Developments in Fabrication of Thin Curved Glass Face Sheets for Deformable Mirrors via Free Form Slumping

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Outline

1. Adaptive Optics and Adaptive Secondary Mirrors
2. Project Motivation
3. Free Form Slumping Process Overview and Benefits
4. Empirical Approach
5. 450mm and 950mm Results

Adaptive Optics and Adaptive Secondary Mirrors

Adaptive Optics

- Adaptive Optics (AO) corrects for how our atmosphere distorts light.
- Effectively takes the ”twinkle” out of stars
- Involves a mirror that is thin enough to be deformed by small actuators
- Using the secondary mirror as your deformable surface is less complex providing higher throughput

Figure 1: Example of AO correction taken from European Southern Observatory site[1]

Project Motivation

Motivation

- ASM projects need large curved face sheets for the deformable surface (~2mm thick)
- **Project goals**: Enable easier/faster fabrication of large adaptive optics and spares
  - Medium-scale secondary mirrors (NASA Infrared Telescope Facility: 244 mm, Automated Planet Finder: 400mm, University of Hawaii-2.2m: 620 mm)
  - Study scaling/cost for large ASM up to 1500 mm diameter mirrors
  - Fabricate Keck telescope adaptive secondary 1.4m

Current Fabrication Process

- Industry standard approach involves a challenging and time-consuming process.
  1. Initial polishing of optical blank (dark blue)
  2. Bonding to sacrificial blank (turquoise)
  3. Grinding optical blank to thickness
  4. Machine to aperture size
  5. De-bonding optic from sacrificial blank
- Success and challenges shown in the development of the Large Binocular Telescope ASM [3]

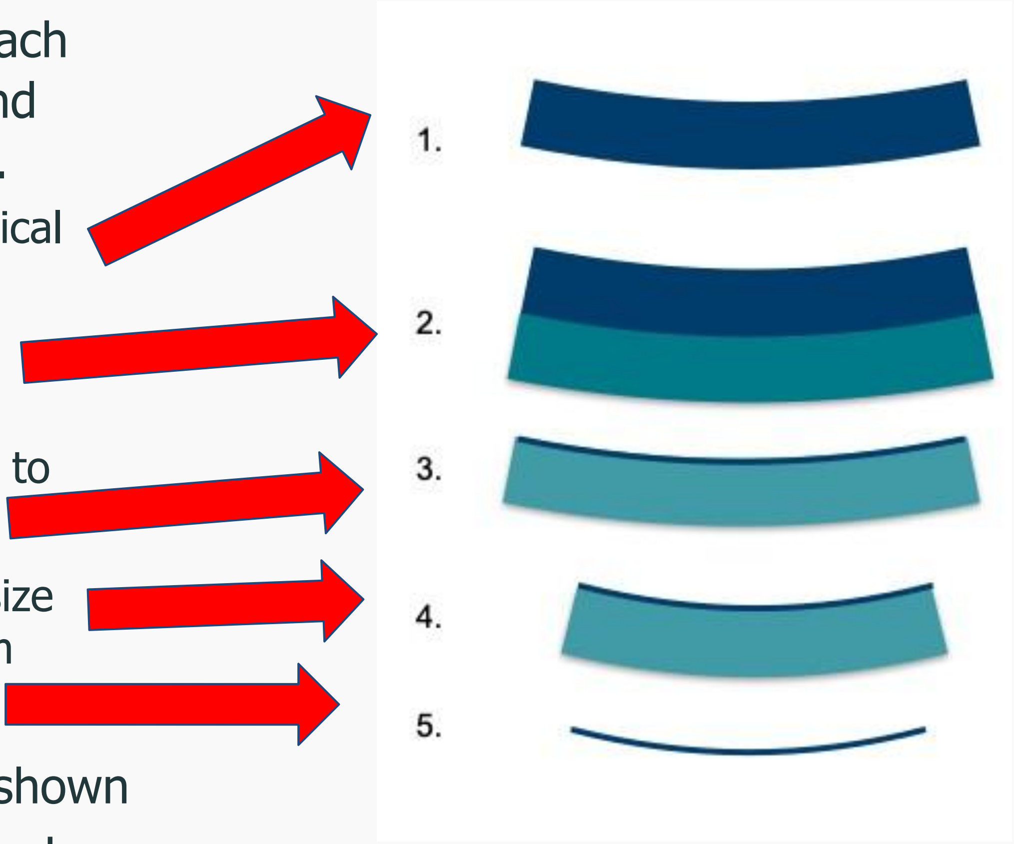


Figure 3: Current industry standard

Free Form Slumping Overview and Benefits

Free Form Slumping Concept

1. Apply Top weight
2. Support shell with annular base
3. Heat in Kiln to slump Glass
4. Cut shell to Aperture

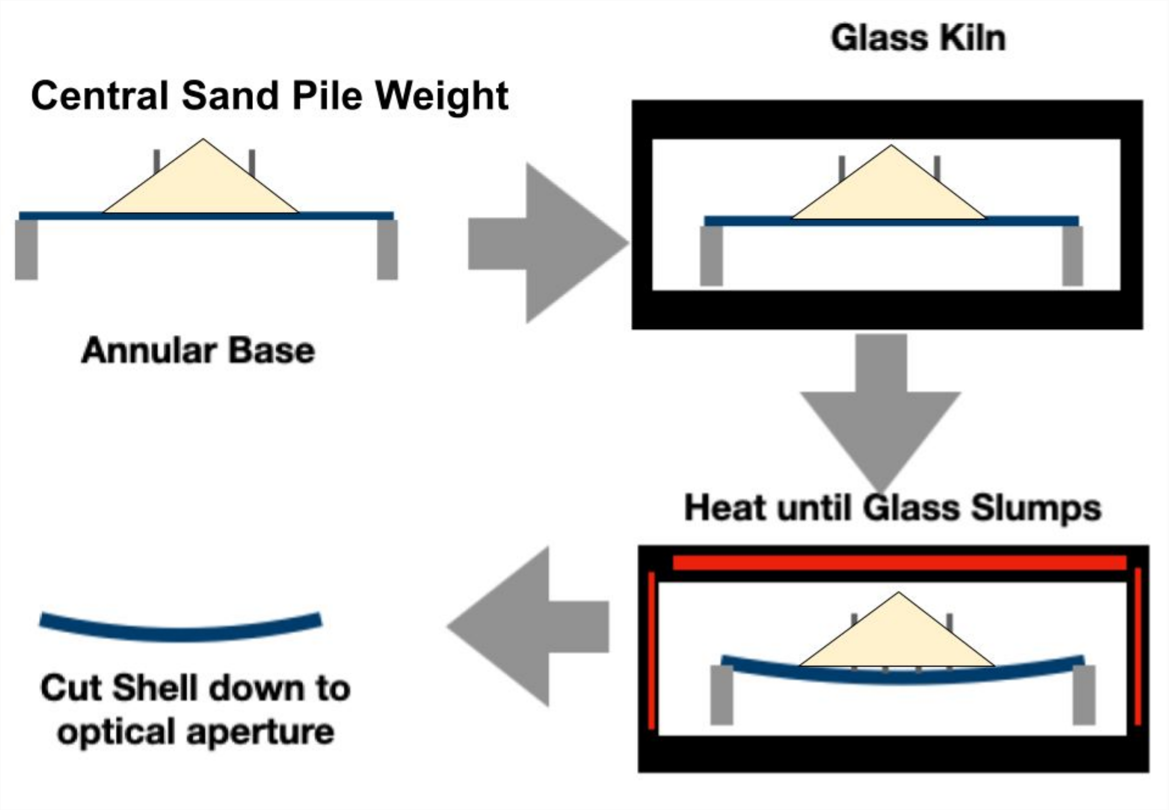


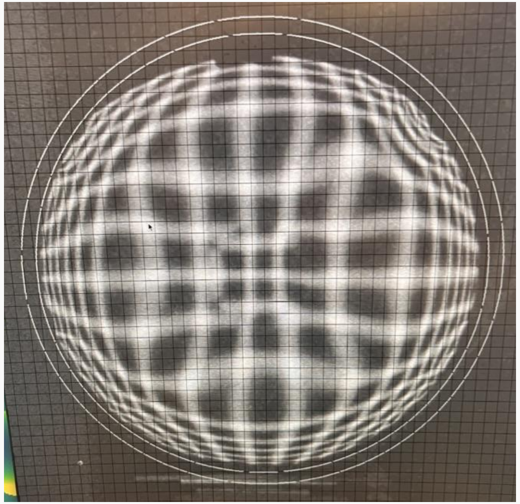
Figure 4: Slumping Process

Benefits of Free Form Slumping and Benefits

- Heat cycles are quick (8-12 hours), offering the ability to change the experiment daily
- Iterative process
- Low material cost, scalable, Borofloat blanks cost in the range of 30-100 $ per sheet
- No need for high-precision optical mold
- Low start-up cost in comparison to the standard method
- Minimal polishing
- Overall quicker timescales (1-2 weeks for slumping) as exemplified by our creation of the IRTF ASM face sheet and UH-2.2m spares[2]

Measurement via Deflectometry

- Need for a wide dynamic range, scalable testing apparatus
- Horizontal and vertical stepped fringe patterns
- Reflection off the slumped shell picked up by the camera
- Slope extraction and surface reconstruction



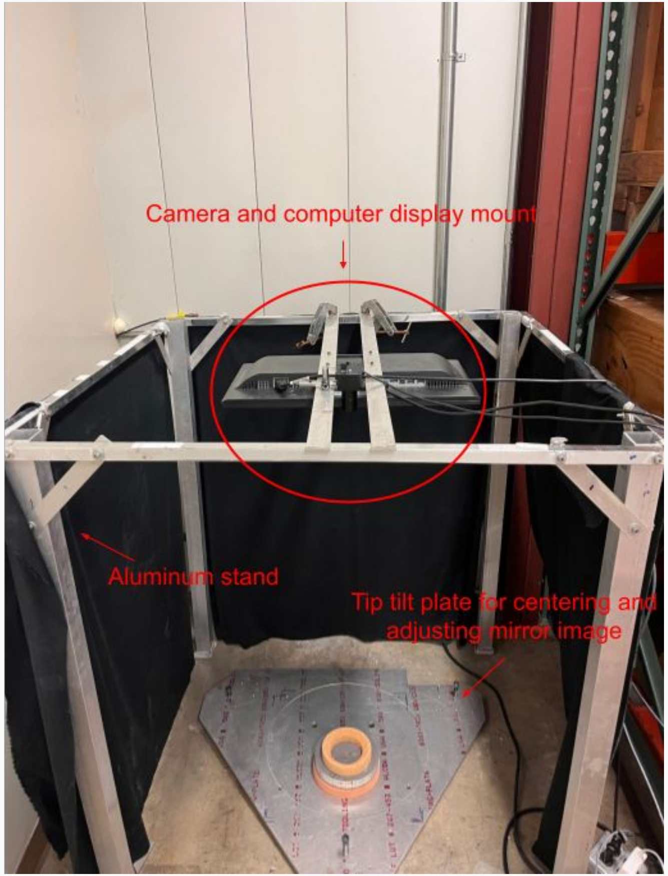


Figure 5: Deflectometry Stand

Empirical Approach

Empirical Approach

- From prior experiments we see dominant aberrations past f/3
- Likely due to unaccounted radial forces
- Found the simplest approach to optimizing weights was iterating experiments.

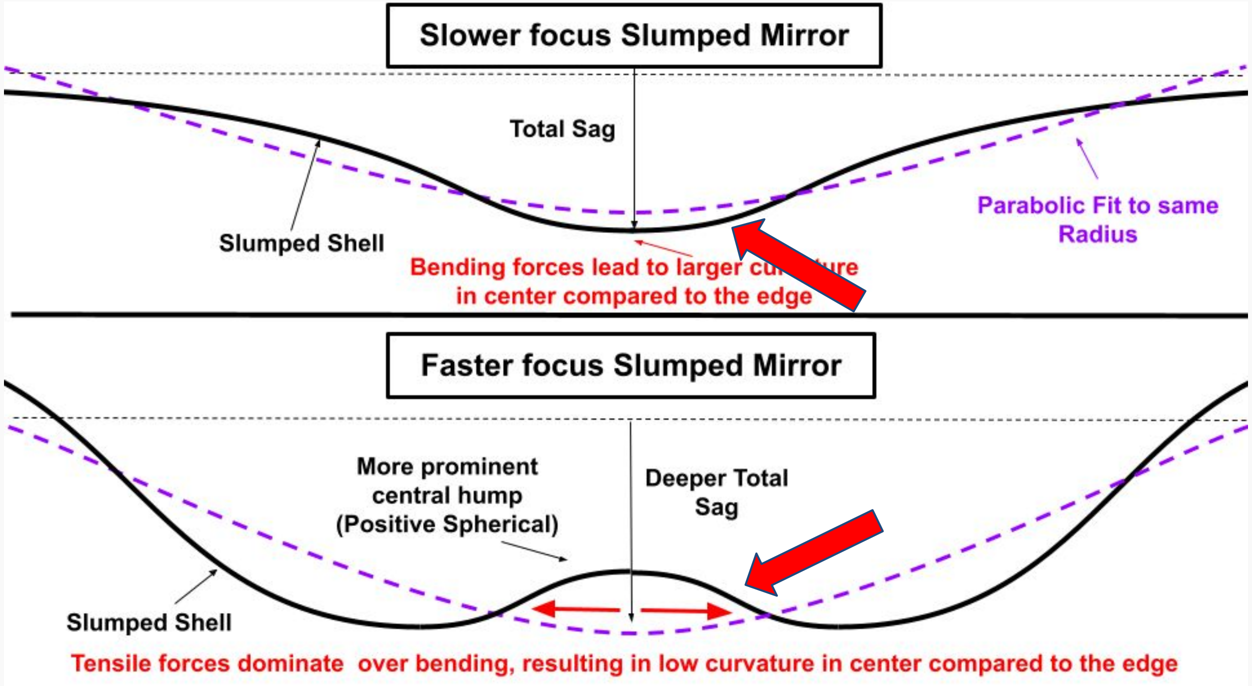


Figure 6: Exaggerated surfaces to show the central hump effect

Empirical Approach

- Goal is less than 100 μm P-to-V error
- Use the ability to quickly iterate on experiments
- New slumping process
  1. Unweighted shell
  2. Central pile shell
  3. Central pile + additional ring/rings shell

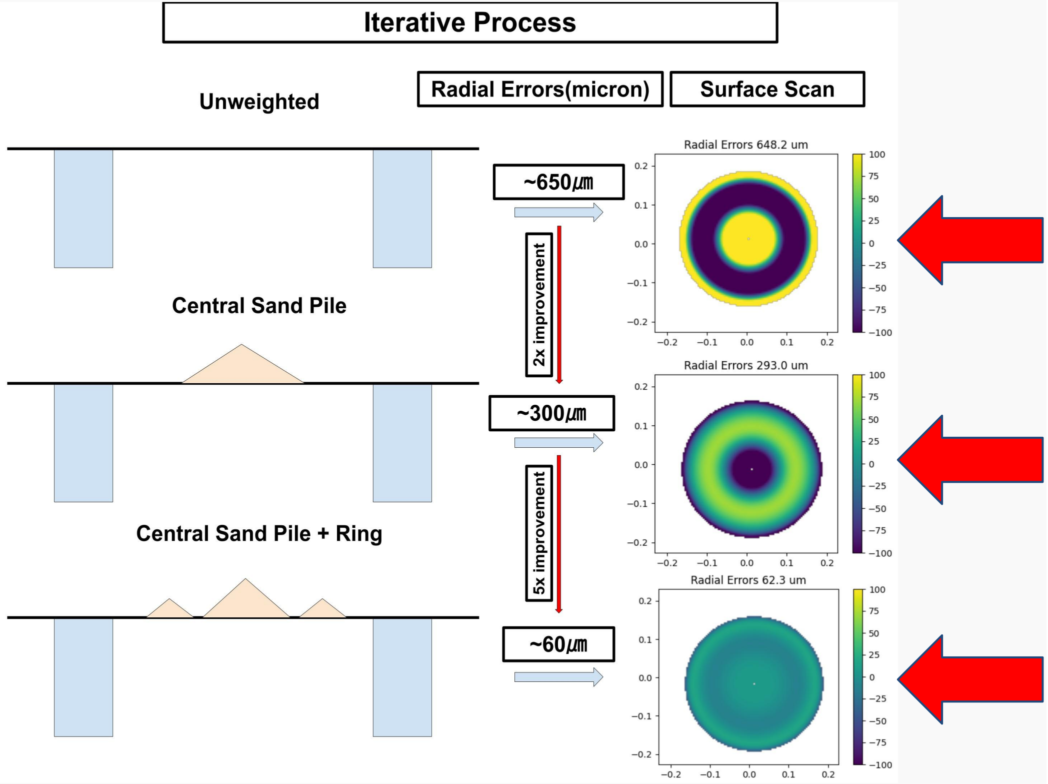


Figure 7: Overview of our iterative process

O Series Example of Approach

Figure 8: Central Pile(750g), Central Pile(750g) + Single Ring(500g), and Central Pile(1000g) + Multi-Ring (1000g, 500g)

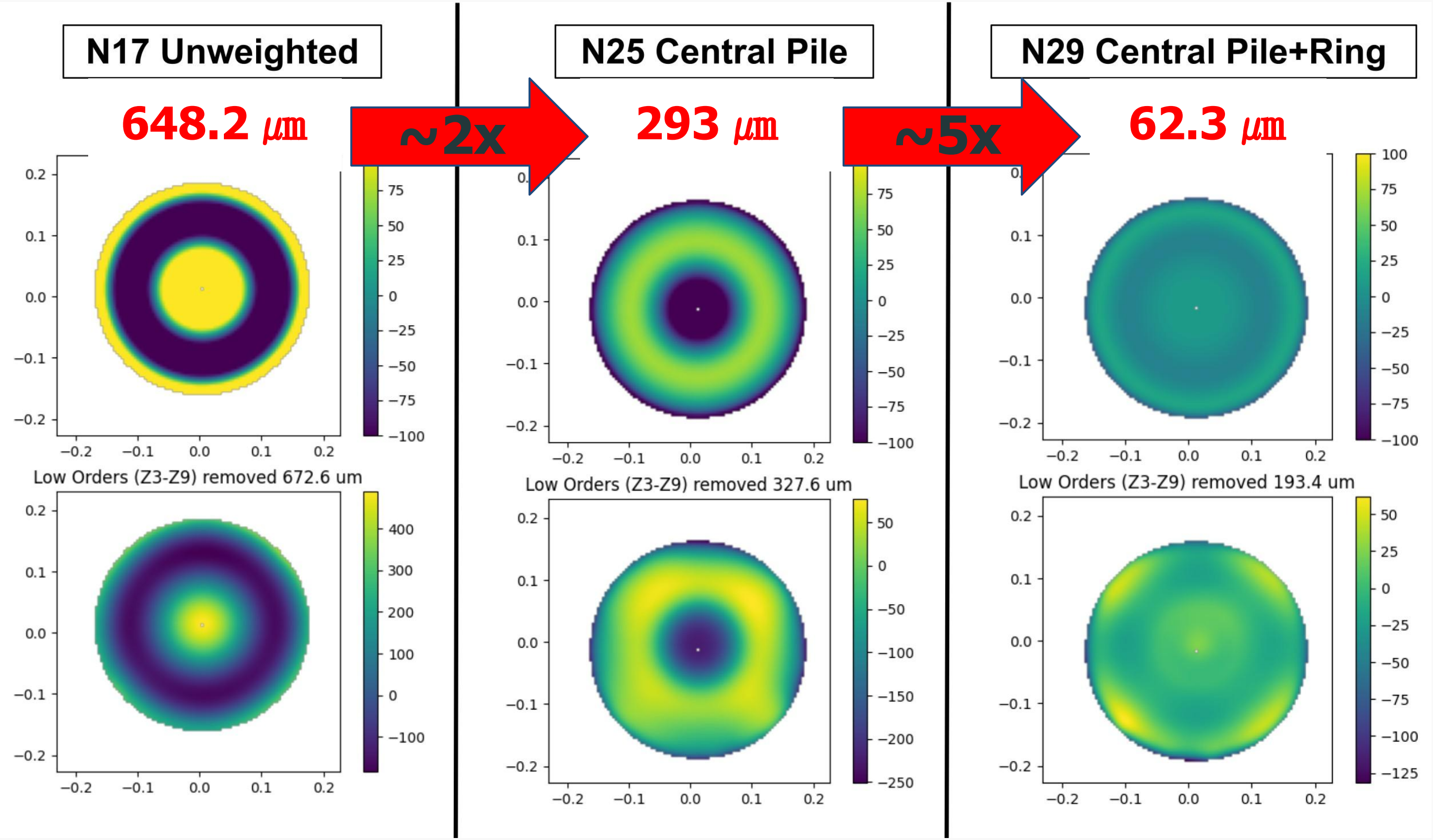
Results

Results

N-Series 450mm Shells

Radial Errors (P-to-V)

Overall Surface Shape

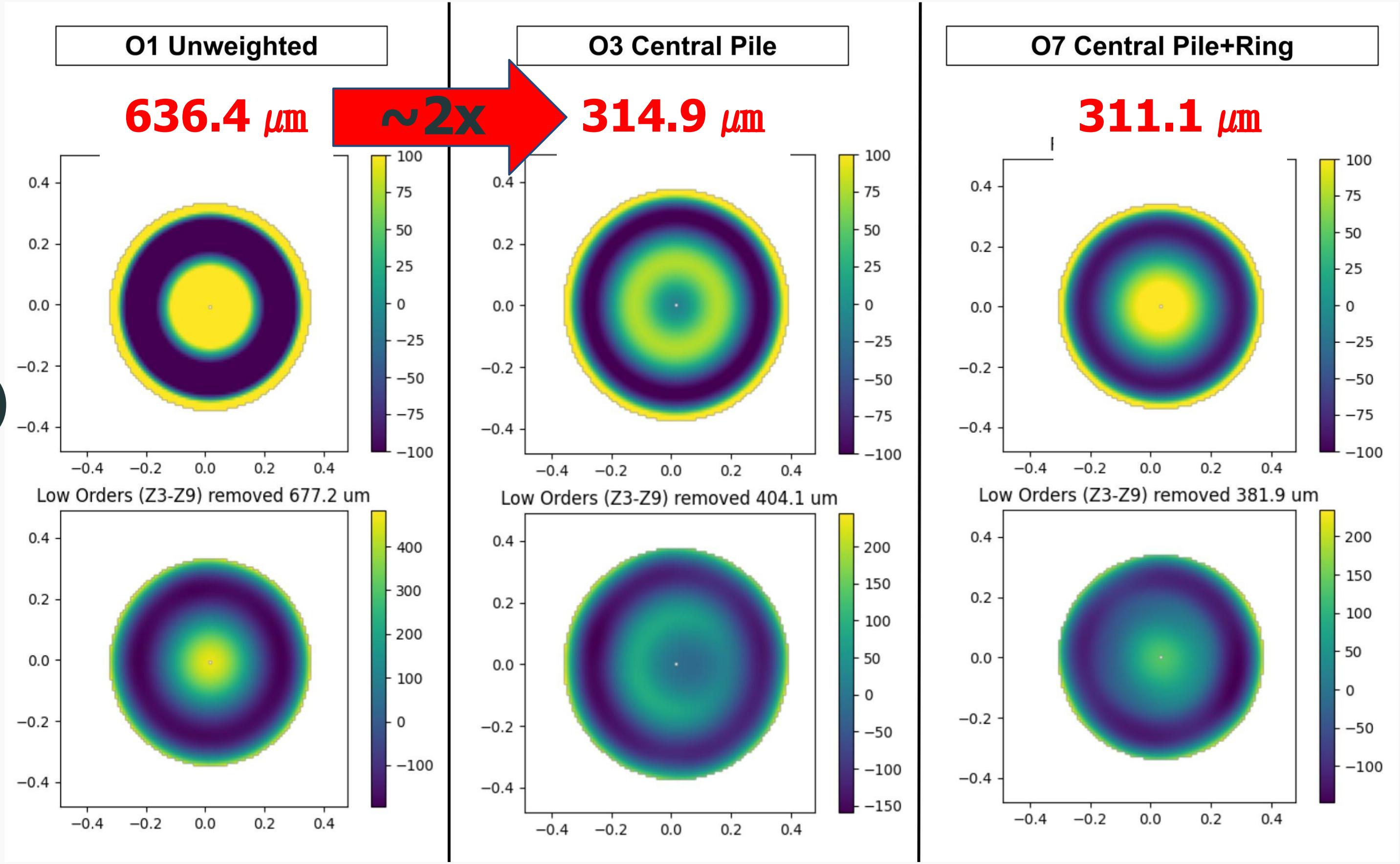


Results

O-Series 950mm Shells

Radial Errors (P-to-V)

Overall Surface Shape



Summary

Summary

- Free Form Slumping is promising for quicker more economical thin-shell fabrication
- Allows correction/progress through an iterative process
- The empirical approach shows promise with the 450mm and 950mm series
- Goal: scale to 1m+ (kiln-limited)

Thanks!

Thank you to Phil and Deno and all the wonderful people working at the UC observatory shops!

References

[1] ESO/P. Weilbacher (AIP). **Neptune from the VLT with and without adaptive optics.** https://www.eso.org/public/images/eso1824b/. Image ID: eso1824b; Release date: 18July2018, 12:00; Credit: ESO/P.Weilbacher (AIP); European Southern Observatory. July 2018.

References ii

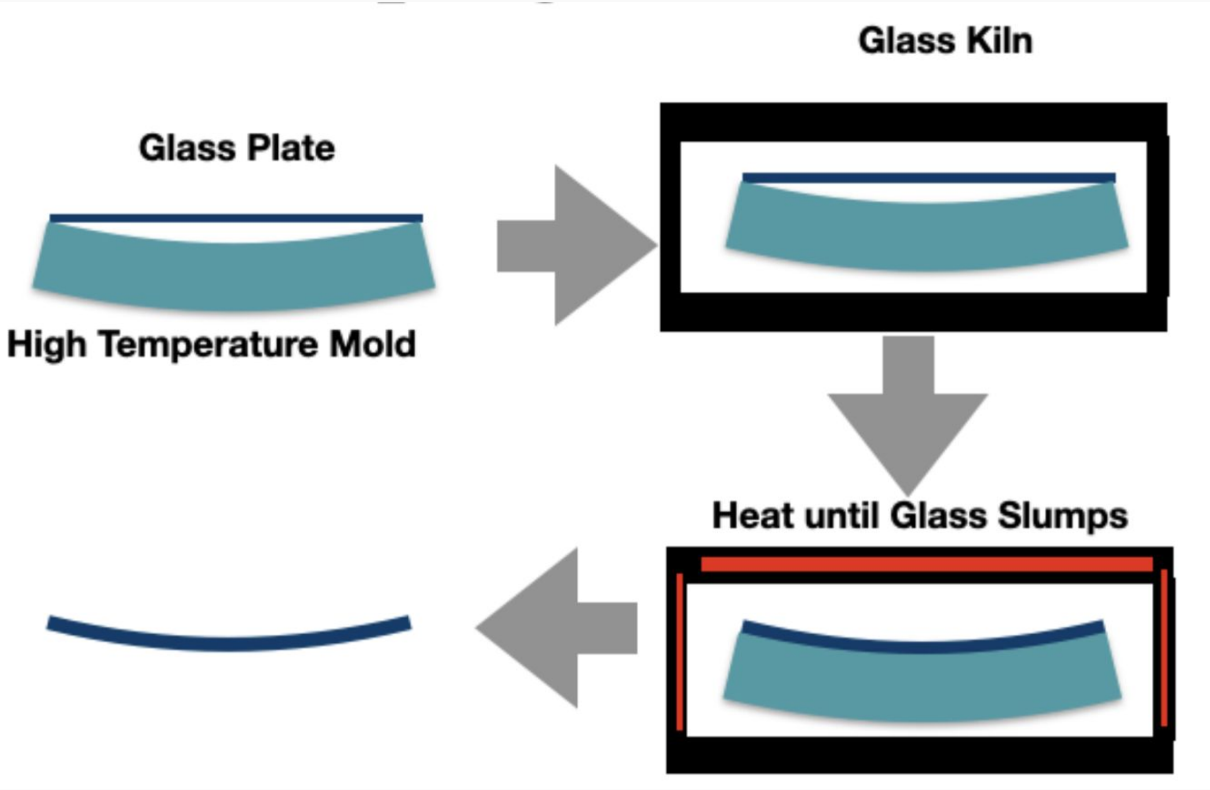
2 Philip M. Hinz, Matt Radovan, and Daren Dillon. **“Generating curved deformable facesheets via free form slumping”.** In: *Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation*. Vol. 12188. Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. Aug. 2022, 121880T, 121880T. DOI: 10.1117/12.2630714.

3 H. M. Martin et al. **“Deformable Secondary Mirrors for the LBT Adaptive Optics System”.** In: *Advances in Adaptive Optics II*. Ed. by B. L. Ellerbroek and D. Bonaccini Calia. Vol. 6272. SPIE. 2006, 62720U. DOI: 10.1117/12.672698. URL: http://spiedigitallibrary.org/terms.

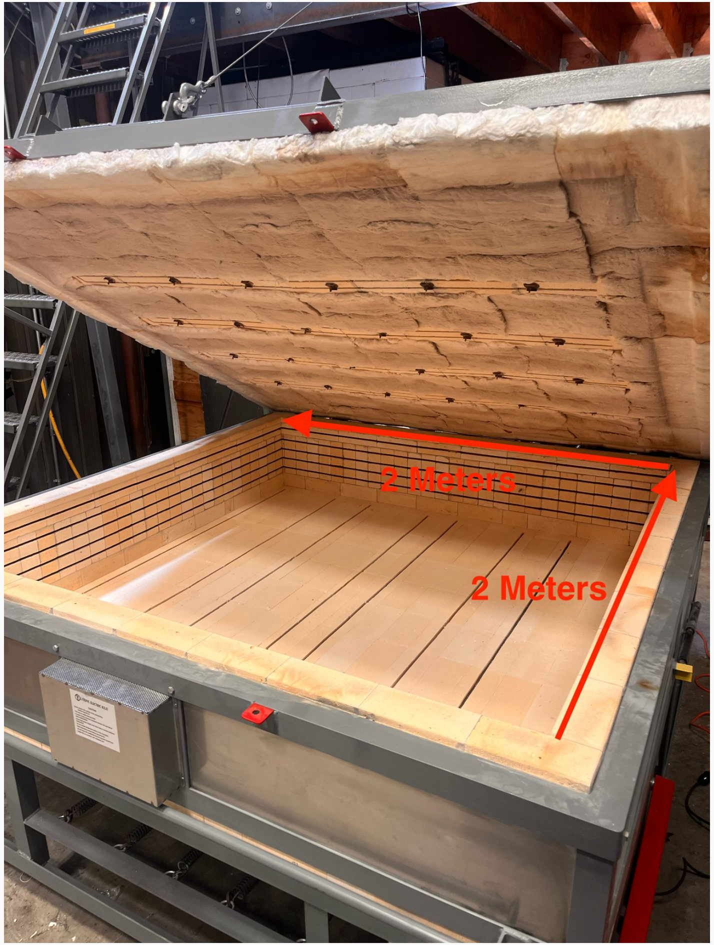
References iii

[4] Demetria L. Miller et al. **"Comparison of Adaptive Optics systems using a conventional secondary and an adaptive secondary".** In: *Advancements in Adaptive Optics*. Ed. by Domenico Bonaccini Calia, Brent L. Ellerbroek, and
Roberto Ragazzoni. Vol. 5490. Proceedings of SPIE. Figure 3; caption: "Comparison of Adaptive Optics systems using a conventional secondary and an adaptive secondary. It can be seen that the adaptive secondary system has the minimum number of surfaces in the path of the infrared science light; primary, secondary and dewar window. In this configuration, the maximum amount of the infrared light enters the science camera and the wavefront sensing system, which requires several re-imaging and image positioning optics, uses the visible light.". Oct. 2004, p. 209. DOI: 10.1117/12.552478. URL:
https://www.researchgate.net/figure/Comparison-of-

Hot Mold Slumping

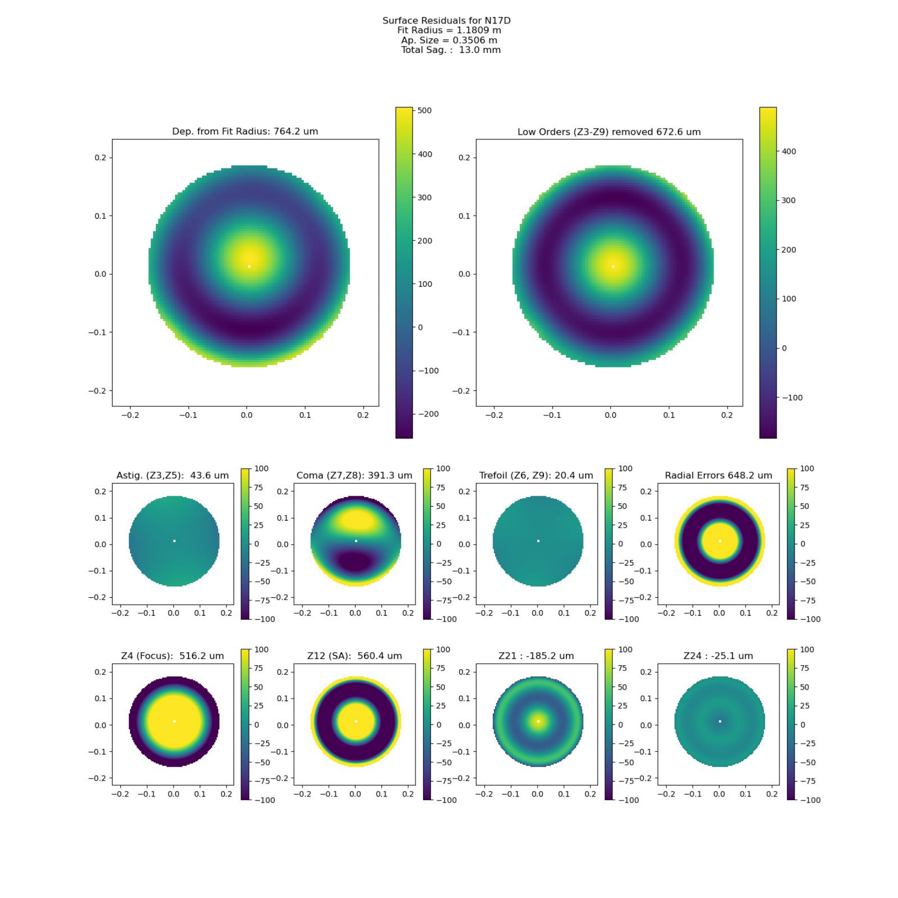


Backup Slides



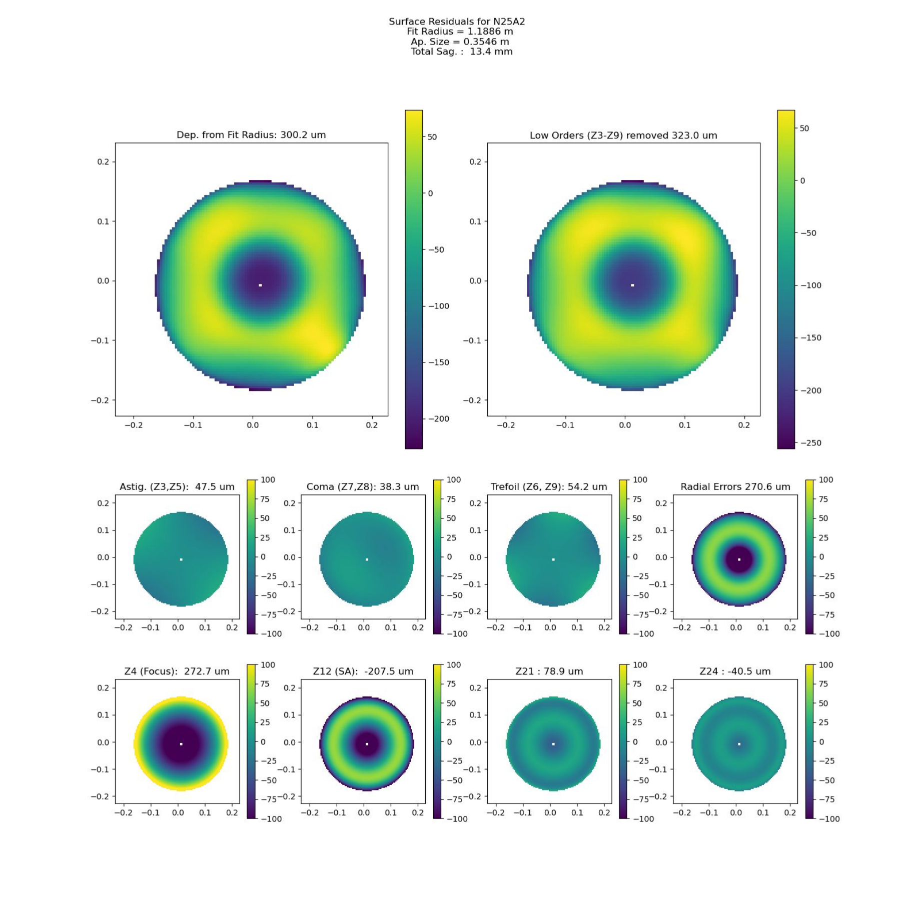
Backup Slides

N17D



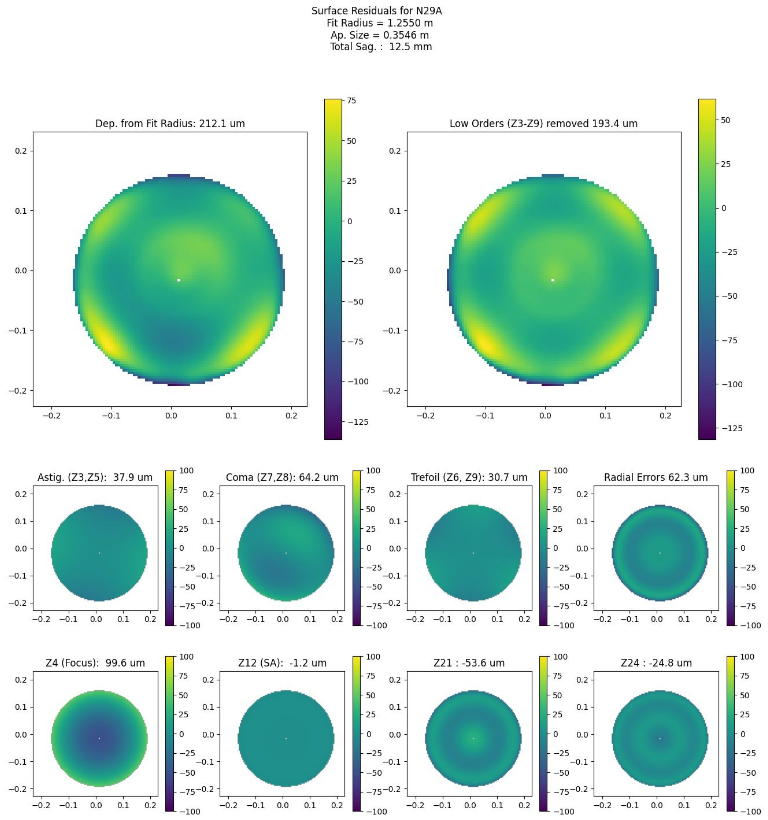
Surface Residuals for N17D
Fit Radius = 1.1809 m
Ap. Size = 0.3506 m
Total Sag. : 13.0 mm
Dep. from Fit Radius: 764.2 um
Low Orders (Z3-Z9) removed 672.6 um
Astig. (Z3,Z5): 43.6 um
Coma (Z7,Z8): 391.3 um
Trefoil (Z6, Z9): 20.4 um
Radial Errors 648.2 um
Z4 (Focus): 516.2 um
Z12 (SA): 560.4 um
Z21 : -185.2 um
Z24 : -25.1 um

N25A

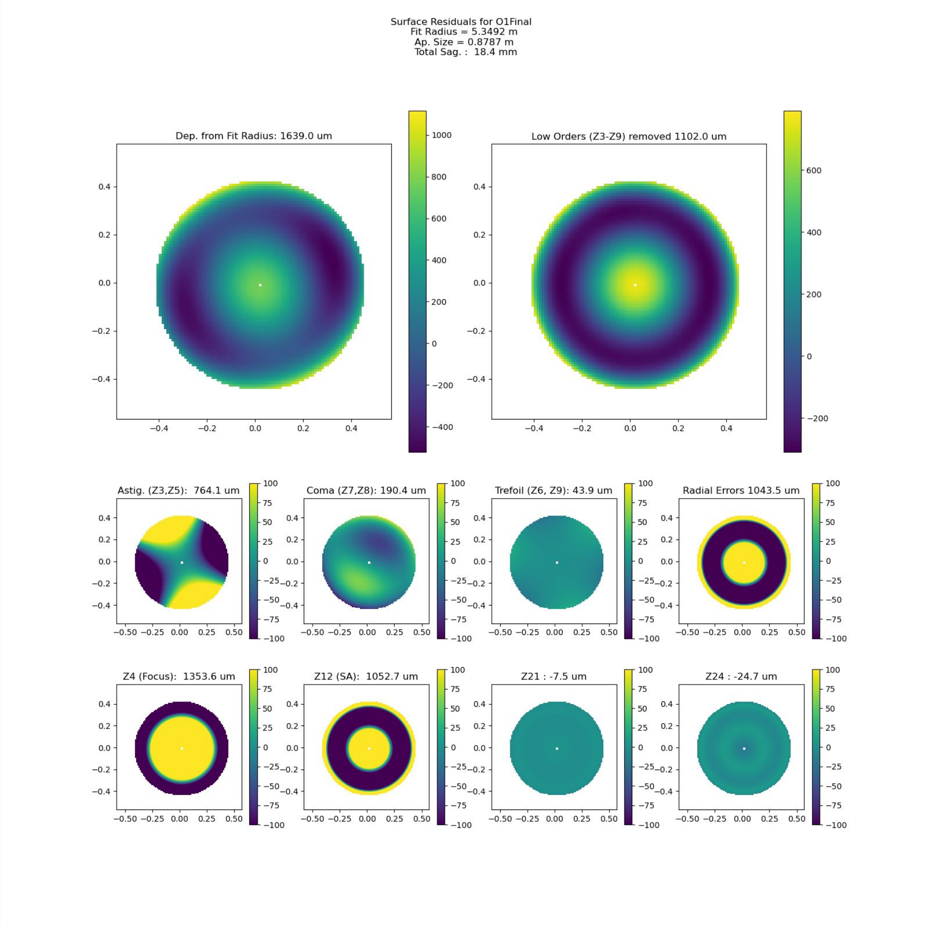


Surface Residuals for N25A2
Fit Radius = 1.1886 m
Ap. Size = 0.3546 m
Total Sag. : 13.4 mm
Dep. from Fit Radius: 300.2 um
Low Orders (Z3-Z9) removed 323.0 um
Astig. (Z3,Z5): 47.5 um
Coma (Z7,Z8): 38.3 um
Trefoil (Z6, Z9): 54.2 um
Radial Errors 270.6 um
Z4 (Focus): 272.7 um
Z12 (SA): -207.5 um
Z21 : 78.9 um
Z24 : -40.5 um

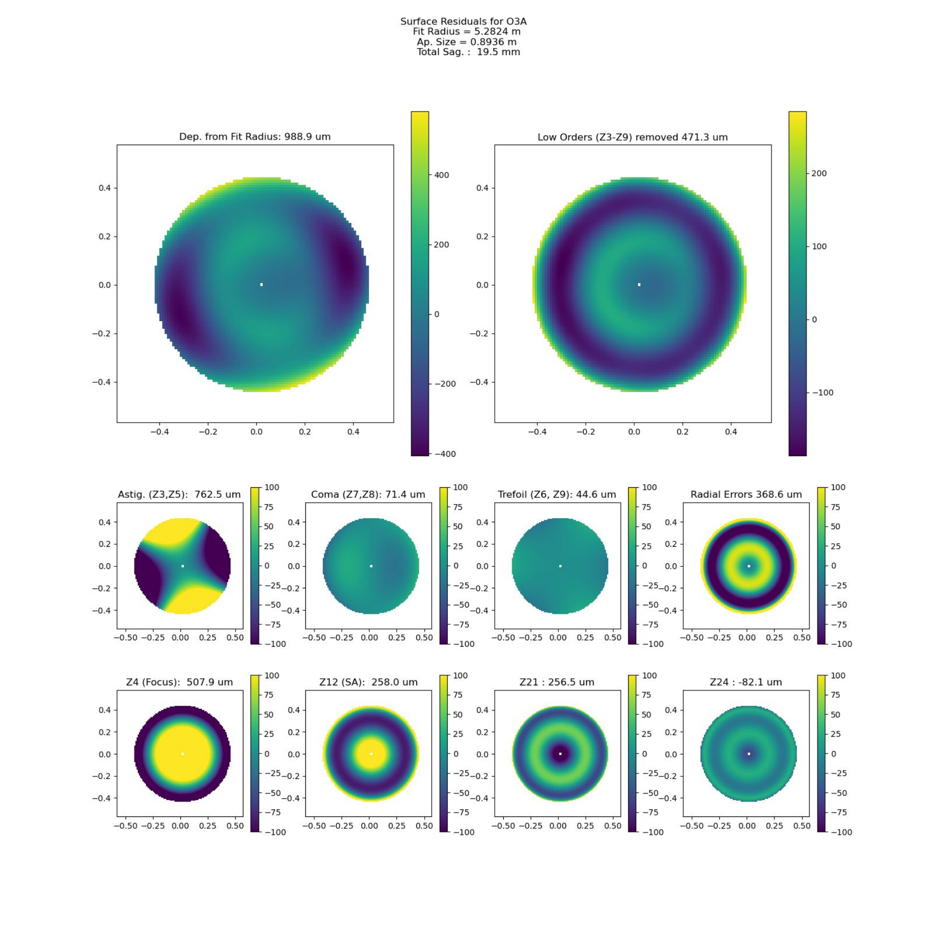
N29A


Surface Residuals for N29A
Fit Radius = 1.2550 m
Ap. Size = 0.3546 m
Total Sag. : 12.5 mm
Dep. from Fit Radius: 212.1 um
Low Orders (Z3-Z9) removed 193.4 um
Astig. (Z3,Z5): 37.9 um
Coma (Z7,Z8): 64.2 um
Trefoil (Z6, Z9): 30.7 um
Radial Errors 62.3 um
Z4 (Focus): 99.6 um
Z12 (SA): -1.2 um
Z21 : -53.6 um
Z24 : -24.8 um

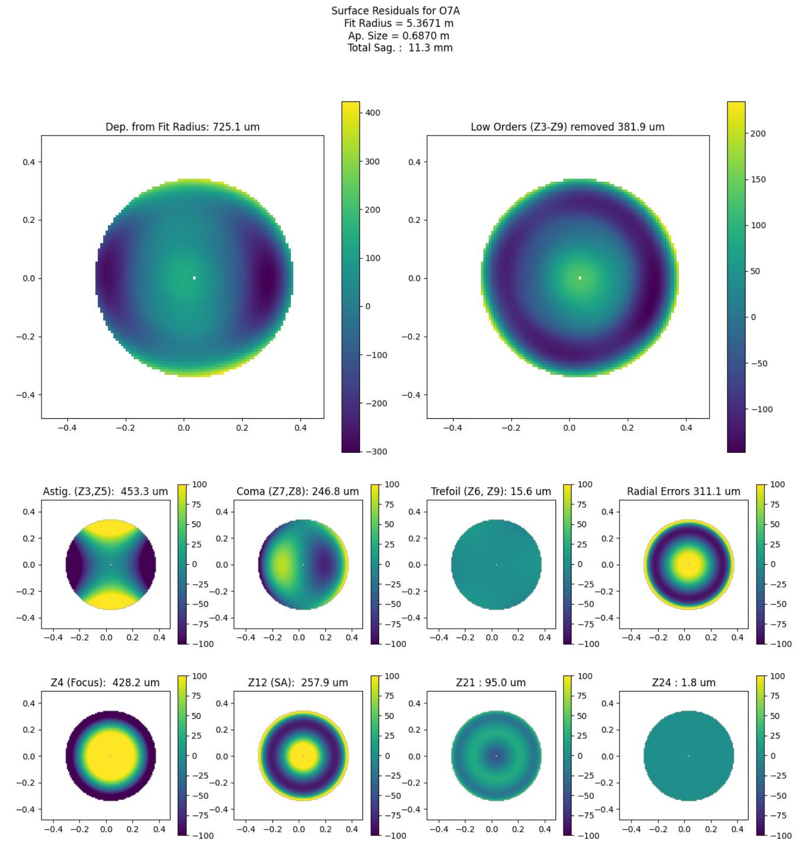
O1


Surface Residuals for O1Final
Fit Radius = 5.3492 m
Ap. Size = 0.8787 m
Total Sag. : 18.4 mm
Dep. from Fit Radius: 1639.0 um
Low Orders (Z3-Z9) removed 1102.0 um
Astig. (Z3,Z5): 764.1 um
Coma (Z7,Z8): 190.4 um
Trefoil (Z6, Z9): 43.9 um
Radial Errors 1043.5 um
Z4 (Focus): 1353.6 um
Z12 (SA): 1052.7 um
Z21 : -7.5 um
Z24 : -24.7 um

O3


Surface Residuals for O3A
Fit Radius = 5.2824 m
Ap. Size = 0.8936 m
Total Sag. : 19.5 mm
Dep. from Fit Radius: 988.9 um
Low Orders (Z3-Z9) removed 471.3 um
Astig. (Z3,Z5): 762.5 um
Coma (Z7,Z8): 71.4 um
Trefoil (Z6, Z9): 44.6 um
Radial Errors 368.6 um
Z4 (Focus): 507.9 um
Z12 (SA): 258.0 um
Z21 : 256.5 um
Z24 : -82.1 um

O7


Surface Residuals for O7A
Fit Radius = 5.3671 m
Ap. Size = 0.6870 m
Total Sag. : 11.3 mm
Dep. from Fit Radius: 725.1 um
Low Orders (Z3-Z9) removed 381.9 um
Astig. (Z3,Z5): 453.3 um
Coma (Z7,Z8): 246.8 um
Trefoil (Z6, Z9): 15.6 um
Radial Errors 311.1 um
Z4 (Focus): 428.2 um
Z12 (SA): 257.9 um
Z21 : 95.0 um
Z24 : 1.8 um

Adaptive Secondary Mirrors

- Using the secondary mirror as your deformable surface is less complex providing higher throughput
- Adaptive Secondary systems make the adaptive surface the secondary mirror (ASM), often 200-1400mm in diameter
- Higher throughput, less stray light, and more thermal sensitivity.

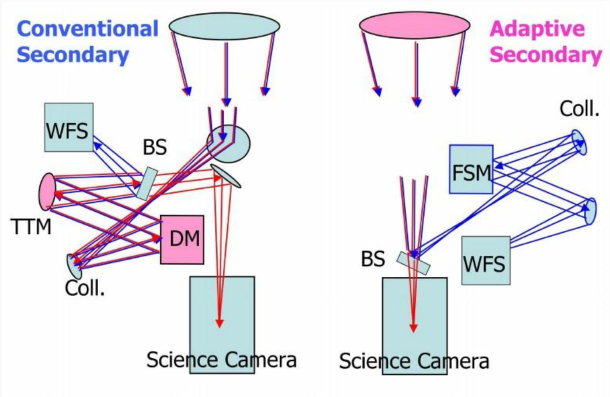
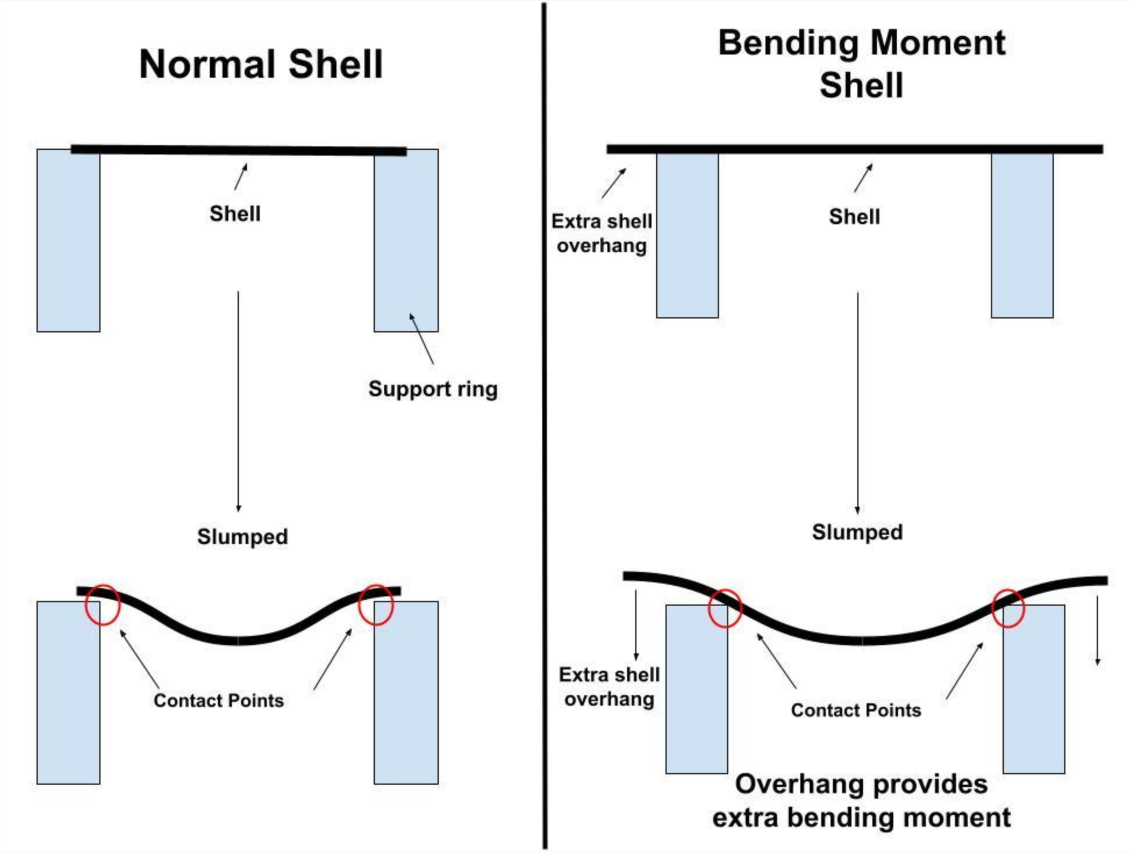
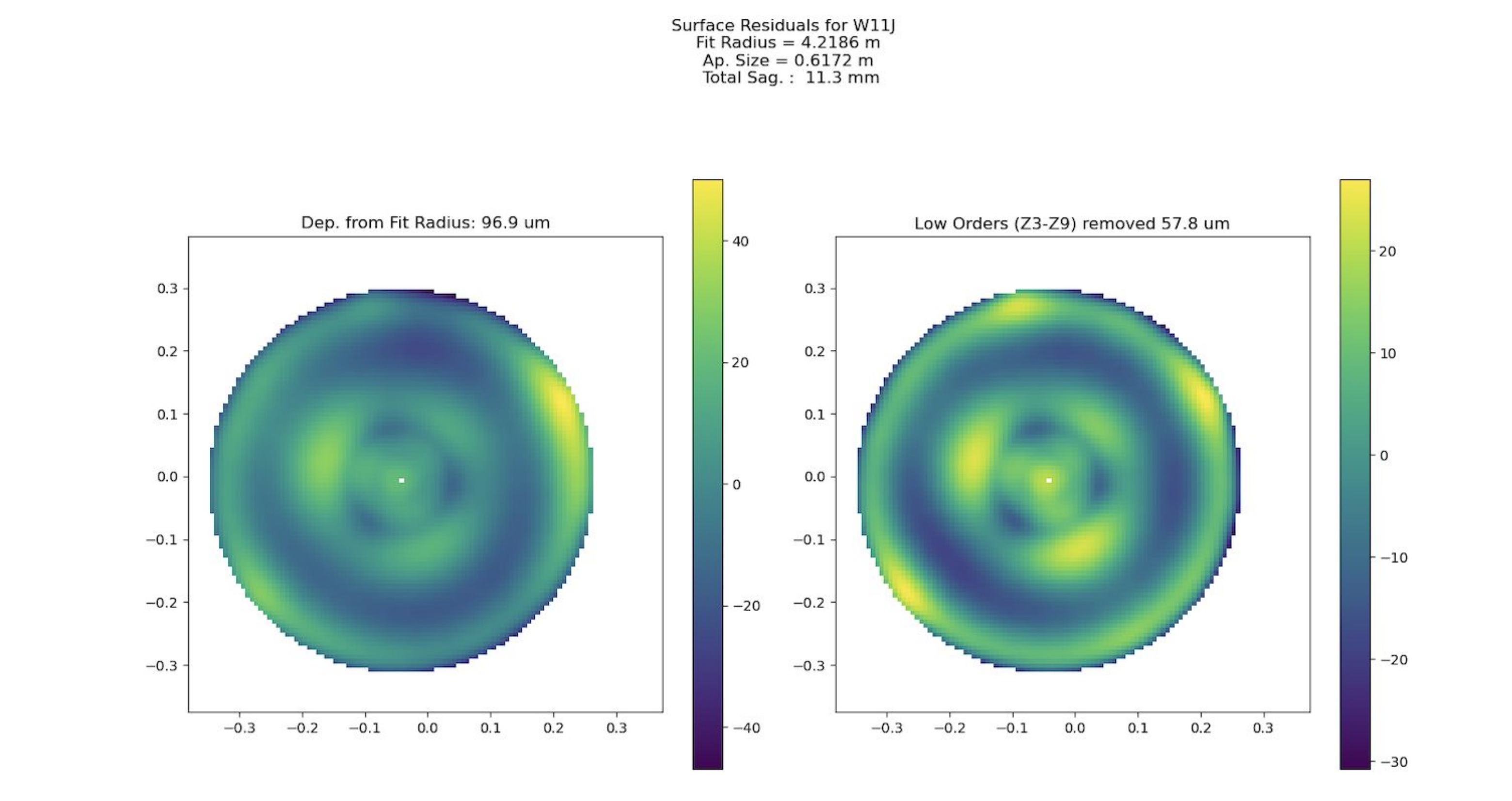


Figure 2: Conventional AO system compared to an adaptive secondary system. Figure from [4]

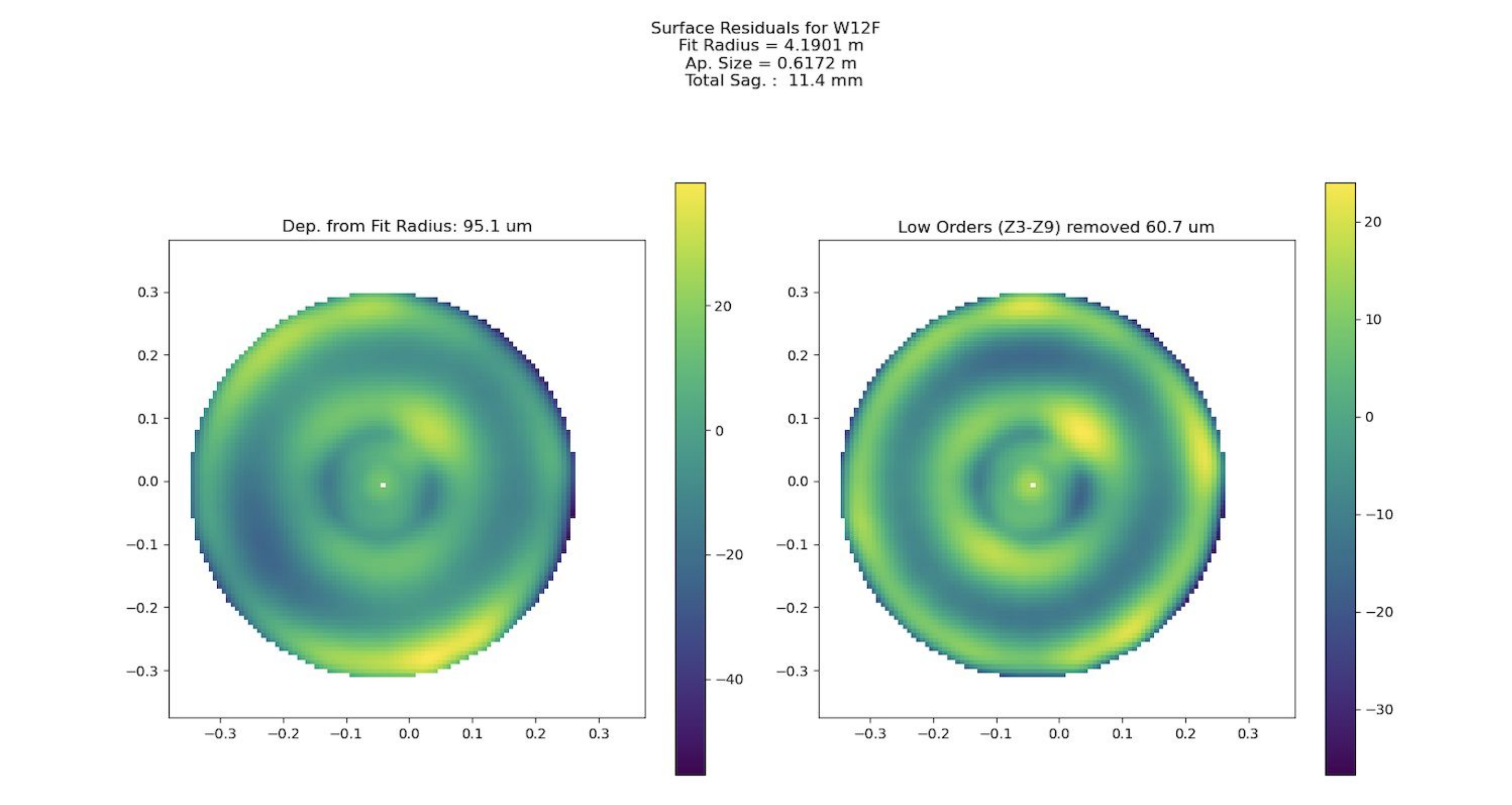
Bending Moment



W11


Surface Residuals for W11J
Fit Radius = 4.2186 m
Ap. Size = 0.6172 m
Total Sag. : 11.3 mm
Dep. from Fit Radius: 96.9 um
Low Orders (Z3-Z9) removed 57.8 um
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
40
20
0
−20
−40
10
−10
−30

W12



Surface Residuals for W12F
Fit Radius = 4.1901 m
Ap. Size = 0.6172 m
Total Sag. : 11.4 mm
Dep. from Fit Radius: 95.1 um
Low Orders (Z3-Z9) removed 60.7 um
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
20
0
−20
−40
10
−10
−30