
The scale of the problem

<table>
<thead>
<tr>
<th>Measure</th>
<th>OJ/laa</th>
<th>IBIS-TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector pixels per pointing</td>
<td>19</td>
<td>10^2</td>
</tr>
<tr>
<td>Pointings</td>
<td>25</td>
<td>10^2</td>
</tr>
<tr>
<td>Total</td>
<td>M</td>
<td>10^6</td>
</tr>
<tr>
<td>Sky pixels</td>
<td>400</td>
<td>10^2</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>100</td>
<td>10^2</td>
</tr>
<tr>
<td>Total</td>
<td>M</td>
<td>10^6</td>
</tr>
<tr>
<td>Unknowns</td>
<td>N</td>
<td>10^6</td>
</tr>
</tbody>
</table>

Number of operations

<table>
<thead>
<tr>
<th>Method/Approach</th>
<th>Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME Matrix Approach</td>
<td></td>
</tr>
<tr>
<td>To invert matrix (brute force)</td>
<td>6 * 10^12</td>
</tr>
<tr>
<td>To invert matrix (iterative)</td>
<td>10^8</td>
</tr>
<tr>
<td>To multiply by the matrix</td>
<td>5 * 10^2</td>
</tr>
<tr>
<td>Correlation Approach</td>
<td></td>
</tr>
<tr>
<td>Matrix multiplication</td>
<td>2 * 10^6</td>
</tr>
<tr>
<td>FFT</td>
<td>2 * 10^2</td>
</tr>
<tr>
<td>Back Projection</td>
<td>M N</td>
</tr>
</tbody>
</table>

Extracting Spectra

So far haven't considered spectra

- Can divide events into pulse height bins and do all of the above for each bin

- Or identify sources, then solve best fit intensity in each pulse height bin

In either case, end up with a spectrum in a new observation space.

Then take out the effects of the combined 'hardware + software instrument', using a response matrix describing that pseudo-instrument, plus standard model fitting techniques.

Point Source Positioning Accuracy

Suppose the telescope length is \( l \) and the mask pixel size is \( m \).

- Ignoring the effects of detector resolution the angular resolution would be \( \frac{m}{l} \).
- But the detector resolution blurs the mask pattern.
  
  \[ \theta = \frac{(m^2 + d^2)^{1/2}}{l} \]

But sources can be positioned with better accuracy than this.

- A guideline is that the point source position uncertainty is about \( \frac{\theta}{n \alpha} \), where the source is detected with significance \( n \alpha \)
  
  \[ \Delta = \frac{(m^2 + d^2)^{1/2}}{n \alpha l} \]

Point Source Sensitivity

Ignoring the effects of detector resolution, and assuming 50% mask transparency the significance of detection of a point source (its flux, divided by the noise) is approximately:

\[ n \alpha = \frac{N_{PE}}{(N_{PE} + N_{BC})^{1/2}} \]

where \( N_{PE} \) is the number of photons detected from the source and \( N_{BC} \) is the total number of events in the detector.

- But finite detector resolution reduces significance by a factor \[ \text{Max} \left( 1 - \frac{d}{3m}, \frac{(m^2 + d^2)^{1/2}}{l} \right) \]

Why bad resolution is good

- The angular resolution of SPI could have been better!

So why didn't it made better?

- Surely it would be advantageous for studying point sources and for studying diffuse emission you can always combine pixels together to have the equivalent of a lower resolution instrument

Answer - you can combine pixels, but for diffuse sources you lose compared with an observation made with a lower resolution instrument.
**Conclusions**

- Coded mask Imaging will never be able to compete with focusing systems using lenses or grazing incidence mirrors in circumstances where those can be used.
- It is a well studied and well understood technique which has already led to important discoveries.
- It is likely to continue to play a valuable role in circumstances where other techniques can be used.

**Imaging requirements**

- Image reconstruction while continuously scanning
- Automatic detection of gamma-ray bursts and new transients
  - On board
  - Rapid
  - Precise location
- Short Bursts ( < a few seconds)
  - Detection in time domain (rate increase)
  - Imaging to find location
- Long Bursts/Transients
  - Detection by differencing images

**New generations of space-qualified processors**

- Tilera 'Opera' (due to be used on the MESTRO mission in 2010)
- Coherent Logic's Hyper-X (due for flight on MISSSE-7 in Nov 2009)

-1000x the 21020 DSP processor used for BAT image reconstruction
When can you use an FFT?
when the pattern with which you want to correlate the data pattern are simply (subsets of) shifts of the same pattern.

- Thin, parallel mask: FFT OK
- Thick mask: FFT approximate
- Tilted mask: FFT not useful

Mask Autocollimation - another hurdle to overcome
- Wide field of view + limited diameter → short mask-detector separation
- Good angular resolution + short mask-detector separation → small mask elements
- High energy response → thick mask
- Thick mask + small mask elements → narrow field of view

One of the instrument concepts rejected partly because of the difficulty of on-orbit image reconstruction.

History of EXIST

AMCS Proposal
- Thin, parallel mask: FFT OK
- Thick mask: FFT approximate
- Tilted mask: FFT not useful

SimDD or Drum (severe constraint on mask supports)
- Symmetric (small FoV)
- Even with hybrid mask

Twister02
- Thick mask: FFT OK
- Tilted mask: FFT approximate
- Tilted mask: FFT not useful

Symone (small FoV)
- Wide field of view
- Narrow field of view

Pl/Sr/Cu Side shield
- Narrow field of view
- Small mask elements

CET Detector Plate (DP: 0.53m²)

Twister02 (occultation btw sub-tels)
Symone (small FoV)

Transmission through Tungsten Mask

1. Bin the data into coarse detector bins, correcting for mean shadow motion (i.e. Time Domain Integration, TDI)
2. Predict the response for each known bright source in the field of view; fit for the intensity of the source; subtract from the binned data array
3. Reconstruct a coarse image by FFT
4. Search the image for possibly significant points, using a low threshold (e.g. $N_{\sigma_1} = 3.9$)
5. For each possibly significant point, make full resolution local images around the location by back projection, using detailed mask information and spacecraft attitude at the time of arrival of the photon
6. Optional subtraction of a reference image
7. If there is a peak greater than a higher threshold (e.g. $N_{\sigma_2} = 7.2$) in one of these local images is considered a valid trigger

<table>
<thead>
<tr>
<th>Step</th>
<th>Operations</th>
<th>Threshold</th>
<th>False Trigger Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$7 \times 10^9$ (FFT)</td>
<td>$7.2\sigma$</td>
<td>$3 \times 10^{-13}$ per pixel per image</td>
</tr>
<tr>
<td></td>
<td>$1.5 \times 10^9$ (Back proj)</td>
<td></td>
<td>$6 \times 10^{-4}$ per image</td>
</tr>
<tr>
<td></td>
<td>$2.2 \times 10^9$ (Total)</td>
<td></td>
<td>0.5 per day</td>
</tr>
<tr>
<td>2</td>
<td>$3 \times 10^{-13}$ per pixel per image</td>
<td>$3.9\sigma$ (stage 1)</td>
<td>$10$ per image (stage 1)</td>
</tr>
<tr>
<td></td>
<td>$7.2\sigma$ (stage 2)</td>
<td></td>
<td>$0.5$ per day (stage 2)</td>
</tr>
</tbody>
</table>

Conclusions

A major aspect of EXIT will be a sort of 'super-Swift'
The HET will be the equivalent of Swift/BAT
HET will have 12 million detector pixels in place of BATs 32768

Despite this increase the on-board computing can be handled thanks to new generation processors, a hybrid mask, and 2-stage image processing / event detection
1. If the time range exceeds that for which TDI is possible, divide the data into sub-periods.
2. For each sub-period
   1. Bin the data into coarse detector bins, correcting for mean shadow motion (e TDI).
   2. Predict the response for each known bright source in the field of view; fit for the intensity of the source; subtract from the binned data array.
   3. Reconstruct a coarse image by FFT.
   3. If there are multiple sub-periods, overlay and combine the images.
   4. Search the image for possibly significant points, using a low threshold ($N_{\sigma 1}$)
   5. For each possibly significant point, make full resolution local images around the location by back projection, using detailed mask information and spacecraft attitude at the time of arrival of the photon.
   6. Optional subtraction of a reference image.
   7. If there is a peak greater than a higher threshold ($N_{\sigma 2}$) in one of these local images is considered a valid trigger.

The EXIST Mission Overview
- A Multi-wavelength Observatory to probe the early Universe through high-z GRBs, survey all scales of BHs and monitor the Transient X-ray sky.
- **High Energy Telescope (HET):**
  1. Wide-field coded-aperture hard X-ray imaging telescope with 4.5m^2 CIT (5-100 keV)
  2. Optical/Infrared Telescope (IRT):
     1. 1.1m visible-IR telescope with HyViSi and Howl282G for both Imaging and spectroscopy (0.3-2.2 µm)
     2. Soft X-ray Image (SXI): 0.6m X-ray telescope with CCD (0.1-10 keV)
- Contributed by Italy/ASI
- EXIST operates 2 yr of scanning sky (similar to Fermi) and 3 yr of follow-up observations (similar to Swift); Immediate follow-up on GRBs and Transients throughout the mission.

Science Goal: high-z GRBs as Cosmic Probe
- $z = 8.2 \pm 0.5$ Myr after the Big Bang
- 4.6% of the current age of the Universe

Science Goal: high-z GRBs as Cosmic Probe
- Rapid follow-up for onboard optical/infrared imaging and spectroscopy

How does EXIST operate?
- HET scans sky at orbital rate with zenith (~30°) pointing; covers sky every 2 orbits.
- Imaging in RF FoV detects GRB or variable AGN or transient, locates it to ~20°.
- Spacecraft slews to bring the location within the FoV of the SXI and HET.
- Typically SXI identifies corresponding X-ray source and positions it to ~2".
- HET places corresponding object on all for spectroscopy if bright enough, or in field for low-resolution spectroscopy. Performs 4 band photometry in all cases. If no XRT target, studies all objects in HET error circle in turn. On-board photometric redshift.
- Follow-up pointing during following 1-2 orbits to make detailed SXI/HET observations of afterglow, light curve of transient, etc. HET continues survey.

GRB 090423: $z \sim 8.26$ (Tanvir et al. 2009)

Gemini-N NIRI

Science Goal: high-z GRBs as Cosmic Probe

How does EXIST operate?
Primary Science Objectives for EXIST
Survey and Study Black Holes on all scales
- stellar to supermassive
• Measure the birth of stellar black holes from cosmic gamma-ray bursts to prompt redshifts, constrain GRB physics and enable GRBs as probes of cosmic structure & reionization of redshifts $z > 7 - 10$
• Identify supermassive BHs in galaxies, whether obscured or dormant, to constrain SMBH properties, their role in galaxy evolution and the origin of the CXB, and accretion luminosity of the universe
• Measure the stellar and intermediate mass BH populations in the Galaxy and Local Group by a generalized survey for which prompt IDs and X-ray/IR spectra distinguish SNe, SGRs & Blazars and complement Fermi, JWST, LSST, USA with prompt alerts for unique objects

Major Factors for Instrument Design
• Sensitivity ($< 0.10$ mCrab in 1yr) ► $~ 4.5$ m$^2$ CZT
• GRB coverage ($> 600$ GRBs) ► Wide FoV ($70 \times 90$)
• High Z GRB redshift onboard ► $1.1$ m Optical/IR Telescope (1.5m dia envelope)
• Angular Resolution ($2.6'$) localization ($< 20'$ for 5) ► 1.25mm fine mask pixel
• 1M (600 km, $1^2$) ► 0.6mm det. pixel
• Mission Cost ($~ $0.8Ð1.2B) 3.7m dia x 5.2m envelope )

The HET Concept Overview
Wide-field Coded-Aperture Hard X-ray Imaging Telescope with 4.5m$^2$ CZT (5 Ð 600 keV)

The EXIST Survey Sensitivity
$\sim 1$ yr, 5 sigma

How do we avoid systematic noise becoming important when the statistical (Poisson) noise is reduced by combining data to build up long integration times?

Scanning

How can we be confident that this has the desired effect?

1) Analysis
2) Monte Carlo simulations
3) Experience with Swift
Components:

- **CBE (W)**
- **HET Total 716**
- **EX-ASIC (20W/pix, 1.5M pixels) 231**
- The rest of FEE & BEE 485
- **IRT Total 165**
- **SXI Total 149**
- **Spacecraft + Payload Common 1663**
- **Total 2803**

ASIC Road Map

<table>
<thead>
<tr>
<th>Type</th>
<th>Channels</th>
<th>Matching Pixel Size</th>
<th>Power (W/phot)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADNAT</td>
<td>1-2 64</td>
<td>3.5 mm</td>
<td>70</td>
<td>ProtoEXIST, 2009</td>
</tr>
<tr>
<td>DB-ASIC</td>
<td>2-3 1284</td>
<td>0.6 mm</td>
<td>60</td>
<td>ProtoEXIST, 2010</td>
</tr>
<tr>
<td>EX-ASIC</td>
<td>2-3 1284</td>
<td>0.6 mm</td>
<td>50</td>
<td>ProtoEXIST, 2011</td>
</tr>
<tr>
<td>BFE-ASIC</td>
<td>2-3 1284</td>
<td>0.6 mm</td>
<td>110</td>
<td></td>
</tr>
</tbody>
</table>

Summary

- **EXIST/HET** will perform a survey, with near full sky coverage every two orbits (~2.5 yr) for capturing GRBs/transients and exploring new variability.
- 5-400 keV wide energy coverage with CZT detectors (~3 - 4 keV res., FWHM) for unveiling distant, obscured sources.
- ~30" localization (5σ), <100 sec slew for rapid onboard Optical/IR imaging and spectroscopy of GRB afterglows.
- **Detect ~300 - 700 GRBs/year, including ~10 - 60 GRBs/year with z>6** (Salvaterra et al, 2008, MNRAS, 385, 199)
- **Detect ~20,000 AGNs from 2 yr. scanning survey (~0.1 mCrab, 5σ) plus additional ~10,000 in 3 yr pointed phase: full survey sensitivity ~0.05 mCrab or ~6 x 10^-13 cgs**

Key changes in EXIST/HET vs Swift/BAT

- CZT: Larger Area (9x) with finer pixels (9x) thicker CZT (2x)
- ~20" vs 3" localization
- 5-600 keV vs 15-200 keV
- Low noise EX-ASIC: lower FWHM and lower threshold
- Sensitivity Improvement
  - ~3x for pointings in the same 15-50 keV band
  - ~7x for survey in the same 15-50 keV band
- Hybrid Mask
  - Cover the wide energy band (5-600 keV) without significant auto-collimation
  - Fast two-step on-board imaging processing
- Scanning Operation
  - Automatically minimize the unknown systematic-driven noise

Power Projection for the EXIST Observatory

<table>
<thead>
<tr>
<th>Components</th>
<th>CZT (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HET total</td>
<td>716</td>
</tr>
<tr>
<td>SX-ASIC (30x48, 11.5M pixels)</td>
<td>527</td>
</tr>
<tr>
<td>The rest of FEE &amp; BEE</td>
<td>485</td>
</tr>
<tr>
<td>HET total</td>
<td>165</td>
</tr>
<tr>
<td>SX-ASIC total</td>
<td>148</td>
</tr>
<tr>
<td>Spacecraft + Payload Common</td>
<td>1663</td>
</tr>
<tr>
<td>Total</td>
<td>3803</td>
</tr>
</tbody>
</table>

Common Questions for Tech Development

- **CZT Supply (300/month) - Currently available (Redlen Tech.)**
- **EX-ASIC develop** (20µW/pixel) from DB ASIC (80µW/pixel) Straightforward power ~ 1/noise and ~5 keV vs ~0.4 keV noise requirements for EXIST vs NuSTAR
- **CZT + ASIC hybrid**
  - NuSTAR: DB ASIC + Gold-stud bond
  - HET: EX-ASIC + TLPS bond (Creative Electron Inc)
- **HET processors: hybrid mask allows efficient two step Imaging processing**
- **HET thermal: follow the heritage of the BAT**
**New Operational Mode: Scanning Coded-Aperture Imaging**

- The sensitivity or dynamic range of coded-aperture telescope is limited by unknown systematic uncertainties in the system.
- Swift/BAT achieves near Poisson performance by aggressive correction on systematics.
- Scanning or slew mode observation allow automatic correction on systematic noises: an extreme version of dithering motion.

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**HET Mask Design & Source Localization**

<table>
<thead>
<tr>
<th>Thin Fine Elements</th>
<th>Thick Coarse Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch (mm)</td>
<td>Hole Size (mm)</td>
</tr>
<tr>
<td>1.25</td>
<td>1.20</td>
</tr>
<tr>
<td>15</td>
<td>13.75</td>
</tr>
<tr>
<td>Hole Size (mm)</td>
<td>Thickness (mm)</td>
</tr>
<tr>
<td>1.20</td>
<td>0.3</td>
</tr>
<tr>
<td>13.75</td>
<td>3</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>Filling Factor</td>
</tr>
<tr>
<td>1.20</td>
<td>25%</td>
</tr>
<tr>
<td>13.75</td>
<td>50%</td>
</tr>
<tr>
<td>Filling Factor</td>
<td>Angular Resolution</td>
</tr>
<tr>
<td>25%</td>
<td>2.4'</td>
</tr>
<tr>
<td>50%</td>
<td>25.8'</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>5o Localization</td>
</tr>
<tr>
<td>2.4'</td>
<td>20''</td>
</tr>
<tr>
<td>25.8'</td>
<td>3.6'</td>
</tr>
</tbody>
</table>

\[ mp = \text{mask pixel pitch} \]
\[ dp = \text{detector pixel pitch} = 0.6 \text{ mm} \]
\[ f = \text{mask-detector separation} = 2.0 \text{ m} \]

Angular Resolution \( \alpha = \arctan \left( \frac{\text{mp}^2 + \text{dp}^2}{f} \right) \)

5o Localization \( 0.7 r/(c+b) \) for 90% radius, \( b=0 \)

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**LEON3F-SHARC Field-programmable Processor**

**Aeroflex Gaisler**

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**Simulated 5y break for EXIST IRT vs. x (R ~ 3000, F ~ 2000x)l**

for a GRB Image brighter than the anomalously faint GRB080913 (x ~ 6.7)

\[ A(x) = 10.0 + x \cdot 2000 \text{ for a GRB Image} \]
\[ F = F \cdot \log(N)/P = 20 \text{ in GRB Image} \]

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**HET Tungsten Mask**

**IRT Baffle**

**Mask Support**

**Side shields IRT**

**Telescope**

**IRT focal plane & Detectors**

**Detector Array Plate**

**Optical Bench (4x)**

**Bus Radiators (4X)**

**Propellant Tank**

**High Gain Antenna (Stowed)**

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**New Operational Mode: Scanning Coded-Aperture Imaging**

- The sensitivity or dynamic range of coded-aperture telescope is limited by unknown systematic uncertainties in the system.
- Swift/BAT achieves near Poisson performance by aggressive correction on systematics.
- Scanning or slew mode observation allow automatic correction on systematic noises: an extreme version of dithering motion.
The MAESTRO Chip

- RBD version of the Tilera TLR26480 processor
  - 7 x 7 tile array
  - IBM BSF 90 nm CMOS process
  - 480 MHz, 70 GOPs, 14 GFLOPs average
  - < 25 Watts Peak (selectable)
  - Possible to nuke cores and reduce power
    - < 270 mW per core
  - Integrated floating point unit in each tile processor
    - IEEE 754 compliant, single and double precision
    - Aurora FPU IP
    - 500 Krads TID
    - Demonstrate NASA TRL-6 by December 2010
    - Software compatible with the Tilera TLR26480
    - Reduced number of cores, slower clock speed, added FPU
    - Tilera TLR26480 information can be found at www.tilera.com

DARPA / DTRA RHBD 2 Program

- Enable Rad-Hard ASICs on advanced commercial fab processes
  - High performance, low power
  - Leverage supported IP & tools
  - Foundry flexible assured sources

<table>
<thead>
<tr>
<th>Hardness Targets</th>
<th>Acceptable RHBD Penalties</th>
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<tbody>
<tr>
<td>Total Ionizing Dose</td>
<td>≤2 Mrad(Si) (OPERA &gt; 500 Krads(Si))</td>
</tr>
<tr>
<td>Single Event Upset</td>
<td>≤1E-10 errors/bit/day (silicon), LET &gt; 20</td>
</tr>
<tr>
<td>Single Event Latchup</td>
<td>LET &gt; 125 MeV-cm²/mg</td>
</tr>
<tr>
<td>Dose Rate Upset</td>
<td>&gt;1E-13 errors/bit/sec</td>
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</tbody>
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Area  ≤ 2X
Speed  ≤ 1.5X
Power  ≤ 2X

The END