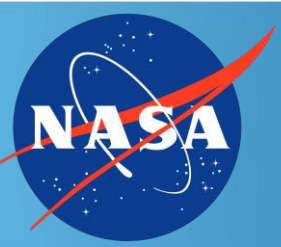




A Comparison of Gravity Sag Measurement Methods

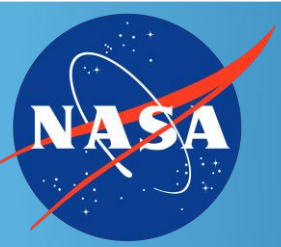
Stephen Cheney
NASA
Marshall Space Flight Center



Agenda



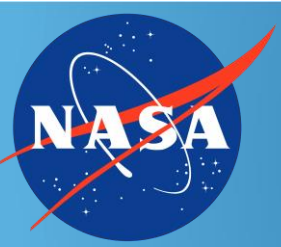
- Gravity sag/G-release introduction
- Introduce methods of measurement
 - Horizontal rotation test
 - Vertical “Face-up/Face-down” test
- Show test set ups
- Show results
- Compare results



What is Gravity Sag



- In this context, we're talking about deflections of optical surfaces due to gravity
- Science requires optical surface tolerances to be controlled on the order of wavelengths of light (typically fractions of nanometers to micrometers)
- Gravity sag changes as function of elevation angle for optics in gravity
- Optics manufactured in gravity and put in space have "G-release"

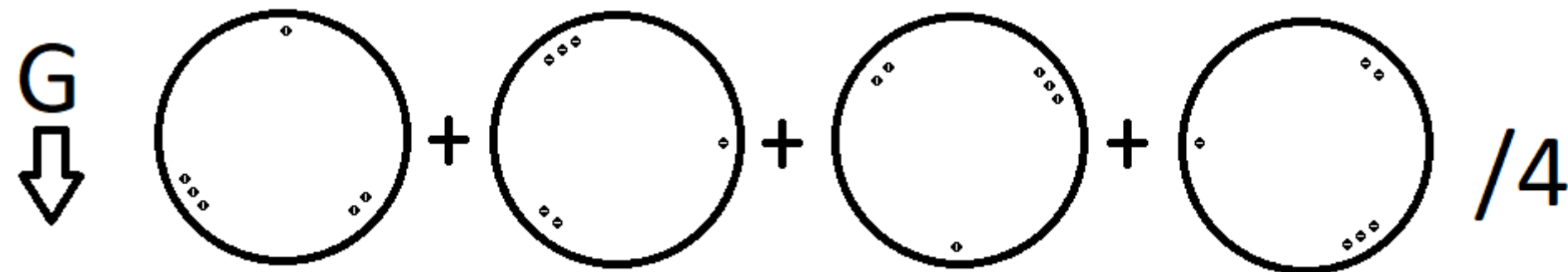


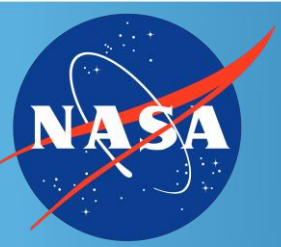
Horizontal Rotation Test

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

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

- 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





Horizontal rotation test set-up

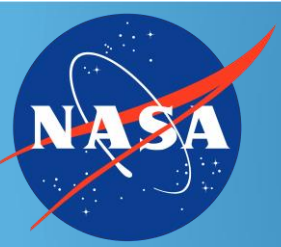


Test mirror:
60 cm
5 m ROC
ULE



For more about this test please see:

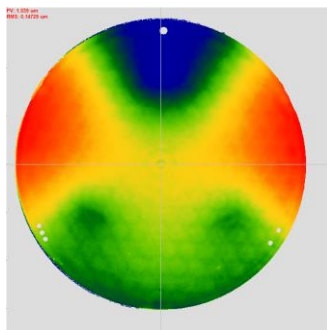
Lis, Tomasz, Stephen Cheney, and H. Philip Stahl. "Absolute characterization of gravity sag for light-weighted optics." *Optical Manufacturing and Testing XIV*. Vol. 12221. SPIE, 2022.



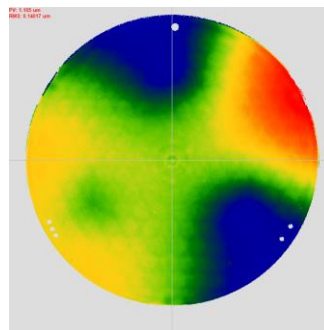
Results (Horizontal rotation test)



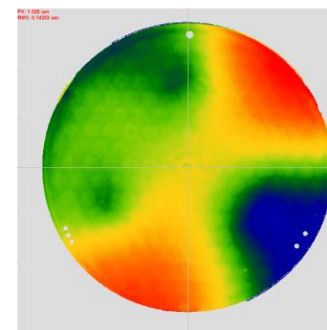
0



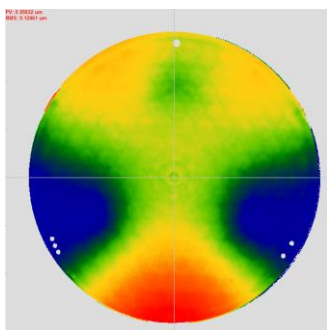
60



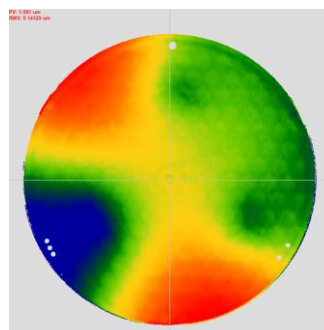
120



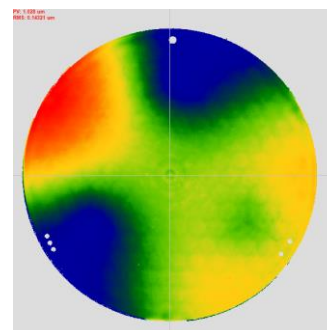
180

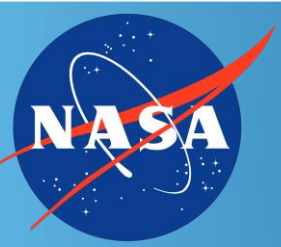


240



300



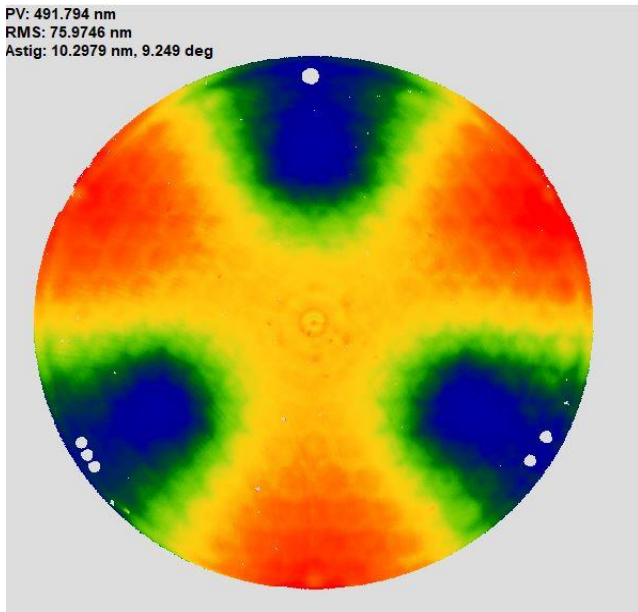


Results (Horizontal rotation test)

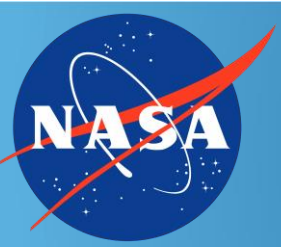


“0-G” figure from N=6
rotation averaged
76 nm RMS

PV: 491.794 nm
RMS: 75.9746 nm
Astig: 10.2979 nm, 9.249 deg



Coef (nm)	Aberration
-0.37	Piston or Bias
0.10	Tilt X
0.07	Tilt Y
-0.76	Power
15.44	Astig X
-2.08	Astig Y
1.96	Coma X
2.85	Coma Y
23.24	Primary Spherical
14.83	Trefoil X
188.60	Trefoil Y
0.50	Secondary Astig X
3.69	Secondary Astig Y
2.32	Secondary Coma X
-3.23	Secondary Coma Y
-21.10	Secondary Spherical
-1.57	Tetrafoil X
2.07	Tetrafoil Y
-7.13	Secondary Trefoil X
-98.09	Secondary Trefoil Y
-0.63	Tertiary Astig X
0.88	Tertiary Astig Y
-1.77	Tertiary Coma X
2.16	Tertiary Coma Y
-2.72	Tertiary Spherical
2.23	Pentafoil X
-0.27	Pentafoil Y
1.04	Secondary Tetrafoil X
-0.88	Secondary Tetrafoil Y
3.81	Tertiary Trefoil X
40.26	Tertiary Trefoil Y
-1.43	Quaternary Astig X
-0.26	Quaternary Astig Y
-0.26	Quaternary Coma X
-0.75	Quaternary Coma Y
10.85	Quaternary Spherical



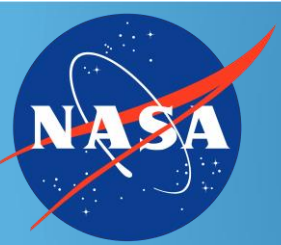
Vertical or “Face-up/Face-down” test

$$\begin{aligned} S(x,y)_{face-up} &= S(x,y)_{G(0,0,0)} - S(x,y)_{G(0,0,-1)} \\ S(x,y)_{face-down} &= S(x,y)_{G(0,0,0)} + S(x,y)_{G(0,0,1)} \\ 0G \text{ Shape} = S(x,y)_{G(0,0,0)} &= [S(x,y)_{face-up} + S(x,y)_{face-down}] / 2 \end{aligned}$$

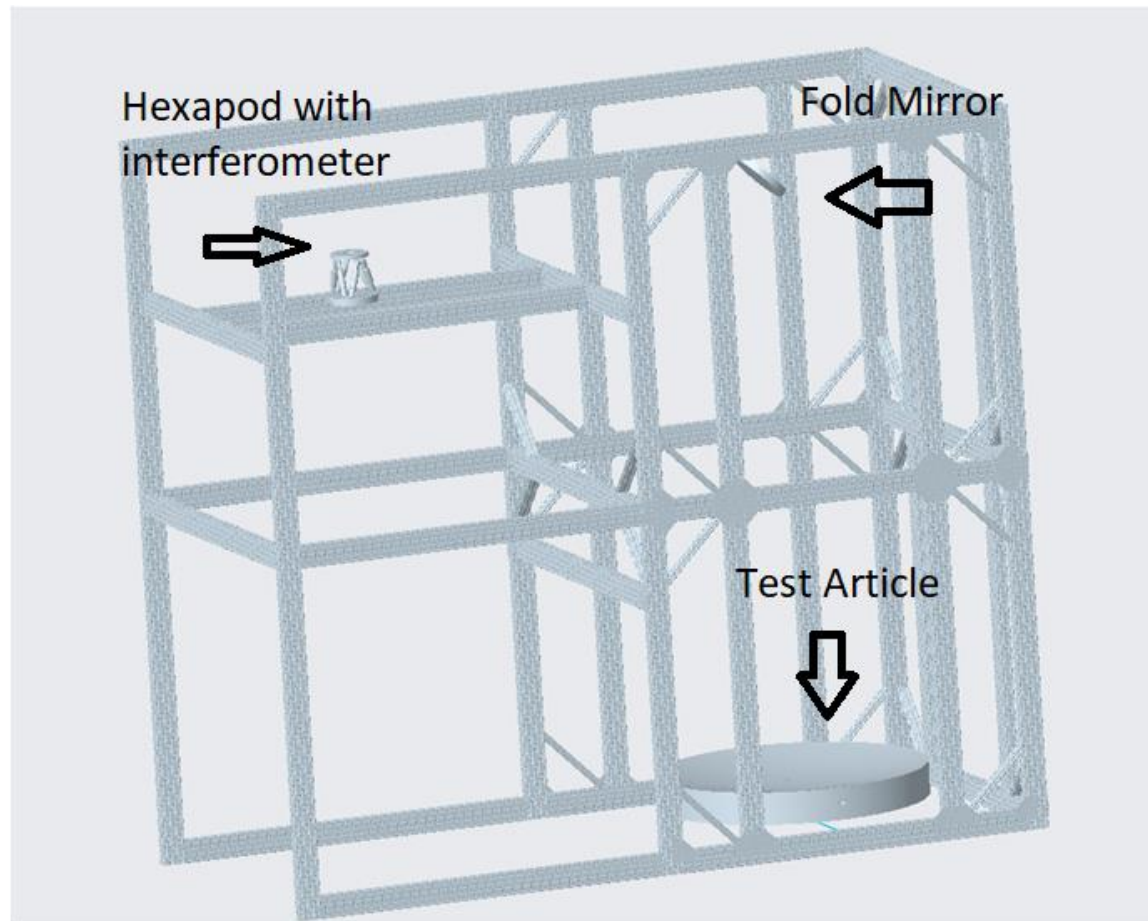


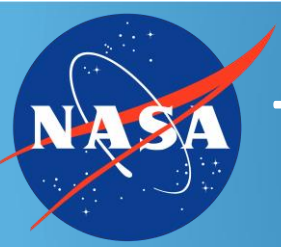
For more about both tests please see:

Stahl, H. Philip. "Absolute characterization of gravity sag." *Optical Manufacturing and Testing XIII*. Vol. 11487. SPIE, 2020.

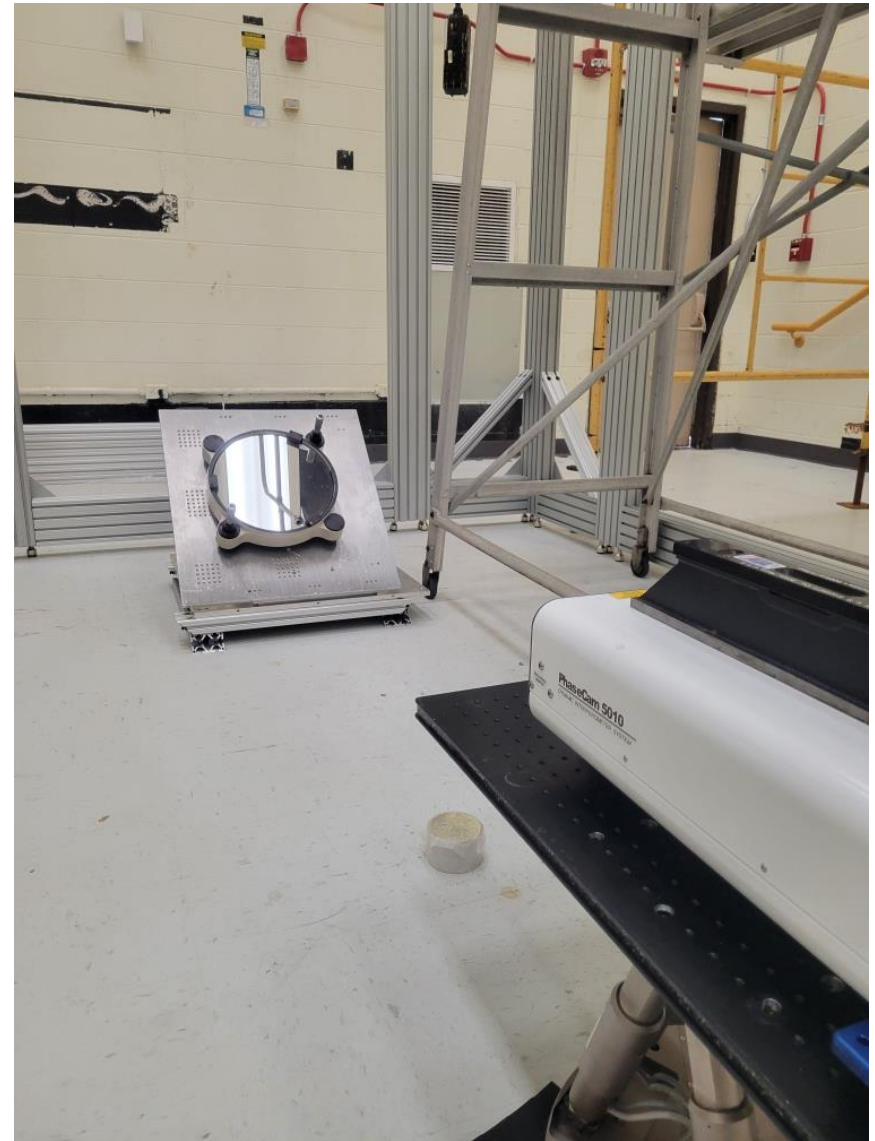
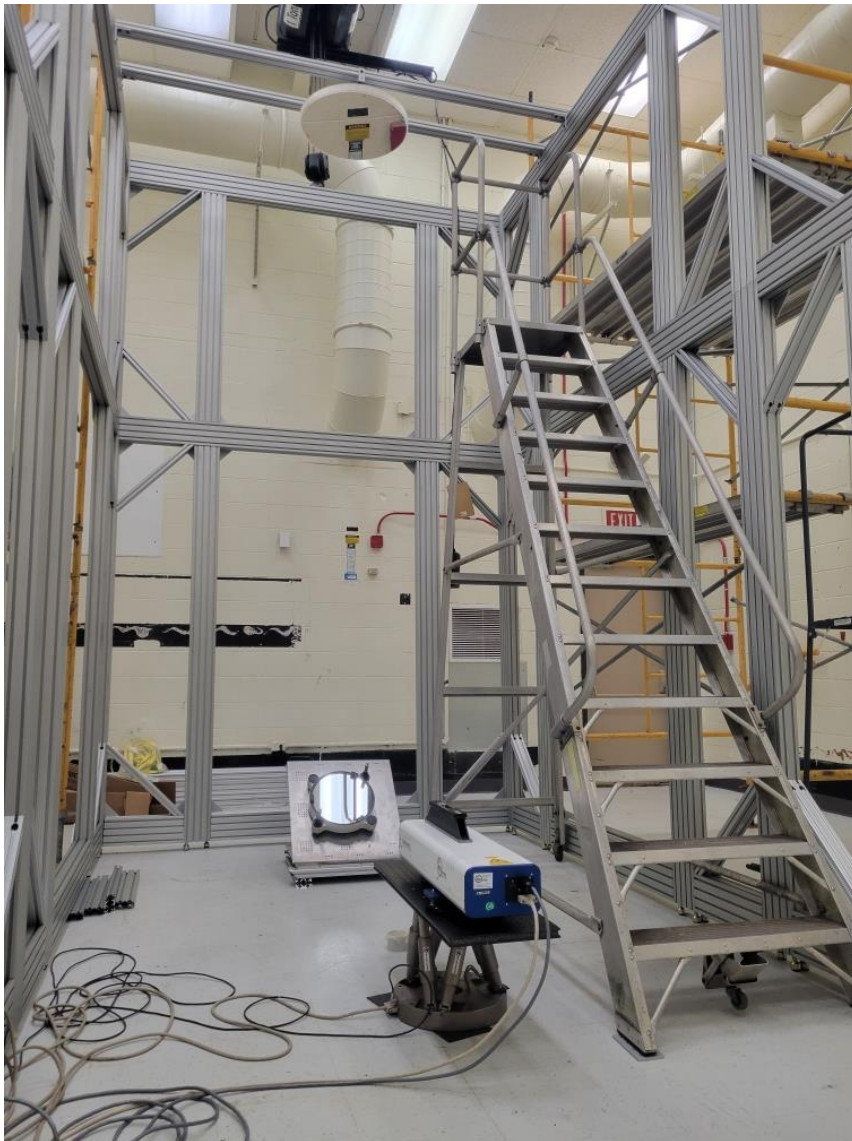


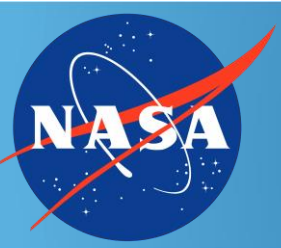
Test Tower



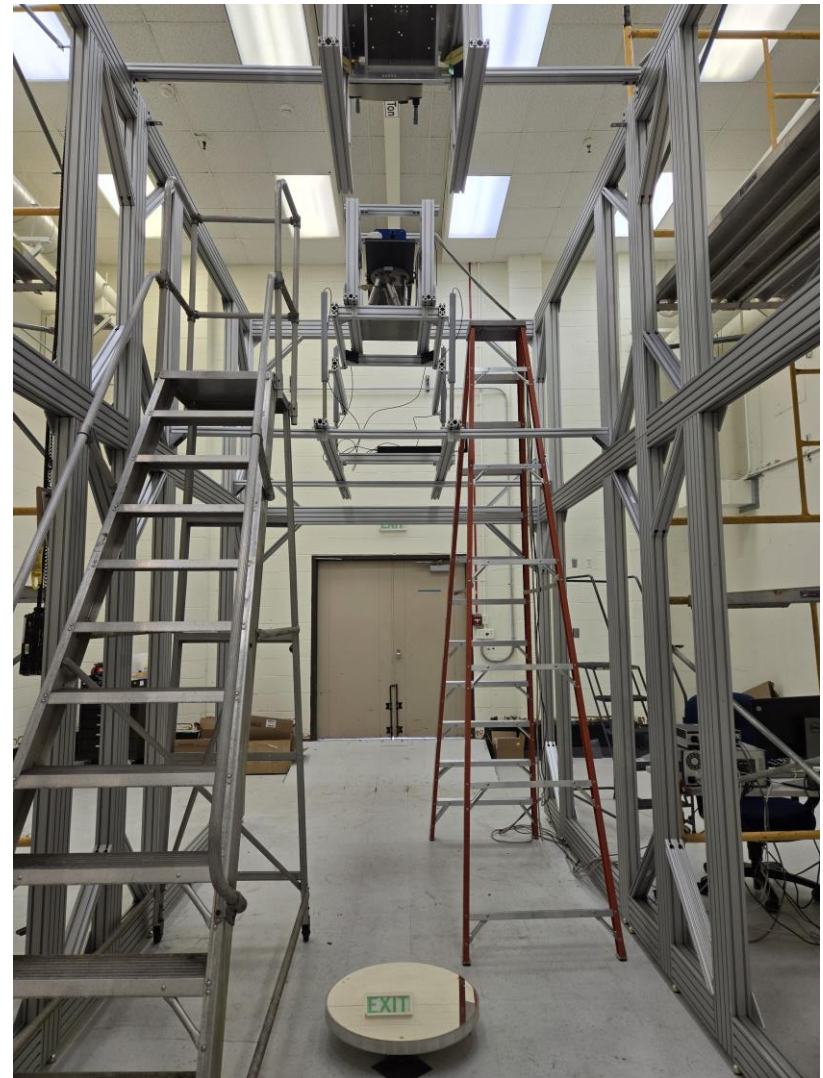


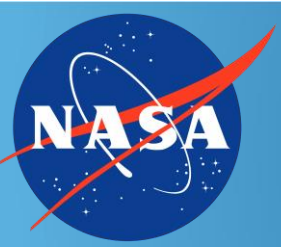
Test Tower (Face-down)





Test Tower (Face-up)

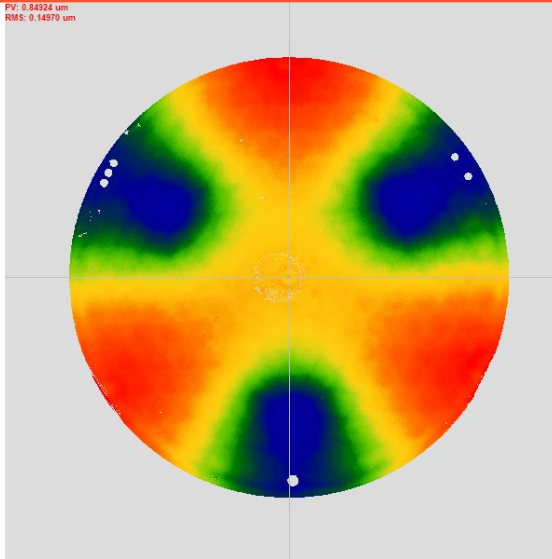




Results (Vertical Test)



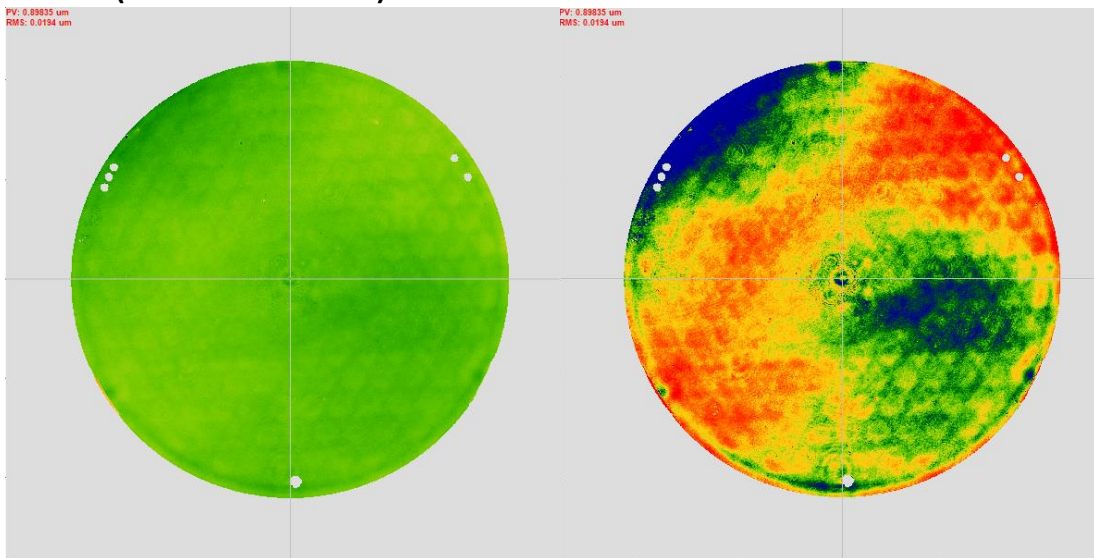
Face down:
150 nm RMS

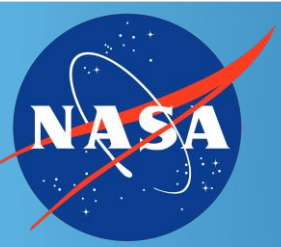


(same Z-scale)

Max contrast

Face up:
19 nm RMS

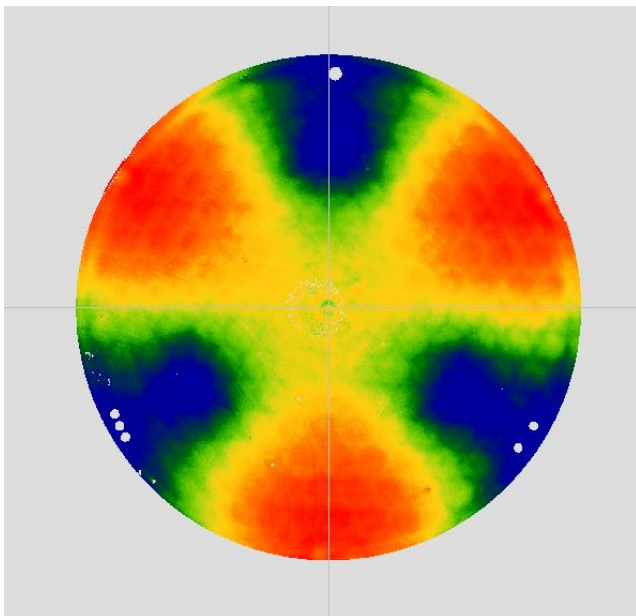




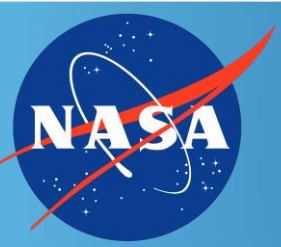
Results (Vertical Test)



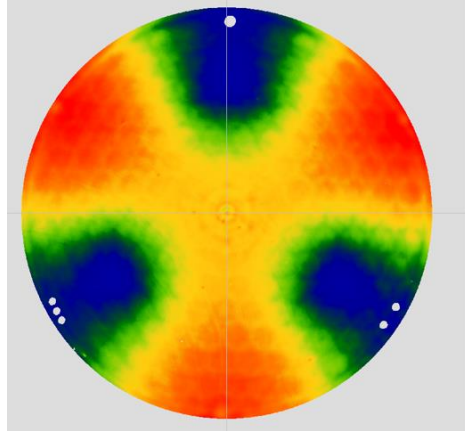
“0-G Figure” from averaged
face-up/face-down
74 nm RMS



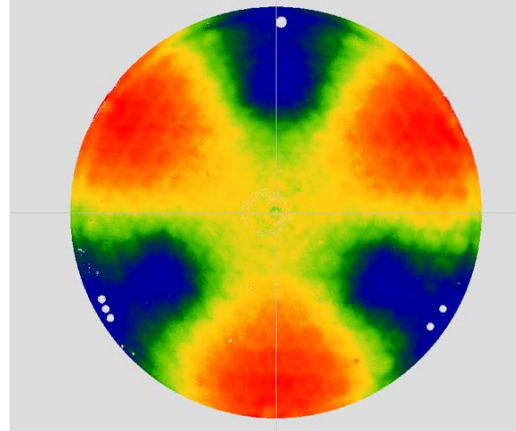
Coef (nm)	Aberration
-0.21	Piston or Bias
0.27	Tilt X
0.33	Tilt Y
-0.48	Power
0.10	Astig X
-0.08	Astig Y
0.49	Coma X
0.66	Coma Y
-0.15	Primary Spherical
11.91	Trefoil X
187.20	Trefoil Y
-3.99	Secondary Astig X
-0.29	Secondary Astig Y
-4.57	Secondary Coma X
6.54	Secondary Coma Y
-16.80	Secondary Spherical
0.30	Tetrafoil X
3.71	Tetrafoil Y
-7.11	Secondary Trefoil X
-97.44	Secondary Trefoil Y
0.75	Tertiary Astig X
2.20	Tertiary Astig Y
0.77	Tertiary Coma X
3.13	Tertiary Coma Y
-0.67	Tertiary Spherical
5.39	Pentafoil X
-2.75	Pentafoil Y
1.95	Secondary Tetrafoil X
-4.18	Secondary Tetrafoil Y
2.53	Tertiary Trefoil X
41.10	Tertiary Trefoil Y
-0.63	Quaternary Astig X
-1.86	Quaternary Astig Y
-0.42	Quaternary Coma X
1.40	Quaternary Coma Y
11.02	Quaternary Spherical



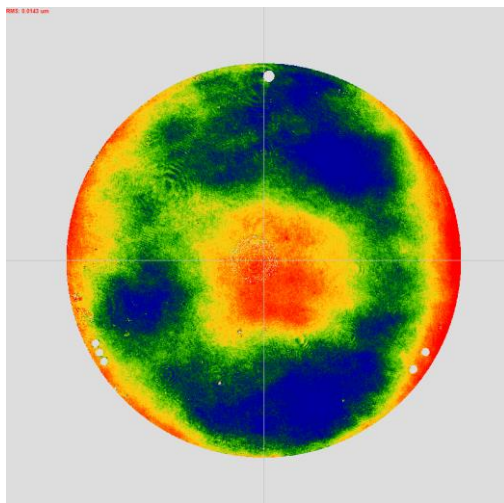
Results (Comparison)



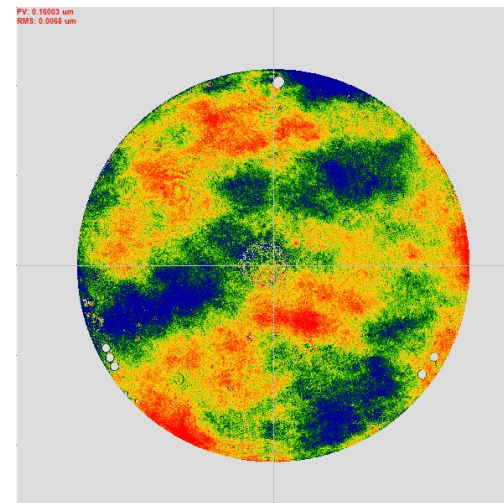
Rotation Test – 75nm



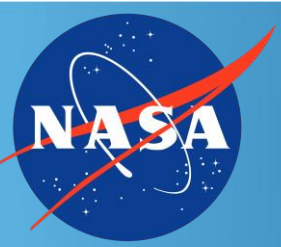
Face-up/Face-down test - 74 nm



Difference – 14 nm



Difference with spherical terms removed – 7 nm



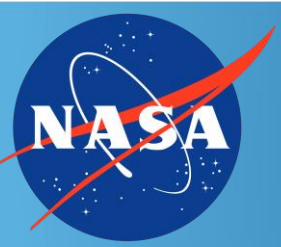
Conclusions/Future Work



Data taken agrees well with theory and clearly highlights the tradeoffs of the different methods. Spherical aberration is a detrimental source of error in generally any imaging system and cannot be simply ignored. If a rotation test's results have a residual spherical below the threshold of the wave front error allowed in the error budget, the test can be used. If the spherical terms cause a WFE higher than the error budget allows, a vertical test would be required to verify if the spherical terms are “real”.

Future Work:

- Increase environmental control of test setups and repeat
- Conduct test with additional mirrors



Thanks!



Questions?