Achieving Large-Scale High-Resolution Full-Shell Replicated X-ray Optics: Budgeting for Sources of Angular Resolution Errors

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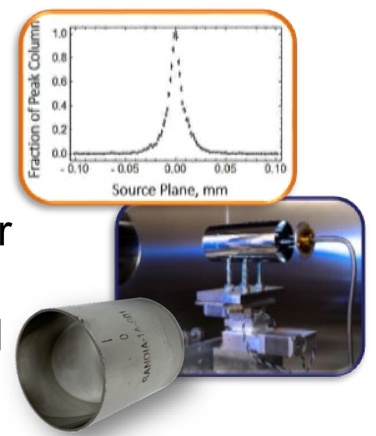
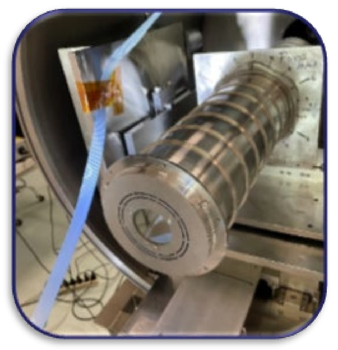
Presented on behalf of the NASA MSFC X-ray Astronomy (ST12) and Optical Systems Design, Fabrication, & Test (ES23) Groups

MARSHALL SPACE FLIGHT CENTER

2025

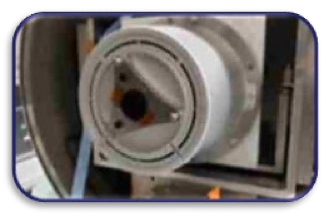


2022 Very-high-resolution of 2.3 ± 0.3 (1σ) arcsecs FWHM measured for MSFC-fabricated optic for the National Ignition Facility.



2023 FOXSI-4 MSFC-fabricated mirror module (2 mirror shells) X-ray calibration indicates high-angular resolution of ~3.0 arcsecs FWHM.

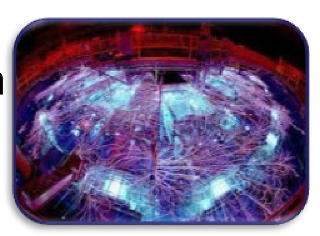
2021 Launch of IXPE with MSFC-fabricated optics (3 modules, 24 shells)



2021 Launch of MaGIXS sounding rocket with MSFC-fabricated mirrors

2020

2019 Launch of Spectrum-Rontgen-Gamma Mission with ART-XC instrument using 7 MSFC-fabricated X-ray mirror modules (28 nested shells each).



2017 First demonstration of MSFC-produced optics for the Sandia Z pulsed energy machine.

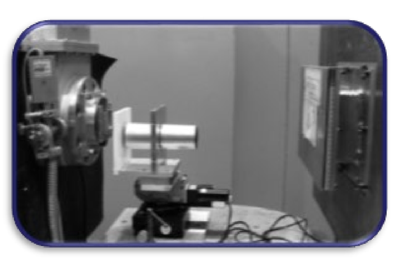
Image Credit: National Technology & Engineering Solutions of Sandia, LLC

2015

2012-2028 Series of FOXSI sounding rocket flights with MSFC-fabricated optics.

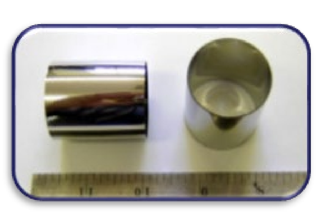
2010

2005-2013 Series of HERO/HEROES balloon flights with MSFC optics (8 modules with over >140 mirrors in total)



2007 First demonstration of X-ray optics for focusing cold neutrons!

2005



2004 Demonstration of the first MSFC-produced miniature X-ray optics for small-animal radionuclide imaging.

2002 100-µm-thick shell developed for Con-X HXT

2001 First flight of balloon payload with MSFC optics with (2 modules, each with 3 mirrors). **Captures the first ever hard X-ray focused images of the sky!**

2000 0.5-m diameter, NiCoP replicated shell was produced as proof of concept for the Con-X Project.

2000

MSFC Replicated X-Ray Optics: 30 Years of Development, Test, and Flight

1995

1993 First MSFC electroformed X-ray optics fabricated in support of the AXAF-S program

1990

*All Images are credited to NASA unless noted otherwise.

INTRODUCTION

There are only a few facilities in the world that develop X-ray optics for spaceflight, of which MSFC is a leader. Decades of investment and internal research have resulted in a comprehensive, end-to-end capability to design, fabricate, align, mount, coat, calibrate, and fly X-ray mirrors and assembles with predictable performance. With a focus on replicated full-shell mirrors, MSFC optics advancements are not only relevant to Astrophysics, but also to Heliophysics and Planetary missions. MSFC's optics also support other government entities such as the National Ignition Facility, National Institute of Standards and Technology, and Sandia National Laboratory.

SPATIAL RESOLUTION ERROR BUDGET

An updated accounting of spatial-resolution-constraining error terms gives context to recent improvements in MSFC replicated optics, as well as guidance and justification for current and future directions of research and development. The budget includes strawman error allocations for a mirror *assembly* that is parametrically *Lynx*-like and where the replicated-optics technology stands relative to these allocations.

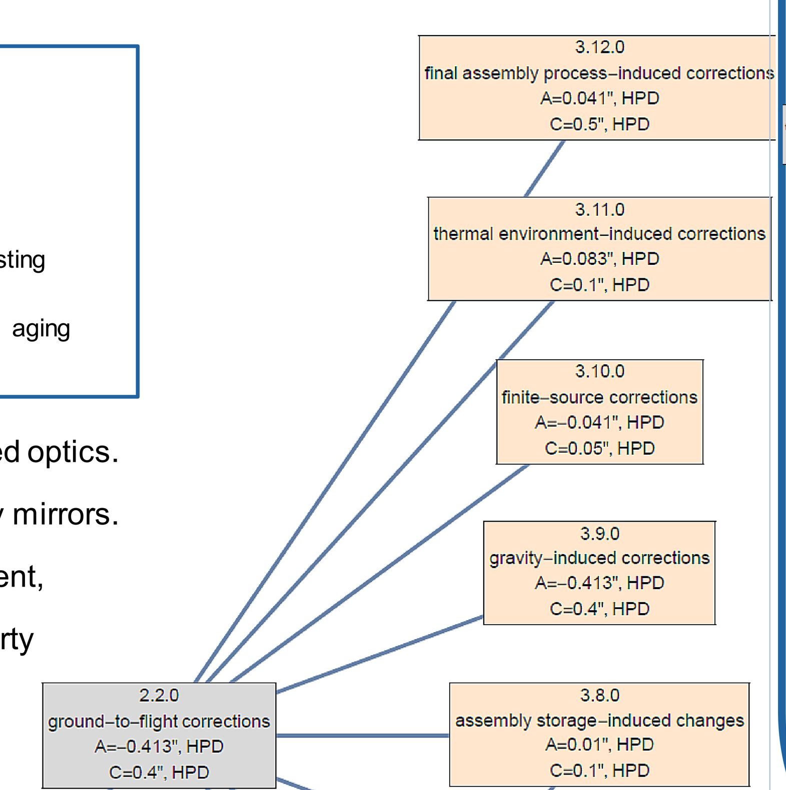
Error budget terms, which can ultimately be mapped to requirements, are grouped into three areas: mandrel, individual mirror shells, and mirror modules. These map to manufacturing, integration, and test (optical and X-ray), which in turn are targets of the MSFC directed research. Ground-to-flight corrections are made to predict performance during flight.

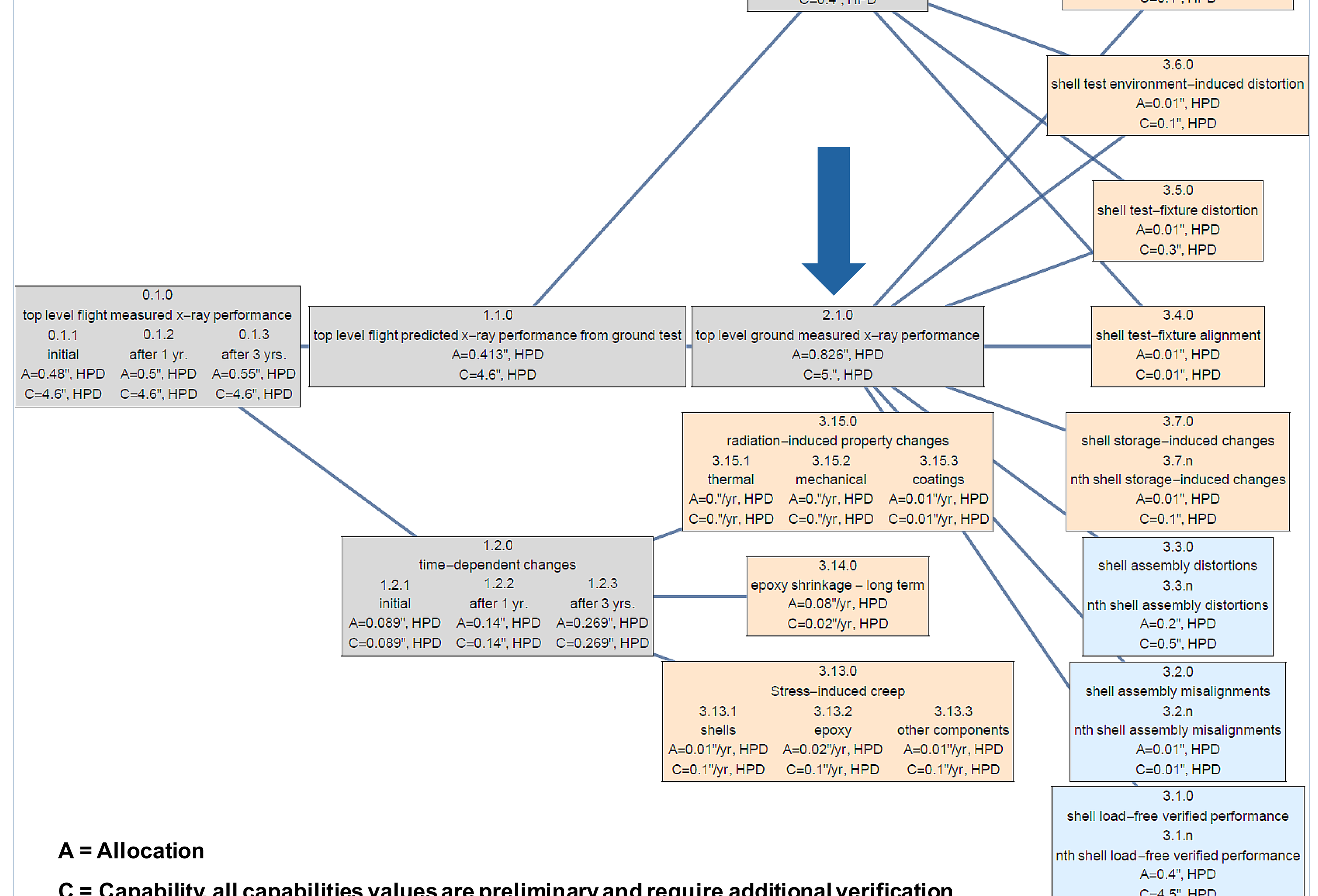
Mandrel
- Diamond turning
- Lap polishing
- Deterministic polishing
- Passivation
- Metrology

Mirror Shell
- Material Properties
- Replication
- Separation
- Direct Polishing
- Coating
- Metrology
- X-ray testing
- Storage, handling, aging

Mirror Module
- Mount design
- Alignment
- Assembly
- Bonding
- Environmental Testing
- X-ray testing
- Storage, handling, aging

While many of the error budget terms are specific to replicated optics. There are general error terms that are common to most X-ray mirrors. These include gravity induced corrections, thermal environment, assembly, storage, epoxy shrinkage, radiation-induced property changes, and other.





A = Allocation

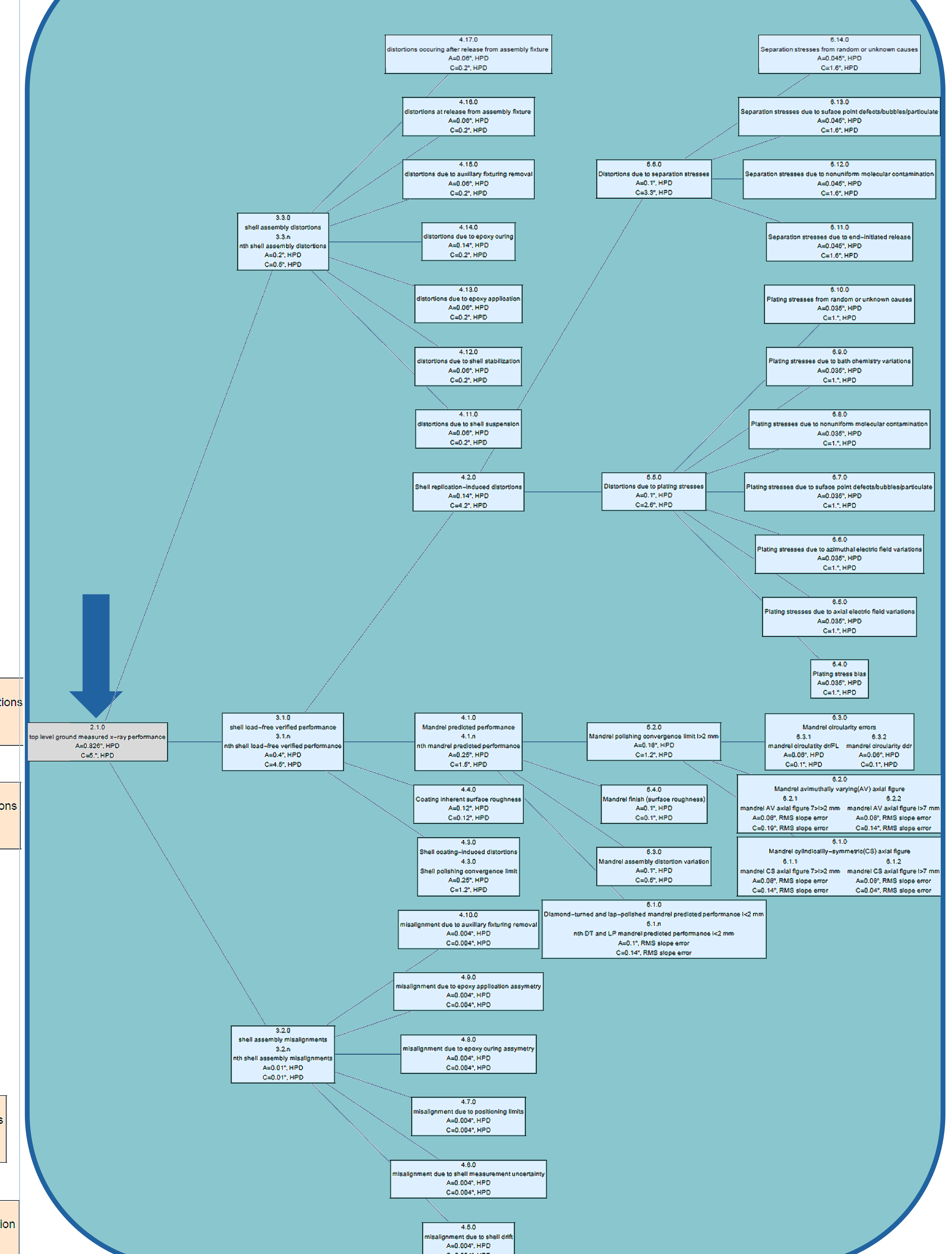
C = Capability, all capabilities values are preliminary and require additional verification

Gray Boxes = Post-Assembly (testing and aging)

Blue Boxes = Individual Mirror Shells and Assembly (fabrication, assembly, and metrology)

Orange Boxes = Generic Terms (common to all X-ray mirrors and assemblies)

Top-Level Ground Measured X-Ray Performance



CONCLUSIONS

The error budget is a tool that allows us to identify limiting factors in our fabrication, assembly, and test processes. We believe that the current tall-pole for achieving sub-arc second replicated full-shell mirror modules is related to the replication process and stresses caused by separating the mirror shell from the mandrel. Research is on-going, and a plan is in-place to address deficiencies.

We would like to thank the NASA Astrophysics Division for the funding that makes this research possible through the Internal Scientist Funding Model (ISFM).

Over the past 2-years, MSFC *flight* mirror assemblies have gone from achieving ~25" FWHM to < 3" FWHM. This is due to dedicated and focused research to improve process steps. There are currently no known showstoppers to achieving sub-arcsecond resolution.

REFERENCES

Numerous papers have been published on MSFC full-shell replicated optics. Error budgets for the Chandra X-Ray Observatory and the Imaging X-ray Polarimetry Explorer (IXPE) aided in building the foundation of this budget, and current work provides direction on reasonable allocations, verified primarily by test and analysis.

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