Characterizing Gravity Sag at Cryogenic Temperatures

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outline

- Introduction
- Mirror development
- Cryo deformation
- Cryo gravity sag
- Conclusions

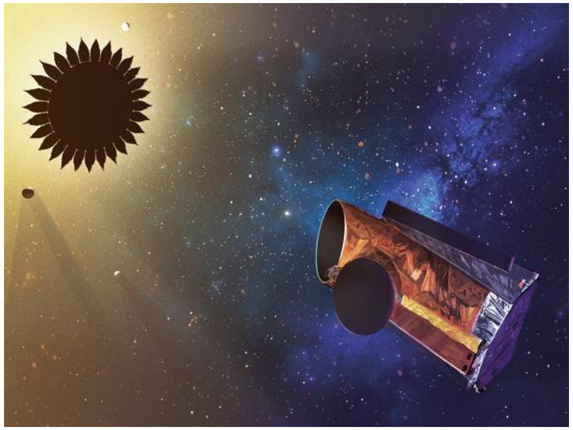
Introduction

What is Gravity Sag?

- Bending of the mirror substrate as it is accelerated by gravity

Why should we care about Gravity Sag?

- Because we want to fly better and better telescopes

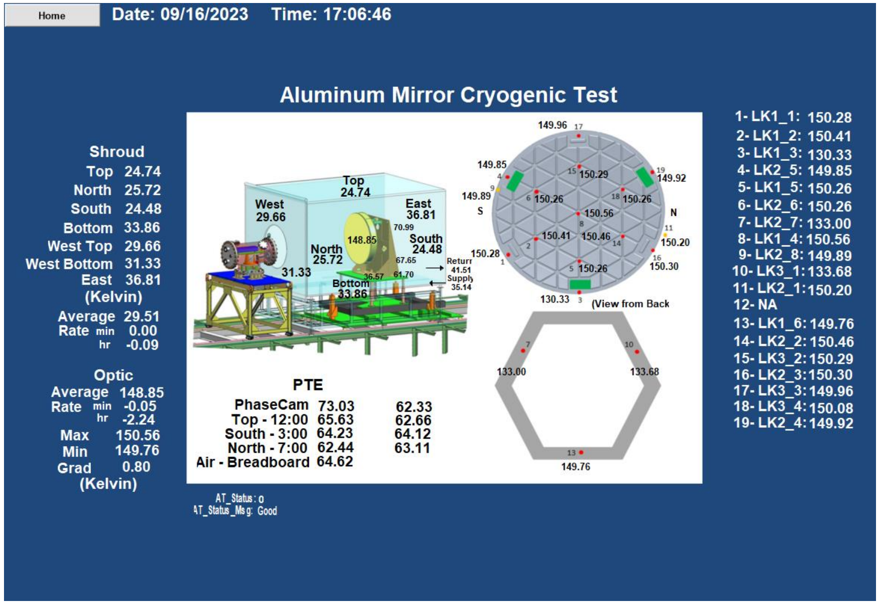


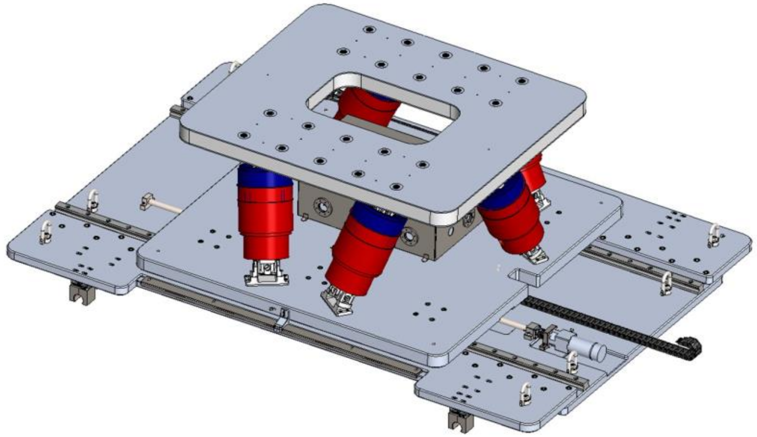
How do cryogenic temperatures affect gravity sag?

- That's what we are talking about today

XRCF

- Adaptable, multi-capable space simulation facility
- 6m dia x 19m test volume; P < 10^{-7} mbar; T: -250C to 100C
- 500m^2 ISO6 cleanroom
- Mirrors up to 4.25m in diameter with RoC < 22.5m to 20 Kelvin
- 518m beamline; 1.46m diameter beam with < 3 mrad divergence
- Hexapod Stage w/ 4,000 kg capacity





MSCF 1.2-m Technology Development Aluminum Mirror

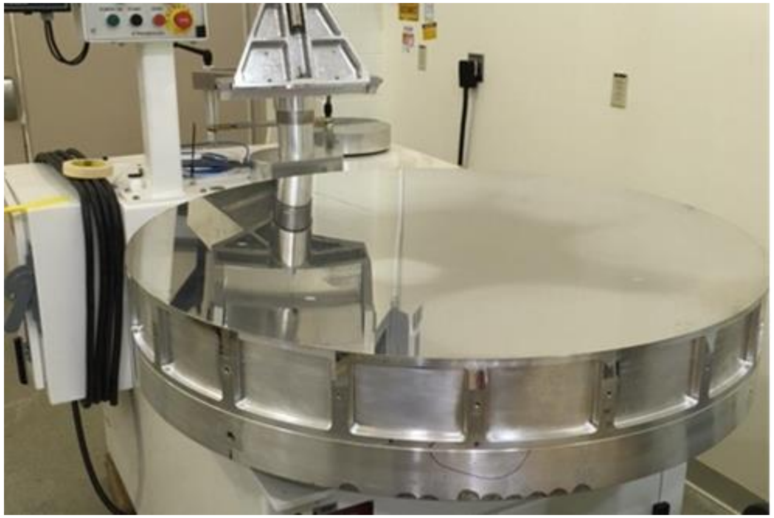
In 2020, MSFC made a 1.2-m aluminum tech development mirror on IRAD

Specifications

Diameter	1.2-m
Thickness	13.8-cm
Radius	5-m
Conic	0 (sphere)
Substrate	112-kg
Assembly	164-kg

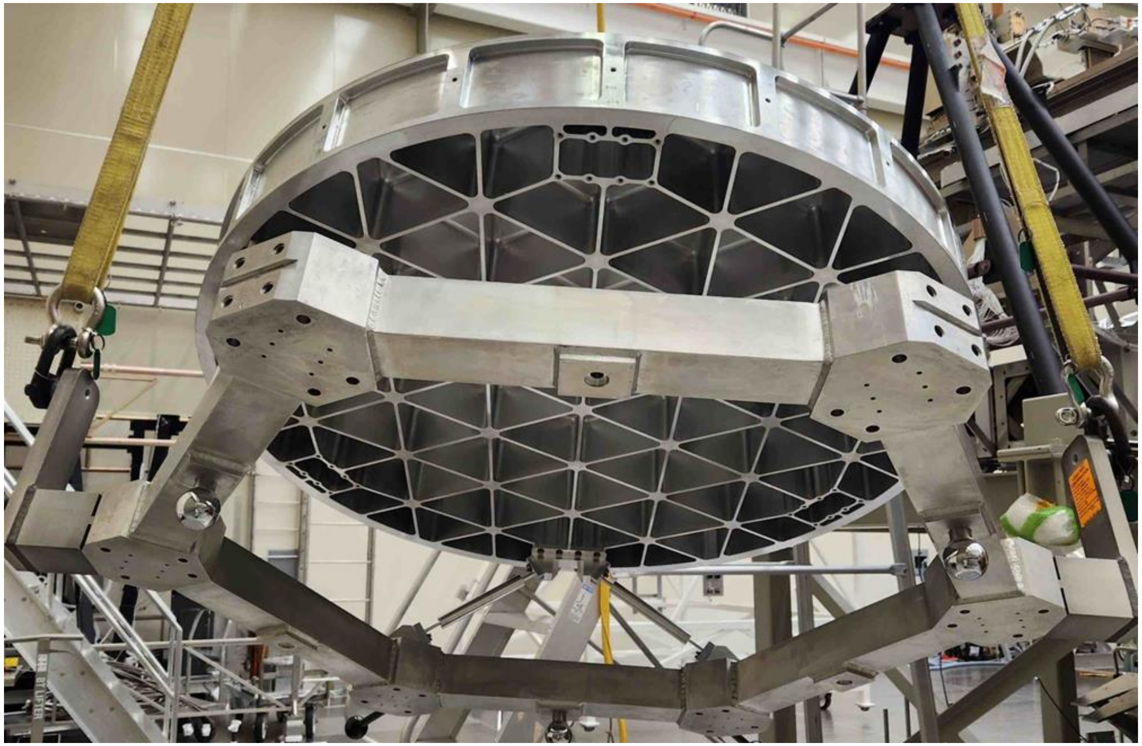
Technology Experiments

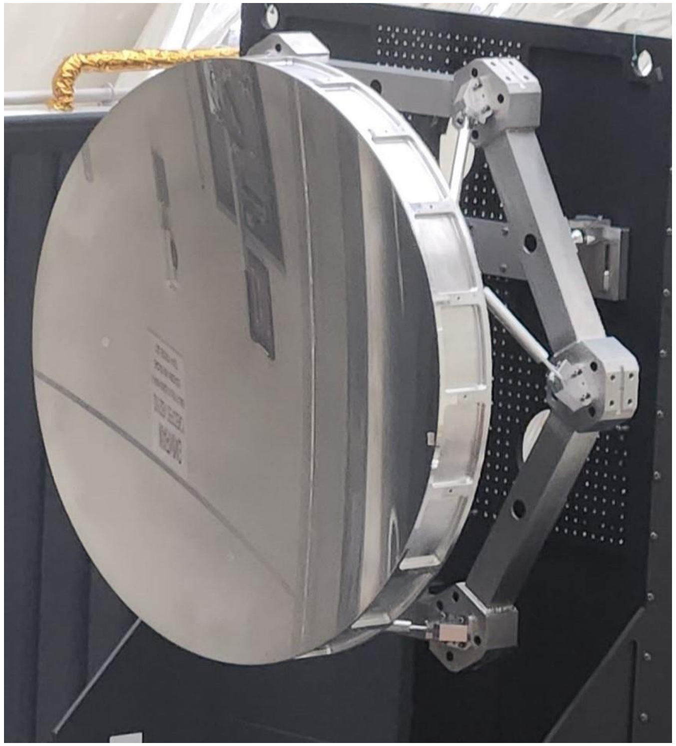
- Cryo-Deformation
- Gravity-Sag
- Cryogenic Gravity Sag



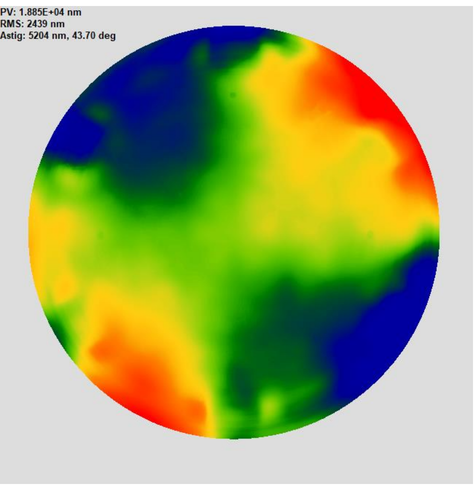
MSCF 1.2-m Technology Development Aluminum Mirror

Single point diamond turned (SPDT) on Moore M-40 to 5 m radius of curvature.
Polished to 700Å rms.
Cryo tested at 3 rotations (0°, 120°, and 240°) to 35K for cryo gravity sag.





Delta rms SFE for 35 K from 290 K



35 K
SFE = 2439 nm rms

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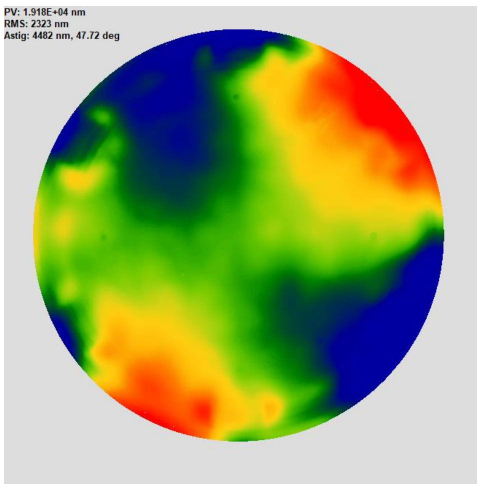

290 K
2323.2 nm rms

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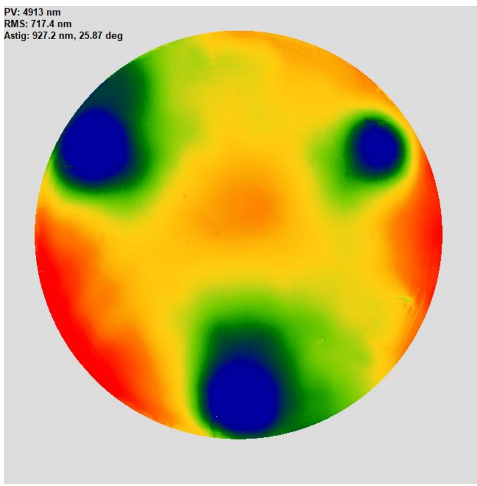
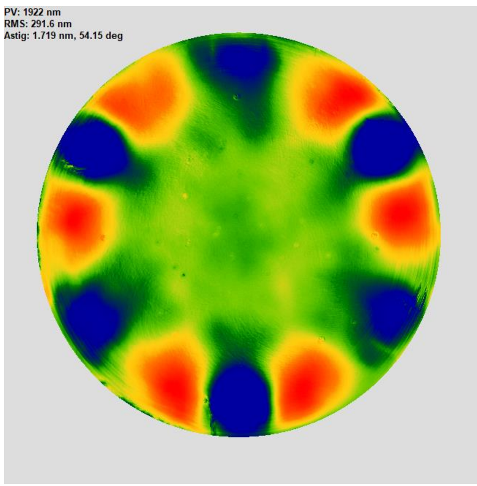


35 – 290 K
717 nm rms

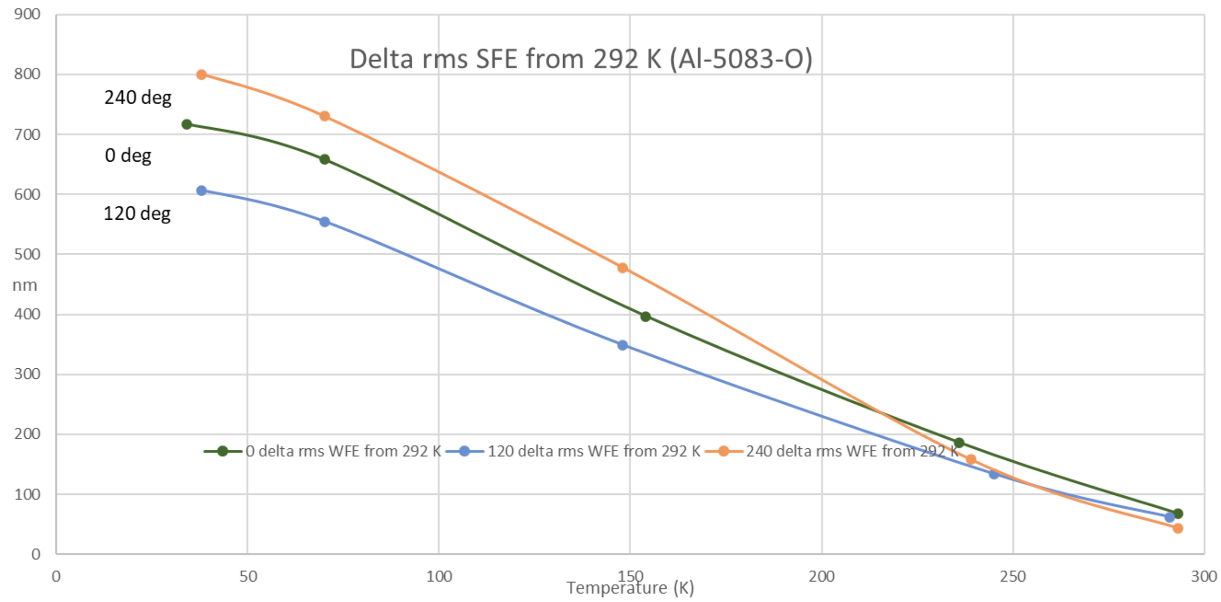


36 Zernike residual
292 nm rms
Trefoil 1233 nm

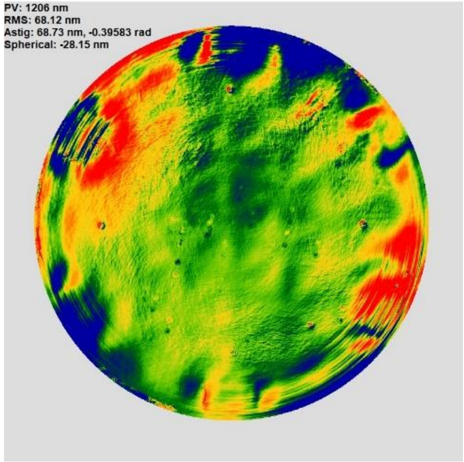
Δ radius of curvature = 21.31 mm +/- 0.15

Cryo Deformation

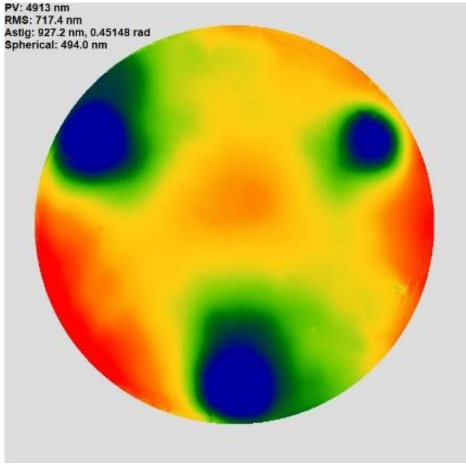
- Mirror was cooled from ~290K to ~35K in three different orientations
- Mount dominated the deformation and caused trefoil in the surface figure



290-293 K

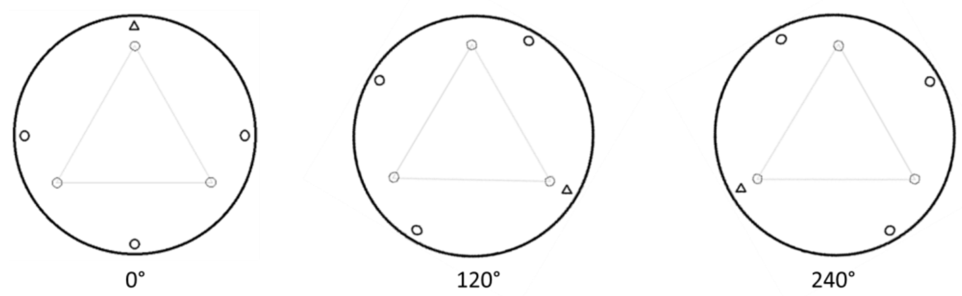


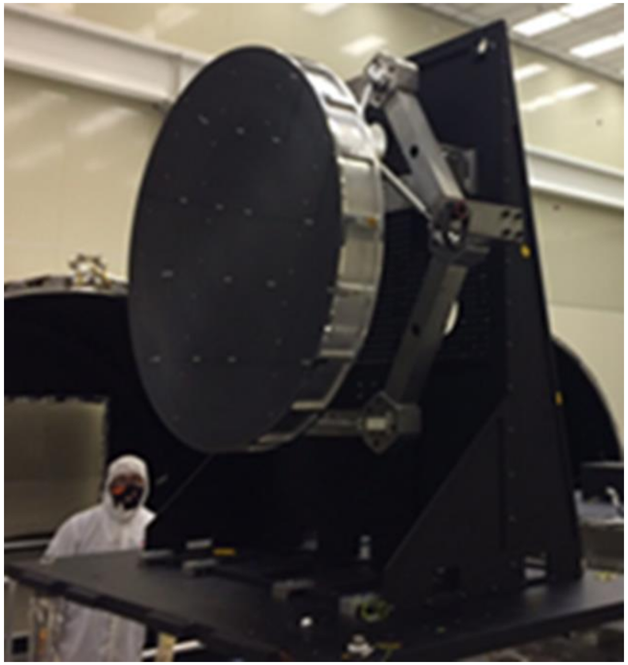
35 -293 K



Gravity Sag Measurements

Used Rotation Test to characterize 1.2-m Gravity Sag as a function of Wavelength





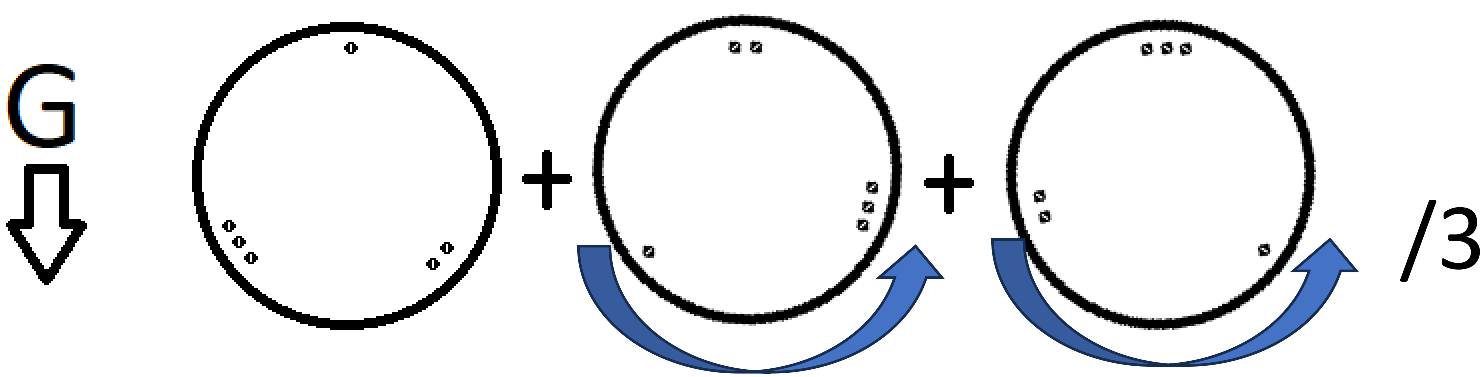
- Mount mirror at 0-deg, 120-deg and 240-deg clocking positions in XRCF
- Measure surface figure as a function of temperature
- Apply rotation algorithm to estimate G-Sag vs Temp

Horizontal Rotation Test

$$S(x,y,\theta_i)_{Horizontal} = \left[S(x,y)_{G(0,0,0)_{symmetric}} + S(x,y,\theta_i)_{G(0,0,0)_{asymmetric}}\right] + S(x,y,\theta = 0)_{G(0,-1,0)}$$

$$\frac{1}{N}\sum_{i=0}^{N-1} S(x,y,(\theta_i = 0)_{Horizontal} = \left[S(x,y)_{G(0,0,0)_{symmetric}} + S(x,y,\theta_i)_{G(0,0,0)_{asymmetric}}\right]$$

- Rotation test is "blind" to rotationally symmetric terms. (I.E. Spherical aberration)Put another way, does not average out Zernike polynomials with no Theta term.
- Polynomials with N-1 Theta terms can be averaged out

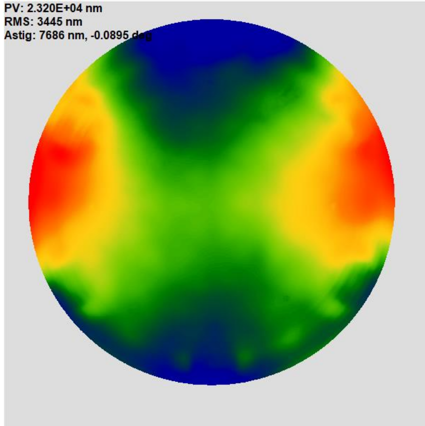


Gravity Sag

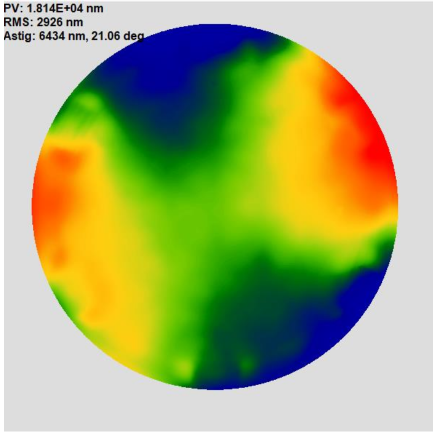
Using horizontal rotation test method to determine 0G and G-sag Shape

Rotated the mirror to three orientations (0°,120°,240°) manually by removing the mirror from the cryo vacuum chamber and rotating with a crane

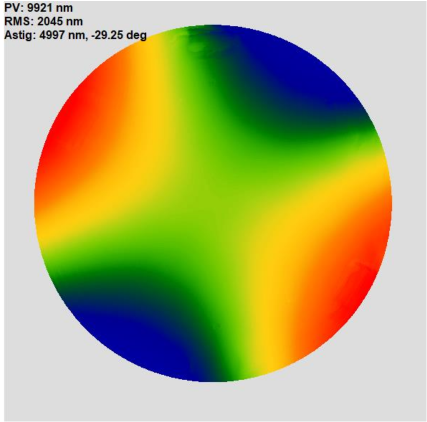
293K raw



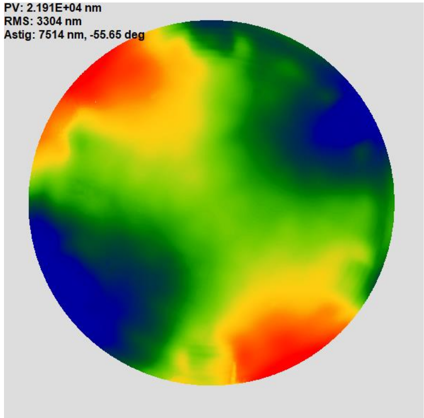
293K 0G



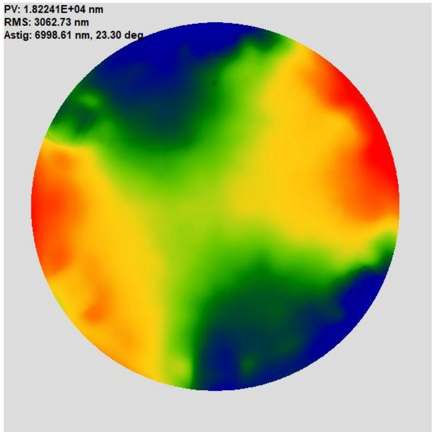
293K G-sag



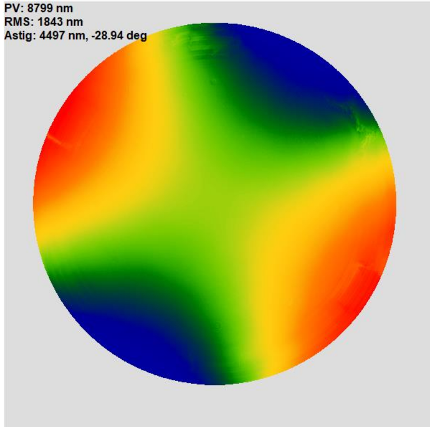
35K raw



35K 0G

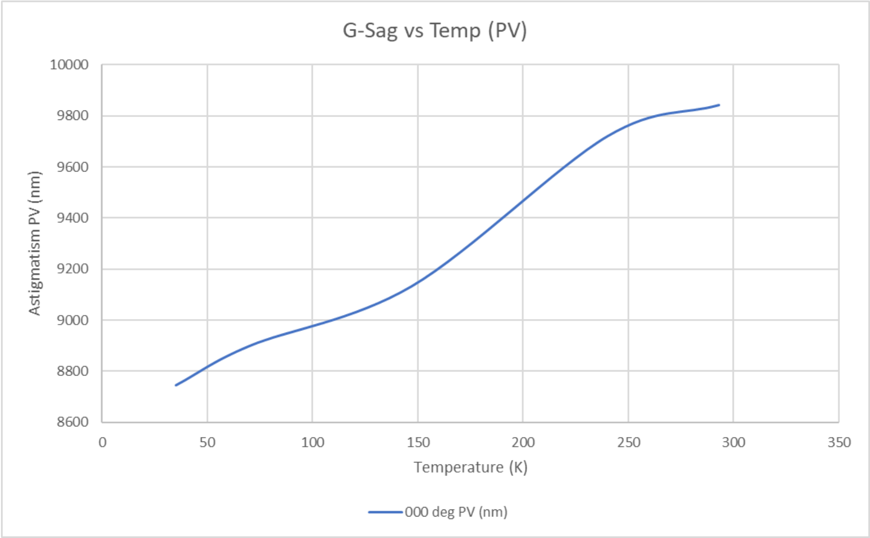


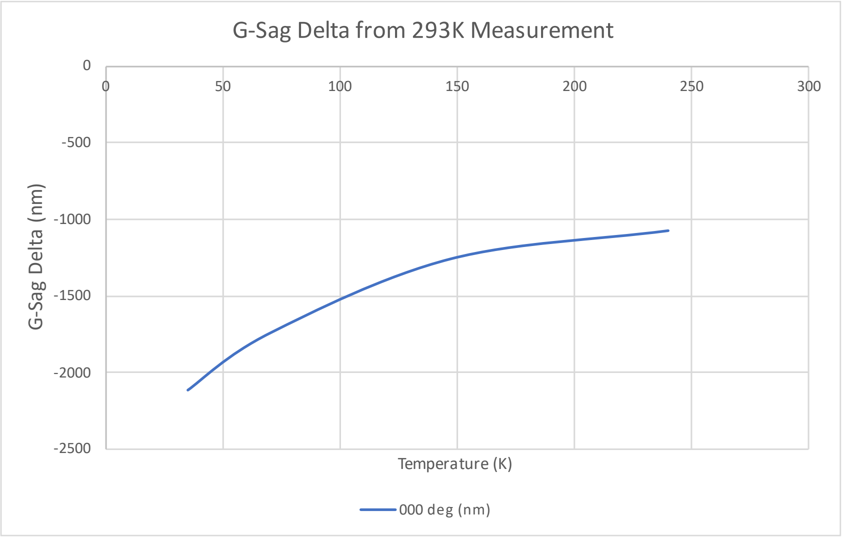
35K G-sag



1.2-m Aluminum Mirror Cryogenic Gravity Sag

G-Sag decreased by ~1 µm (from 9.8 to 8.8 µm) as a function of Temp (from 293K to 35K)



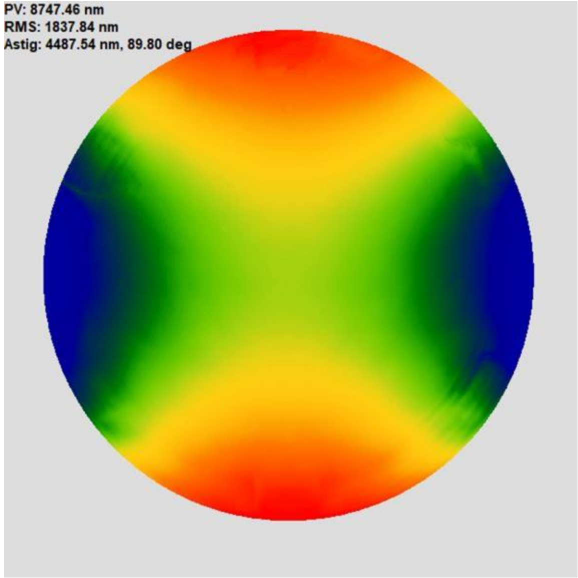


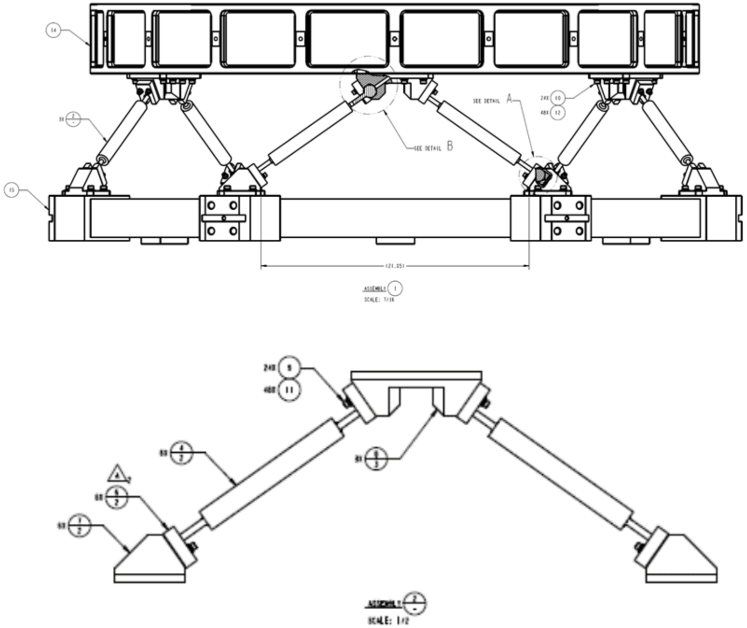
Aluminum Young's Modulus and Strength increase with decreasing Temperature

1.2-m Aluminum Mirror Gravity Sag

G-Sag is large because the strut intersection point is at back of mirror instead of mid-point

35K G-Sag Estimate
8.75 micrometer PV





Conclusions and Future Work

Conclusions

- 1.2m mirror was tested using the horizontal rotation test to determine the gravity sag at multiple temperatures.
- Cryo G-Sag testing demonstrated that the total G-sag decreased by ~1 µm over the temperature range (~293K to ~35K).
- The mount can instill a significant amount of deformation into the surface figure.

Future Work

Modulus of Elasticity testing of 5081 to correlate the 1.2m Al mirror data to models.

Thank you

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Backup Slides

N-Rotation Test

The horizontal rotation test makes use of the 'N-rotation' algorithm where the interferometer measures a surface at N-rotation angles, i.e. N=3 (0°, 120°, 240°) or N=6 (0°, 60°, 120°, 180°, 240°, 300°).

Averaging removes all test errors with angular dependence up to (N-1) Theta; and, all higher angular order errors that are not harmonics of N.

So, an N=3 rotation test will remove 2-Theta errors (i.e. coma, secondary coma, tertiary coma, etc.; and, astigmatism, secondary astigmatism, tertiary astigmatism, etc.).

An N=6 rotation test is required to remove error terms up to 5-Theta (i.e. trefoil, tetrafoil, and pentafoil).

Analytical Removal

Horizontal Rotation Test

Because horizontal gravity sag is asymmetric, rotation tests can absolutely quantify gravity sag –thus allowing its removal from a surface measurement.

$$S(x,y,\theta_i)_{Horizontal} = \left[S(x,y)_{G(0,0,0)_{symmetric}} + S(x,y,\theta_i)_{G(0,0,0)_{asymmetric}}\right] + S(x,y,\theta=0)_{G(0,-1,0)}$$

Rotating a mirror in angles around its surface normal that are symmetric with its flight mount, only rotates the mirror’s asymmetric component. The gravity sag does not rotate, nor does its rotationally symmetric component.

Averaging these N-rotation measurements results in a measurement consisting of only the mirror’s symmetric surface shape and its gravity-sag.

Back rotating each data set to theta = 0 before averaging, removes the gravity sag term, leaving only the mirror’s symmetric and asymmetric terms.

$$\frac{1}{N}\sum_{i=0}^{N-1} S(x,y,(\theta_i=0)_{Horizontal} = \left[S(x,y)_{G(0,0,0)_{symmetric}} + S(x,y,\theta_i)_{G(0,0,0)_{asymmetric}}\right]$$

Gravity Sag Measurements

Collect all raw unprocessed data from the horizontal rotation test.

Remove tip/tilt and piston from each of the surface maps.

Back-rotate the data so that each data point is aligned.

Average the back-rotated data which will remove the gravity sag and any rotationally symmetric errors up to N-1 Theta and leaves the 0-G figure and the rotationally asymmetric terms.

Subtracting the step 4 data (0-G/rotationally asymmetric terms) from the back rotated data will leave only the G-sag term