Computing challenges in Coded Mask Imaging

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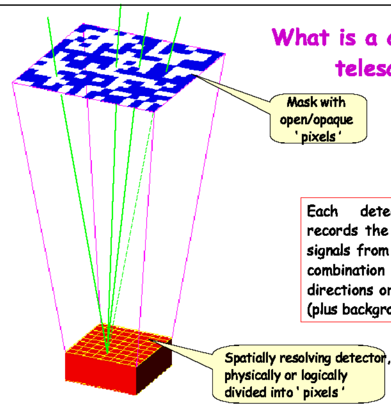
The Coded Mask Technique

is the worst possible way of making a telescope

Except when you can 't do anything better !

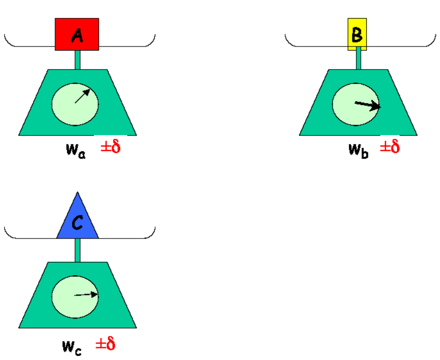
- Wide fields of view
- Energies too high for focussing, or too low for Compton/Tracking detector techniques
- Very good angular resolution

What is a coded mask telescope?

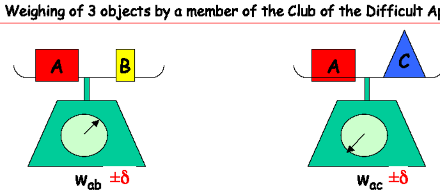


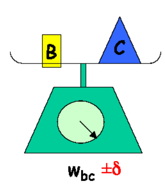
Each detector pixel records the sum of the signals from a different combination of incident directions or 'sky pixels' (plus background)

1) The simplist 's approach to weighing 3 objects



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





$A= (W_{ab}+W_{ac}-W_{bc})/2 \;\pm 0.85\,\delta$

$B= (W_{ab}-W_{ac}+W_{bc})/2 \;\pm 0.85\,\delta$

$C= (-W_{ab}+W_{ac}-W_{bc})/2 \;\pm 0.85\,\delta$

In general:-

N objects (unknowns)
N measures of selected combinations
Uncertainty reduced by factor ~ $N^{1/2}/2$

Only works because <u>we have supposed that the uncertainty is independent of the quantity being measured</u> - the equivalent of a background limited observation

Mask

Patterns
- Hexagonal or rectangular
- Cylclic or non-cyclic
- Random, URA, MURA, …

Construction

Low energies (e.g. 10-20 keV)
- etched metal foil (often gold-plated to increase absorbtion)
- usually self supporting (grid or bars connect isolated elements)
- Additional ' Spider ' or supporting bars ═ part of the mask pattern

High energies (e.g. 1 MeV)
Blocks of Tungsten a few cm thick
- can have a ' substrate ' (e.g. Carbon fibre honeycomb)

The Coded Masks for Integral

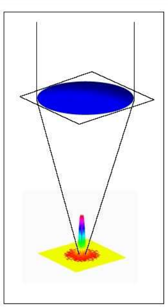
JEM-X
Energy: 3-100 keV
535mm dia
0.5mm Tungsten
3.3 mm pitch
Resolution 3 arc min

IBIS
Energy: 15-10000 keV
1064 mm square
16 mm Tungsten
11.2 mm pitch
Resolution 12 arc min

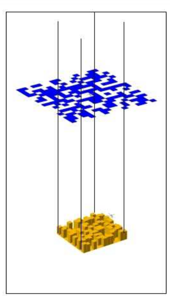
SPI
Energy: 20-8000 keV
770 mm dia
3 cm thick Tungsten
60 mm pitch
Resolution ~ 2.5°

Position sensitive detectors for coded mask telescopes

Detector Technology	Approx Energy Range (keV)	Examples	Notes
CCD	0.5-10	HETE-2 SXC	1-d 33 arc sec resolution !
Gas-filled Proportional Counter	2-50	Spacelab-2 TTM, SAX-WFC RXTE ASM HETE-2 WXM Integral : JEM-X	Space Shuttle Mir-Kvant Space Station 1-d 1-d
Arrays of semiconductor detectors	5-100	Legri (CZT) Integral : ISRI (CdTe)	MiniSat-01
Anger Camera	50-1000	Sigma Exite-2	On Granat Balloon
Array of Scintillator detectors	100-10000	New Hampshire DGT Integral : PIXIT	Balloon
Aray of Germanium detectors	20-10000	SAGE Integral : SPI	Balloon



Point Source Response Function



A coded mask telescope has the worst PSF imaginable

The response to a point source isn't just 'a bit blurred',

it fills the whole detector plane !

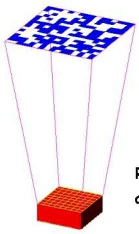
The Point Source Response Function

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 '

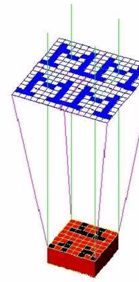
Recorded pattern is Convolution of source distribution and the mask pattern, plus some background B

$$D = S \otimes M + B$$

Suppose we form an image as †

$$I = M \otimes D = M \otimes S \otimes M + M \otimes B$$
$$= M \otimes M \otimes S + M \otimes B$$
$$= ACF(M) \otimes S + M \otimes B$$

where ACF indicated the Autocorrelation function.
If ACF(M) were a Delta function and if $M \otimes B$ 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.

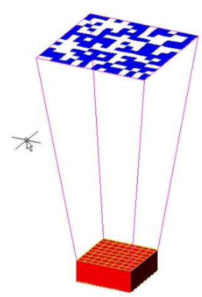
ii) For uniform background, $M \otimes B$ is not zero, but it is at least FLAT.

If you can:
- Arrange that coding is cyclic
- Use Binned (discrete) arrays
- Be prepared to subtract a DC level

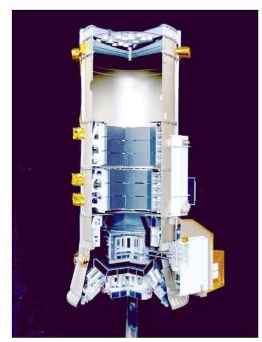
Then this is just what is needed

'Optimum coded ' designs or 'URAs'

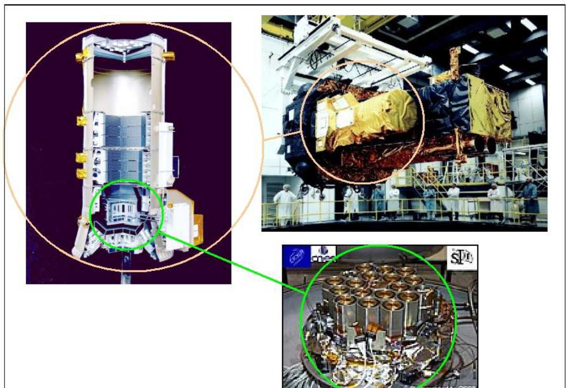
URAs are closely related to ' Cyclic Difference Sets '. Different families of cyclic difference sets yield Mask patterns which look quite different but which all have the desired properties - all have an ACF of the same form.



Imaginary



(More) real



Some aspects of *real* systems

- Non cyclic
- Mask Closed element absorbtion
- Mask Open element transparency
- Mask Element Thickness
- Obstructions in Mask Plane
- Detector finite position 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

Mask

Detector

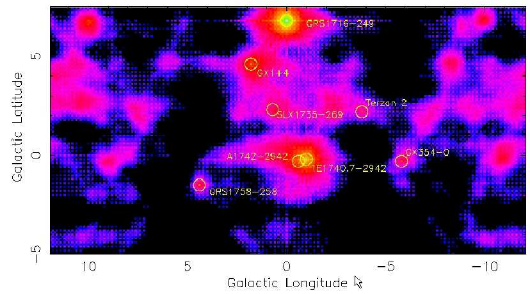
Other

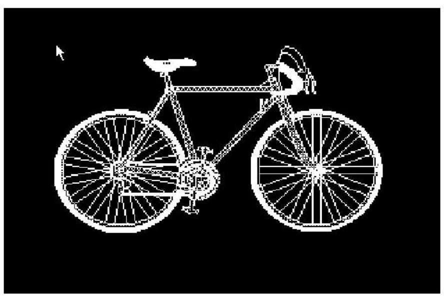
Correlation with the Mask Pattern used with Real (Imperfect) Coded Mask Telescopes

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)

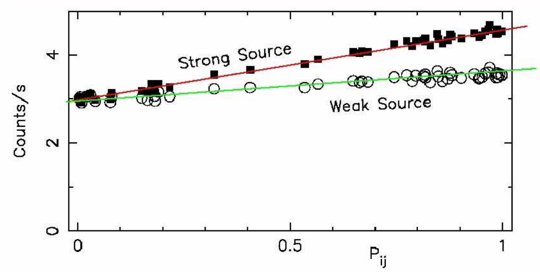
Simulated Image Reconstruction





Mask Pattern
used in simulation

Detected count rate versus source / detector-pixel transmission factor



Peak height in Correlation map	⊗	Slope of line	⊗	Source strength
		Intercept	⊗	Background per pixel

Data points with P_{ij} ~ 0.5 (`grey` mask elements) are of little value in defining the slope

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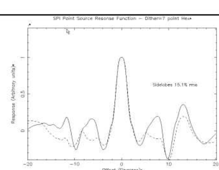
The realities lead to



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

Fortunately coded mask telescopes are not very sensitive !

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

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 (IROS)

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' ;

$S_0, S_1, S_2, S_3, \ldots S_{M-1},$

One measures N linear combinations of the S_j,

$$D_i = \sum_{j=0}^{M-1} h_{ij}\, S_j \qquad (i = 0, N-1)$$

Objective - given the D, deduce the S

If $M=N$, in principle, it 's easy. Using matrices we can write

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

$$\lfloor D \rfloor = \lfloor H \rfloor \cdot \lfloor S \rfloor$$

Matrix approach - the case of M=N

number of unknowns = number of measurements

Starting from

$$\lfloor D \rfloor = \lfloor H \rfloor \cdot \lfloor S \rfloor$$

one can obtain the intensities S of the sky pixels utilising the inverse matrix

$$[S] = [H]^{-1} \cdot [D]$$

- For an imaginary (ideal, URA/optimum) cyclic system, this is (almost) exactly equivalent to the correlation method
- For a real system, in principle it allows you to get rid of ALL ghosts/sidelobes.

Matrix approach - 1st problem: 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

⇨ OVER determined problem ⇨ Use Moore-Penrose Generalised Inverse

Matrix approach 2nd problem: Noise Amplification

Starting from

$$\lfloor D \rfloor = \lfloor H \rfloor \cdot \lfloor S \rfloor$$

one can obtain the intensities S of the sky pixels utilising the inverse matrix

$$[S] = [H]^{-1} \cdot [D]$$

BUT, in fact one obtains a measure D with uncertainties added

$$[D] = [H] \cdot [S] + [n]$$

where $[n]$ is a matrix of noise. Consequently one has

$$[S] = [H]^{-1} \cdot [D] + [H]^{-1} \cdot [n]$$

and if there are large values in H^{-1} the noise can become enormous

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 int account Equivalent to correlation methods

  Fast for few photons (bursts)

The scale of the problem

		SPI-like		IBIS-like	
Measurements					
Detector pixels per pointing		19	100	10^4	10^4
Pointings		25	200	1	25
Total	N	475	10^5	10^5	$2.5\ 10^6$
Unknowns					
Sky pixels		400	500	$2\ 10^4$	$2\ 10^4$
Backrounds		19	500	10	10
Total	M	419	1000	$2\ 10^4$	$2\ 10^4$
		Number of operations			
ME Matrix Approach					
To invert matrix (brute force)	N^4	6.10^{10}	$2\ 10^{17}$	10^{16}	$4\ 10^{21}$
To invert matrix (iterative)	$M\ N^2$	10^8	$4\ 10^{11}$	$2\ 10^{12}$	10^{15}
To multiply by the matrix	M.N	10^5	$5\ 10^8$	$2\ 10^8$	$5\ 10^9$
Correlation Approach					
Matrix multiplication	M.N	$2\ 10^5$	$5\ 10^8$	$2\ 10^8$	$5\ 10^9$
FFT	(M+N).ln(M+N)	10^4	$2\ 10^6$	$4\ 10^5$	N.A
Back Projection					
	$M\ N_{photons}$				

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 m/l .

But the detector resolution blurs the mask pattern.

Roughly $m \rightarrow (m^2+d^2)^{1/2}$.

Thus the angular resolution (Full Width at Half Maximum) of the PSF is about

$$\theta = \frac{(m^2+d^2)^{1/2}}{l}$$

But sources can be positioned with better accuracy than this.

A guideline is that the point source position uncertainty is about θ/n_σ

where the source is detected with significance n_σ

$$\Delta = \frac{(m^2+d^2)^{1/2}}{n_\sigma l}$$

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 :

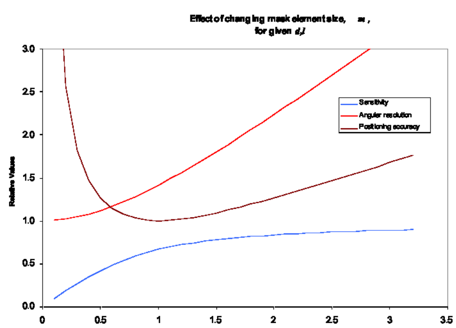
$$n_\sigma = \frac{N_{phot}}{(N_{phot}+N_{BG})^{1/2}}$$

where N_{phot} is the number of photons detected from the source and N_{BG} is the total number of events in the detector.

.

But finite detector resolution reduces significance by a factor

$Max\,(\,1\text{-}d/3m\,,\ \ (m/d)(1\text{-}m/3d)\,)$



Why bad resolution is good

- The angular resolution of SPI could have been better !

So why didnt wasnt it made better?

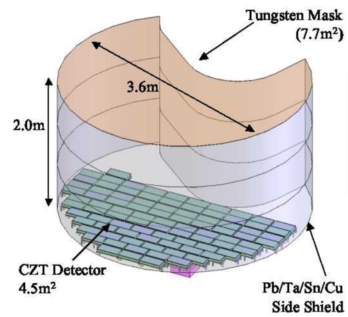
Surely it would be advantageous for studying point sources and for studying diffuse emission you can always combine pixels together to have the equivalent of a lower resolution instrument

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

	Instrument 1	Instrument 2	
Angular Resolution	4 deg	1 deg	
Point Source sensitivity	S	S	phot/s
Diffuse source sensitivity	S/16	S	phot/s/deg^2
Diffuse source sensitivity (smoothed to 4 degree resolution)	S/16	S/4	phot/s/deg^2

Conclusions

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

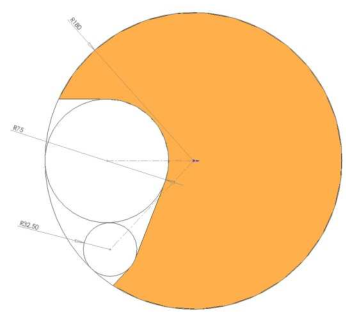


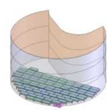
GRB detection
Survey

Continuous scanning mode:
360° per orbit
(~ 4' per sec)

The EXIST High Energy Telescope (HET)

HET Mask Design





3.6 m dia meter with cutouts of 1.5m and 0.65m dia circles

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

Either way imaging and location in a few sec

Field of view	90° × 70°	⇒ ~4×10^7 pixels
Resolution	2' on-axis	
	1' at edge of f.o.v.	
Oversampling	2×2	

Coded mask image reconstruction :

1. Cross-corelation
   - a) Brute force 4×10^{15} 'operations' per image ✗
   - b) FFT 7×10^{9} " " " ?
2. Back projection 3×10^{12} 'operations' per sec* ✗

*assuming 40000 events per sec

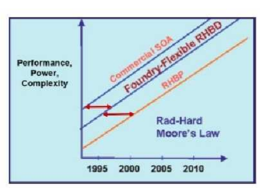
New generations of space-qualified processors

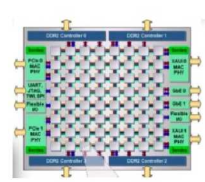
Eg

Tilera 'Opera' (due to be used on the MISTRO mission in 2010)

Coherent Logix's Hyper-X (due for flight on MISSE-7 in Nov 2009)

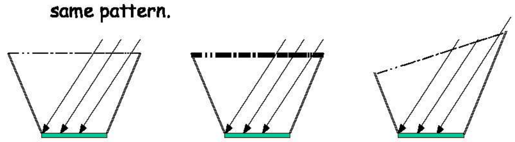
~1000× the 21020 DSP processor used for BAT image reconstruction





When can you use an FFT ?

when the pattern with which you want corelate the data pattern are simply (subsets of) shifts of the same pattern.

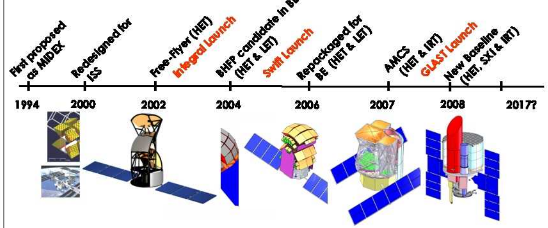


Thin, parallel mask: FFT OK

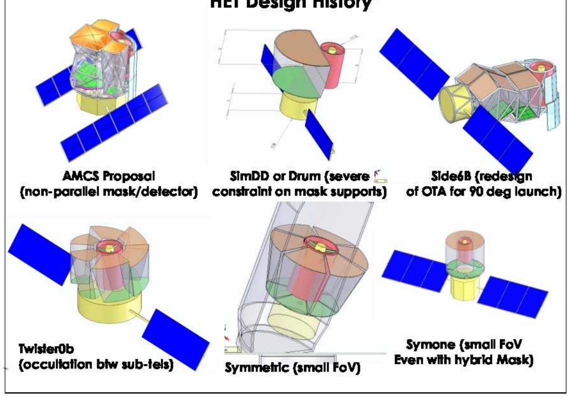
Thick mask: FFT approximate

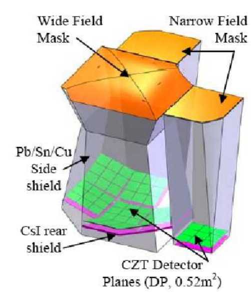
Tilted mask: FFT not useful

History of *EXIST*



HET Design History





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

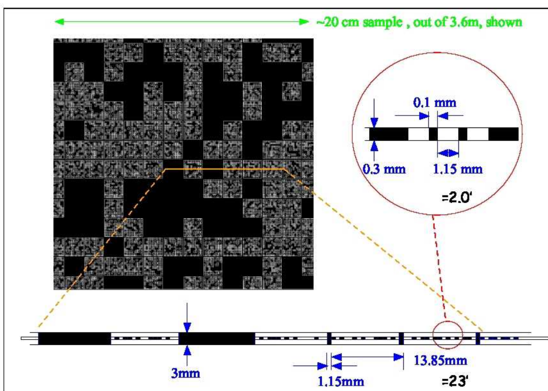
Mask Autocollimation - another hurdle to overcome

Wide field of view + limited diameter
-> short mask-detectotr separation

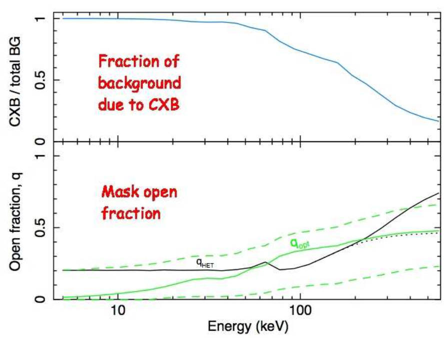
Good angular resolution + short mask-detector separation
-> small mask elements

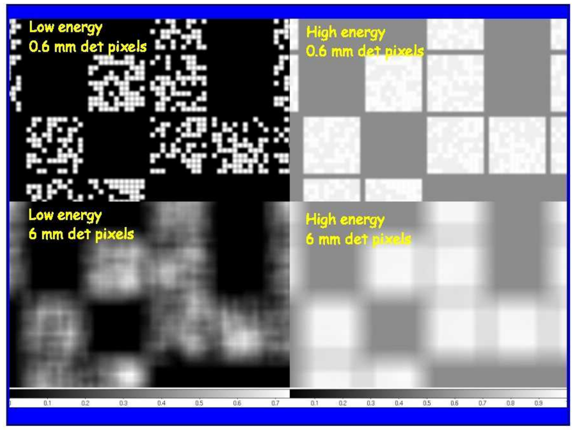
High energy response -> thick mask

Thick mask + small mask elements
-> narrow field of view

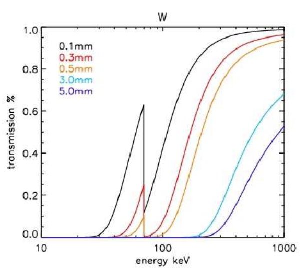


c.f. Skinner & Grindlay *"Coded Masks with two spatial scales"* A&A 276, p. 673 (1993)





Transmission through Tungsten Mask



1. Bin the data into coarse detector bins, correcting for mean shadow motion (ie 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. $N_{\sigma 1} = 3.9\sigma$)
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. $N_{\sigma 2} = 7.2\sigma$) in one of these local images is considered a valid trigger

1 step

Operations: 7×10^9 (FFT)

Threshold: 7.2σ

False trigger rate:
3×10^{-13} per pixel per image
6×10^{-6} per image
0.5 per day

2 step

Operations: 7×10^7 (FFT)
1.5×10^8 (Back proj)
2.2×10^8 (Total)

Threshold 3.9σ (stage 1)
7.2σ (stage 2)

False trigger rate:
3×10^{-13} per pixel per image
10 per image (stage 1)
0.5 per day (stage 2)

Conclusions

A major aspect of EXIT will be a sort of 'super-Swift'

The HET will be the equivalent of Swift/BAT

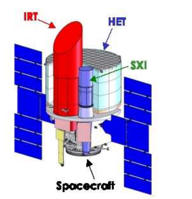
HET will have 12 million detector pixels in place of BATs 32768

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 (ie 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

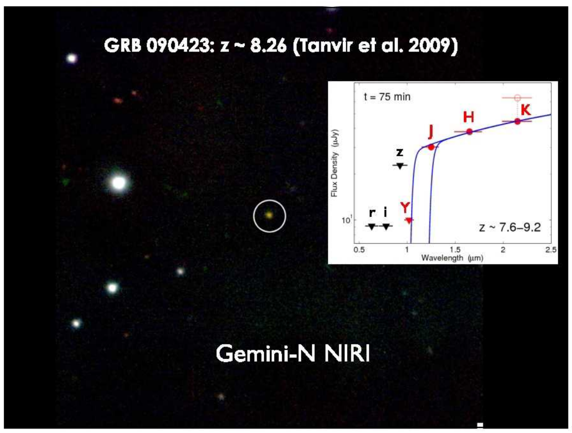
The *EXIST* Mission Overview

- 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.

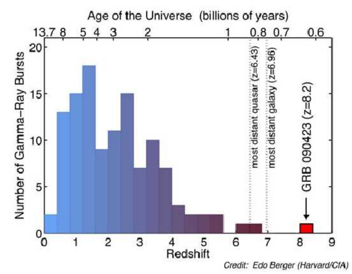


- **High Energy Telescope (HET):** wide-field coded-aperture hard X-ray imaging telescope with 4.5m² CZT (5 – 600 keV)
- **Optical/Infrared Telescope (IRT):** 1.1m visible-IR telescope with HyVISI and Hawaii2RG for both imaging and spectroscopy (0.3 – 2.2 μm)
- **Soft X-ray Image (SXI):** 0.6m X-ray telescope with CCD (0.1 – 10 keV) contributed by Italy/ASI

- 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

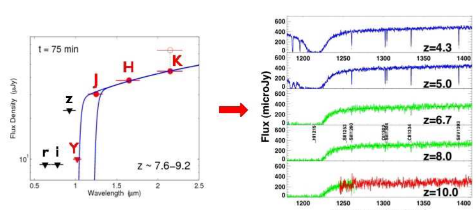


Science Goal: high-z GRBs as Cosmic Probe



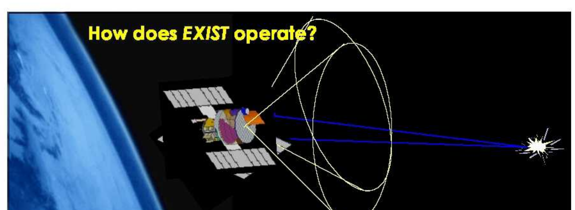
z = 8.2 is ~630 Myr after the Big Bang
4.6% of the current age of the Universe

Science Goal: high-z GRBs as Cosmic Probe



Rapid follow-up for onboard optical/infrared imaging and spectroscopy

How does *EXIST* operate?



1. HET scans sky at orbital rate with zenith (±~30°) pointing; covers sky every 2 orbits
2. Imaging in 90° FoV detects GRB or variable AGN or transient. Locates it to ~20"
3. Spacecraft slews to bring the location within the FoV of the SXI and IRT
4. Typically SXI identifies corresponding X-ray source and positions it to ~2"
5. IRT places corresponding object on slit for spectroscopy if bright enough, or in field for low resolution spectroscopy. Performs 4 band photometry in all cases. If no XRT ident, studies all objects in HET error circle in turn. On-board photometric redshift.
6. Follow-up pointing during following 1-2 orbits to make detailed SXI/IRT observations of afterglow, light curve of transient, etc. HET continues survey

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 measure prompt redshifts, constrain GRB physics and enable GRBs as probes of cosmic structure & reionization at redshifts z >7-10

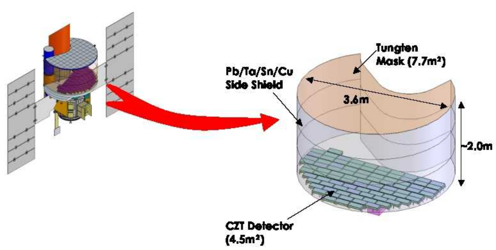
• Identify **supermassive BHs** in galaxies, whether obscured or dormant, to constrain SMBH properties, their role in galaxy evolution and the origin of the CXB, and *accretion* luminosity of the universe

• Measure the stellar and intermediate mass **BH populations in the Galaxy and Local Group** by a generalized survey for Transients for which prompt IDs and X-ray/HX/IR spectra distinguish SNe, SGRs & Blazars and complement Fermi, JWST, LSST, LISA with prompt alerts for unique objects

Major Factors for Instrument Design

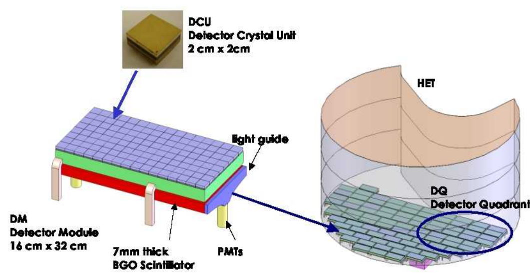
• Sensitivity (~0.10 mCrab in 1yr)	► ~4.5 m^2 CZT
• GRB coverage (>~500 GRBs) Full Sky in a few Orbits	► Wide FoV (70 x 90°)
• High Z GRB redshift onboard	► 1.1 m Optical/IR Telescope (1.5m dia envelop)
• Angular Resolution (2.6') Localization (20" for 5σ)	► 1.25mm fine mask pixel 0.6mm det. pixel 2m mask-det. distance
• LEO (600 km, *i* ~22°)	► EELV (e.g. Atlas V-401: 3.7m dia x 5.2m envelope)
• Mission Cost (~$0.8–1.2B)	

The HET Concept Overview



Wide-field Coded-Aperture Hard X-ray Imaging Telescope with 4.5m^2 CZT (5 – 600 keV)

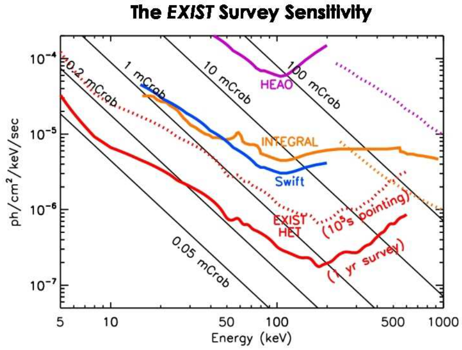
Detector Packaging Overview



1 DM = 27 DCUs
~4.5W/DM
Sits on optical bench

HET = 88 DMs or 4 DQs
1 DQ = 22 DMs
4.5 m^2

The *EXIST* Survey Sensitivity



~ 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?

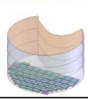
Scanning

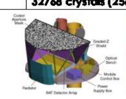
How can we be confident that this has the desired effect ?

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

EXIST/HET vs *Swift*/BAT

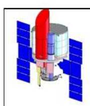
Parameters	EXIST/HET	SWIFT/BAT
Telescope	4.7m² CZT Det. + 6.5m² W Hybrid Mask	0.5m² CZT Det. + 2.7m² Pb Mask
Energy Range	5 – 600 keV (5mm thick CZT) 600 – 3000 keV (BGO for GRBs)	15 – 200 keV (2mm thick CZT)
Sensitivity (5σ)	0.1–0.4 mCrab (<150 keV, ~1yr survey)	1mCrab (<150 keV, ~2 yr survey)
Field of View	70°x90° (10%)	50°x100° (50% coding)
Angular & Positional Resol.	1-2′ resolution 20″ pos for 5σ source (90% conf. rad)	17′ resolution 3′ pos for 5σ source
Sky Coverage	Nearly full sky every two orbits (3hr)	10s orbits – a few days
Spectral Resolution	2 – 3 keV (3% at 60 keV, 0.5% at 511 keV)	3 – 4 keV (5% at 60 keV)
Timing Resol.	10 μsec	100 μsec
CZT Detector	2x2x0.5cm³, 0.6mm pix, 12M pix 11264 crystals	4x4x2mm³, 4mm pixel, 32k pix 32768 crystals (256 modules)



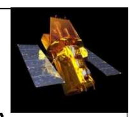


Summary

- **Exist/HET will perform a survey, with near full sky coverage every two orbits** (~3hr) for capturing GRBs/transients and exploring new variability
- **5–600 keV** wide energy coverage with CZT detectors (**<3 – 4 keV res., FWHM**) for unveiling distant, obscured sources
- **<20″ 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, 189)
- **Detect ~20,000 AGNs** from 2 yr scanning survey (~0.1 mCrab, 5σ) & additional ~10,000 in 3 yr pointed phase: full survey sensitivity ~0.05 mCrab or ~5 x10^{-13} cgs

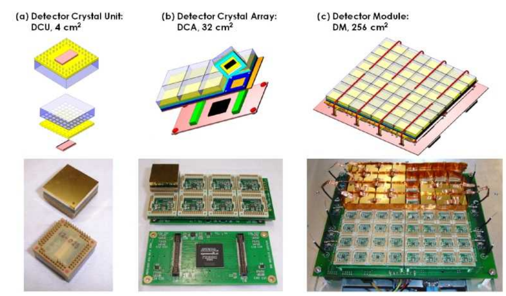


Key changes in *EXIST*/HET vs *Swift*/BAT



- CZT: Larger Area (9x) with finer pixels (9x) thicker CZT (2.5x)
  - 20″ vs 3′ localization
  - 5 – 600 keV vs 15 – 200 keV
- Low noise EX-ASIC: lower FWHM and lower threshold
- Sensitivity improvement
  - ~5x for pointing in the same 15 – 50 keV band
  - ~3x for survey in the same 15 – 50 keV band
  - ~7x for survey for 5 – 15 keV (HET) vs. 15 – 50 keV (BAT) 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

ProtoEXIST1 CZT detector plane (RadNET ASICs)



Hong et al. 2009, NIM A. 605, 364 (astro-ph/0903.5363)

Power Projection for the *EXIST* Observatory

Components		CBE (W)
HET Total		716
EX-ASIC (20μW/pix,11.5M pixels)	231	
The rest of FEE & BEE	485	
IRT Total		165
SXI Total		149
Spacecraft + Payload Common		1663
Total		2803

ASIC Road Map

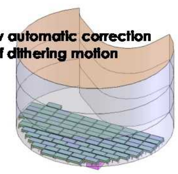
Type	Channels	Matching Pixel Size	Power (μW/pix)	
RADNET	1-D 64	2.5mm	70	*ProtoEXIST1*, 2009
DB-ASIC	2-D 1024	0.6mm	80	*ProtoEXIST2*, 2010
EX-ASIC	2-D 1024	0.6mm	20	*ProtoEXIST3*, 2011
BFE ASIC	2-D 1024	0.6mm	<10	

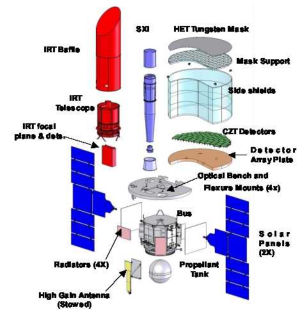
Common Questions for Tech Development

- CZT Supply (300/month) : Currently available (Redlen Tech.)
- **EX-ASIC develop (20μW/pixel) from DB ASIC (80μW/pixel)**
  Straightforward: power ~ 1/noise and ~2 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

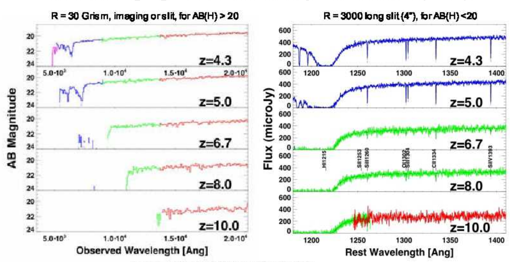
New Operational Mode: Scanning Coded-Aperture Imaging

- 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





Simulated Ly-breaks for EXIST IRT vs. z (*R = 3000, T = 2000sec*) for a GRB 3mag brighter than the anomalously faint GRB080913 (z = 6.7)



Assumed model (which IRT tests!):

AB(H) = 15.5 at T =200s, then GRB lightcurve decays: F ~ T^{-1} ν^{-1} Log(NH) = 20 in GRB host

Metallicity vs. z: z < 6, [Fe/H] = -2 6 < z < 7, [Fe/H] = - Z > 7, [Fe/H] = -4

Simulated spectra shown in IRT bands: 0.3 – 0.9μm, 0.52 – 0.9μm, 0.9 – 1.38μm, 1.38 – 2.1μm

EOR & Fe/H can be measured vs. z!

HET Mask Design & Source Localization

	Thin Fine Elements	Thick Coarse Elements
Pitch (mm)	1.25	15
Hole Size (mm)	1.20	13.75
Thickness (mm)	0.3	3
Filling Factor	25%	50%
Angular Resolution	2.4'	25.8'
5σ Localization	20"	3.6'

mp= mask pixel pitch
dp = detector pixel = 0.6 mm
f = mask-detector separation = 2.0 m

Angular Resolution (r) = atan (sqrt (mp^2+dp^2)/f)
5σ Localization = 0.7 r/(σ+b) for 90% radius, b~0

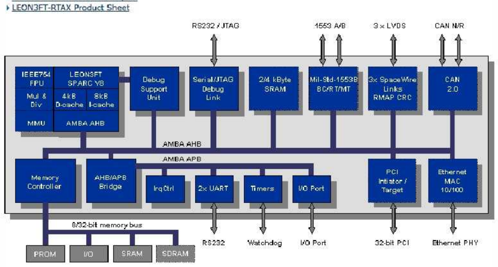
LEON3FT-RTAX Fault-tolerant Processor

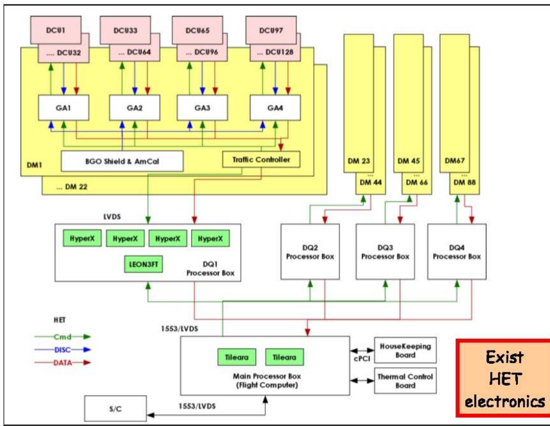
Aeroflex Gaisler

Introduction

The LEON3FT-RTAX processor is a SOC design based on LEON3FT core, implemented in the RTAX2000S radiation-tolerant FPGA. The processor is delivered as a programmed and tested RTAX2000S device, with several package and quality options. The combination of the RTAX2000S radiation-tolerance and the fault-tolerant capabilities of LEON3FT makes LEON3FT-RTAX suitable for any space application. To validate the fault-tolerance properties of the LEON3FT-RTAX design, a heavy-ion error-injection test campaign was carried in November 2005. The test was fully successful and confirmed the suitability of the LEON3FT-RTAX processor for critical space applications.

- LEON3FT-RTAX Data Sheet and User's Manual
- LEON3FT-RTAX SEU Test Report
- LEON3FT-RTAX Product Sheet



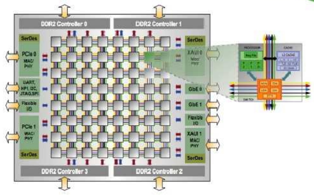


TILERA — TILE64™ Processor

Product Brief

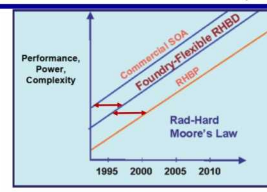
Overview

The TILE64™ family of multicore processors delivers immense compute performance to drive the latest generation of embedded applications. This revolutionary processor features 64 identical processor cores (tiles) interconnected with Tilera's iMesh™ on-chip network. Each tile is a complete full-featured processor, including integrated L1 & L2 cache and a non-blocking switch that connects the tile into the mesh. This means that each tile can independently run a full operating system, or multiple tiles taken together can run a multi-processing OS like SMP Linux.



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

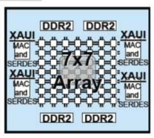


Hardness Targets	
Total Ionizing Dose	> 2 Mrad(Si) (OPERA > 500 Krad(Si))
Single Event Upset	< 1E-10 errors/bit-day (Adams), LET_{Th} > 20
Single Event Latchup	LET_{TH} > 120 Mev-cm^2/mg
Dose-Rate Upset	>1E10 rad(SiO_2)/sec

Acceptable RHBD Penalties	
Area	≤ 2X
Speed	≤ 1.5X
Power	≤ 2X

The MAESTRO Chip

- **RHBD version of the Tilera TLR26480 processor**
  - 7 x 7 tile array
  - IBM 9SF 90 nm CMOS process
  - 480 MHz, 70 GOPs, 14 GFLOPs average
  - < 28 Watts Peak (selectable)
    - Possible to no-op 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 Krad 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



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