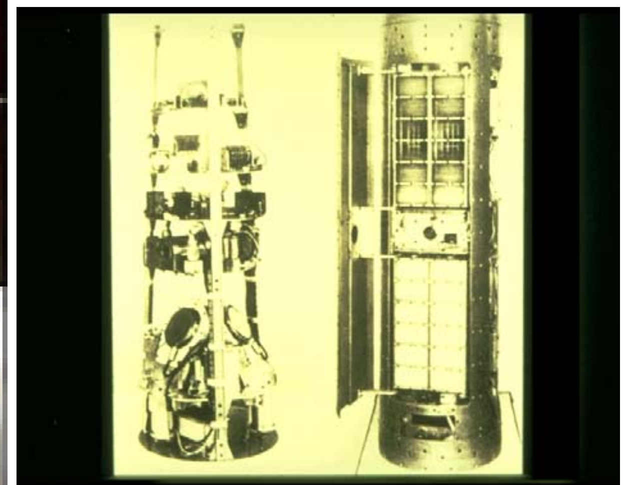
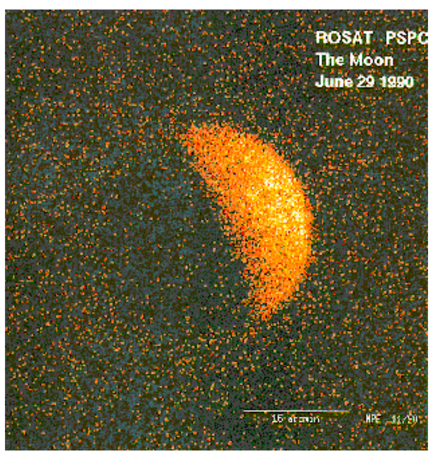
Optics Requirements for X-ray Astronomy & Developments at the Marshall Space Flight Center

Birth of X-Ray Astronomy

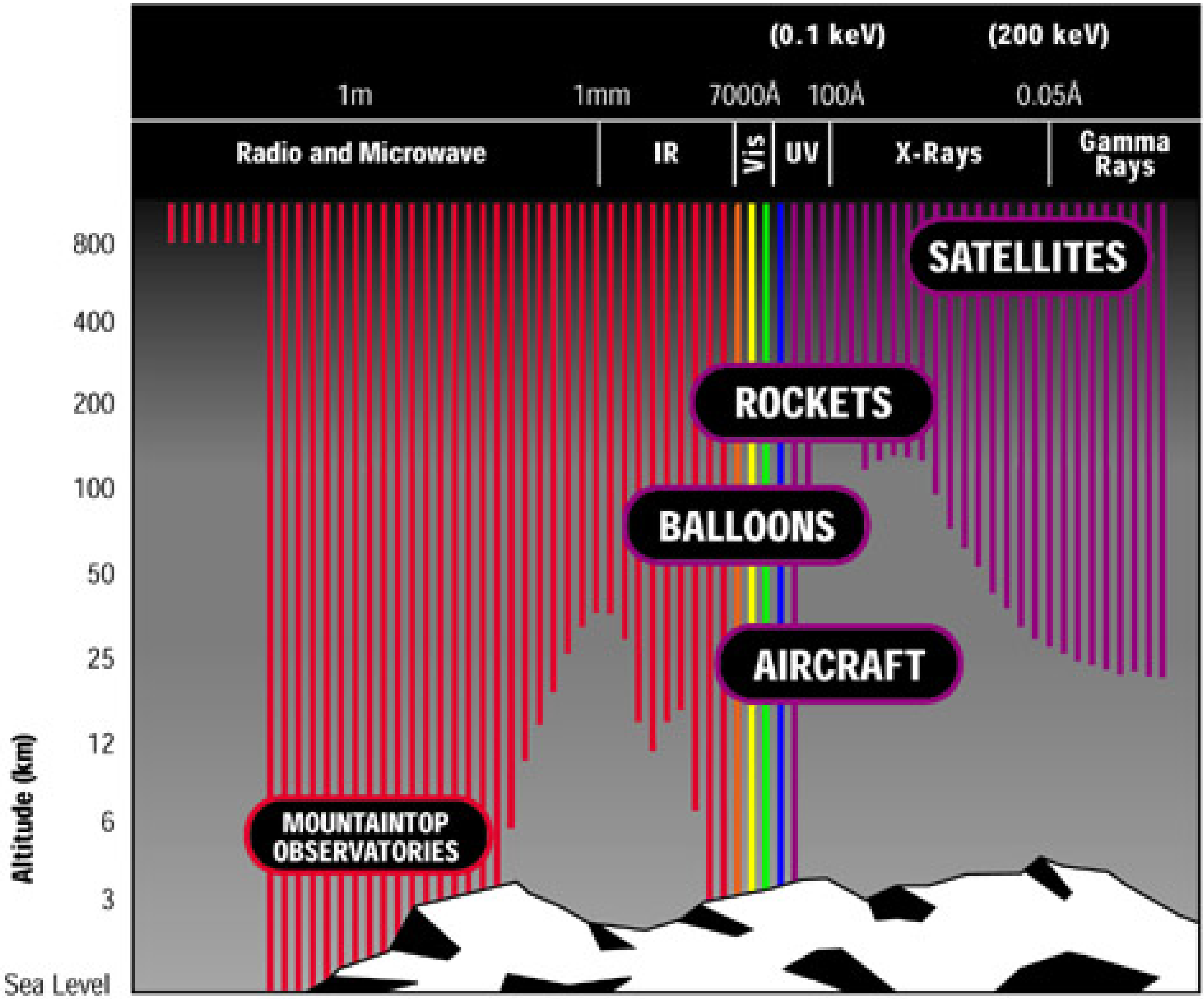
- In 1962, Riccardo Giacconi and colleagues at AS&E flew sounding rocket to look at x-ray fluorescence from the moon
- Lunar signal was overshadowed by very strong emission from the Scorpious region
- Discovered the first extra-solar x-ray source, Sco X-1, and pervasive x-ray background
- This was the effective birth of x-ray astronomy





The Atmosphere Protects Us

Altitude (km)

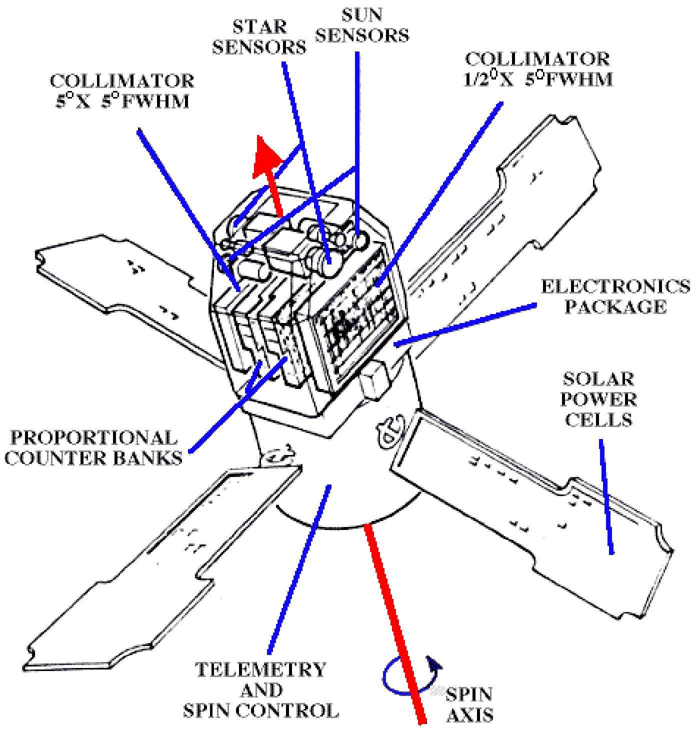


X-Ray Astronomy

First X-Ray Satellite

The UHURU spacecraft was launched in 1970

It weighed just 140 pounds, not much more than the rocket experiment



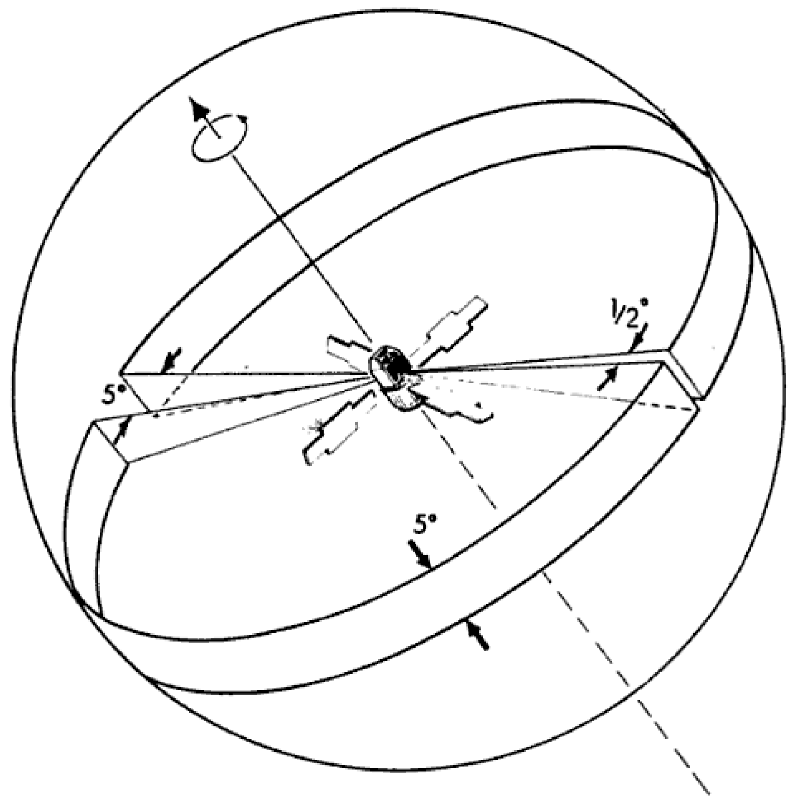
X-Ray Astronomy

UHURU

Used a simple collimator system, to locate x-ray sources in sky

It operated for 3 years and discovered 339 sources in the whole sky

OBSERVATIONS OF GALACTIC X-RAY SOURCES 307



5. Scan geometry of the UHURU X-ray detectors shown as the projection on a . As the satellite rotates the X-ray detectors view in a 5° band, 90° from the spin axis.

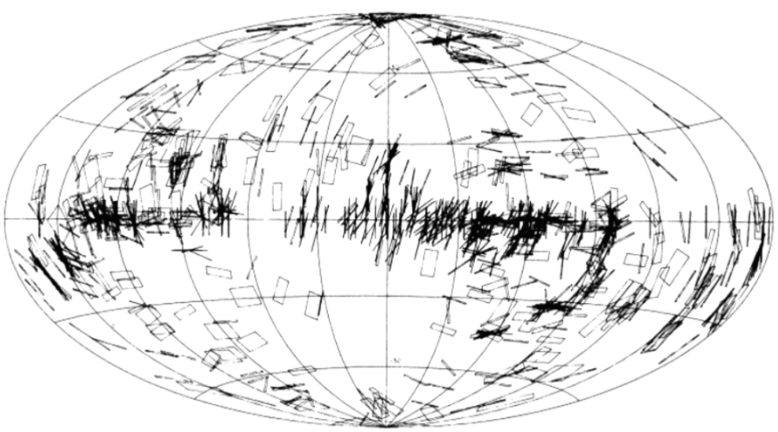
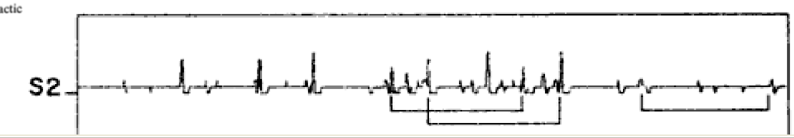


FIG. 3.—Lines of position which result from the computer scan of superposed data are plotted on an equal area projection of the sky in galactic coordinates. The line widths are $\pm 1\ \sigma$ as determined by the minimum χ^2 fits. There are 1171 lines on the plot.



X-Ray Astronomy

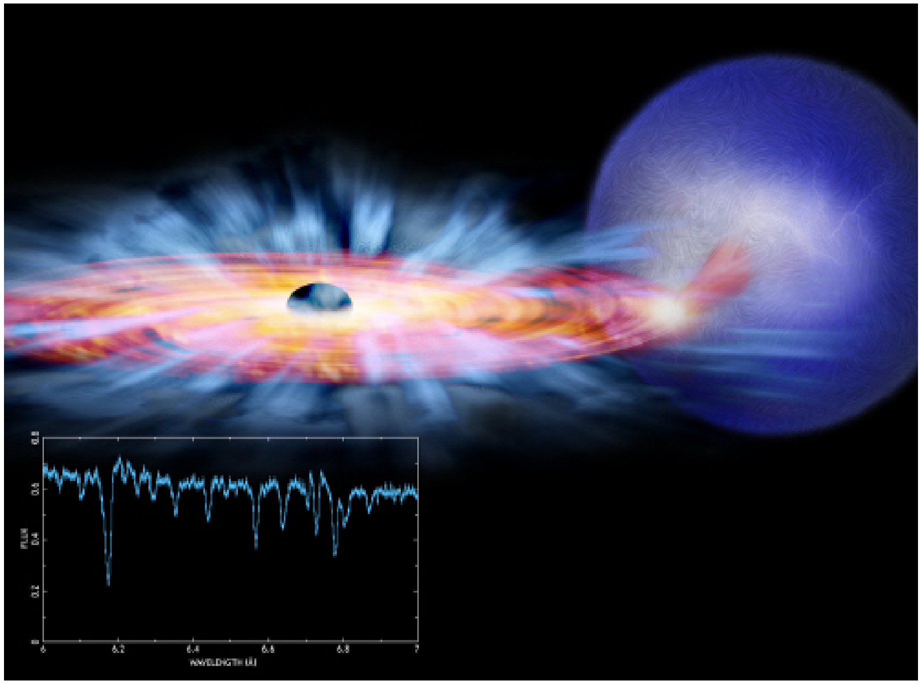
Early observations

From these early observations a picture emerged of a typical x-ray source:

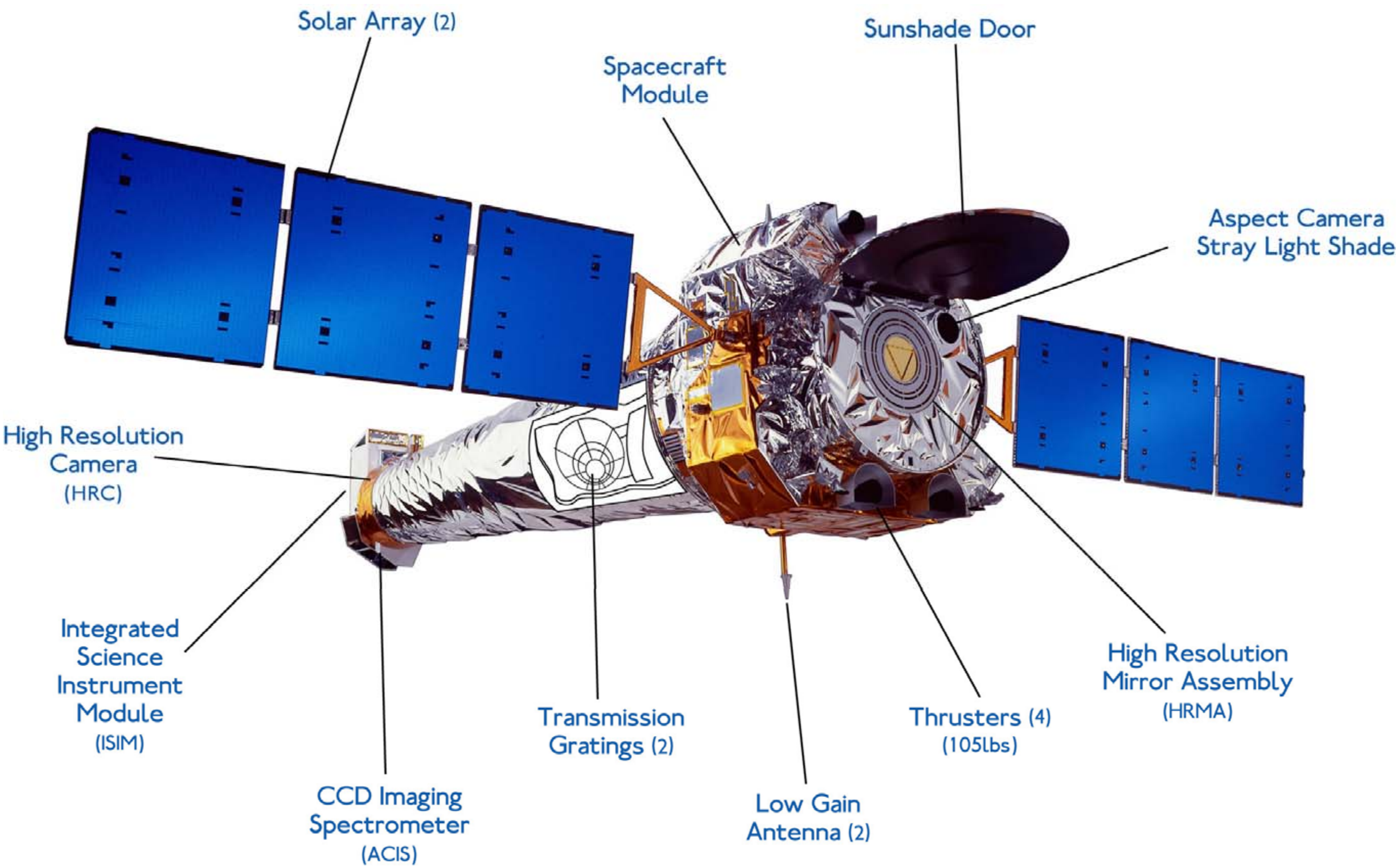
A compact object (neutron star, black hole, white dwarf) orbiting around a normal star

Matter streams down on to the compact object forming an accretion disk

As the matter spirals down and is compressed it gets very hot and emits x rays



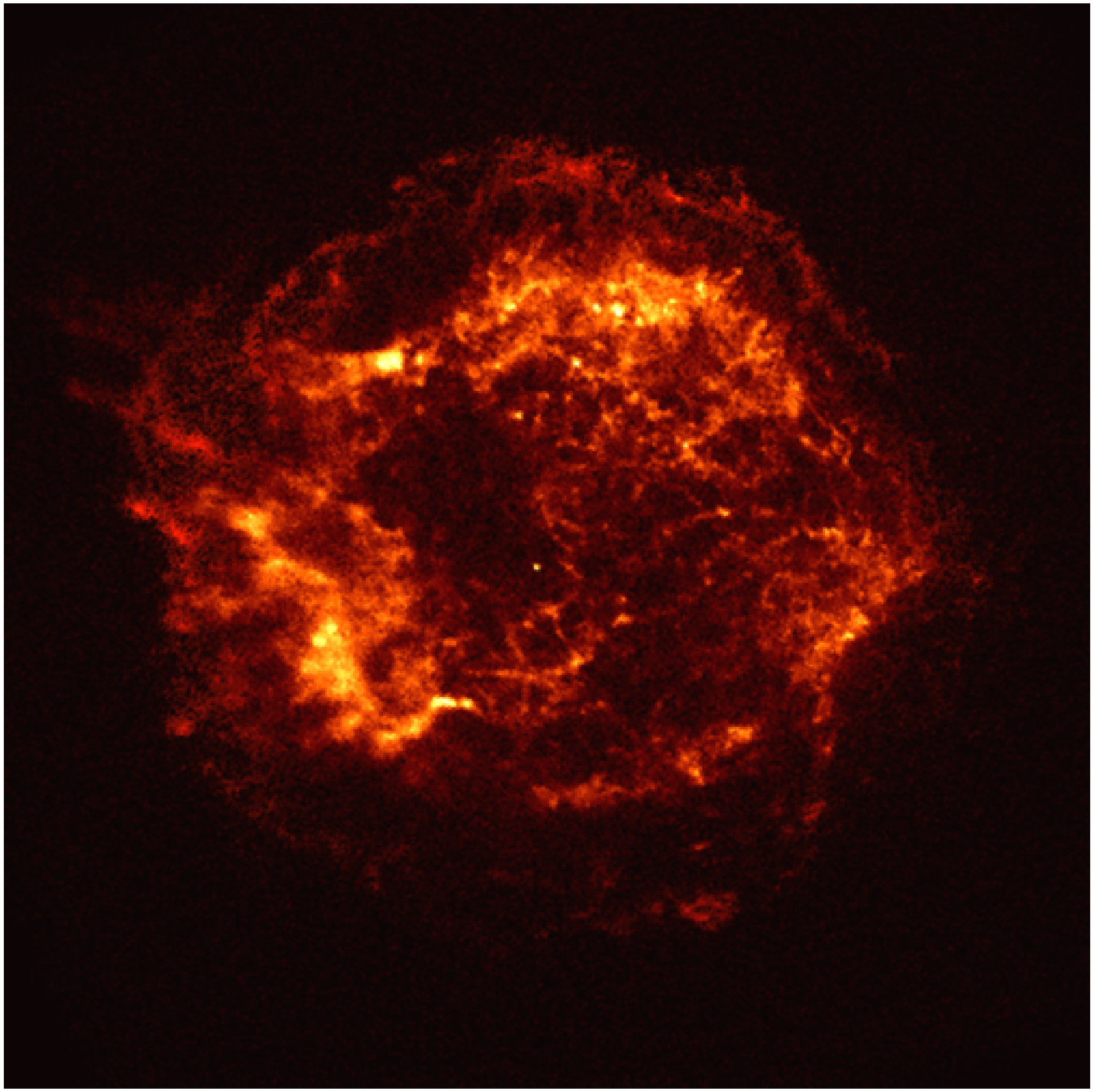
Today .. The Chandra Observatory



Today .. The Chandra Observatory

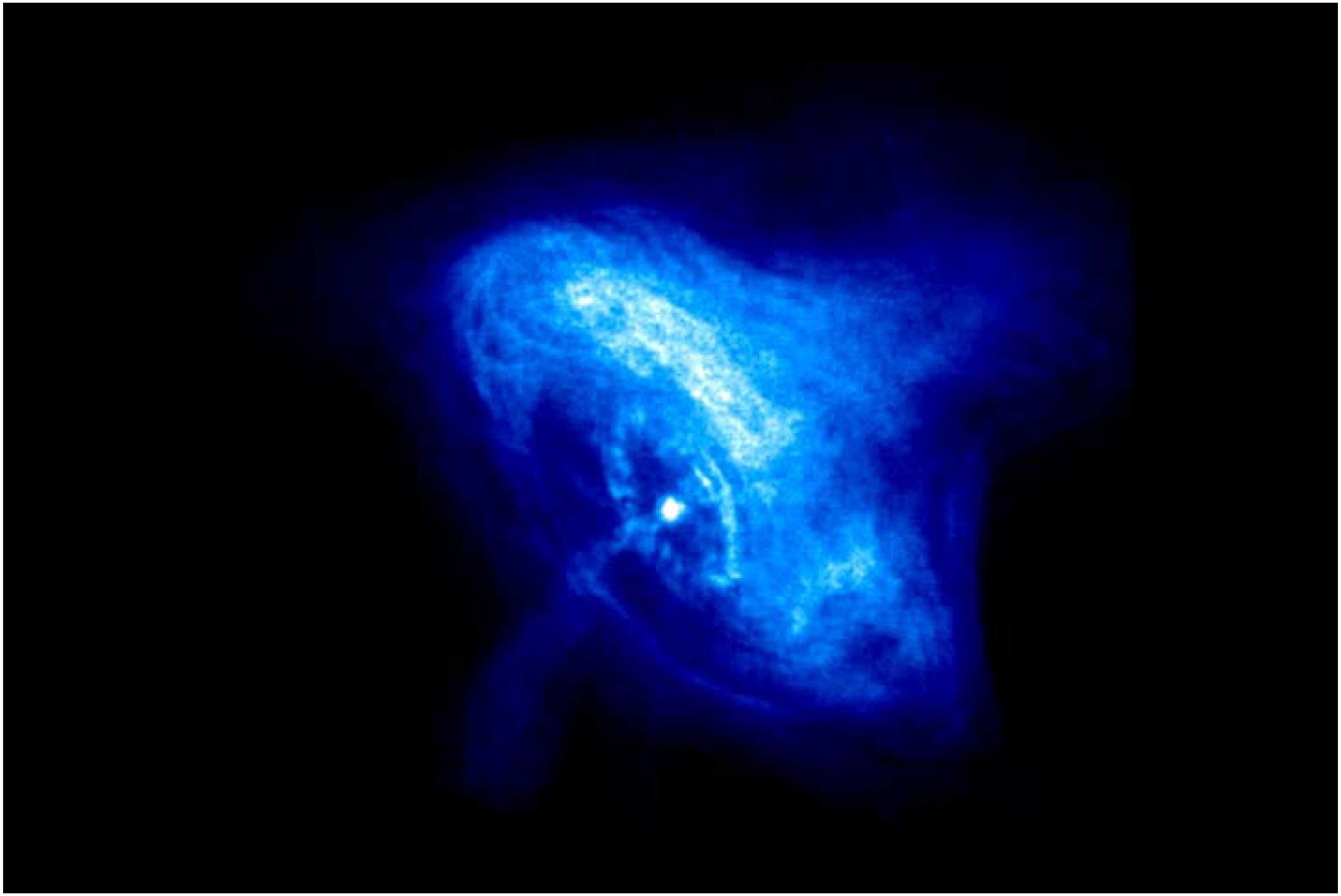
- School-bus-size x-ray observatory
- 100,000 times more powerful than UHURU
- Uses special mirrors to form highly detailed images
- In deep fields, more than 1000 new sources per square degree

Chandra Images : Cas-A Supernova Remnant



Chandra Images : Center of our Galaxy

The Crab Nebula and its Pulsar



X-Ray Optics

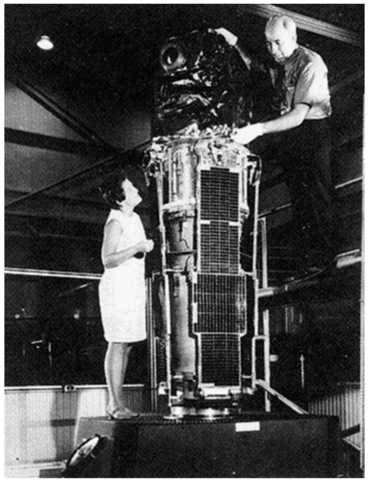
Why focus x rays ?

1) Imaging - obvious

2) Background reduction

- Signal from cosmic sources very faint, observed against a large background
- Background depends on size of detector and amount of sky viewed
  - Concentrate flux from small area of sky on to small detector

$\Rightarrow$ *enormous increase in sensitivity*



First dedicated x-ray astronomy satellite – UHURU →

mapped 340 sources with large area detector (no optics)

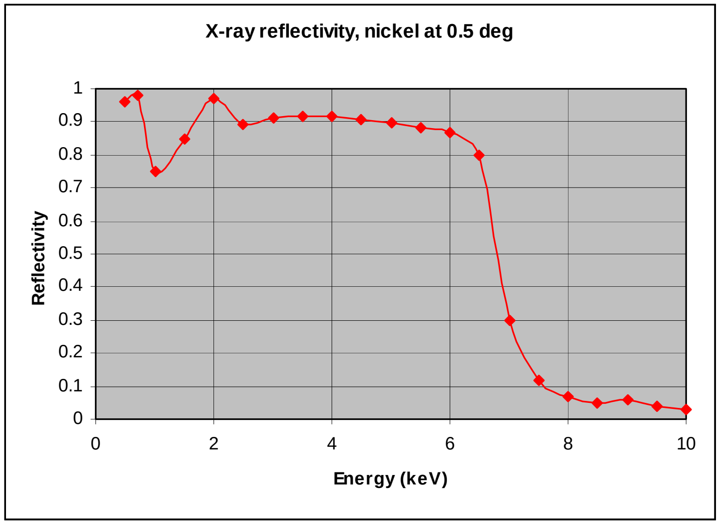
Chandra observatory - ~ same collecting area as UHURU

- ***5 orders of mag more sensitivity --- 1,000 sources / sq degree in deep fields***
- ***1 background count / keV year !***

X-Ray Optics has revolutionized x-ray astronomy

X-Ray Optics

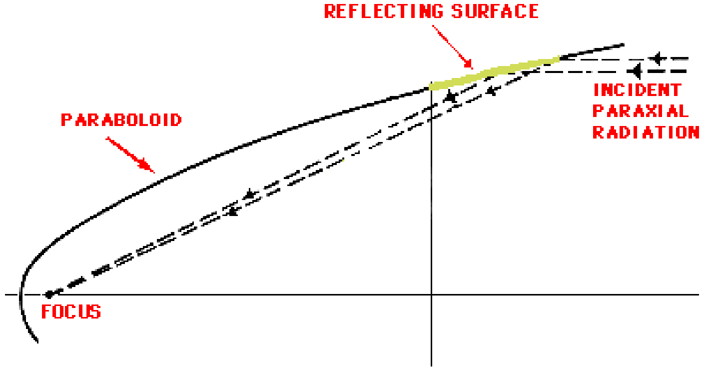
- ***X Rays undergo total external reflection at shallow graze angles***
  - ***Critical angle (away from absorption edges)***
    - > ~ θ_c (deg) = 0.93 λ (nm) $\sqrt{\rho}$ (g/cm^3)

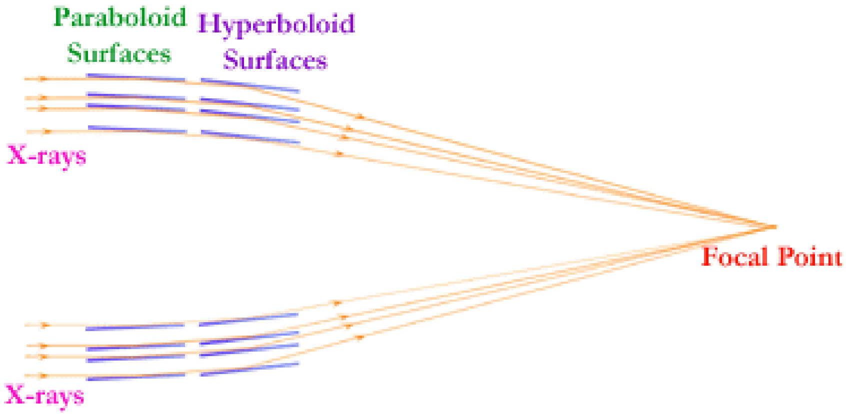


- ***Can use this phenomenon in focusing x-ray telescopes***

  Reflect x rays to a common focus

  Single parabola gives severe off-axis distortions, …
  Wolter-1 geometry adopted

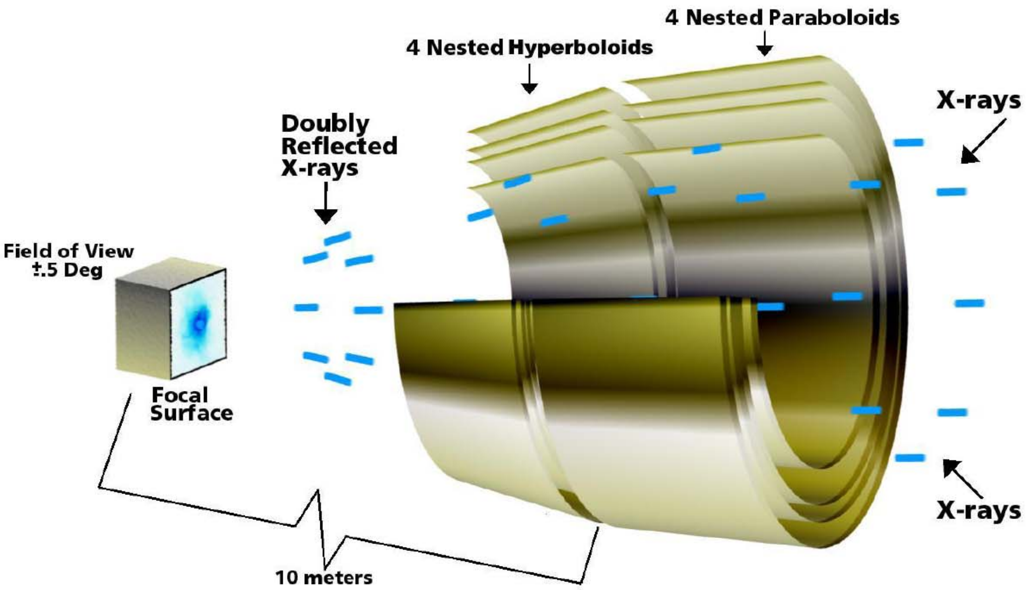




Approaches to Fabrication

- ***X-ray optics are very challenging to fabricate. Because of very short wavelength of x-rays the mirror surface must be smooth to ~ 0.5 nm rms.***

- ***Also, for good angular resolution, the figure must be accurate to < 1 micron.***



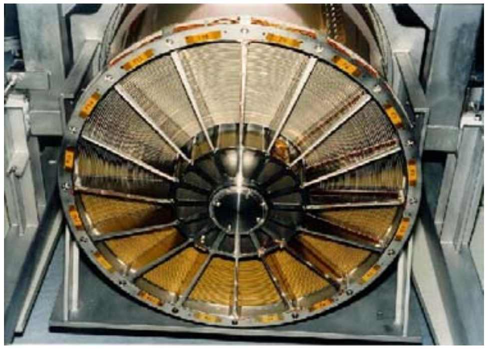
Approaches to Fabrication

Classical Optical grinding and polishing

Chandra, Rosat, Einstein

Advantage: Superb angular resolution

Disadvantage: High cost, large mass, difficult to nest

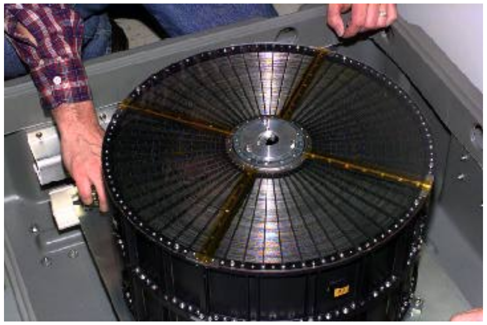


Electroformed Nickel Replication

XMM, JETX/Swift, SAX

Advantage: High nesting factor, good resolution

Disadvantage: Medium cost, mass (high density of nickel)



Segmented foil

ASTRO-E, ASTRO-F, ASCA, BBXRT

Advantage: Light weight, low cost

Disadvantage: Relatively poor angular resolution (arc-minute-level)

Approaches: Chandra

Approaches: Chandra

- **Fabricated using thick ceramic, which is meticulously polished and figured, one shell at a time.**

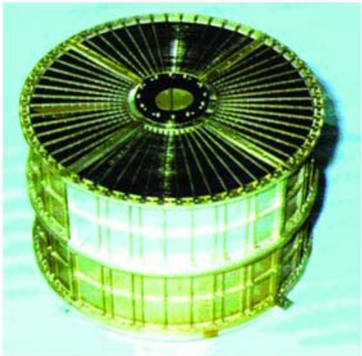
- **Obtain superb angular resolution ------ 0.5 arcsec HPD**

- **But very costly to fabricate ($500M) and very heavy (1000 kg)**

- ***So, other approaches to x-ray optics have been used that trade the superb angular resolution for ease of fabrication and lighter weight (and cost)***

Approaches: Foil Optics

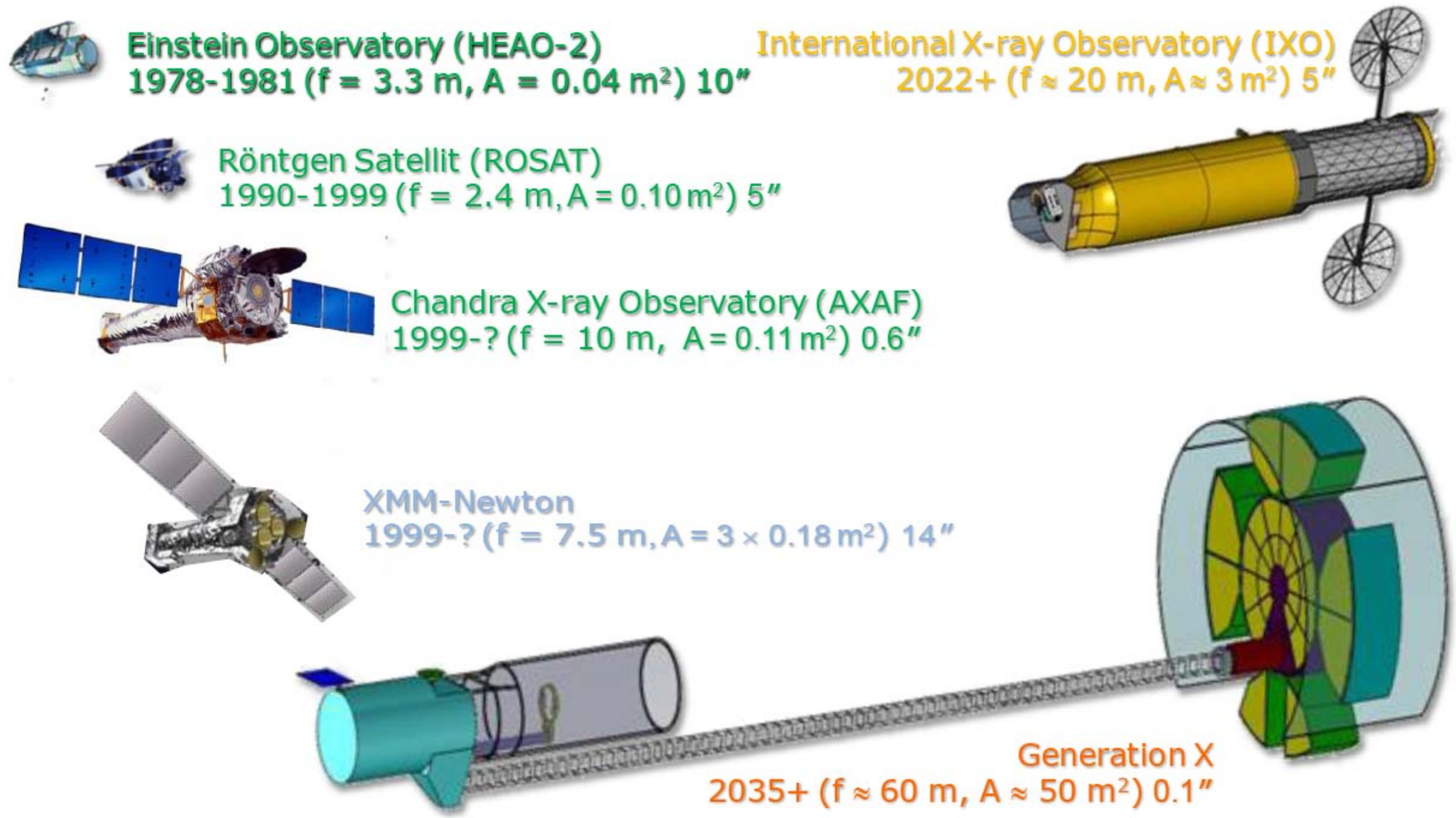
- Fabricated using very thin aluminum foils as reflectors. Foils held in slots in housing.
- Obtain poor angular resolution – 1-2 arcminute HPD
- But extremely light weight allowing for many individual reflectors, and thus large collecting area



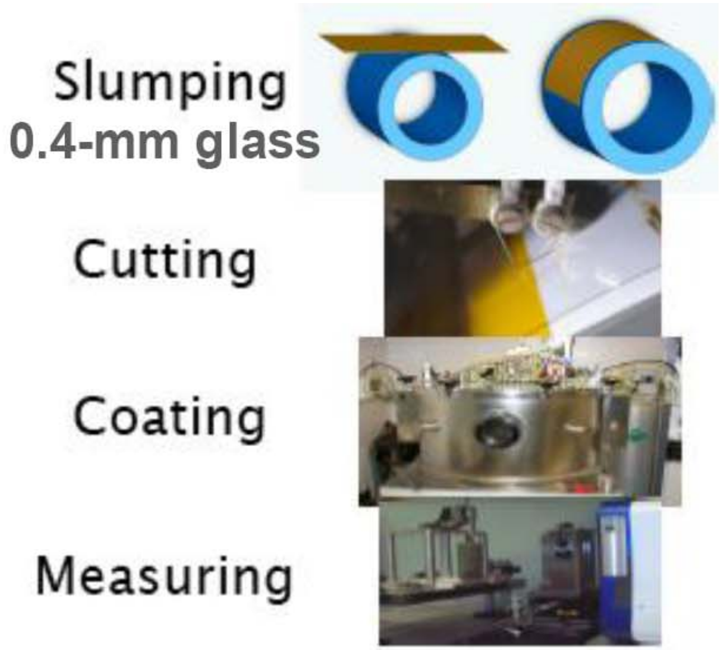
Approaches: Electroformed Nickel Replication (ENR)

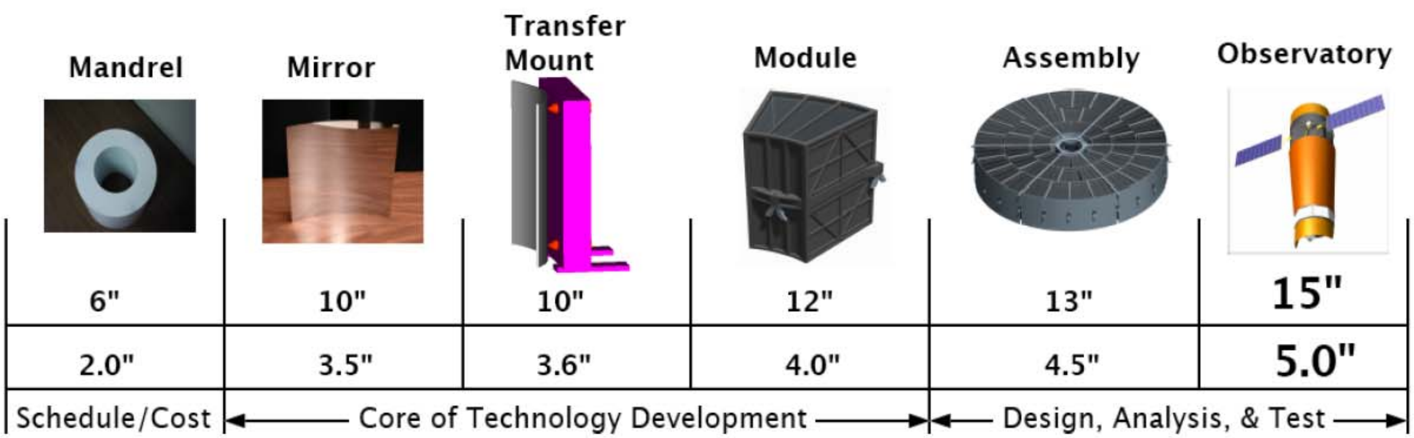
- Electroform thin nickel shells from superpolished and figured masters (mandrels)
- Obtain intermediate level angular resolution (~ 15 arcsec HPD)
- But considerably less expensive to fabricate and considerably lighter
- Electroformed nickel optics are being fabricated at MSFC for various programs.

Challenges for Future Missions



Mirror Fabrication for (near) Future Missions





Mirrors for (far) Future Missions – Active Optics

How can we achieve sub-arcsec resolution with thin optics ?

One option is to utilize active control of mirror figure, as is done in optical astronomy

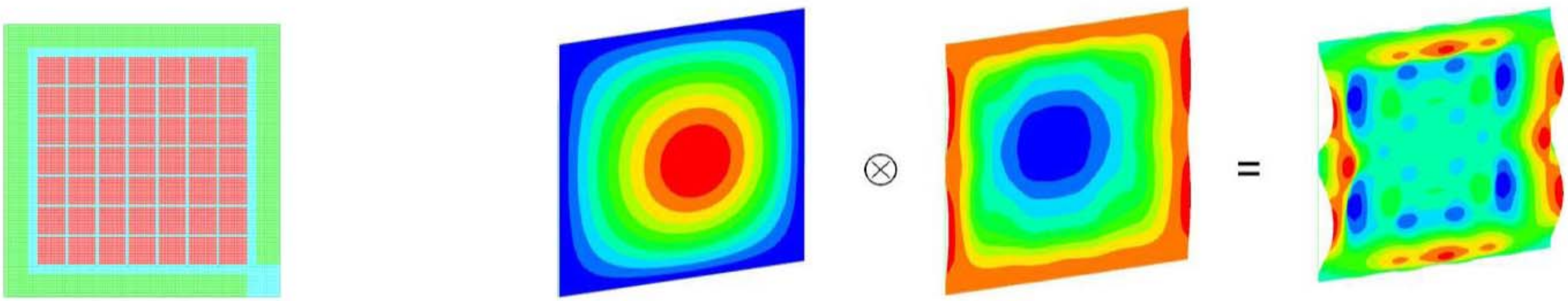
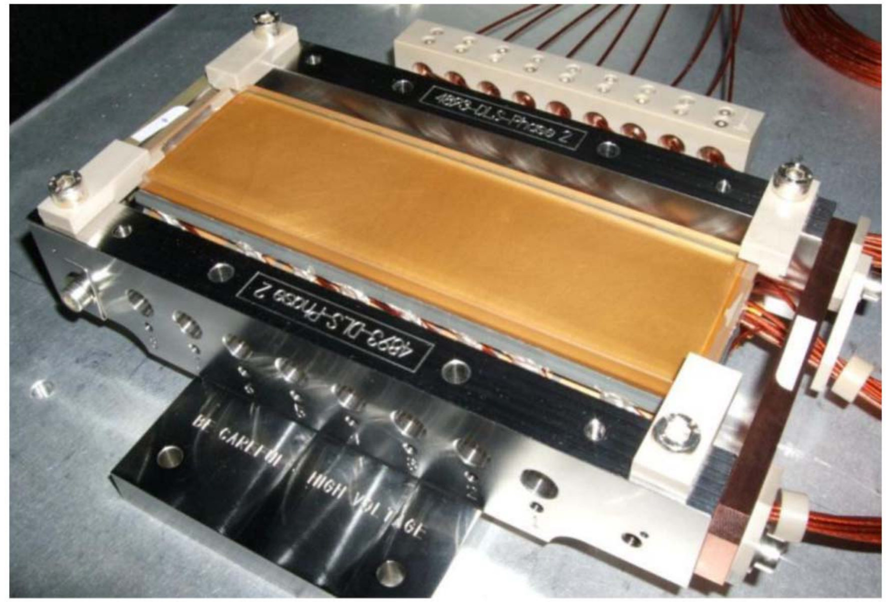


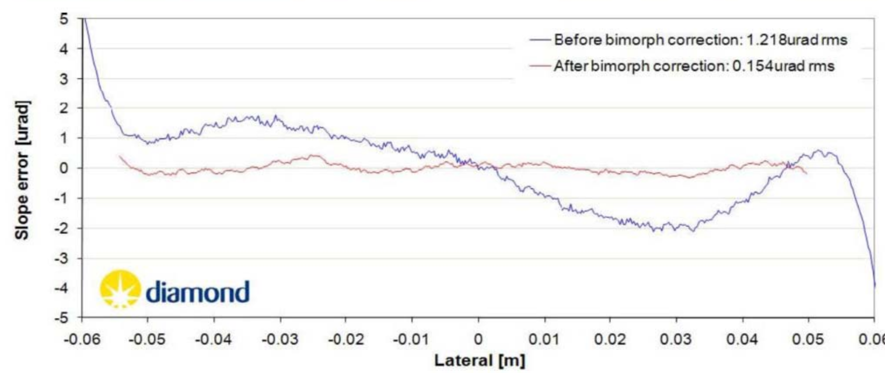
Figure 3: By appropriate adjustment of an array of surface-tangential actuators, a controlled deformation corrects the figure of a distorted mirror at the longer spatial wavelengths. The left panel schematically represents such an array on the back of a thin mirror segment. The right panel illustrates the application of a correction map to an error map, resulting in a mirror with low-spatial-frequency distortions removed.

Mirrors for (far) Future Missions – Active Optics

Technique has been used for synchrotron x-ray optics, but in its infancy in x-ray astronomy.

- ***Difficulty is the football-field-size areas that must be controlled.***
- ***Algorithms needed that converge***
- ***Power requirements and stability, etc***

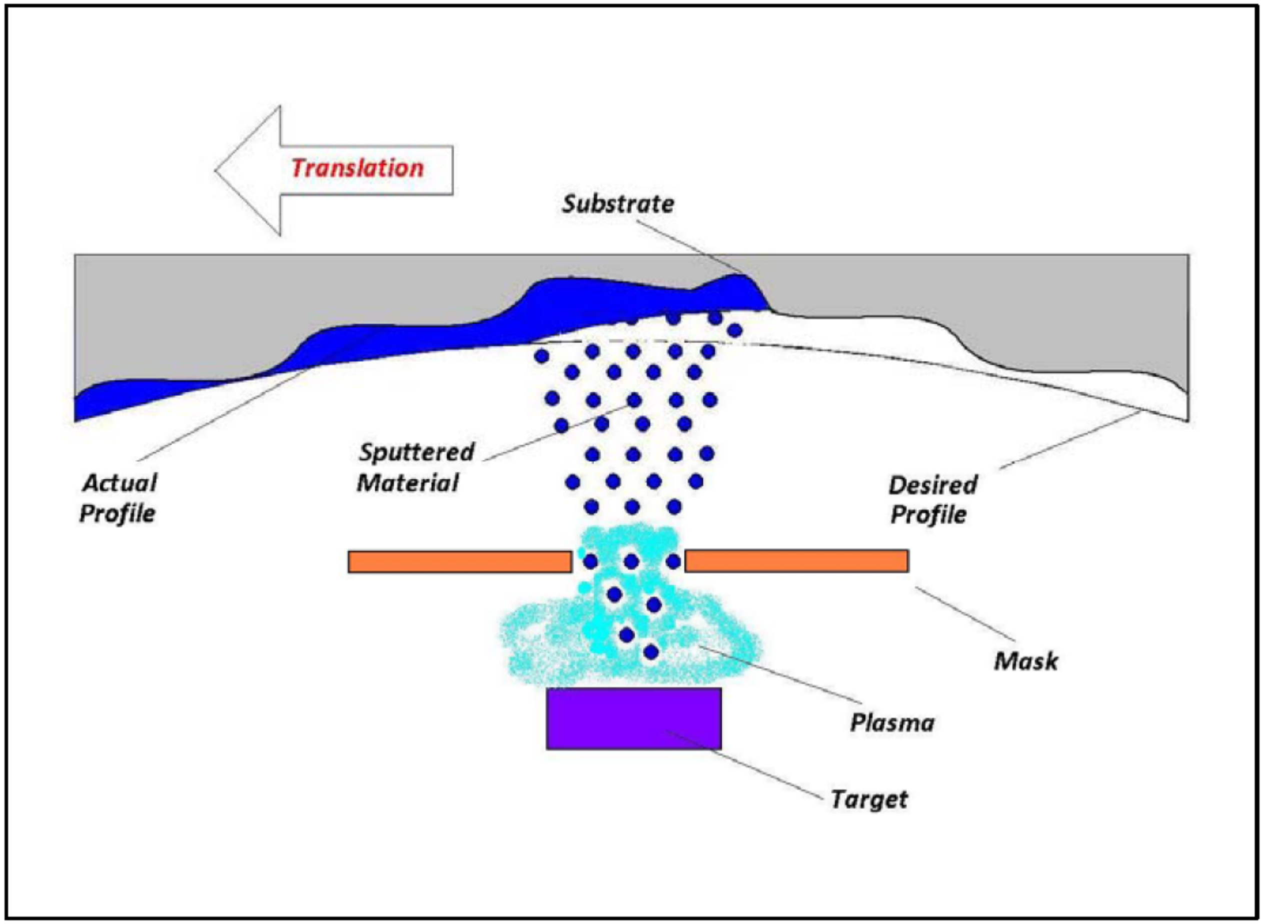




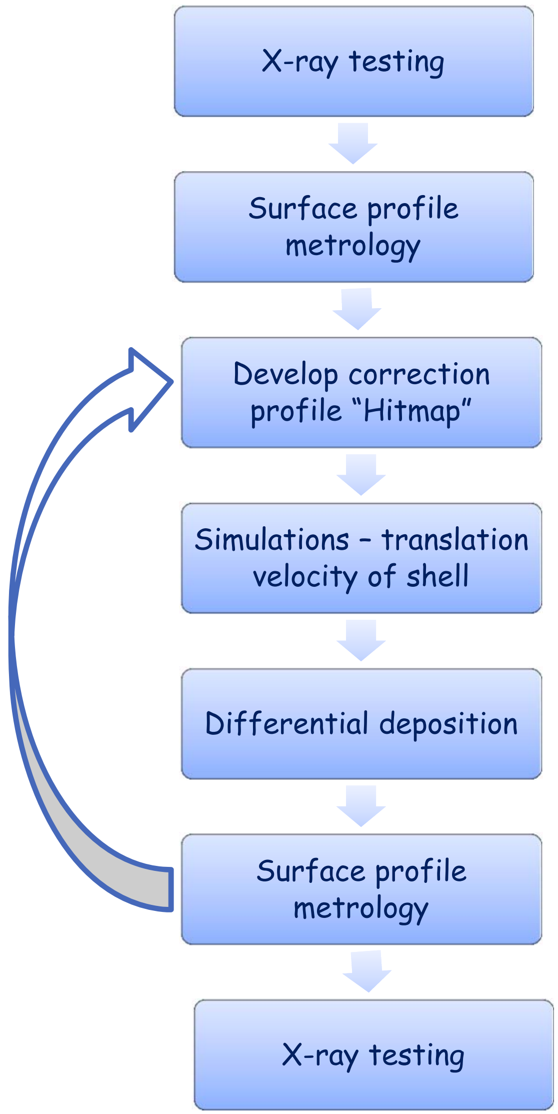
Mirrors for Future Missions – Differential Deposition

Vacuum deposit a filler material to compensate for figure imperfections

Proof of concept work underway at MSFC



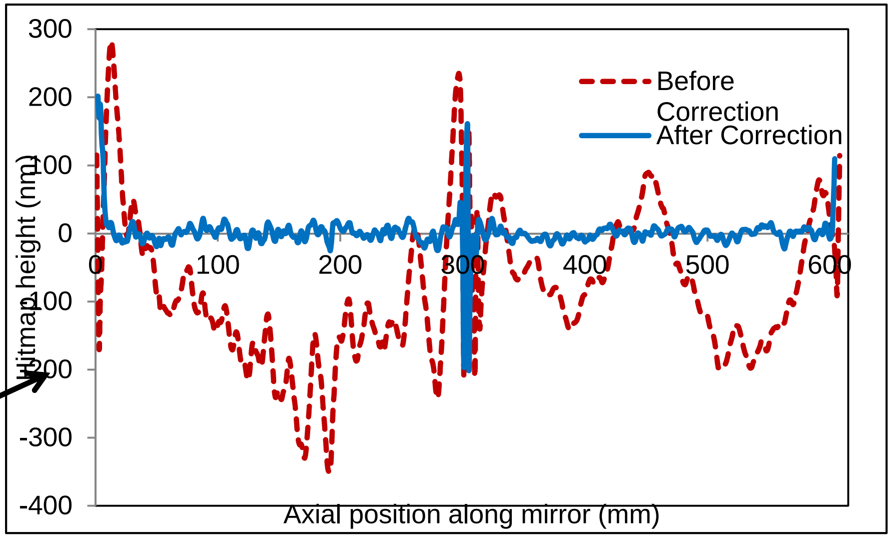
Process sequence - differential deposition

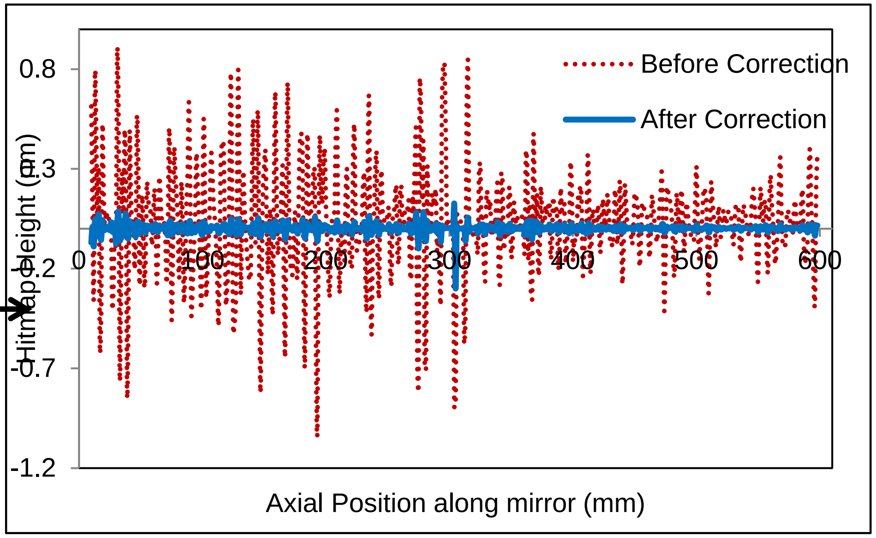


Theoretical performance improvement

Simulations performed on X-ray shell profile of 8 arc sec simulated HPD

Correction stage	Average deposition amplitude (nm)	Slit-size (mm)	Angular resolution (arc secs)
1	300	5	3.61
2	40	2	0.68
3	4	1	0.22
4	1	0.25	0.14





Possible practical limitations

- ***Variation of sputtered beam profile along the length of mirror – particularly for short focal length mirrors***
- ***Deviation in the simulated sputtered beam profile from actual profile, beam non-uniformities, etc***
- ***Positional inaccuracy of the slit with respect to mirror***
- ***Stress effects***
- ***Metrology uncertainty***

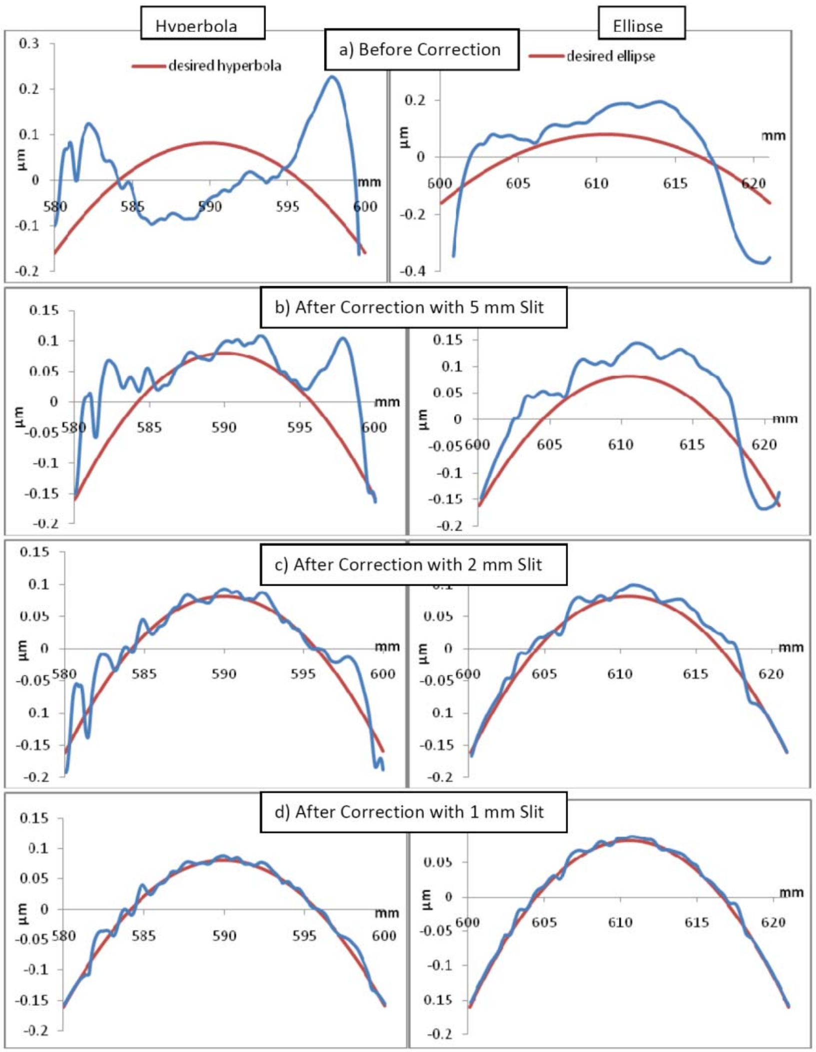
Metrology limitation

Simulations performed on X-ray shell of 8 arc sec simulated HPD

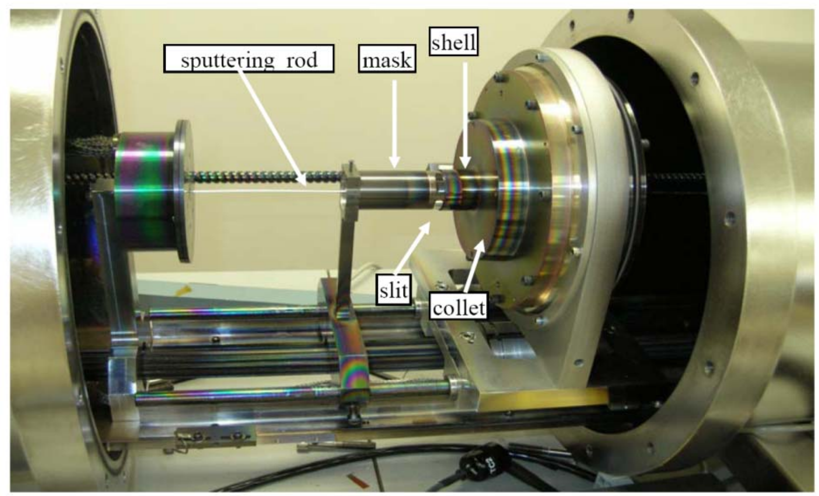
Correction stage	Average deposition amplitude (nm)	Slit-size (mm)	Metrology uncertainty (nm)	Angular resolution (arc secs)
1	300	5	± 0	3.6
			± 10	3.6
			± 50	7.3
2	40	2	± 0	0.6
			± 1	1
			± 5	2
			± 10	3.5
3	4	1	± 0	0.2
			± 0.5	0.2
			± 1	0.5
			± 2	0.8

- *Potential for ~arc-second-level resolution – with MSFC's metrology equipment*
- *Sub-arc sec resolution could be possible with the state-of-art metrology equipment*

Mirrors for Future Missions – Differential Deposition



Correction stage	Average deposition amplitude (nm)	Slit-size (mm)	Amplitude uncertainty (nm)	Angular resolution (arcsec)
1	300	5	± 0	3.6
			± 10	3.6
			± 50	7.3
2	40	2	± 0	0.6
			± 1	1.0
			± 5	2.0
			± 10	3.5
3	4	1	± 0	0.2
			± 0.5	0.2
			± 1	0.5
			± 2	0.8



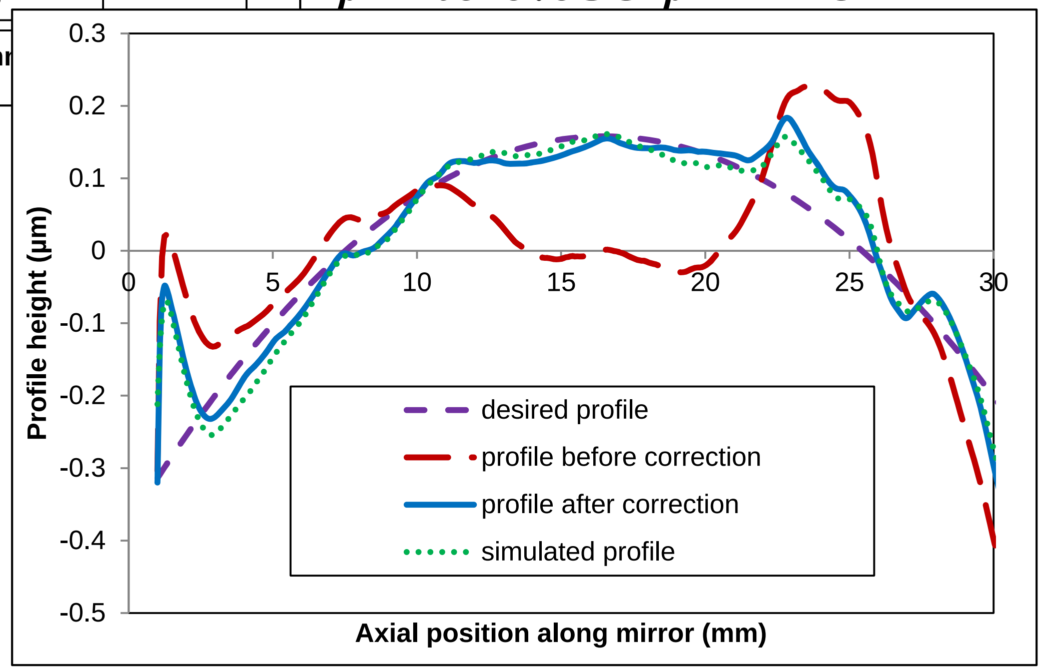
Material and process selection

Platinum-Xenon				Platinum-Argon			
power	pressure	roughness	deposition rate	power	pressure	roughness	deposition rate
75	15	1.950	0.130	75	15	2.060	0.140
90	15	2.043	0.230	90	15	1.933	0.190
75	30	1.895	0.170	75	30	1.868	0.160
90	30	1.810	0.250	90	30	2.083	0.220
Nickel-Xenon				Nickel-Argon			
power	pressure	roughness	deposition rate	power	pressure	roughness	deposition rate
75	**15**	**1.915**	**0.290**	75	15	1.995	0.180
90	15	2.070	0.360	90	15	1.778	0.240
75	30	3.093	0.240	75	30	2.260	0.220
90	30	3.630	0.310	90	30	2.210	0.290
Tungsten-Xenon				Tungsten-Argon			
power	pressure	roughness	deposition rate	power	pressure	roughness	deposition rate
75	15	1.965	0.300	75	15	1.900	0.120
75	30	1.805	0.290	75	30	2.125	0.290
90	30	1.993	0.370	90	30	-	-
75	50	2.075	0.290	75	50	1.998	0.310
90	50	2.423	0.370	90	50	1.868	0.370
Units: power-Watts, pressure-mTorr, roughness- Å rms, deposition rate – Å/sec							

Proof of concept on few-cm-scale medical imaging optics

Figure error improvement from 0.11 µm to 0.058 µm rms

Slope error improvement from 12 arc sec to 7 arc sec rms



X-Ray Astronomy Group

Current Status

- Since submitting this RFI response we have been notified of APRA /ARA funding

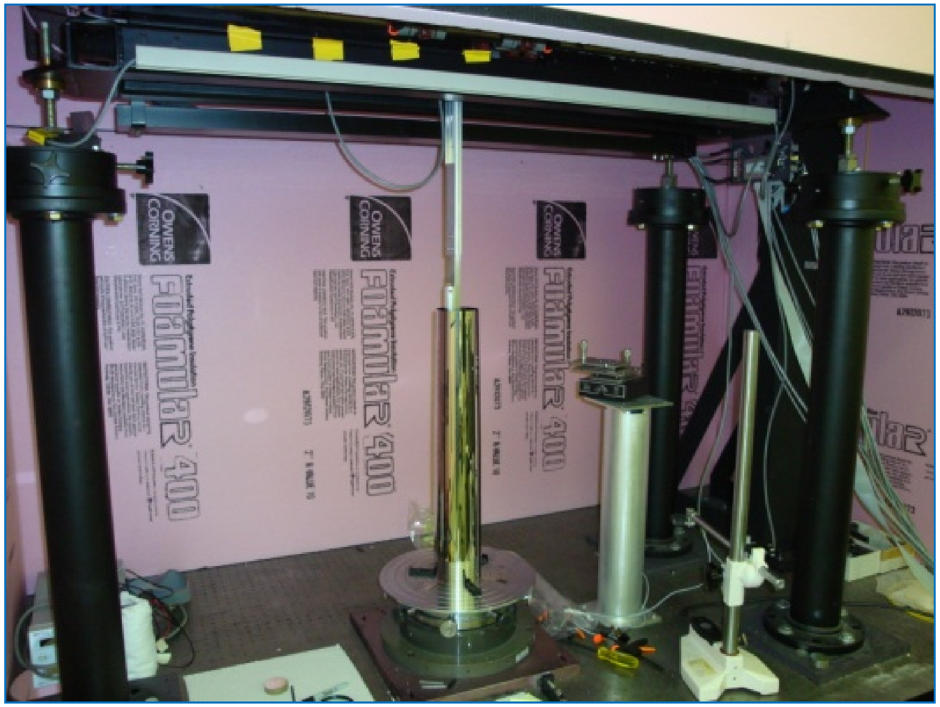
- This will allow us to build a custom system and demonstrate the technique on larger full shell (MSFC) and segmented (GSFC) optics

- We hope to be able to demonstrate < 5 arcsec performance in 3 years

- To go beyond this, (arcsecond level) is very difficult to judge as we have not yet discovered the problems.

  - May necessitate in-situ metrology, stress reduction investigations, correcting for gravity effects, correcting for temperature effects
  - Some of this will become obvious in early parts of the investigation
  - Top-of-head estimate – ~ 5 years total and additional $2-3M

Long Trace Profiler



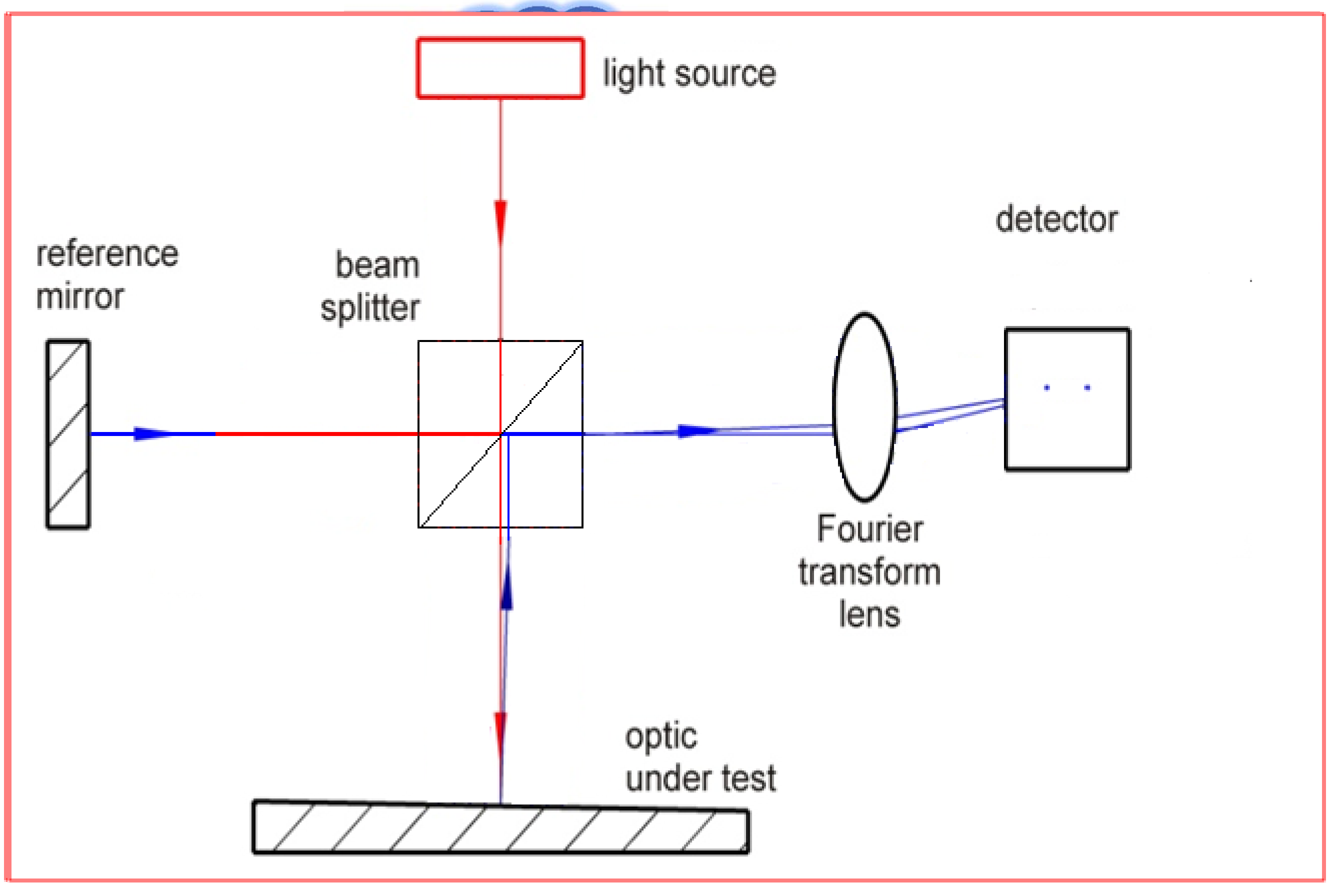
☹Time taken to measure is about 5 mins for 300 mm sample length

- Pencil beam interferometry
- Measure spatial wavelengths starting from 1 mm upto several 100's of mm
- Laser beam scans point-by- point - slope data
- Position of the beam at the detector – direct measure of the slope
- Accuracies possible <1 urad
- Multiple measurements – 2D topography

Increase the speed ?

- Make use of advanced technology
- Higher resolution 2D detectors
- Stable optical sources
- Increase the speed & accuracies of measurements
- Higher density data – complete information of mandrel or shell
- Multiple beams – simultaneous measurements?

Multi-beam LTP



- *Proof-of-concept*
- *To study the limitations of the approach*

- *Number of beams – 5 to 10*
- *Spatial separation of beams – 1 to 2 mm*

Multi-beam LTP Requirements

- **Target – decrease the time of measurement – reasonable accuracy**

- **Existing systems**
  - linear array detector – 25 μm X 2.5 mm pixel size
  - 1 m focal length FT lens
  - Lens and detector → 0.25 μrad

- **2D detector requirements**
  - multiple beams in one plane and beam translation on other plane
  - angular range +/- 15 mrad
  - Detector atleast 20 mm X 20 mm area
  - < 8 μm pixel size

fl (mm)	500	550	600	700	800
pixel (μm)					
4	0.12	0.11	0.10	0.09	0.08
8	0.24	0.22	0.20	0.17	0.15
10	0.30	0.27	0.25	0.21	0.19
14	0.42	0.38	0.35	0.30	0.26
18	0.54	0.49	0.45	0.39	0.34

Resolution (μrad)

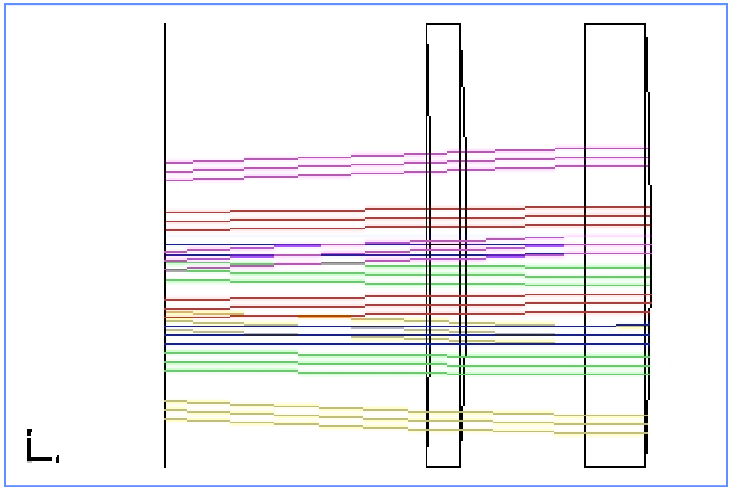
2D CCD detector & FT lens

- **Detector Procured (1st Vision's JAI AM-1600GE)**
  - 36 mm x 24 mm area
  - 7.4 x 7.4 μm pixel size
  - 3.04 fps
- **Custom designed FT lens**
  - 500 mm focal length
  - 50 mm diameter
  - Low distortion – minimize the effects of lens on systematic errors

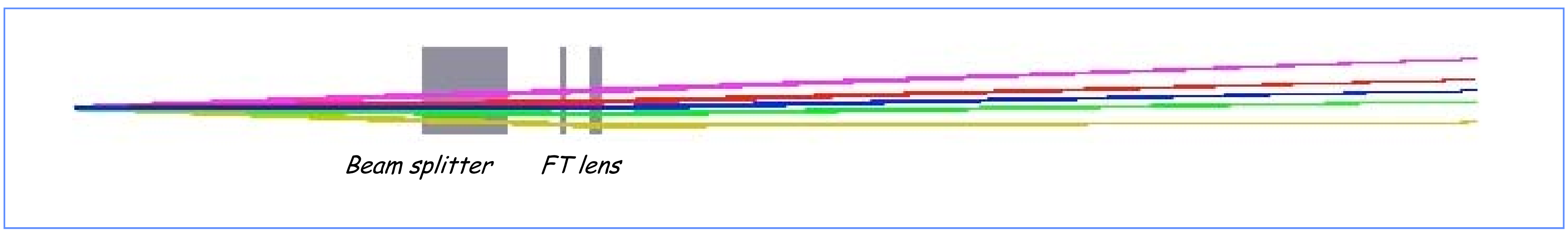
FT lens design

- Less number of elements – two element system

- **Air-spaced doublet lens**



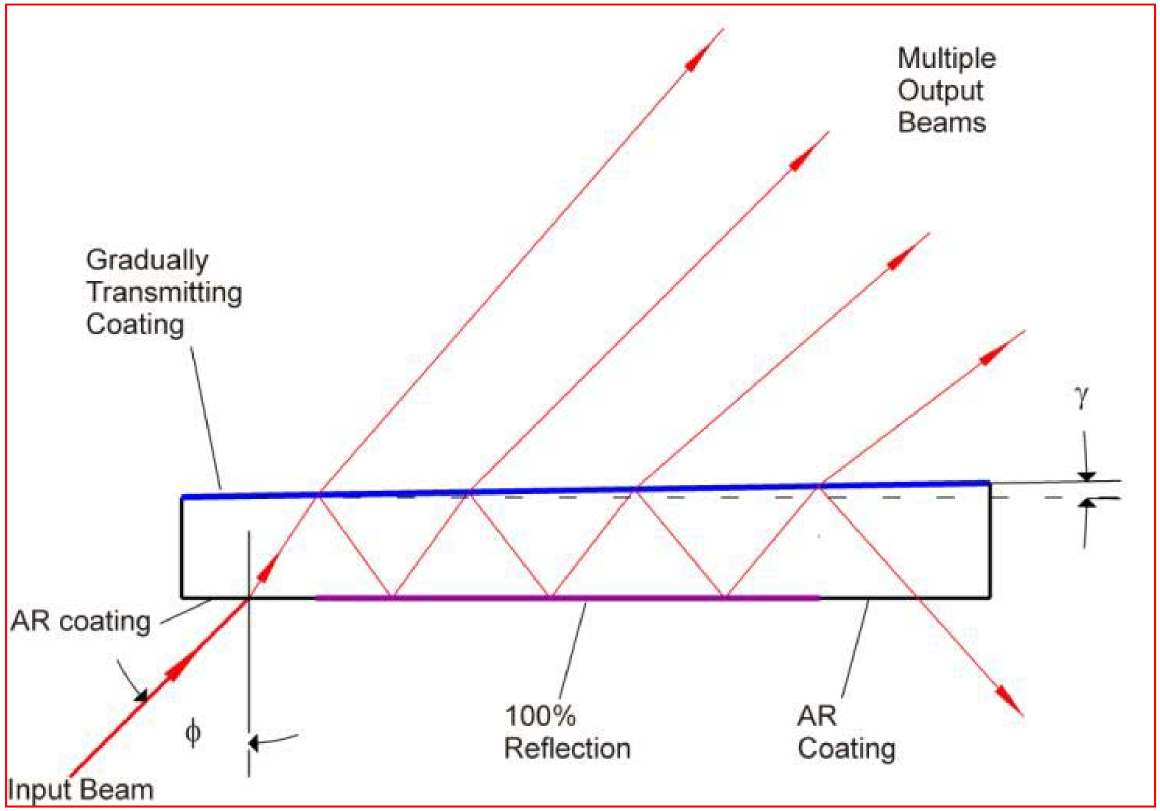
#	Type	Comment	Curvature	Thickness	Glass	Semi-Diameter
0	STANDARD	It has no distortion for config		infinity		0.00E+00
1	STANDARD			200		1.00E+00
2	COORDBRK			0		0.00E+00
3	STANDARD	PBS CUBE		50	S-BSL7	2.50E+01
4	STANDARD	SPACE TO LENS		30		2.50E+01
5	STANDARD	LENS 1	-739.8	4.00	S-NSL5	2.50E+01
6	STANDARD	LENS 1 BackSurf	-420.2	13.166		2.50E+01
7	STANDARD	LENS 2	plano	7.515	S-NPH2	2.50E+01
8	STANDARD	Lens 2 BackSurf	-628.4	504.114		2.50E+01
9	STANDARD	Image				2.00E+01



- *Anti-reflection coating*

Multiple beam generation

- *Multiple beams of almost equal intensity*
- *Spatial separation (2.4 mm)*
- *Angular separation (250 µrad)*
- Wedged etalon approach
- *Customized coating on one side*
- *100% reflection coating on the other*

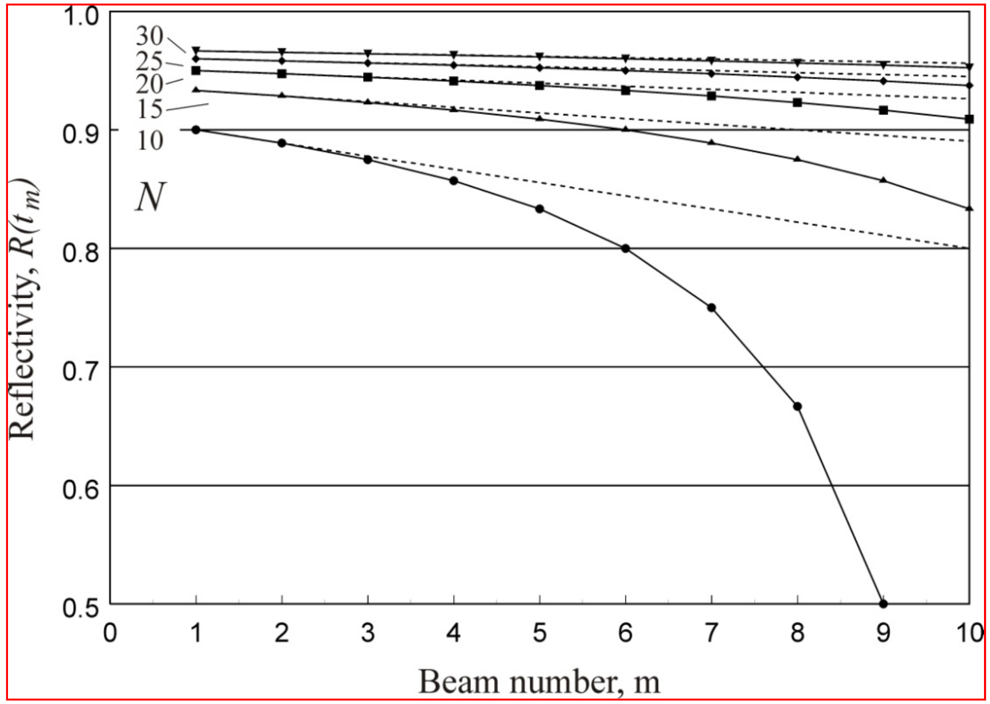


- *Dimension – 50 x 50 x 3 mm*
- *Wedge – 60 µrad*

Coating – wedged etalon

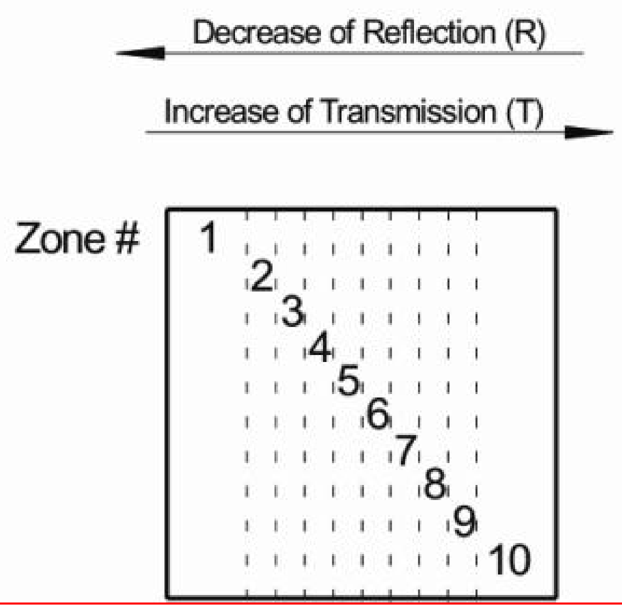
Possible approaches

- *Continuous ideal gradient coating*
- *Linear approximation to ideal*
- *Multilayers*
- *Discrete coatings – each with constant reflectivity*



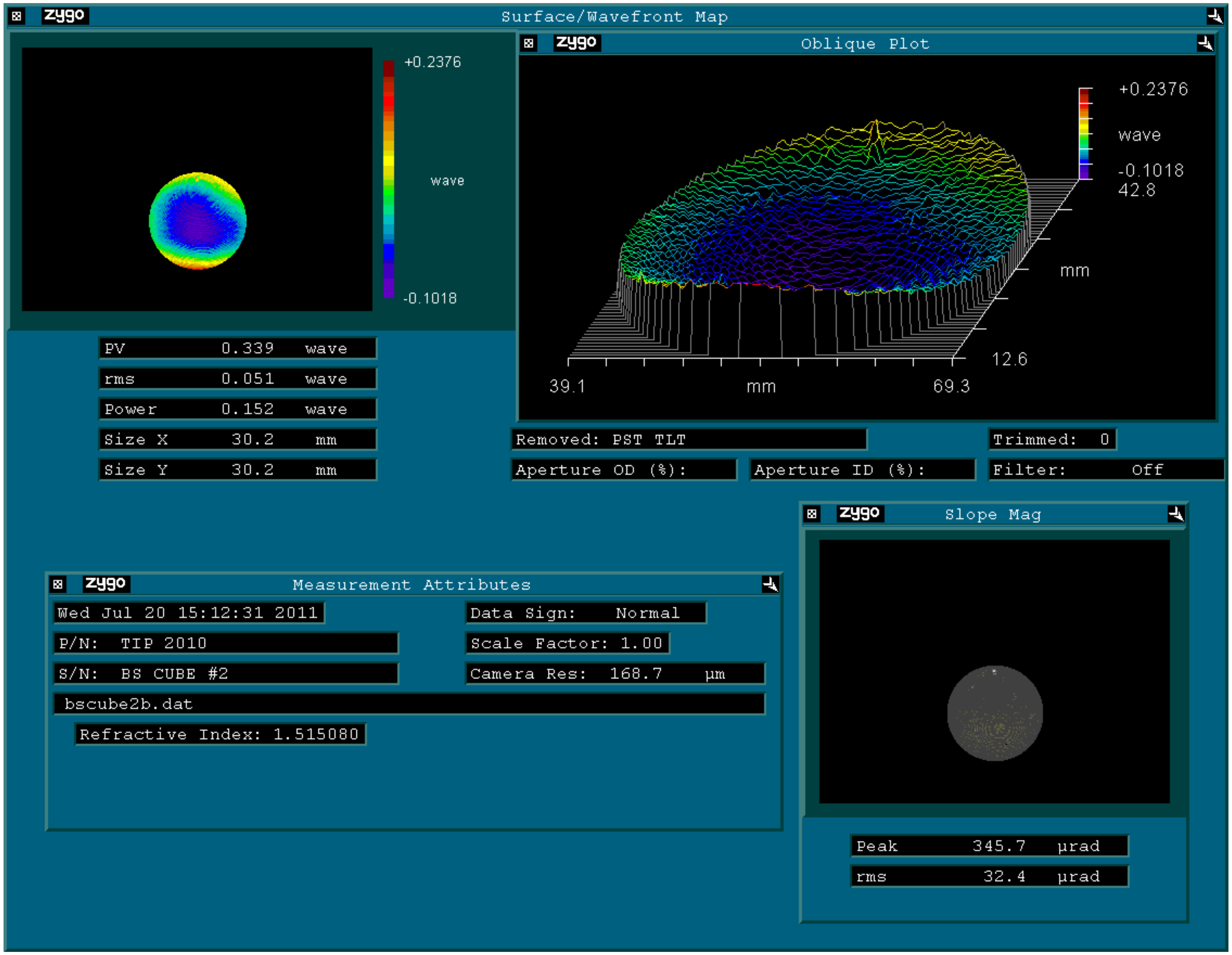
Multiple beam generation – wedged etalon

- *Silver coating with step reflectivity approach*



Zone	1	2	3	4	5	6	7	8	9	10
R_Z, %	93.33	92.86	92.31	91.67	90.91	90.00	88.89	87.50	85.71	83.33
T_Z, %	6.67	7.14	7.69	8.33	9.09	10.00	11.11	12.50	14.29	16.67

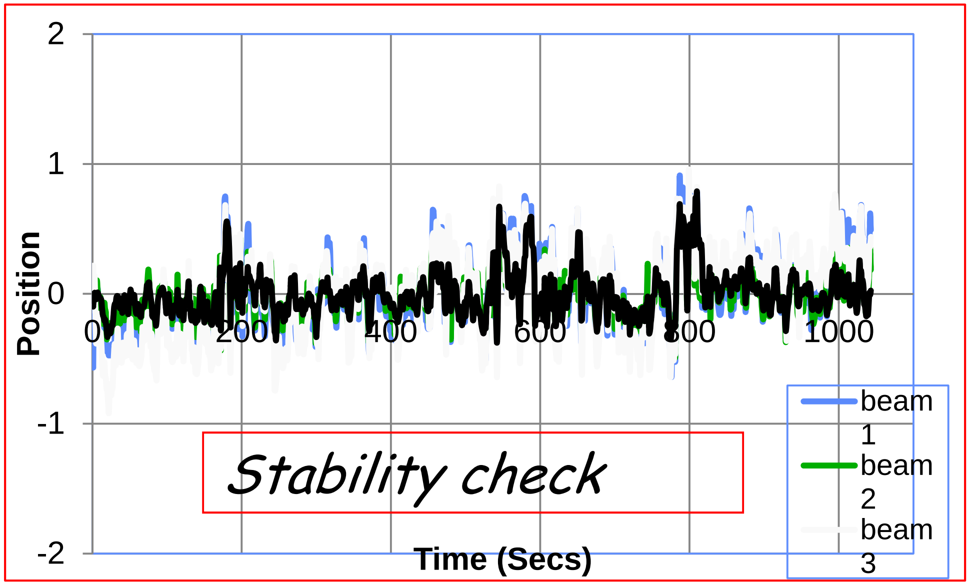
Cube beamsplitter

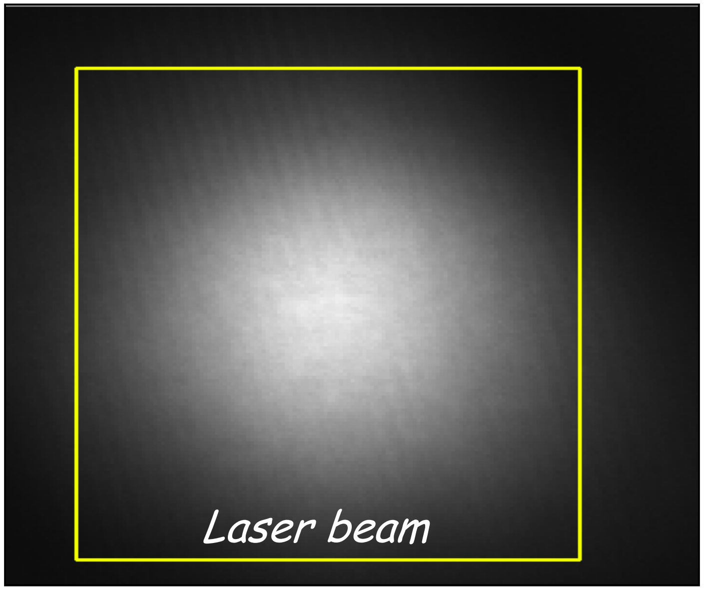


- *Purchased 50mm X 50 mm beam splitter - tested with zygo for wavefront error*
- *Analysis of test result in progress*

Software

- *Berkeley National Labs - provided software code*
- *3 beams – being adapted to new detector for multiple beams – Maxima of single peak*
- *Tests are underway to check the speed of readout & processing – 0.5 fps for full frame of 4872x3248 – 1.3 fps for partial frame of 4872x800*





X-Ray Astronomy Group

Future work

- Immediate work
  - ✓ Replace detector
  - ✓ Etalon test & analysis
  - ✓ *Detector software*
- Assemble components
- *Test measurements*
- *Modular approach*