Thoughts on capabilities required for the X-ray Surveyor telescope

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Caveats, assumptions, warnings

- My intent is to be thought-provoking, not to provoke—apologies for any omissions, mistakes or mischaracterizations
- Assessments based on:
  - Reading optics teams' presentations and talking with them
  - Study of NASA reports and SPIE papers from HEAO-2 and AXAF development programs
  - Great reviews by Lester Cohen and Mark Schattenburg
  - Personal experiences
    - Work on x-ray astrophysics missions (CCDs for *Chandra*, telescopes for *NuSTAR*)
    - Development of x-ray optics for non-proliferation, medical imaging, axion detection and free electron lasers
    - Interactions with industry for national security space projects
- I can sometimes be pessimistic …

BLUF

- No matter how compelling the science, I don't see the Decadal selecting the X-ray Surveyor (XRS) without a believable, affordable plan for making the x-ray telescope
  - A prototype, with demonstrated sub-arcsecond performance, is not a plan
  - "The scientific excellence of the mission is necessary but, unfortunately, not sufficient" -Weisskopf, *PNAS*, (Apr 2010)

- Today's X-ray telescope "ecosystem" is significantly compromised, compared to when AXAF began

- Situation is critical and requires immediate action to:
  - Engage with industry as soon as possible
  - Leverage other communities
  - Have optics teams perform a serious self-assessment, followed by a friendly murder board
  - Identify common needs and coordinate activities
  - Develop a plan for fabricating the optics required by XRS science

Ecosystem: then …

- Political situation
  - Ideal timing, in terms of exciting X-ray astronomy results and the Decadal process
    - AXAF proposal submitted in 1976
    - *Einstein* flies in 1979; ubiquity and importance of of x-ray emission established
    - AXAF #1 recommendation in 1982 “Astronomy and Astrophysics for the 1980s”

Mission	Mirrors	HRMA	Scientists
HEAO-2	Perkin Elmer	AS&E; SAO; Perkin Elmer	SAO; AS&E
Chandra	Perkin Elmer	Kodak	MSFC; SAO

- Technology
  - *Chandra* telescope leveraged facilities, expertise, and experience gained from producing the HEAO-2 (*Einstein*) mirrors
  - Truly amazing engineering done by industrial partners (…that are still doing amazing things)
    - Perkin-Elmer → Hughes Danbury Optical System → Goodrich/ISR → United Technologies
    - Kodak → ITT → Exelis → Harris
    - TRW → NGC/Space Park

“generation of the AXAF/TMA Hyperbolic and Parabolic optical blanks on a specially designed grinder adapted to operate with features of the basic Perkin-Elmer overhead F-25 milling machine and roller polishing machine developed on the HEAO-B program.”

“AXAF TECHNOLOGY MIRROR ASSEMBLY PROJECT REPORT” John Russo (March 1983)

Ecosystem: … and now (political)

- Different situation now than when AXAF was first considered:
  - “Neither in 1963 nor, indeed, in 1976—when Ricardo and his Co-[PI] Harvey Tananbaum submitted their unsolicited proposal “For the Study of the 1.2 Meter X-ray Telescope National Observatory”—did one know how to build the subarc-second telescope” –Weisskopf, *PNAS* (April 2010)
  - If this is situation in a few years, hard to see XRS being highly rated
- This is my motivation for focusing on a credible plan and reasonable estimate of required resources
- Although we don’t how Cost and Technical Evaluation (CATE) will be performed, or to what end, more input can only be a good thing
  - See the NRC-authored “The Space Science Decadal Surveys: Lessons Learned and Best Practices” (2015) and Aerospace “Cost Estimating of Space Science Missions “ (April 2013) for some details
- If industry is going to be involved in making the telescopes—and I don’t see how this won’t be the case—make them a ***partner*** as soon as possible

Ecosystem: … and now (technology [1])

- Of three mirror technologies (adjustable, glass segments; silicon segments; integral shell), mixed leverage of recent x-ray astronomy satellite missions (with less stringent angular resolution requirements)

Technology	leverages	A lot, some, a little
Si segments	*NuSTAR* - mounting	A little
Actuated, glass segments	*NuSTAR* – mounting? Others?	A little
Integral shell	HERO, FOXSI, ART-XC; DOE projects	A lot

- Minimal industrial partnership, both traditional and "disrupters"—not sure why this is, but it is a great opportunity
  - The aerospace firms are absolutely interested in "Big Science", self-evident by participation in JWST and WFIRST
  - Senior managers at Harris, Northrop Grumman, Raytheon and Lockheed Martin have all expressed interested
  - Industry has tremendous depth and capabilities—and they are willing (and do) spend IRAD to develop technologies and capture future missions

Ecosystem: … and now (technology [2])

- XRS with respect to the other Surveyors
  - LUVOIR, HabEX and Far-IR Surveyors directly benefit from development efforts for US and international ground-based observatories (TMT, GMT and E-ELT) and and satellite missions for US government sponsors
    - All three concepts invoke combinations of segmented; larger primary with petals; light-weighted; think *JWST*, but even bigger

- XRS only derives minimal benefit from these efforts
  - Techniques and methods that might have some utility for XRS
    - Metrology; precision alignment; deterministic finishing; high-volume manufacturing; Mod&Sim
  - Funding small studies could provide definitive answers in short order

- NASA technology funding for XRS
  - Integrated effort small compared to all the IR/Vis/UV efforts
  - 3 teams × (5−10 years) × ($1−2M + IRAD) ≈ $20−40M (guesstimate) is not insignificant, but ***relatively*** small compared to the optical telescope juggernaut

- One way to bridge this deficit
  - Look to capabilities outside of non-traditional optics industry
  - Leverage adjacent technology communities

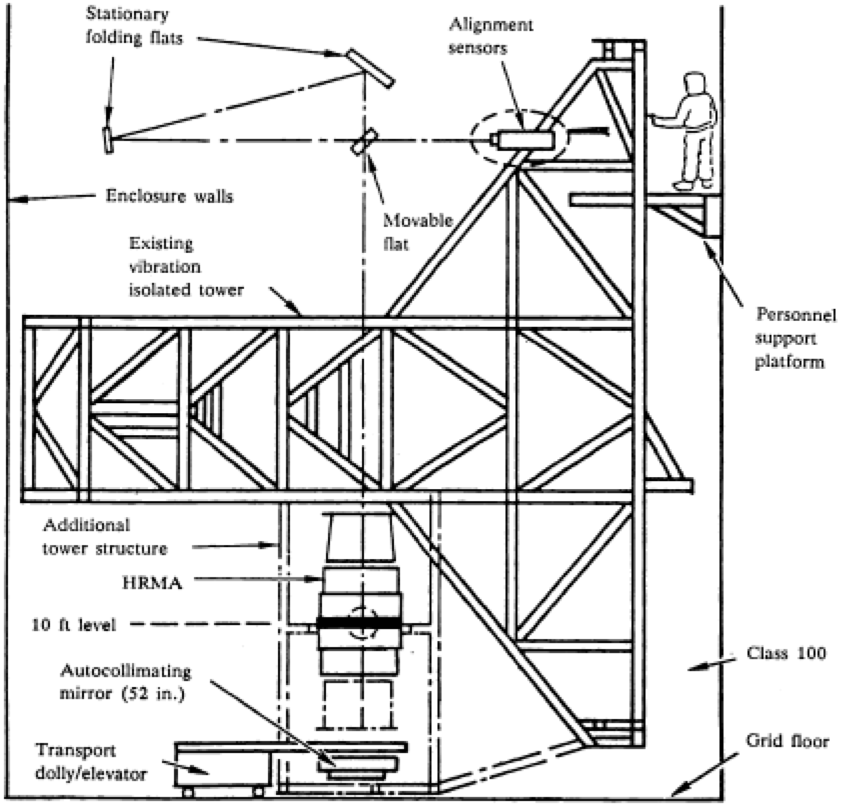
Are there opportunities for non-traditional industrial partners ?

Teams must answer this question, but there seems to be potential

- Segmented silicon
  - X-ray mirrors
    - Production of silicon "blanks"
    - Semiconductor production: silicon etch, metrology and potentially even coating
  - Assembly
    - Robotic manufacturing
- Segmented, actuated glass
  - X-ray mirrors
    - Semiconductor production: pizeo application, implantation?
  - Assembly
    - Robotic manufacturing
- Full-shell approaches
  - X-ray mirrors
    - Additive and advanced manufacturing techniques

Ecosystem: examples of industry infrastructure available today

Old school

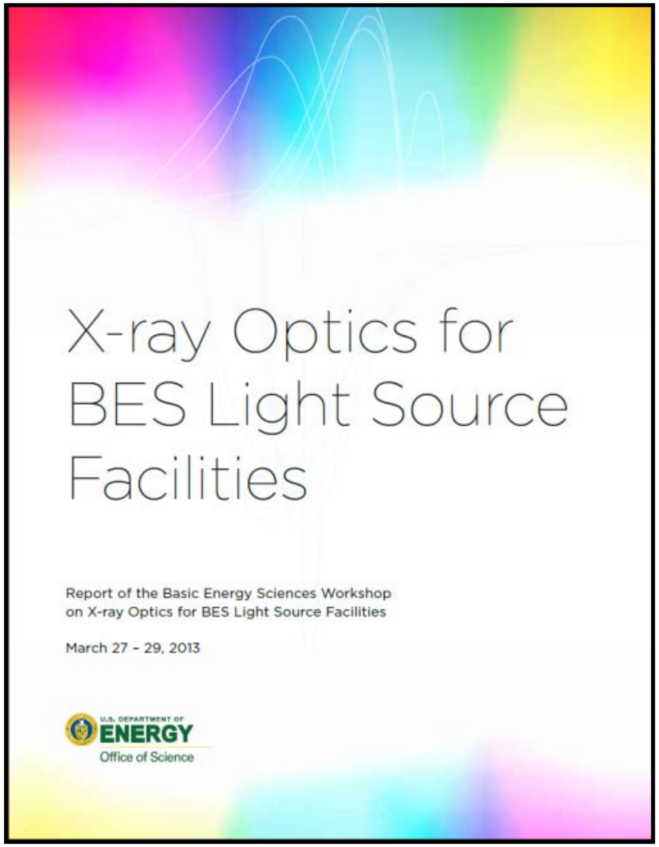


The core of this facility still exists. Some of the AXAF engineers are still active in industry; Figure 9 from Spina, *SPIE*, 1113:2 (1989)

Disruptive

Robotic manufacturing at Raytheon/Tucson (Apr 2016)
http://www.popularmechanics.com/military/research/a20456/raytheon-factory-robots-make-missiles/

DOE has recently studied optics needs for U.S. x-ray light sources



Technology needs identified and review

1. Grating Optics
2. X-ray Mirrors
3. **Optical & X-ray Metrology**
4. **Simulation & Modeling**
5. Nanodiffractive Optics
6. Crystal Optics
7. **Thin Film Optics**
8. **Adaptive X-ray Optics**
9. Refractive Optics

- Of these nine technologies, there are potentially **six** where DOE/SC/BES needs match those of XRS
- Technologies exist across the DOE complex at: Lawrence Berkeley, Argonne, Brookhaven, SLAC and Lawrence Livermore
- Thin-film, Metrology, Mod &Sim and Adaptive X-ray Optics are the most promising areas for collaboration

http://science.energy.gov/~/media/bes/pdf/reports/files/BES_XRay_Optics_rpt.pdf

Self-identify highest risks

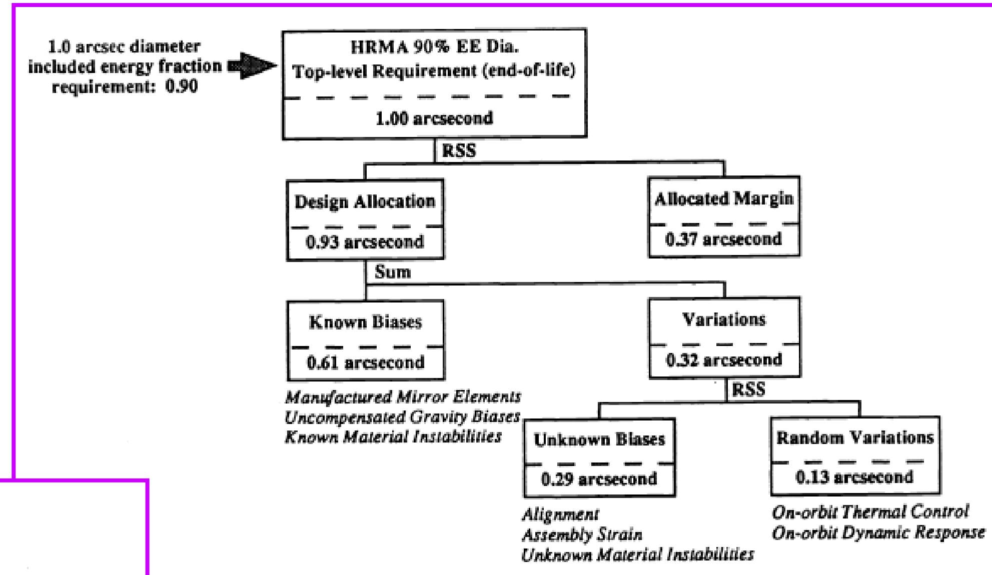
- Strongly suggest that each team produces a risk-registry and then presents to a common red-team or murder board
  - This happens, to some extent, during review of funding proposals and will certainly occur during the Decadal
  - So own it, now, and benefit from it

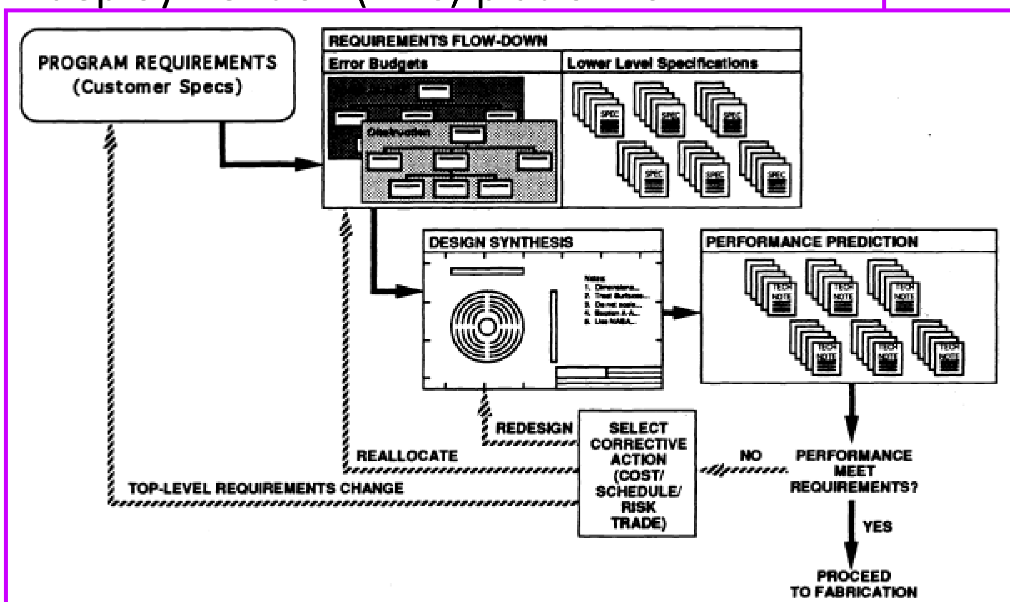
- Some logistics and ground-rules to sort through, but this exercise will only strengthen each effort and find areas of mutual needs

- Examples
  - Adjustable, segmented glass
    - State-of-the-art AO systems have a few thousand actuators; XRS would require orders of magnitude more; this is a wicked-hard controls problem, where computational resources goes as N^2; have you engaged AO controls community?
  - Segmented silicon
    - Even if your mirror substrates are inherently stress free, once you apply coatings, your parts will (elastically?) deform; have you engaged the x-ray light source or EUVL communities who fabricate diffraction-limited optics that meet sub-nm thickness requirements?
  - Integral shells
    - How well does differential deposition scale, both in correcting large number of shells and shells with large surface area? How does the correction change with: temperature? mounting stress? coating stress? Have you developed a dynamic FEA model to account for the influence of these effects, which will likely become more important as you move from several to a few to < 1 arcsec performance

Good news: same error budget formalism used for Chandra is applicable today

- XRS angular resolution goals will be similar to those for *Chandra* — **re-use these tools!**
- (Most) physics accounted for in previous flow-down procedures and prediction models
- Many more shells may require deployment on (HPC) platforms





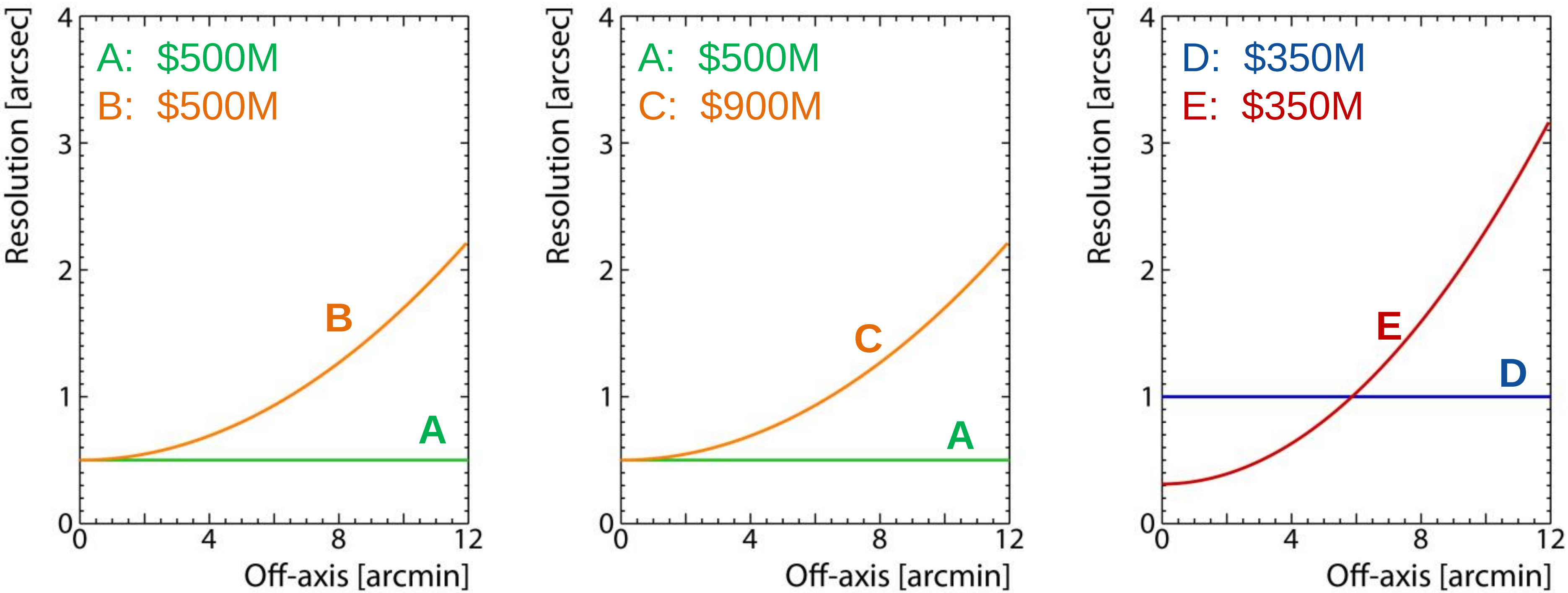
Figures 6 (top right) and 7 (bottom left) from Carey & Mundy, *SPIE* 209:463 (1994)

- Adjustable optics will require additional development to incorporate adjustable
- There is (significant) benefit in have all teams use the same tools
  - Use scare resources once, not three times, to develop the same tool
  - Apples-to-apples comparisons
  - Identify common challenges –and solutions—for all approaches

What is the angular resolution requirement?

- Let's hope that the XRS instrument concept would support all science drivers
- But plan on having costs (parametric or small number of point designs) for different performance curves to understand science versus resources

Assuming the same effective area for all designs, which is the best option for each of these three scenarios?



Recommendations

- Acknowledge the situation and embrace the challenge
- Identify common needs (e.g., x-ray testing facilities, thin-film deposition capabilities, HPC-based FEA) and have this peer-reviewed by friendly but independent teams
- Engage industry
- Look for help from adjacent fields: adaptive optics, DOE x-ray light source facilities, additive manufacturing, robotic-enabled, serial production
- Develop a credible optics development plan, that would include:
  - Common error budget and modeling tools (this is foundational!)
  - Arc-second level prototypes, as key milestones
  - Parametric models of telescope performance versus resources to understand costs