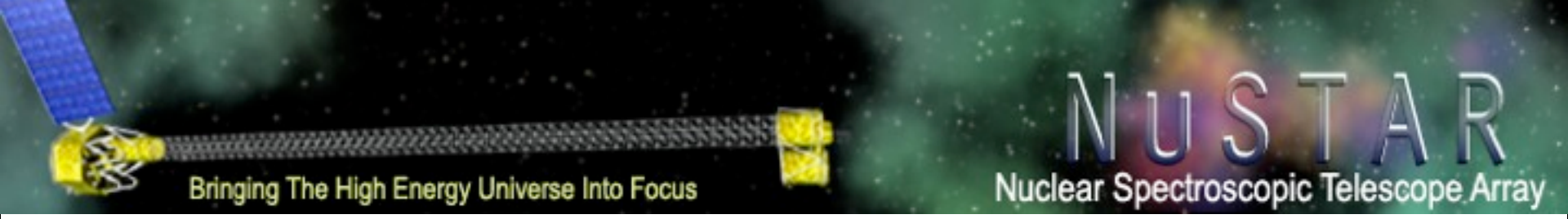
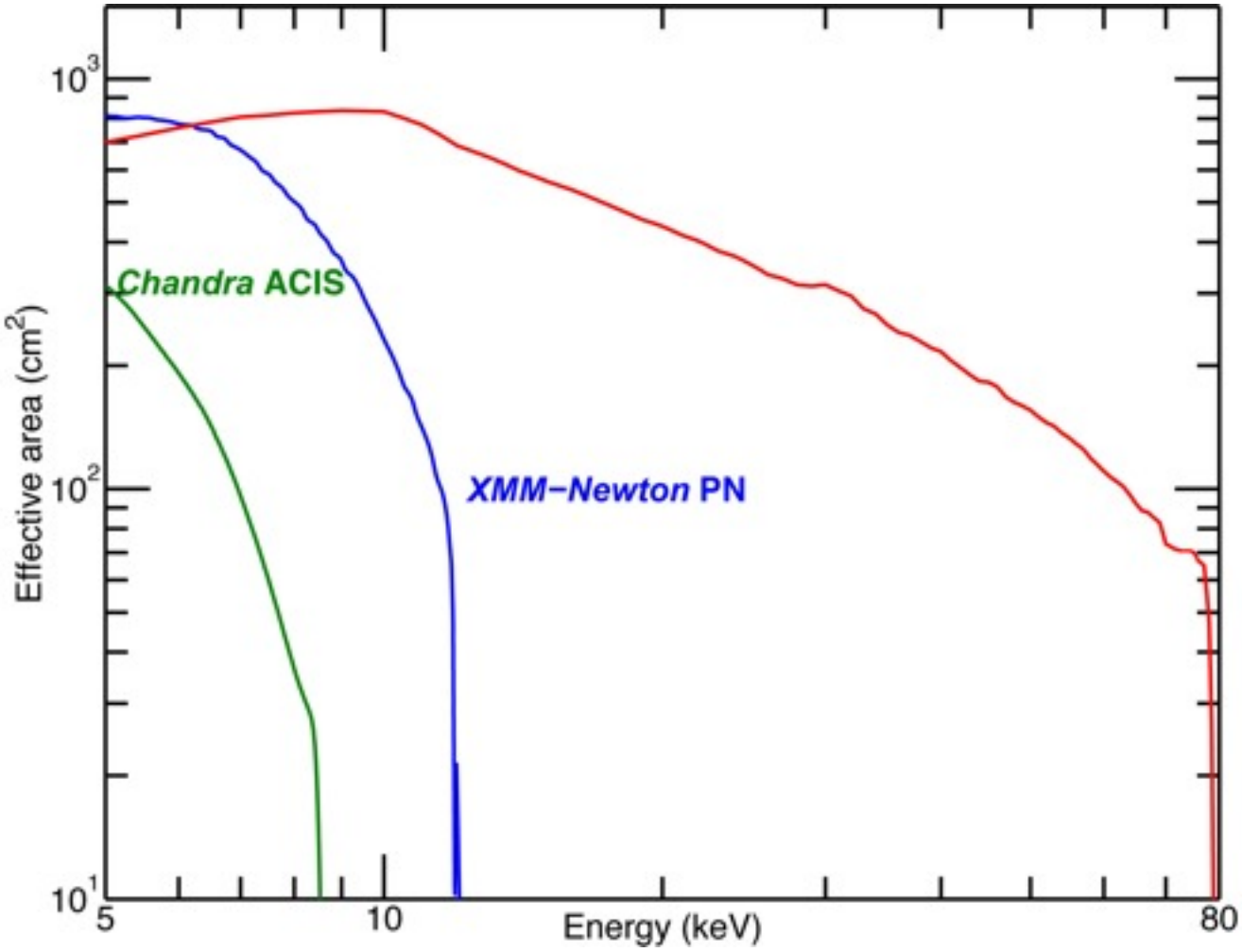


The Nuclear Spectroscopic Telescope Array.

Kristin Kruse Madsen
California Institute of Technology

Brian Grefenstette, Fiona A. Harrison

Effective Area



Mission Overview

NuSTAR

Pegasus XL launch

6° inclination
≥600 km circular

Spacecraft

- Three-axis attitude control
- Single string

Instrument

- Two hard x-ray telescopes
- 10 meter focal length
- Two CdZnTe detectors

Mission Profile:

Launch Feb 2012

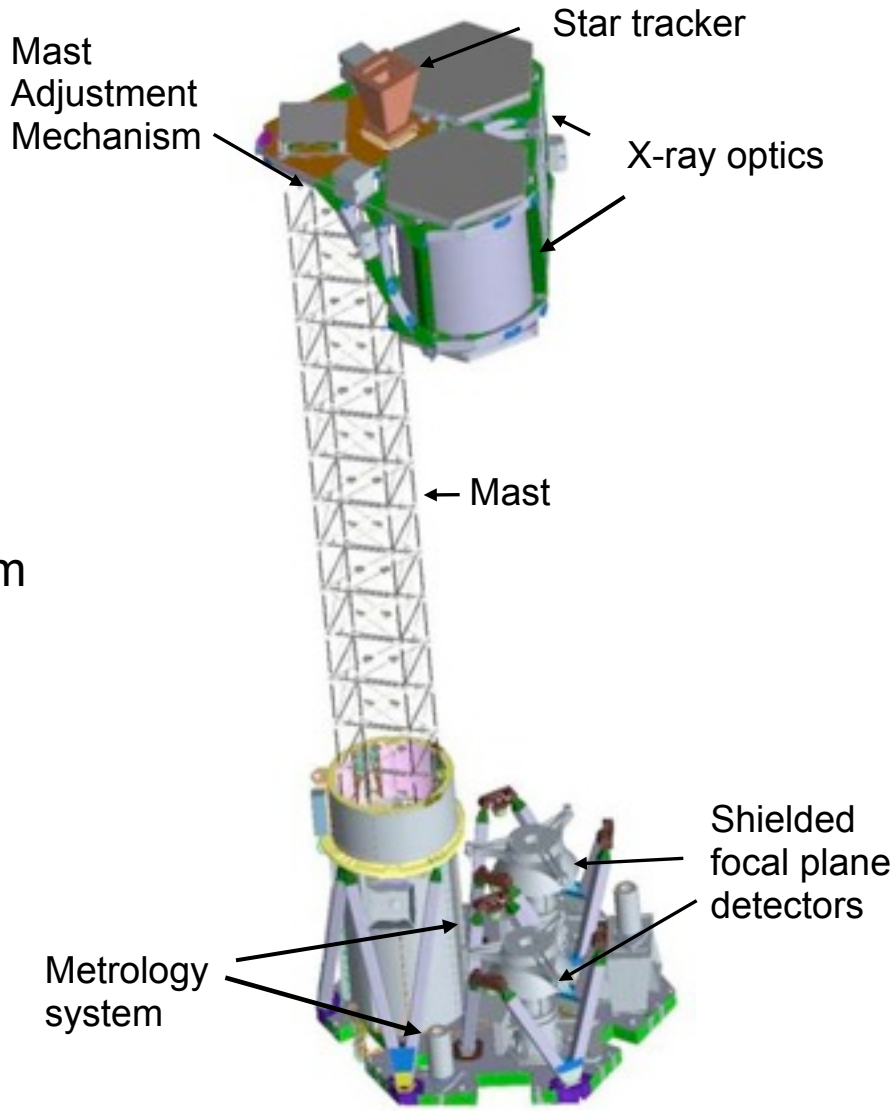
Primary mission lifetime: 2 yrs

Science Targets

- Supernova remnants
- Deep sky survey
- Galactic center survey
- High energy galactic targets
- High energy extra galactic targets
- Solar observations

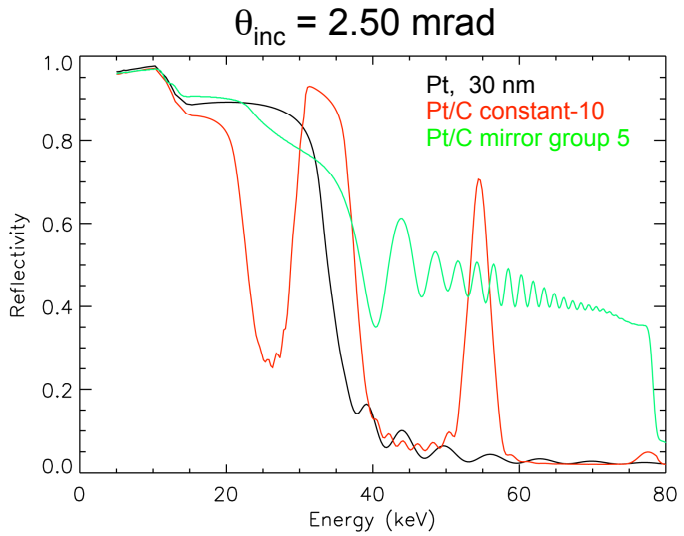
Payload Description

- Two identical coaligned grazing incidence hard X-ray telescopes
  - 12 arcmin FoV, 45” HPD
- Extendable mast provides 10-m focal length
  - Single-use adjustment mechanism
- Simple laser metrology system to remove mast flexure
- Star camera head + metrology provides fine aspect



Extendable Mast

Optics



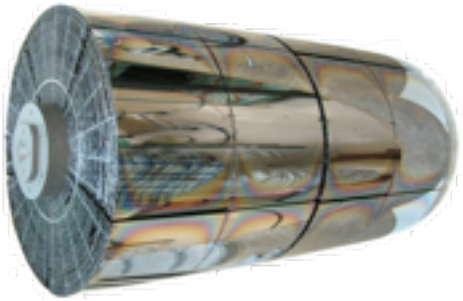
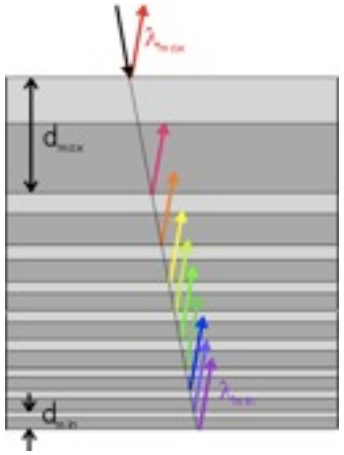


Fig: HEFT optic



Conical Wolter I approximation

Parameter	Value
Minimum radius	5.44 cm
Maximum radius	19.12 cm
Primary Mirror length	22.7 cm
Focal Length	1015 cm
Number of Shells	130
Depth Graded Multilayers:	
Inner shells (1 - 89)	Pt/C
Outer shells (90 - 130)	W/Si

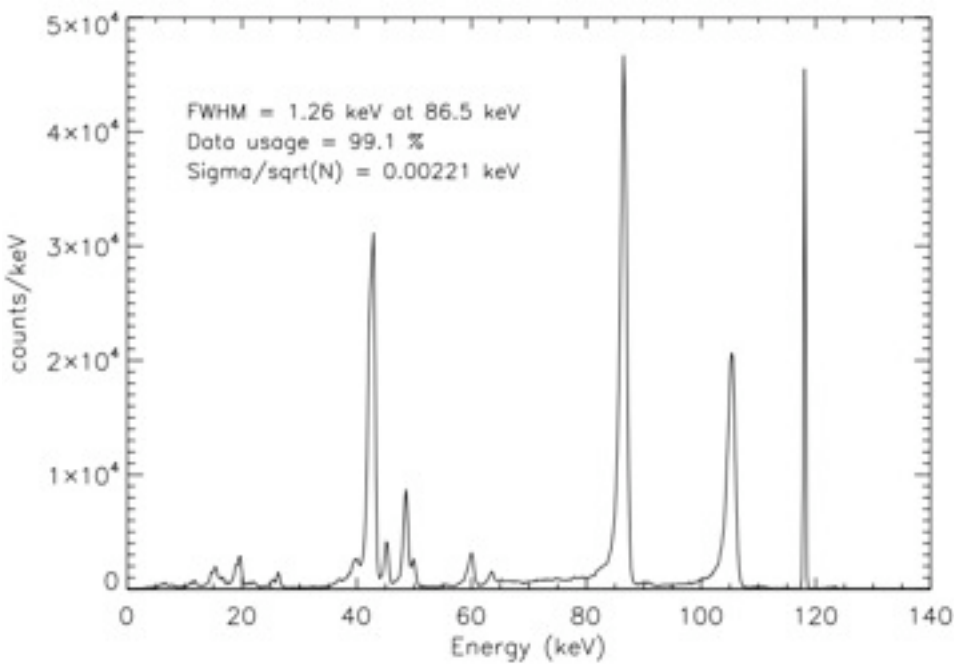
Substrates:

Slumped Borosilicate t=0.21 mm

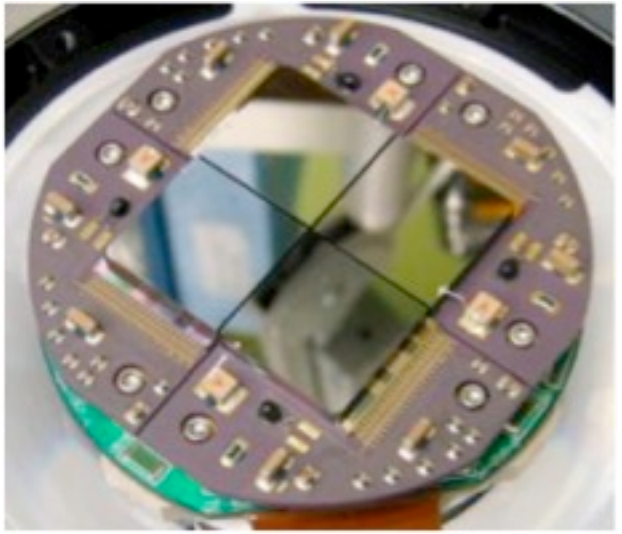
National Aeronautics and Space Administration
Goddard Space Flight Center

DANISH NATIONAL SPACE CENTER

Focal Plane Detectors



- CdZnTe
- 4 crystals (2 x 2 cm)
- 32 x 32 pixels/crystal
- pixel pitch 0.6 mm
- DE = 1 keV @ 60-80 keV
- Data rate = 200 cts/s/FP
- Timing = 1ms



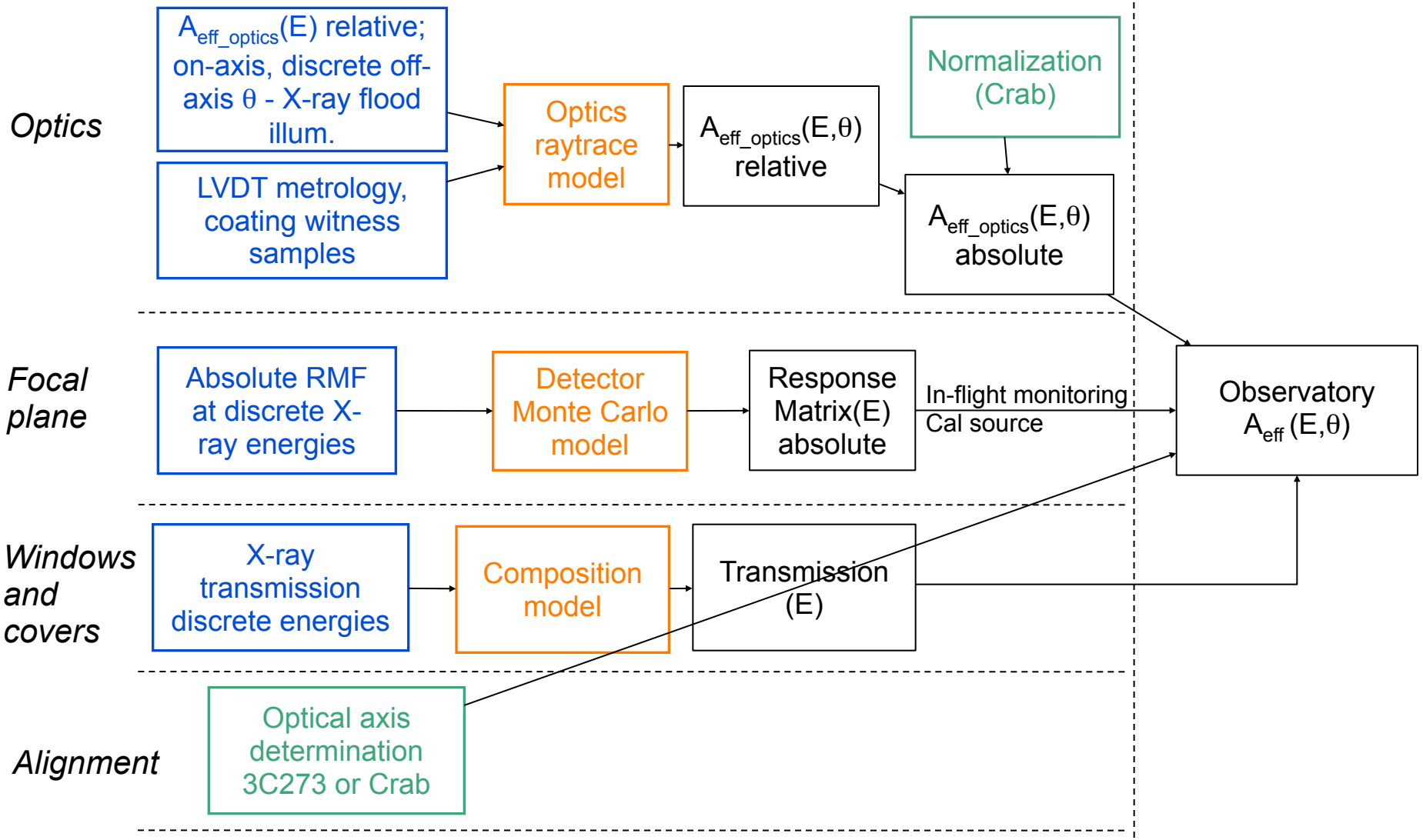
Calibration Requirements

Alignment	Requirement	Rationale
Optical Axis Knowledge	15"	Throughput determination
Effective Area		
Absolute effective Area: 6 -10 keV - central 2' x 2'	15%	Cross calibration with low-energy missions
Absolute effective area: 6 - 10, 10 - 30, 30 - 79 keV bands - 11' x 11'	25%	Hardness ratio determination, surveys
Absolute effective area in each 2 keV bin between 60 - 80 keV	12%	^{44}Ti yield measurement
Relative effective area in each 2 keV bin between 6 and 79 keV over central 8' x 8'	5%	Spectral index fitting, bright sources
Relative effective area in each 2 keV bin 60 - 79 keV in central 8' x 8'	3%	Continuum modeling and subtraction ^{44}Ti
Point Spread Function		
Integrated PSF 70-90% encircled energy over 11'x11'	10%	Mapping diffuse features/point sources
PSF as function of radius out to 70% encircled energy	3%	Flux determination. Remove point sources in diffuse emission
PSF as function of azimuth out to 70% encircled energy over 11' x 11'	10%	Mapping diffuse extended features, jets

Calibration Approach

- Combination of ground and in-flight calibration
- Ground calibration used for
  - Accurate relative effective area of optics
  - Absolute detector response at fixed energies
  - Throughput of windows and blankets
- In flight calibration for
  - Optical axis alignment and determination
  - Overall area normalization
  - PSF measurement
  - Verification of area/redistribution matrix

Calibration Approach Effective Area - $A_{eff}(E,\theta)$

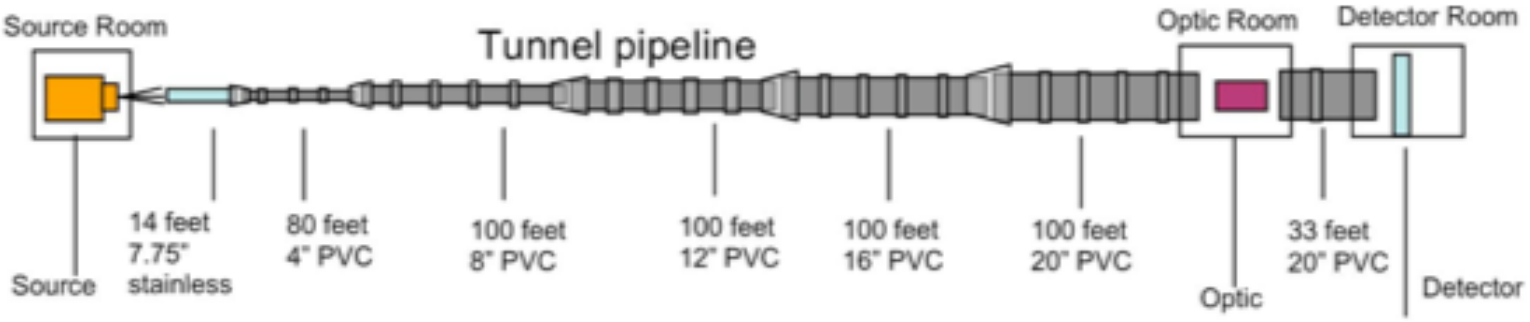


NuSTAR

Ground Calibration

Ground Calibration - Optics

- Calibration facility on-site at Nevis
  - 150-m bremsstrahlung W tube source gives intense beam up to 80 keV
  - Calibrated germanium detector, silicon detector, and NuSTAR EM used to measure input and focused beam
  - Used on and off axis with movable mask to determine relative throughput as function of energy and discrete off axis angles
  - Currently operational



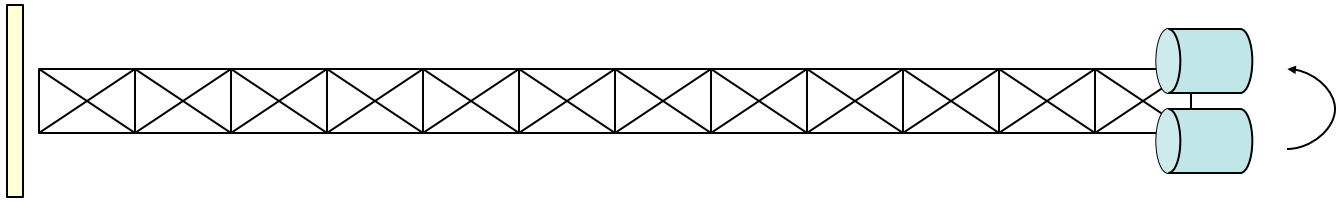
Ground Calibration - focal plane

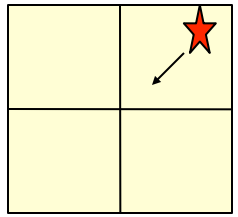
- Quantum efficiency maps
  - Flood illumination with radioactive sources calibrated against standardized detectors
    - ^{55}Fe(6 keV), ^{155}Eu(43, 86.5 keV), ^{241}Am(14, 60 keV), ^{57}Co(6, 14 keV)
    - Select clean, isolated lines with known branching ratios
  - Source calibration utilizing *RHESSI* spare and CIT Ge with collimated sources and GEANT4 model
    - Agreement to <1% on Am and Eu activities
  - CdZnTe model uncertainties allocated 4% for absolute QE
    - Spatial dependence of detailed line shapes, inter pixel and pixel-to-pixel charge collection variations difficult to accurately model

In-flight Calibration

Mast Adjustment/optical axis determination

- Require ‘bright’ point source steady on timescales of one day
  - Initial alignment determined from pointing grid scan
    - Brightest “point” determines optical axis orientation
  - Adjustment made to locate optical axis at specified point near focal plane center
  - Grid scan repeated to determine location of optical axis to required (15” 3-sigma) accuracy
- This calibration done entirely in-flight





In-Flight Calibration Targets

Purpose	Source	RA (J2000)	Dec (J2000)	Variability	Extent
Optical axis Mast adjustment Redistribution matrix	3C273	12 29 06.69	+02 03 08.6	1 - 2% on 1-day timescales	Point source with weak 20” jet
PSF determination	Cygnus X-1	19 58 21.68	+35 12 05.8	Depends on state (~10% in hard state in 1	Point source
Absolute flux calibration Alternate mast adjustment and optical axis	Crab	05 34 31.97	+22 00 52.1	33 ms pulse period for point source	Point source in extended nebula (3-4 arcmin for E<10 keV)

EXTRAS

Integration Time Requirements

- Time allocated to initial in-flight calibration = 15 days
  - Optical axis adjustment determination: 3 +3 days
    - 4 x 4 raster, 1000 x-rays/point will take 8 hours (600 s exposure/point assuming 3C273
  - Optical axis calibration: 1 day
    - 5 x 5 fine raster, 2000 x-rays/point
  - PSF calibration: 4 days
    - Limiting cases is 40-79 keV; 2-5 cps (Cyg X-1) on-axis takes 2 hours to characterize the PSF wings to 3%, 36 hours at largest off-axis angle
  - Effective area normalization: 4 days
    - Limited (statistical) by off-axis, high energy response

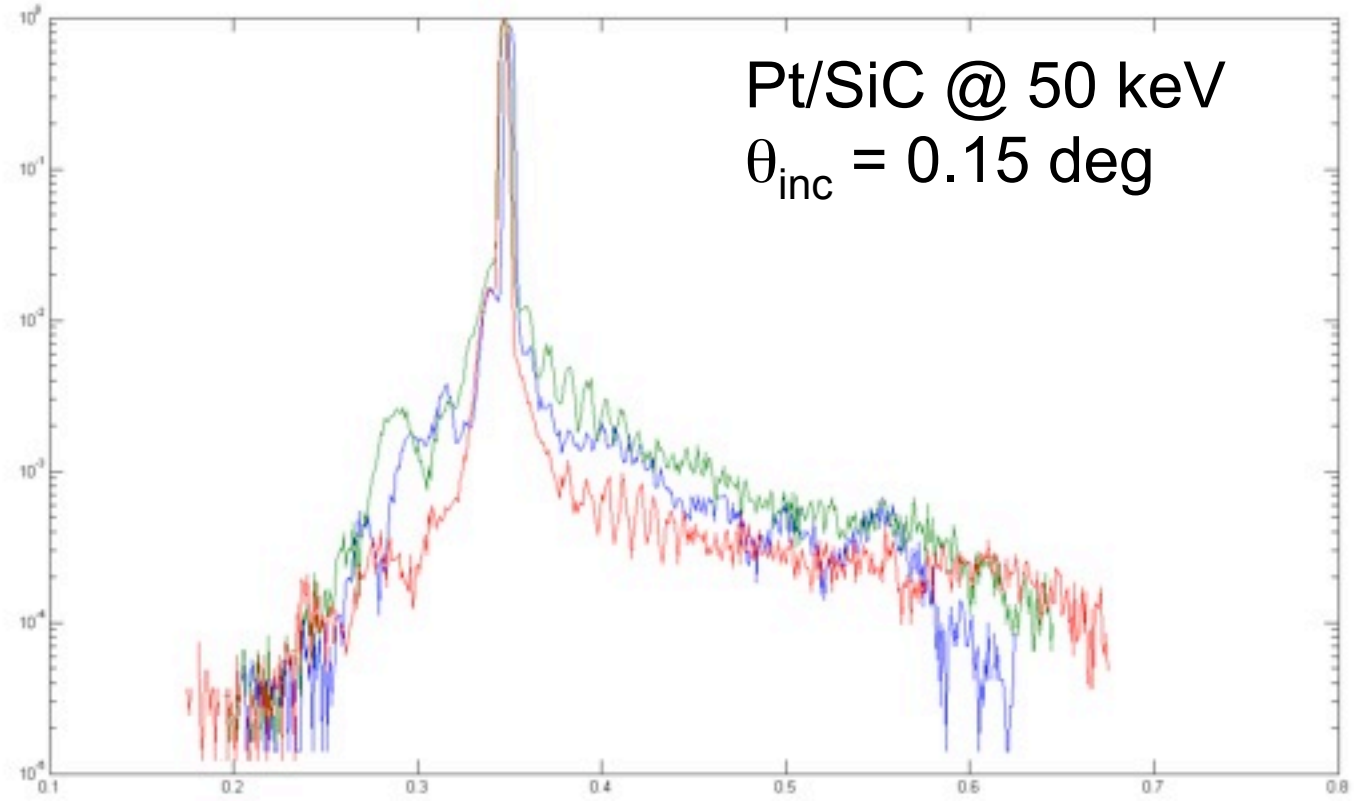
Ground Calibration - Optics

- Level 4 Requirements
  - Relative effective area between 6 – 60 keV over central 8’ x 8’ in 2 keV bins to 4%
  - Relative effective area between 60 - 79 keV over central 8’ x 8’ in 2 keV bins to 3%

Ground Calibration – Focal Plane

- Level 4 Focal plane calibration requirements
  - Absolute quantum efficiency for each pixel in each keV bin to <5% absolute between 6 – 80 keV
  - Photopeak relative efficiency for each pixel to 2% for each keV bin between 6 – 80 keV
  - Transparency of the focal plane entrance window to 0.5% in each keV bin from 6 – 80 keV
- Calibration-related requirements
  - The uncertainty in the position bias correction in the measurement of X-ray position < 100 microns

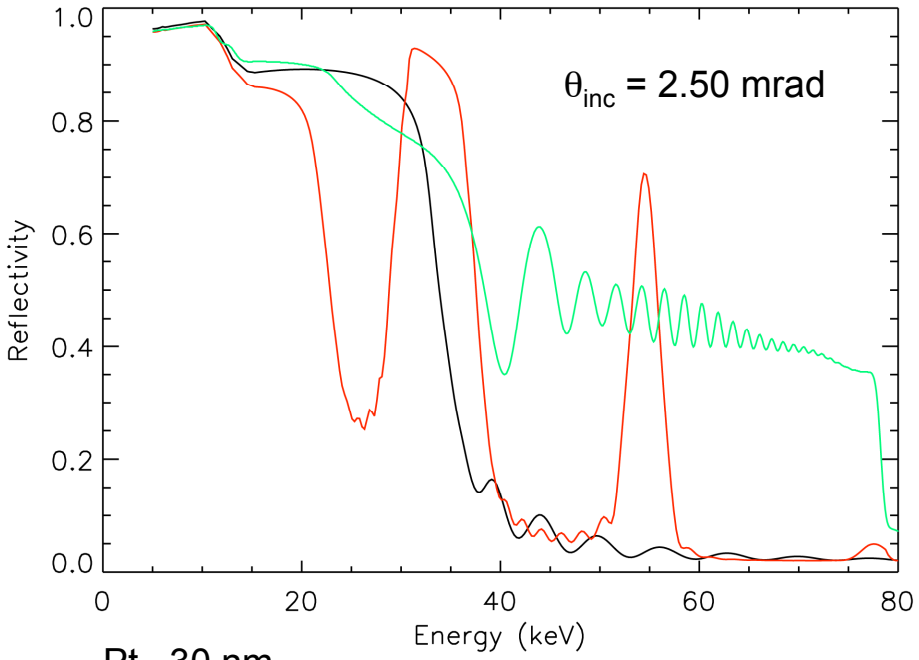
Scattering



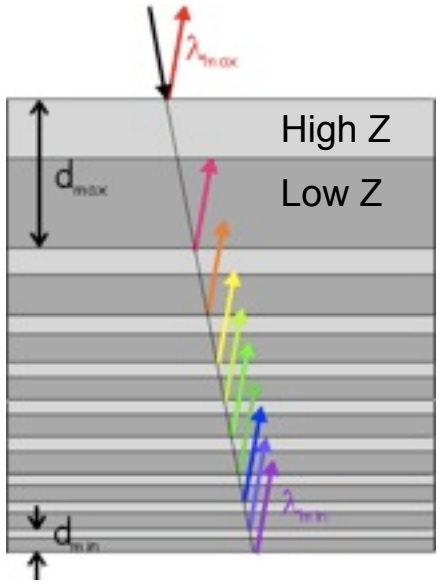
Depth Graded Multilayers

Bragg law:

$$m\lambda = 2d\sin(\theta_{inc})$$



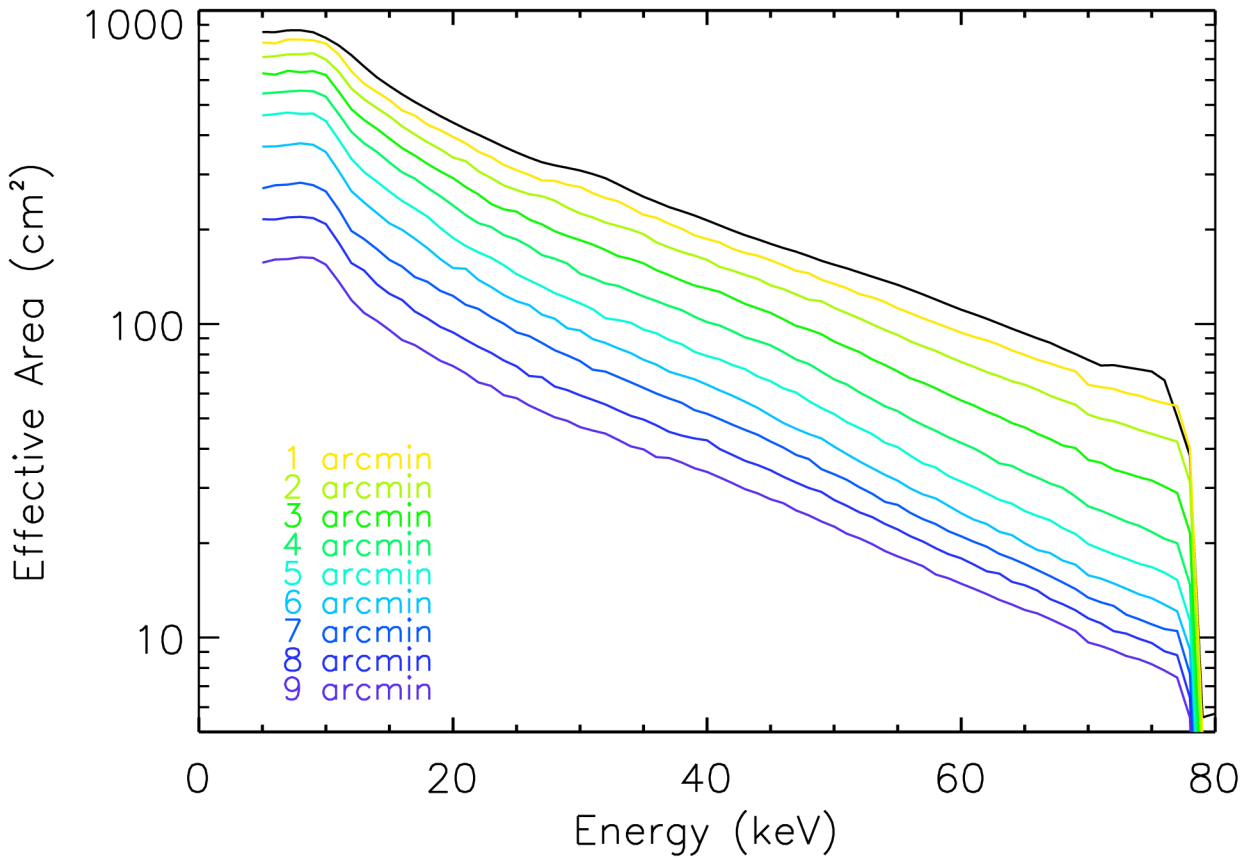
Pt, 30 nm
Pt/SiC constant-10, D=10 nm, G=0.38
Pt/SiC mirror group 5



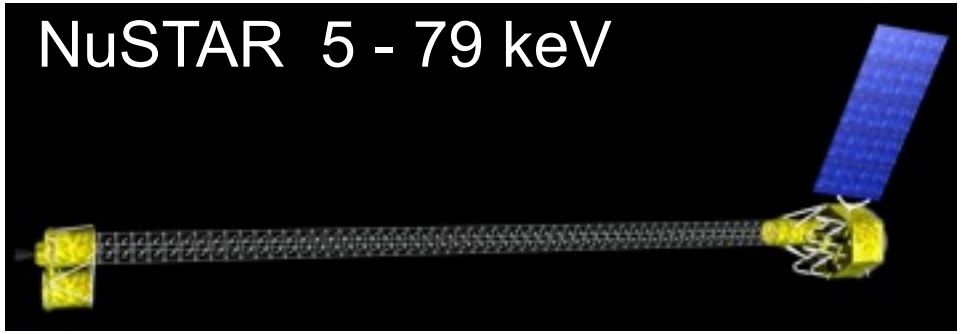
Depth Grading:

$$D_i = \frac{a}{(b+i)^c} \qquad i = 1,N$$

Effective Area



Focusing Optics



Point Spread Function

- Require bright, flat spectrum point source
  - Require flux at high energy to calibrate over entire energy range
  - Can be time variable but must be bright so that PSF wings are above detector background level
- Calibration sequence consists of pointing grid covering off axis angles
  - 6 x 6 grid 12 arcminutes on a side
  - Integration time sufficient to constrain PSF wings
- This calibration done entirely in-flight