Development and Calibration of the ART-XC Mirror Modules for the Spectrum Rontgen Gamma Mission

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SRG Overview

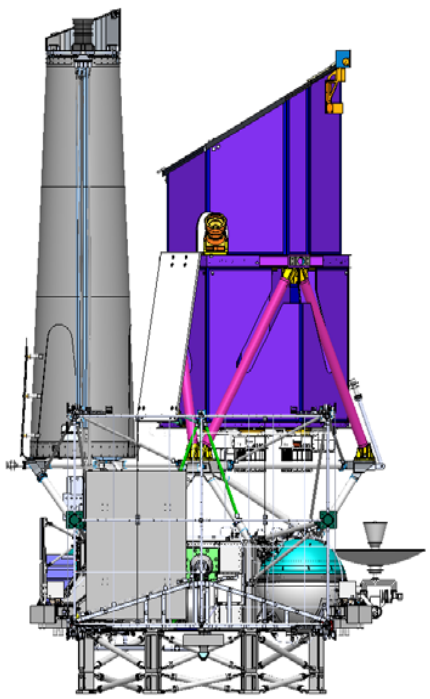
✓The Spectrum-Röntgen-Gamma (SRG) mission is a Russian-lead X-ray astrophysical observatory that carries two co-aligned X-ray telescope systems.

✓The primary instrument is the German-led **e**xtended **RO**entgen **S**urvey with an **I**maging **T**elescope **A**rray (eROSITA), a 7-module X-ray telescope system that covers the energy range from 0.2-12 keV.

✓The complementary instrument is the **A**stronomical **R**oentgen **T**elescope – **X**-ray **C**oncentrator (ART-XC or ART), a 7-module X-ray telescope system that provides higher energy coverage, up to 30 keV.

Parameter	ART	eROSITA
Energy Range	5-30 keV	0.2-12 keV
Effective Area	455 cm^2 at 8 keV	2500 cm^2 at 1 keV
Field of View	32 arcmin	1 deg
System Angular Resolution (on axis)	1 arcmin	15 arcsec
Energy Resolution	1.4 keV at 14 keV	130 eV at 6 keV

ART-XC eROSITA

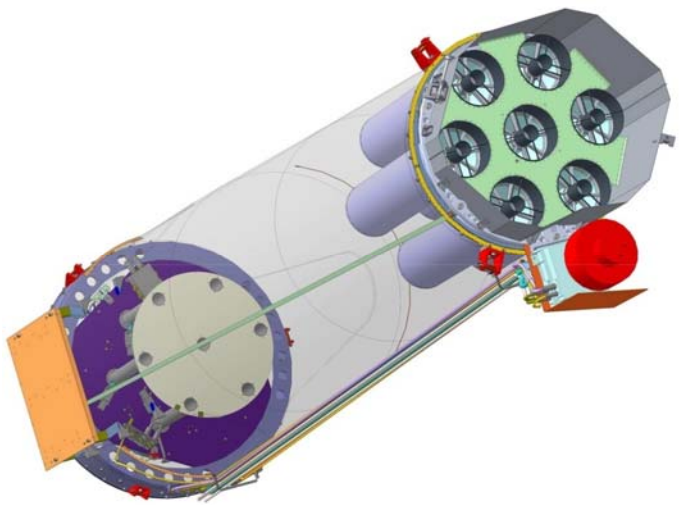


ART-XC Optics Configuration

MSFC has designed and is fabricating

- ***four*** ART x-ray optics modules under an International Reimbursable Agreement between NASA and with IKI (delivery – February 2014)
- ***three + one spare*** ART modules under Agreement regarding Cooperation on the ART-XC Instrument onboard the SRG Mission between NASA and IKI (delivery – March 2014)

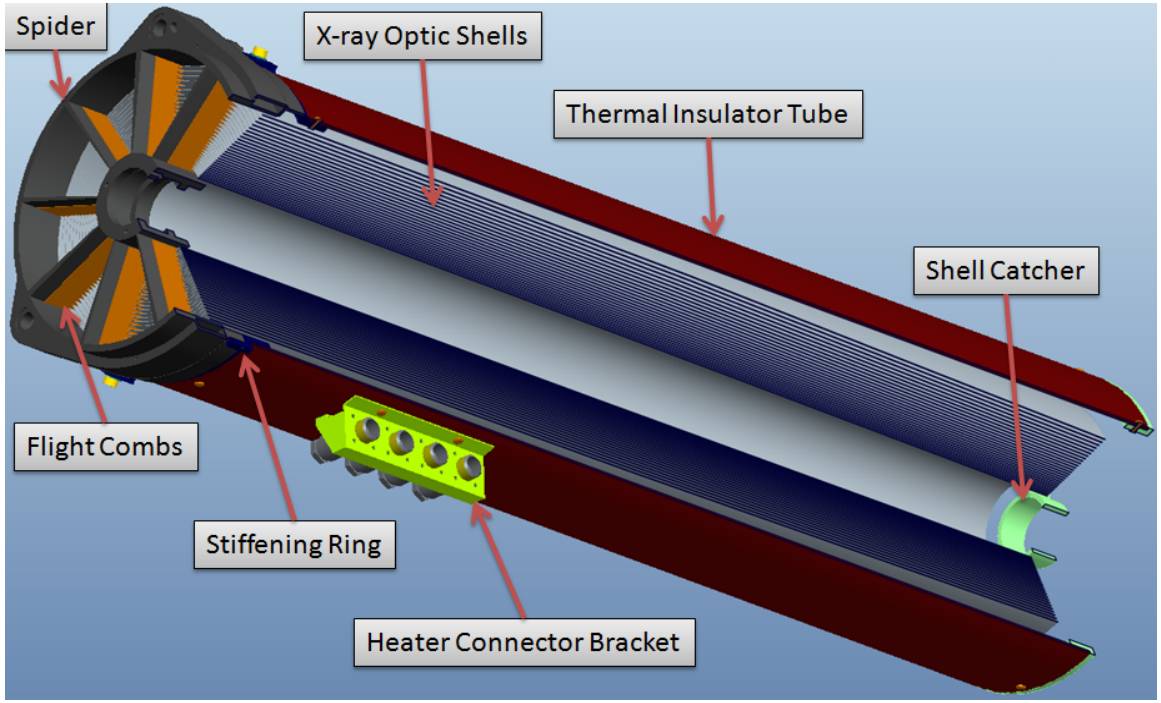
Parameter	Value
Number of Mirror Modules	7=4+3
Number of Shells per Module	28
Shell Coating	> 10 nm of iridium (> 90% bulk density)
Shell Total Length, inner and outer diameters	580 mm, 50 mm, 150 mm
Encircled Half Energy Width	Less than 1 mm diameter, center of field of view Less than 2.5 mm diameter, 15 arcmin off axis
Mirror Module Effective Area	≥ 65 cm^2 at 8 keV (on axis)
Module Focal Length	2700±1 mm



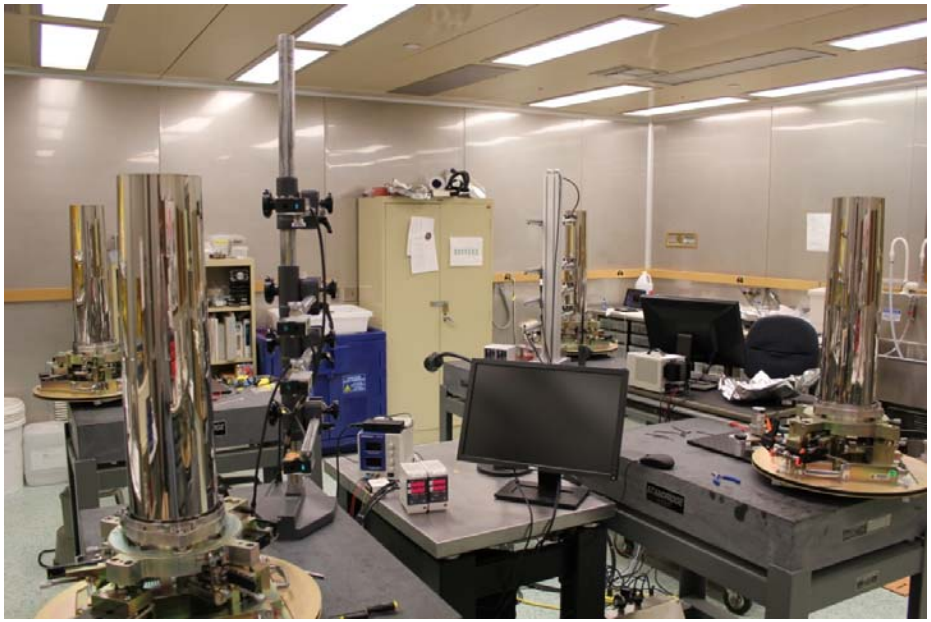
Schematic representation of the ART-XC instrument

Mechanical Design

- One spider design permits increasing the thickness of outer shells for given weight budget (15 kg / Module)
- Shells are electroformed NiCo, 250 – 325 microns thick



ART-XC Mirror Production



ART-XC Mirror Status

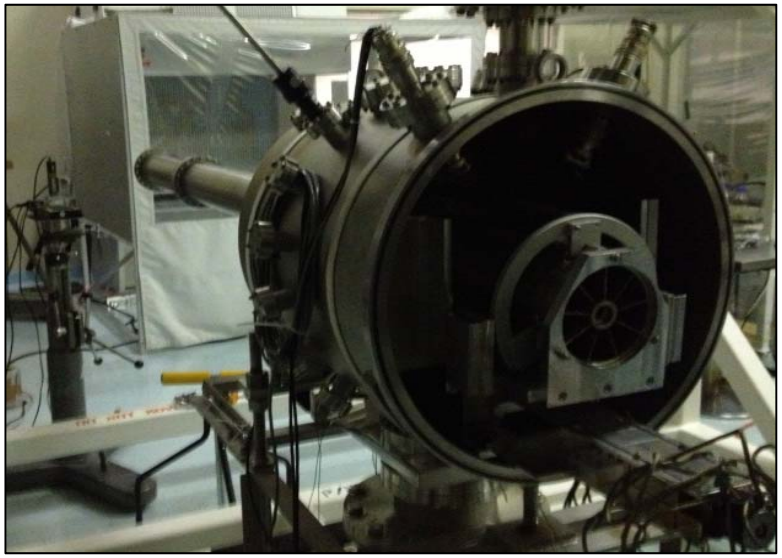
- All shells fabricated for 1st four module
- 75% of shells fabricated for 2nd four modules
- Qualification (engineering) unit tested and delivered to IKI
- 1st flight module undergone extended x-ray calibration
- 2nd module under calibration now

ART-XC: MSFC Test Facility

MSFC STRAY LIGHT FACILITY

- ~ 104 m Beamline
- 1-m diameter main tube
- 3m x 10m instrument chamber

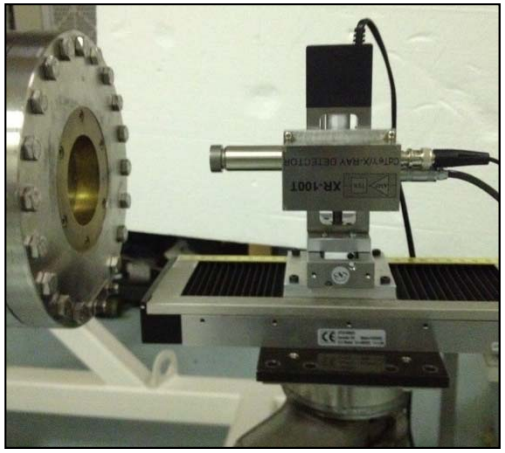
- **FOR ART testing:**
- Bell housing for smaller, shorter-focal-length optics
- Contains Tip, Yaw and linear stages all computer controlled
- Cu x-ray source system, 50kV, 1 mA, 0.5 mm spot

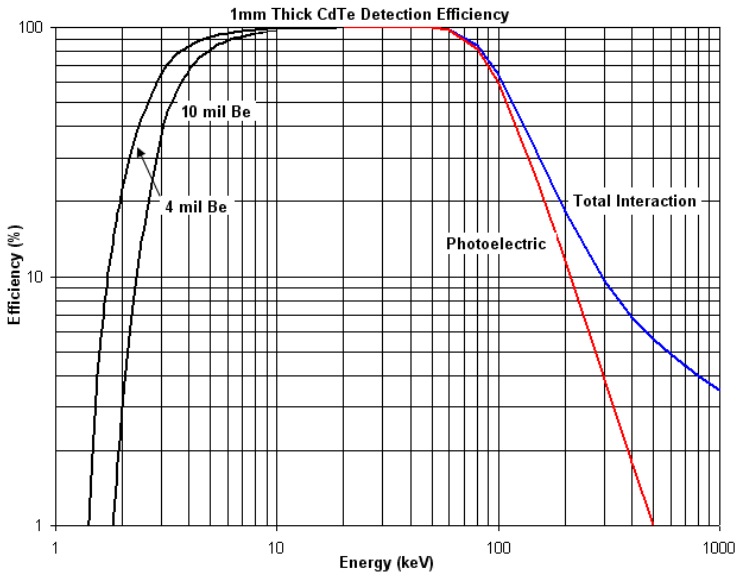


ART-XC: MSFC Test Facility

CdTe Detector

- 5 x 5 x 1 mm
- High rate capability (>105 c/s)
- Series of laser-cut W pinholes





CCD Camers

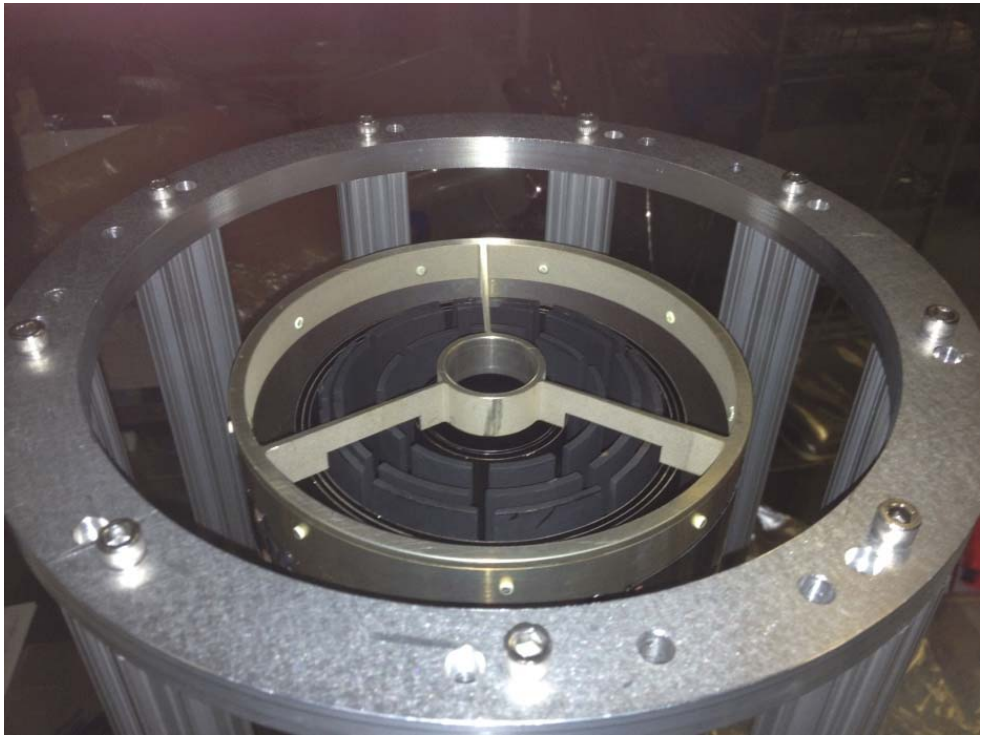
- 2k x 2k pixels
- 13.5 micron each
- Frame / sec readout capability

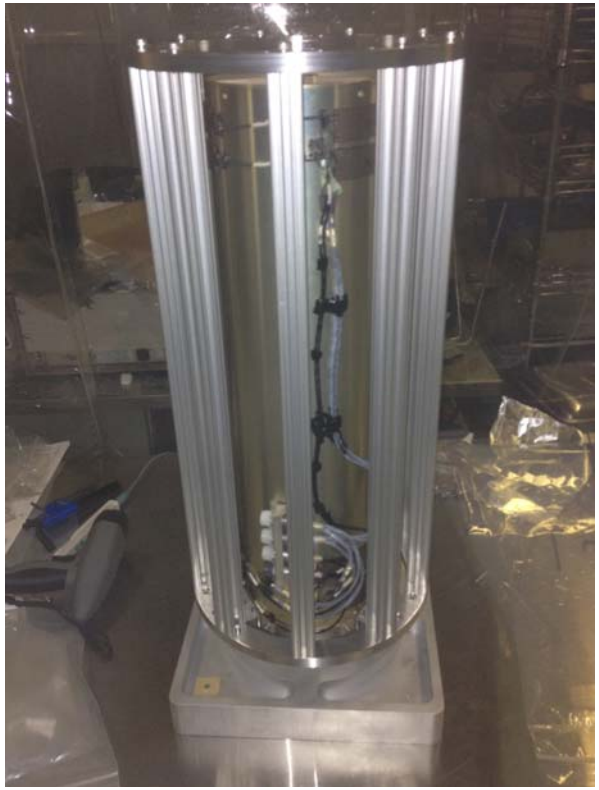
Qualification Unit

✓Three inner shells (1,2,4)

✓Three outer shells (25,26,27)

✓Three mass simulators to replace missing shells (diameters are 74, 101.3 and 126.4 mm)



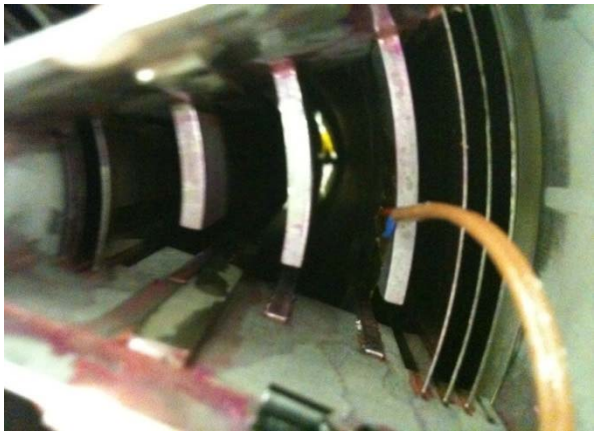


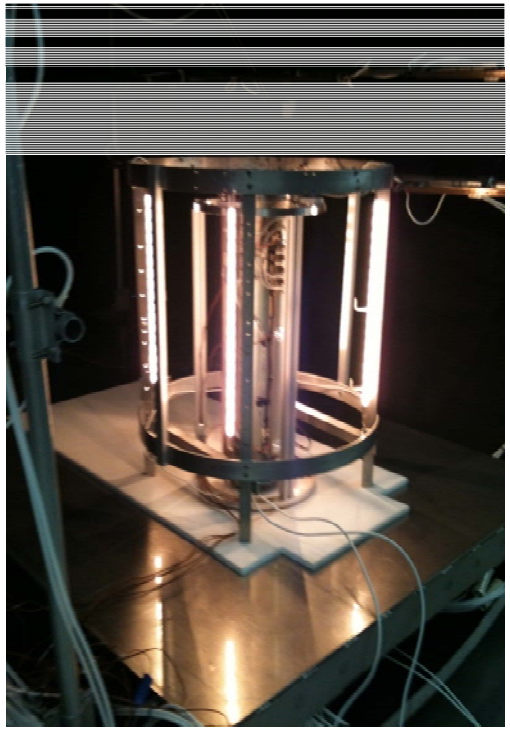
Qualification unit with handling fixture mounted on the shipping base

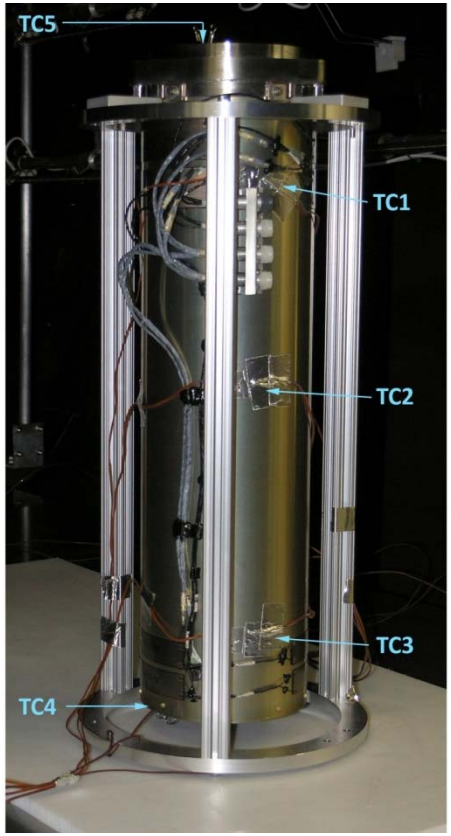
ART-XC: Qualification Unit

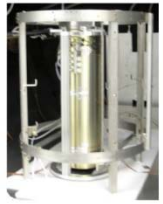
Effective area and resolution of qualification unit measured as follows:

- Initial test
- Post vibration test #1
- Post thermal (survival temperatures) test
- Post acoustic test
- Post module modification (stabilizers added)
- Post vibration test #2
- Final (post shock test)

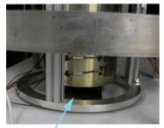








With Lamp Array

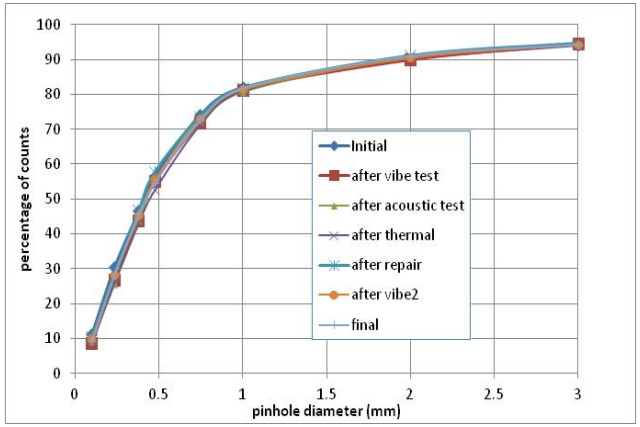


OWS

ART-XC X-ray Module
Thermal Cycle Test
ET20-2013-686
March 13, 2013
Chamber V7

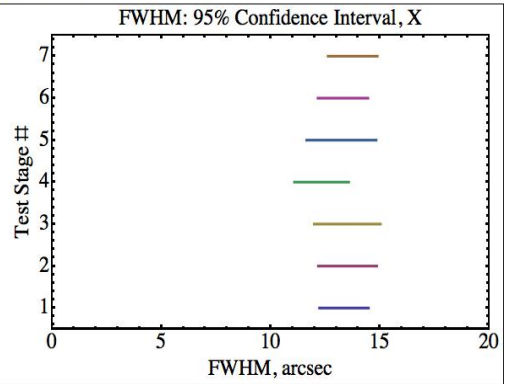
ART-XC: Qualification Unit X-ray Results

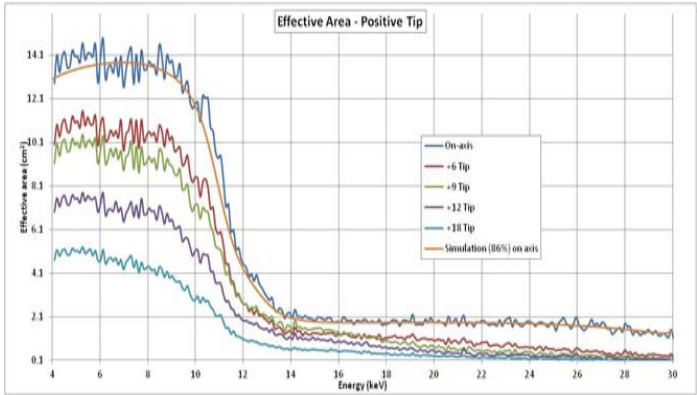
Test	Effective Area (cm^2)	Error (cm^2)
Initial	13.56	0.35
Post vibration test # 1	13.26	0.49
Post thermal test	13.01	0.47
Post acoustic test	13.81	0.38
Post module modification (stabilizers)	Not tested	
Post vibration test # 2	13.49	0.38
Final (post shock)	13.71	0.38



FWHM Summary vs. Stage of Testing for X Scans, arcsec

Stage #	Test Stage	95% CI X Min	95% CI X Max
1	Initial	12.23	14.47
2	Post Vibe 1	12.18	14.85
3	Post Thermal	11.99	15.02
4	Post Acoustic	11.08	13.57
5	Post Mod	11.64	14.82
6	Post Vibe 2	12.16	14.45
7	Final (post shock)	12.62	14.88





Flight Unit X-ray Calibration Requirements

CCD CAMERA

Point Spread Function (PSF) – FIRST MODULE
Measure the PSF at each focus position and off-axis angle listed below:

NOMINAL FOCUS
Offset angles (36 measurements)
Range: -18, -12, -7, -3, 0, 3, 7, 12, 18 arcmin at four different azimuthal angles: 0, 45, 90, 135

NOMINAL – 7 MM
Offset angles (68 measurements)
Range: -18, -15, -12, -9, -7, -5, -3, -1, 0, 1, 3, 5, 7, 9, 12, 15, 18 arcmin at four different azimuthal angles: 0, 45, 90, 135

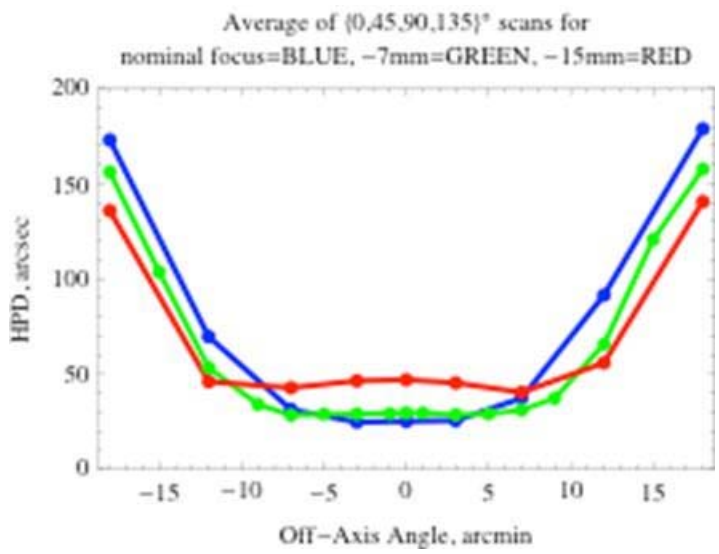
NOMINAL – 15 MM
Offset angles (36 measurements)
Range: -18, -12, -7, -3, 0, 3, 7, 12, 18 arcmin at four different azimuthal angles: 0, 45, 90, 135

Point Spread Function (PSF) – REMAINING MODULES
Measure the PSF at each off-axis angle listed below:

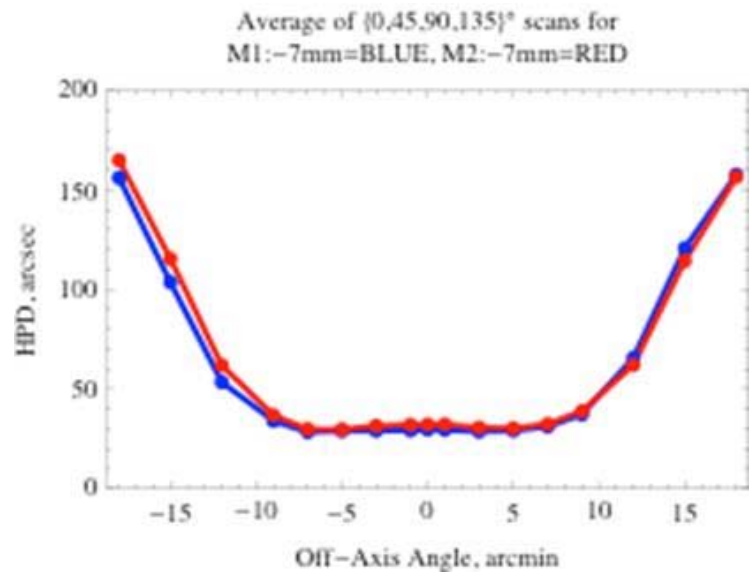
NOMINAL – 7 MM
Offset angles (68 measurements)
Range: -18, -15, -12, -9, -7, -5, -3, -1, 0, 1, 3, 5, 7, 9, 12, 15, 18 arcmin at four different azimuthal angles: 0, 45, 90, 135

Flight Unit X-ray Calibration (CCD)

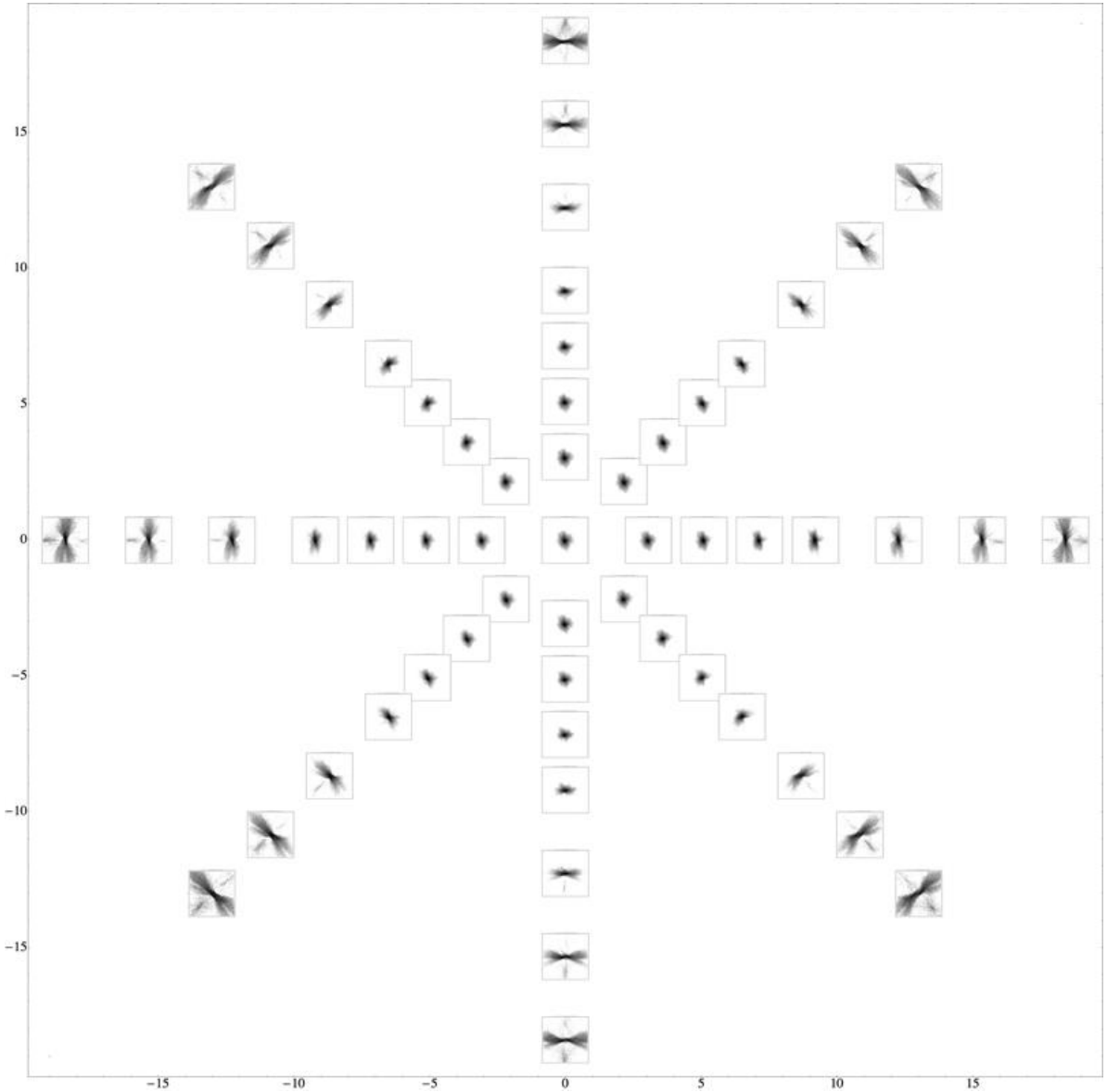
- M1 Half Power Diameter vs. Off-Axis Angle for Several Focus Positions
  - Field of view with HPD < flight pixel size expands with de-focus
  - 7 mm defocus position is preferred for flight for best survey sensitivity



- M1 vs. M2 Half Power Diameter vs. Off-Axis Angle at Preferred Focus Position
  - Modules are very similar
  - Repeatability of calibration results confirmed



Flight Unit X-ray Calibration (CCD)

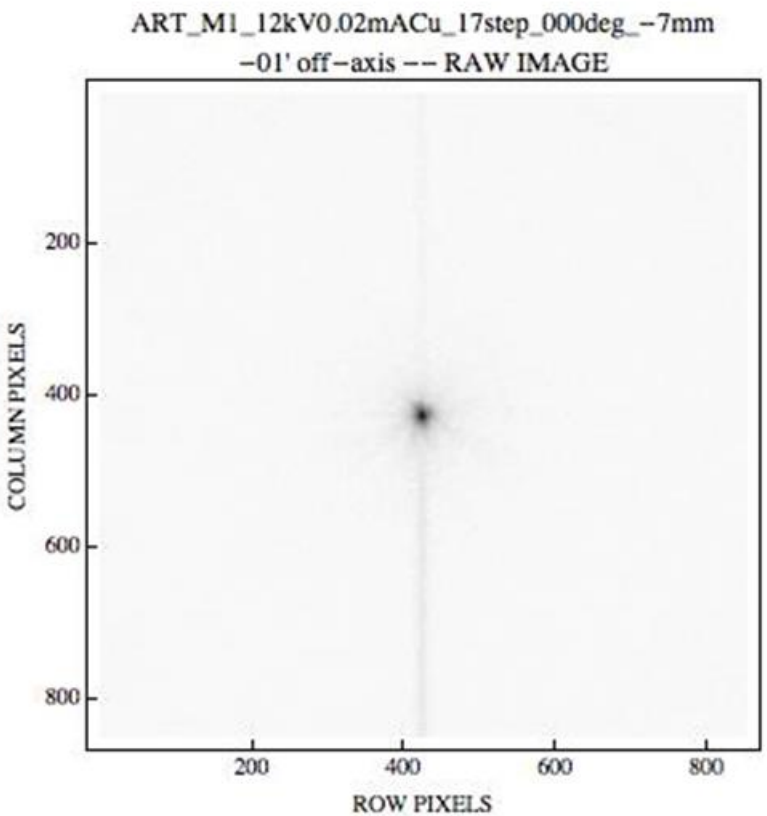


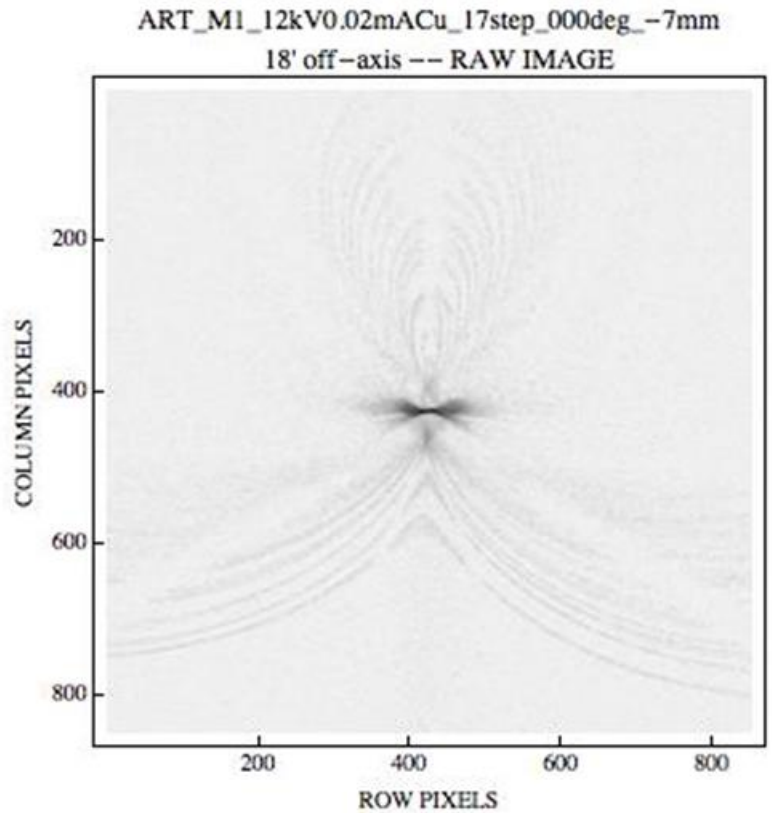
True-to-scale images at 7mm from focus, as a function of off-axis angle in arcmin

Flight Unit X-ray Calibration (CCD)

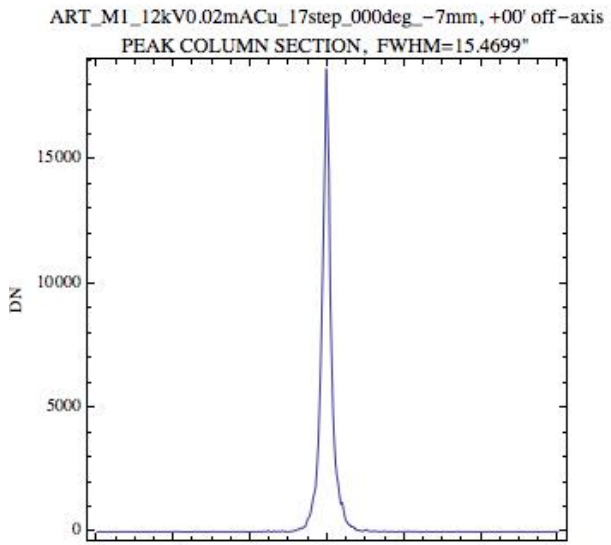
Comparison of on-axis and 18 arcmin off-axis raw images

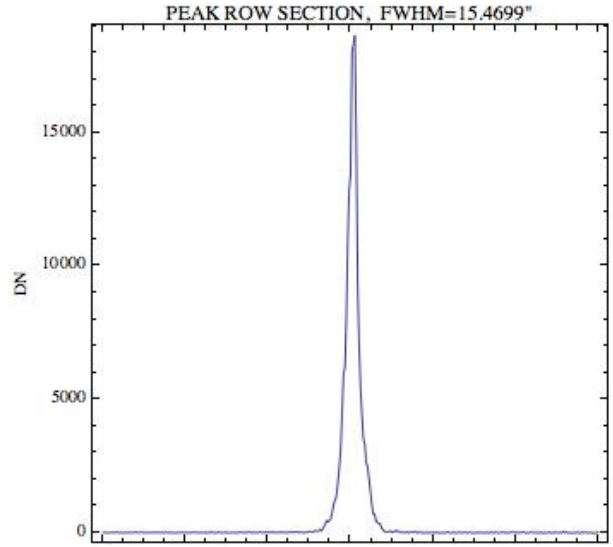
Off-axis image shows extended wing structure due to singly reflected x-rays
Vertical line below on-axis image is an artifact of CCD readout smear -- removed in analysis
X-rays from 8 keV Cu-K lines
1 pixel = 2 arcsec



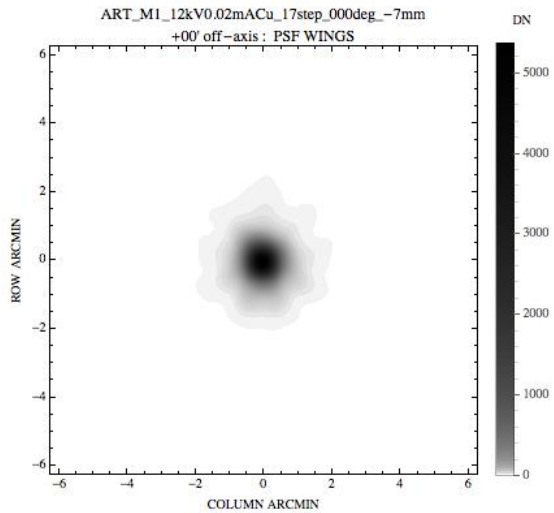


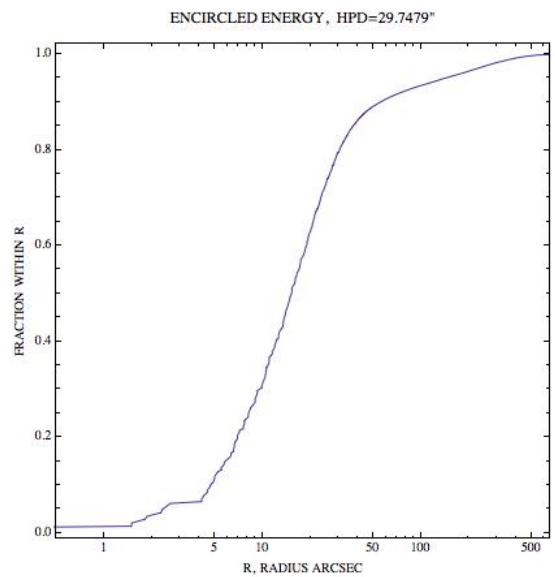
Flight Unit X-ray Calibration (CCD)





FWHM on axis

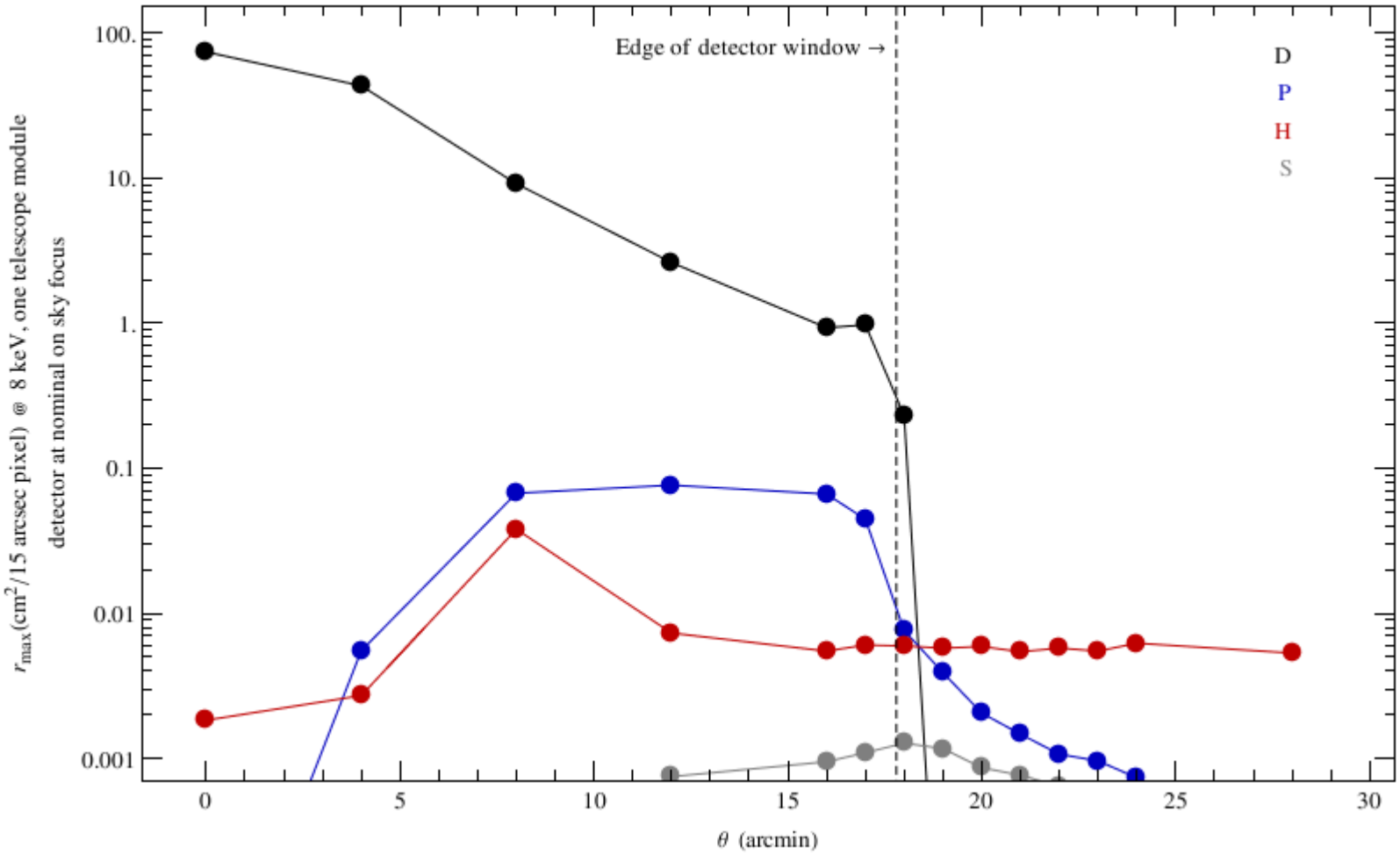




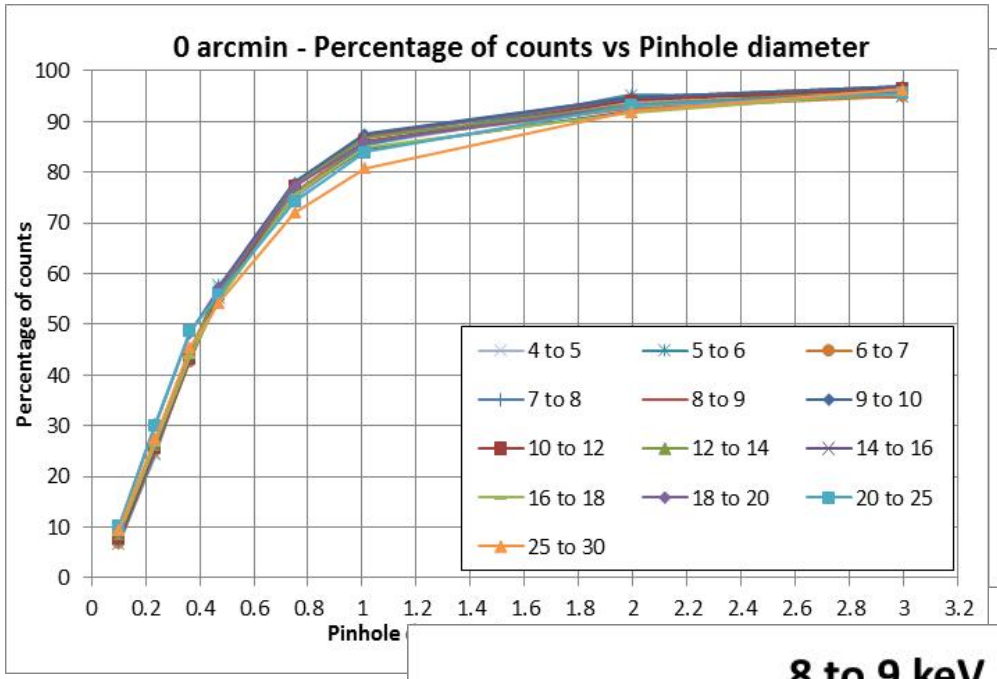
PSF on axis

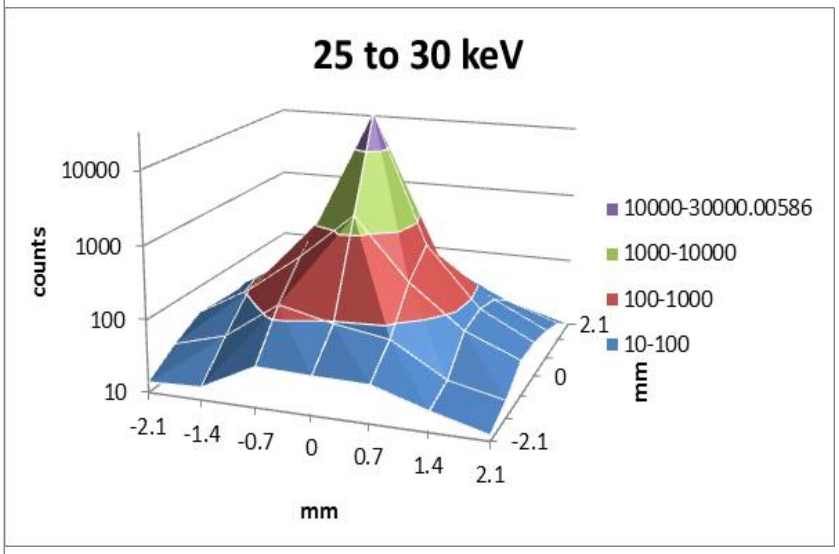
Modeled Stray Light

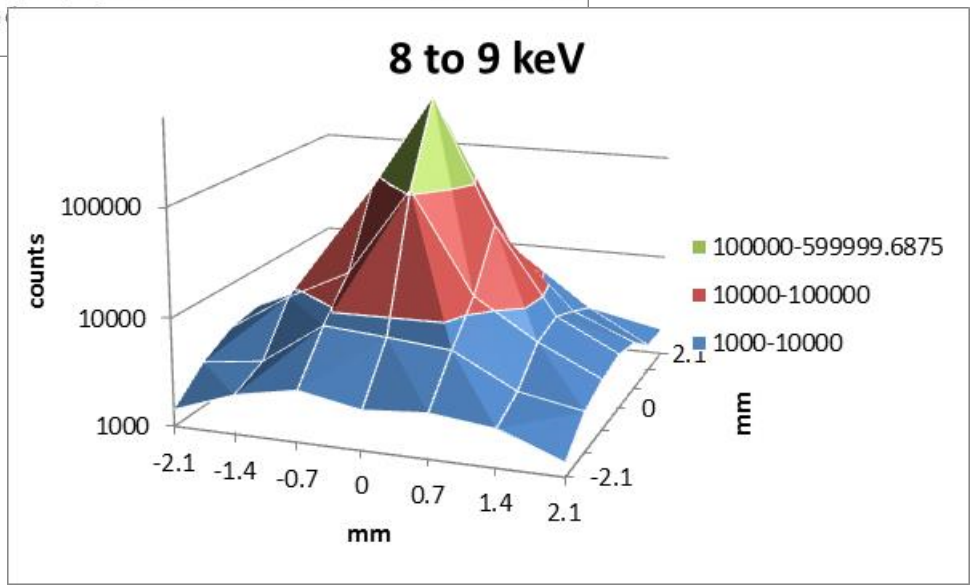
Modeled stray light reaching the detector on orbit, in terms of brightest pixel. Curves represent (double reflected (black) and singles from the P (blue) and H (red) segments. Straight-throughs are depicted in gray.



Flight Unit X-ray Calibration (CdTe)



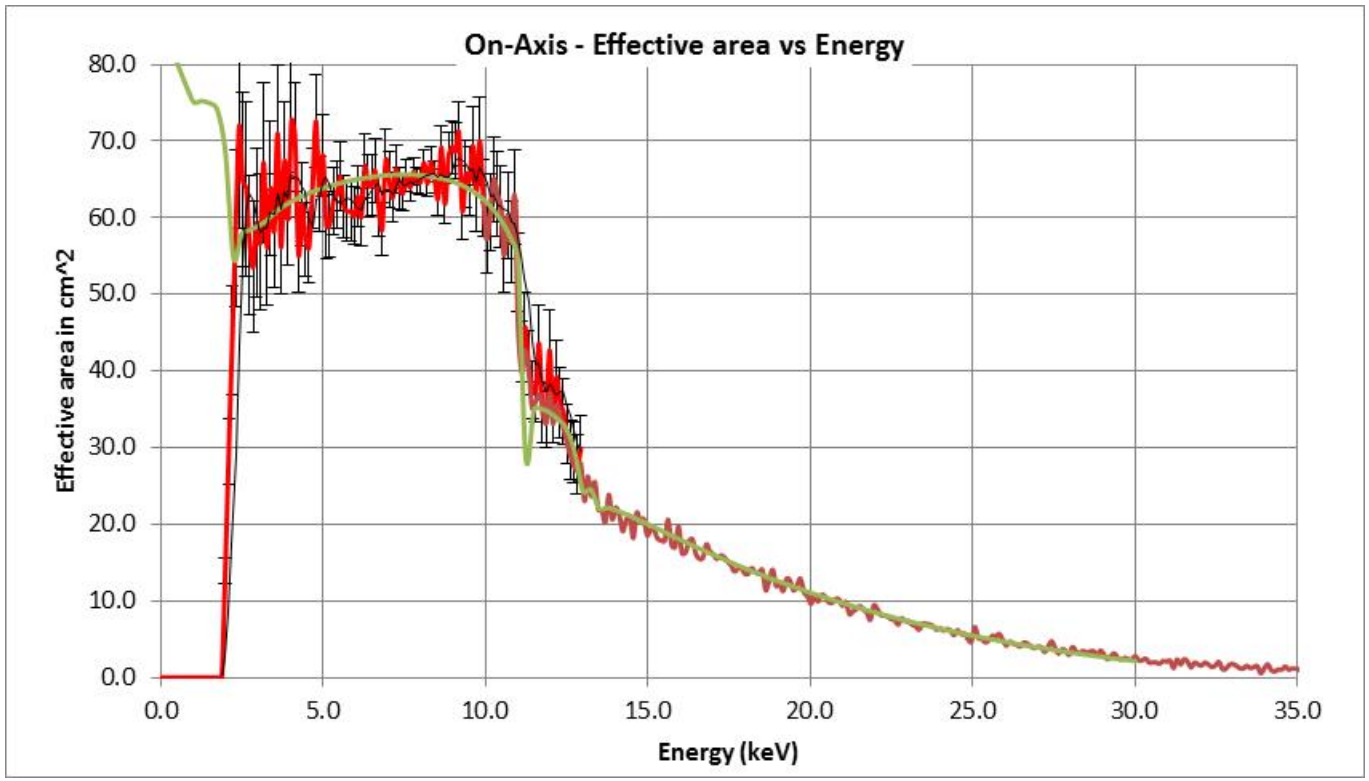




On axis measurements

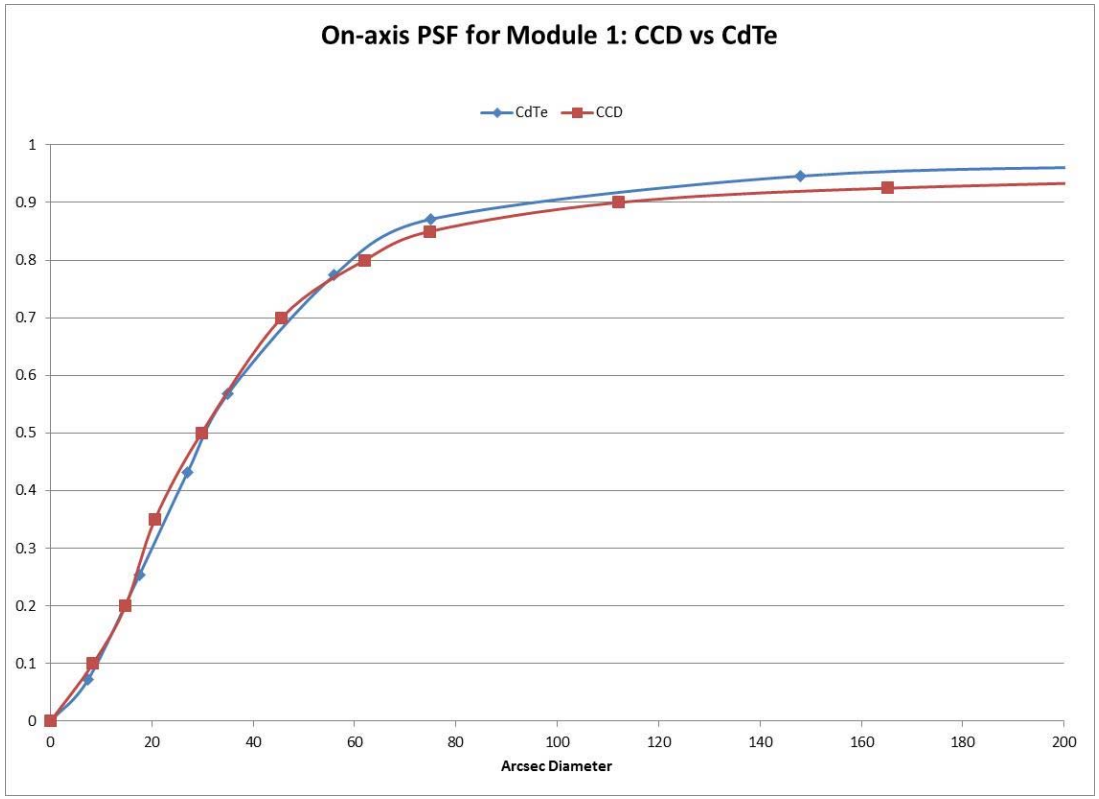
Flight Unit X-ray Calibration (CdTe)

Flight Module 2 measured effective area (104m) compared with (91%) model



On-axis effective area (infinite source) = 68 cm^2 (requirement = 65cm^2)

Flight Unit X-ray Calibration (Comparison)

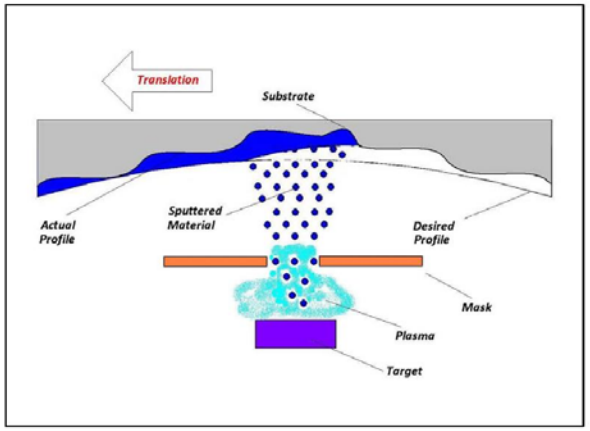


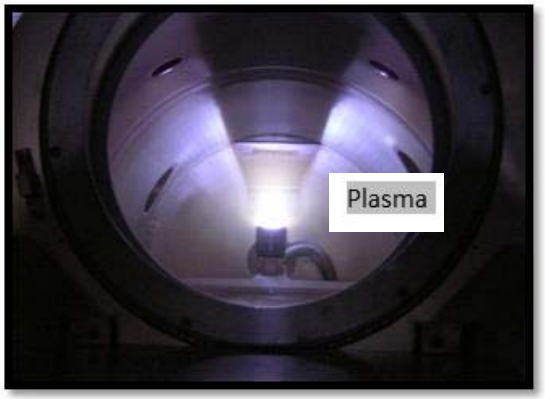
Reasonably good agreement between CCD and CdTe

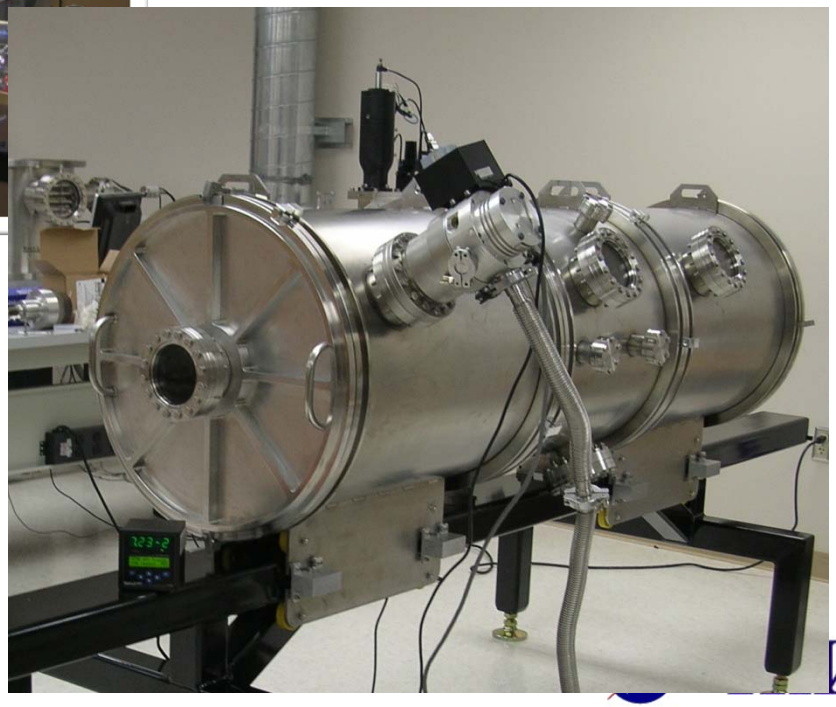
Flight Unit X-ray Calibration: CONCLUSION

- ART-XC Flight Module Calibration and data processing has begun
- CCD and CdTe data agree well
- The first two modules meet effective area requirement (65 cm^2 / module @ 8 keV) and greatly exceed angular resolution requirement (30 arcsec, defocused, vs ~ 60 arcsec)
- Calibration will be concluded by late February / early March 2014

Differential Deposition (K.Kilaru, C. Atkins, D. Broadway)

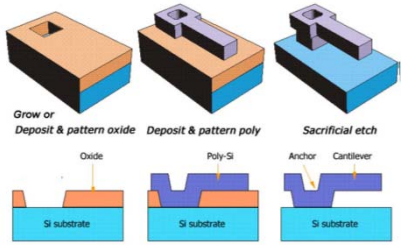




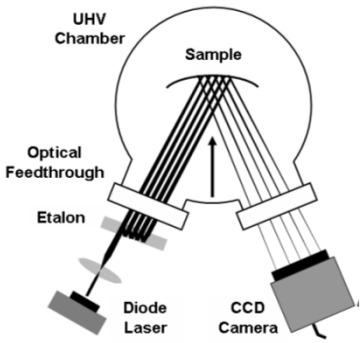


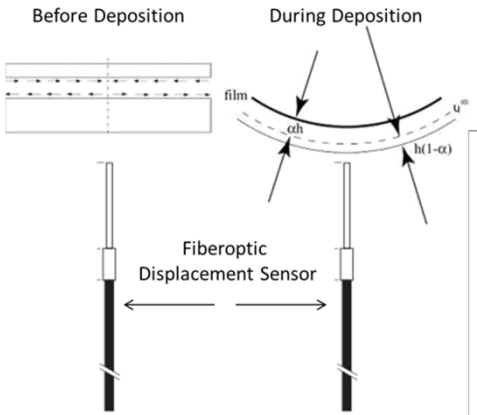
Stress Measurement in Coatings (D. Broadway)

Methods of In-Situ Stress Measurement: All aim to measure the change in curvature of the substrate from which stress is calculated from the Stoney equation: $\sigma h_{film} = M\frac{h^2}{6}\kappa$



Our Method: We exploit the known spherical deformation and infer the substrate curvature by measuring the sag of the wafer (just one point).





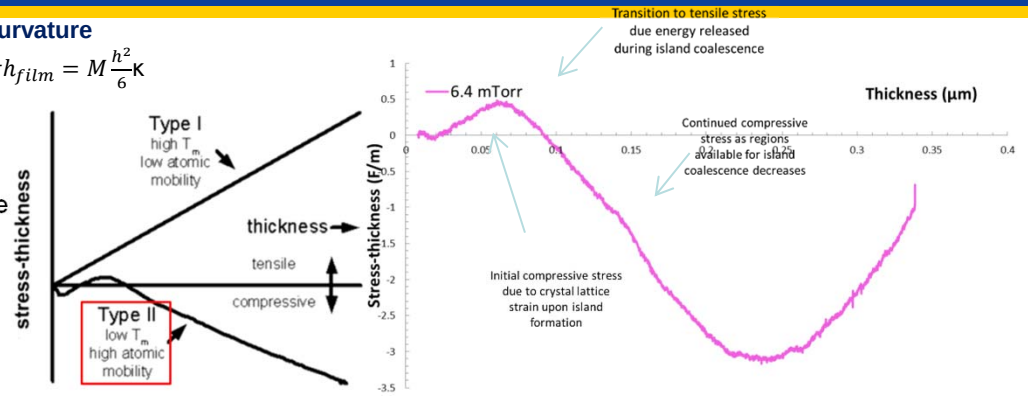


Figure 1- After R. Abermann, Vacuum 41, 1279 (1990) (left); Measured In-Situ (right)- Data matches measured curves from several published experiments.