ASTRONOMICAL OPTICS

EXTREME SCIENCE WITH EXTREME TECHNOLOGY

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FAMILY VACATION IN HAWAII
MAUNAKEA VISITOR INFORMATION STATION

Onizuka Center for International Astronomy above the clouds

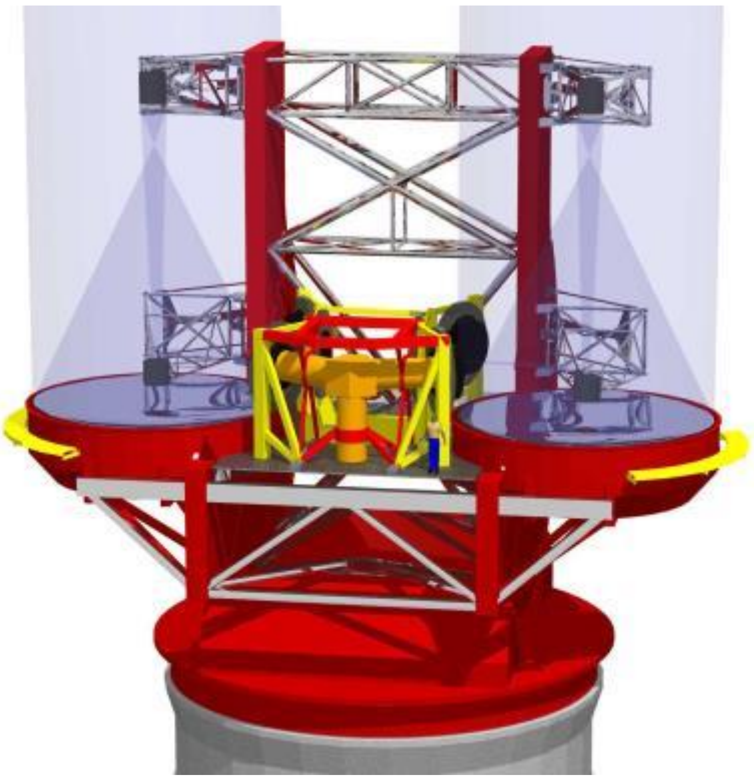
W. M. KECK TELESCOPE

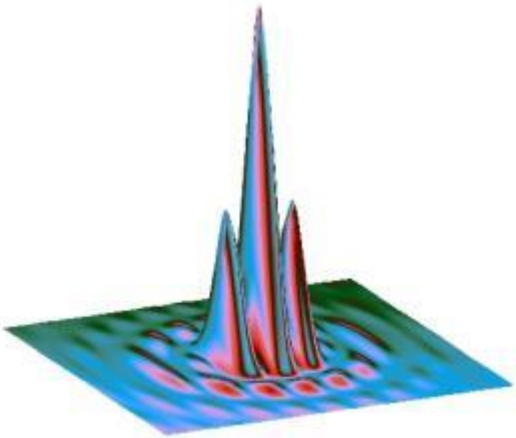
TWO BEAUTIFUL 10M SEGMENTED TELESCOPES

When I studied Astronomy and Physics in late 90s, this telescope was my dream instrument.

http://www.ifa.hawaii.edu/images/aerial-tour/kecks.html

LBTI
HIGH RESOLUTION IN THE 23 M BASELINE DIRECTION





Unique common-mount dual-aperture system, LBT Interferometer, w/ 23 m resolution capabilities.

Optimized for observations in the thermal infrared w/ secondary Adaptive Optics system.

http://www.lbto.org/

LARGE BINOCULAR TELESCOPE

TWO 8.4M PRIMARY MIRRORS ON A SINGLE STRUCTURE

One of UA's latest achievements, which is currently the world largest and most unique telescope on a single structure.

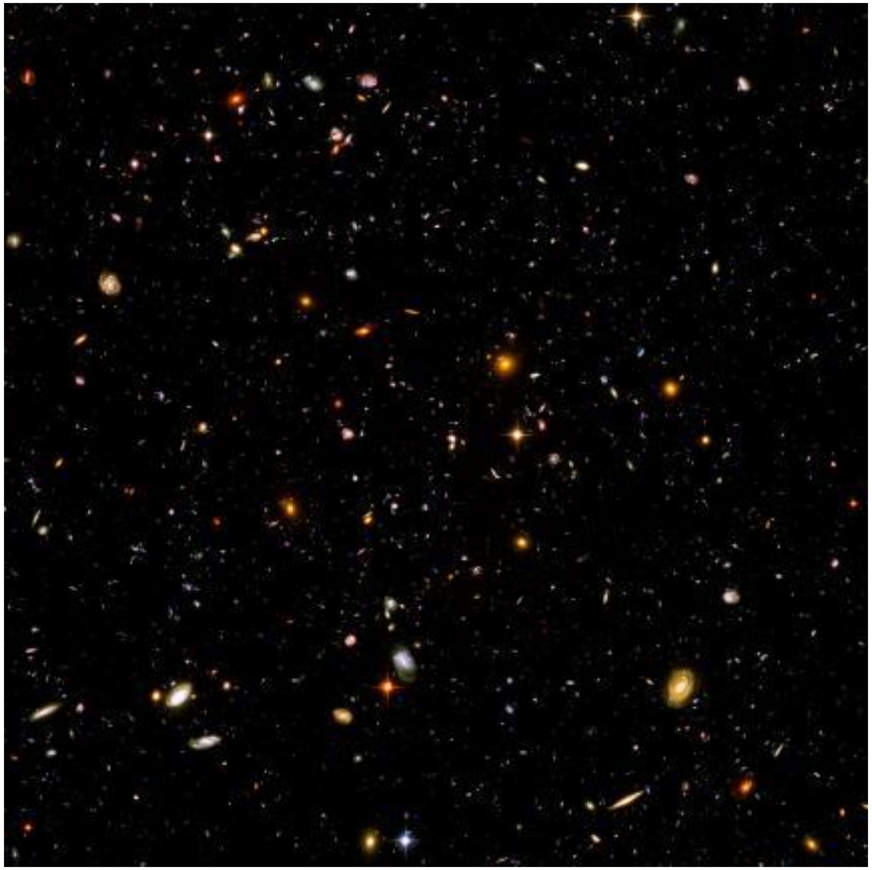
Image from LBT office

THREE GIANTS

FOR THREE BIG QUESTIONS

1. EARLY UNIVERSE

DEEP FIELD IMAGING: HUBBLE ULTRA DEEP FIELD



2.4 arcminutes = 0.04 degree

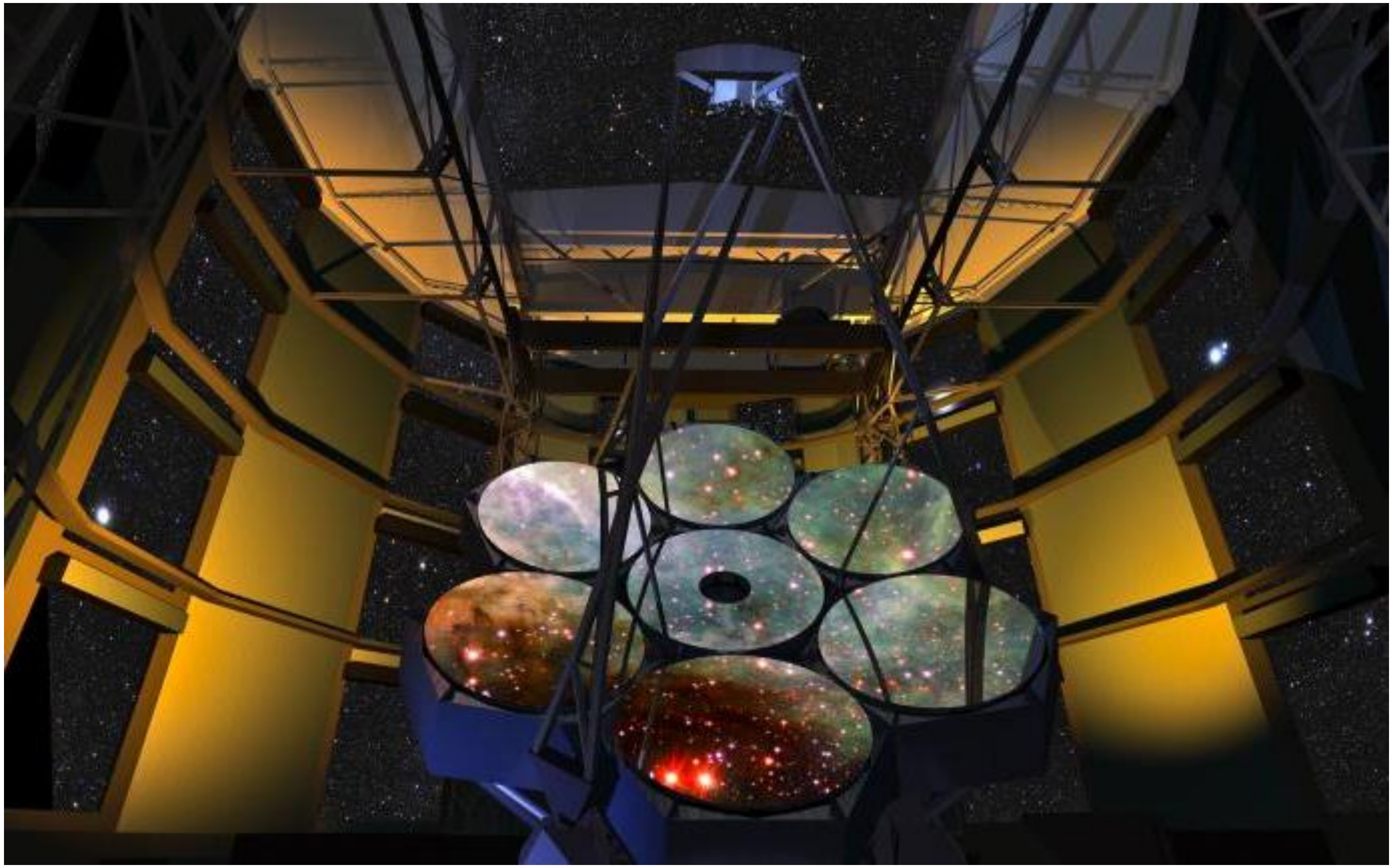
(Note: Full Moon = ~0.5 degree)

Looking back approximately 13 billion years (between 400 and 800 million years after the Big Bang).

Image from http://en.wikipedia.org/wiki/Hubble_Deep_Field

GIANT CAMERA

GMT, 24.5M PRIMARY USING SEVEN 8.4M SEGMENTS



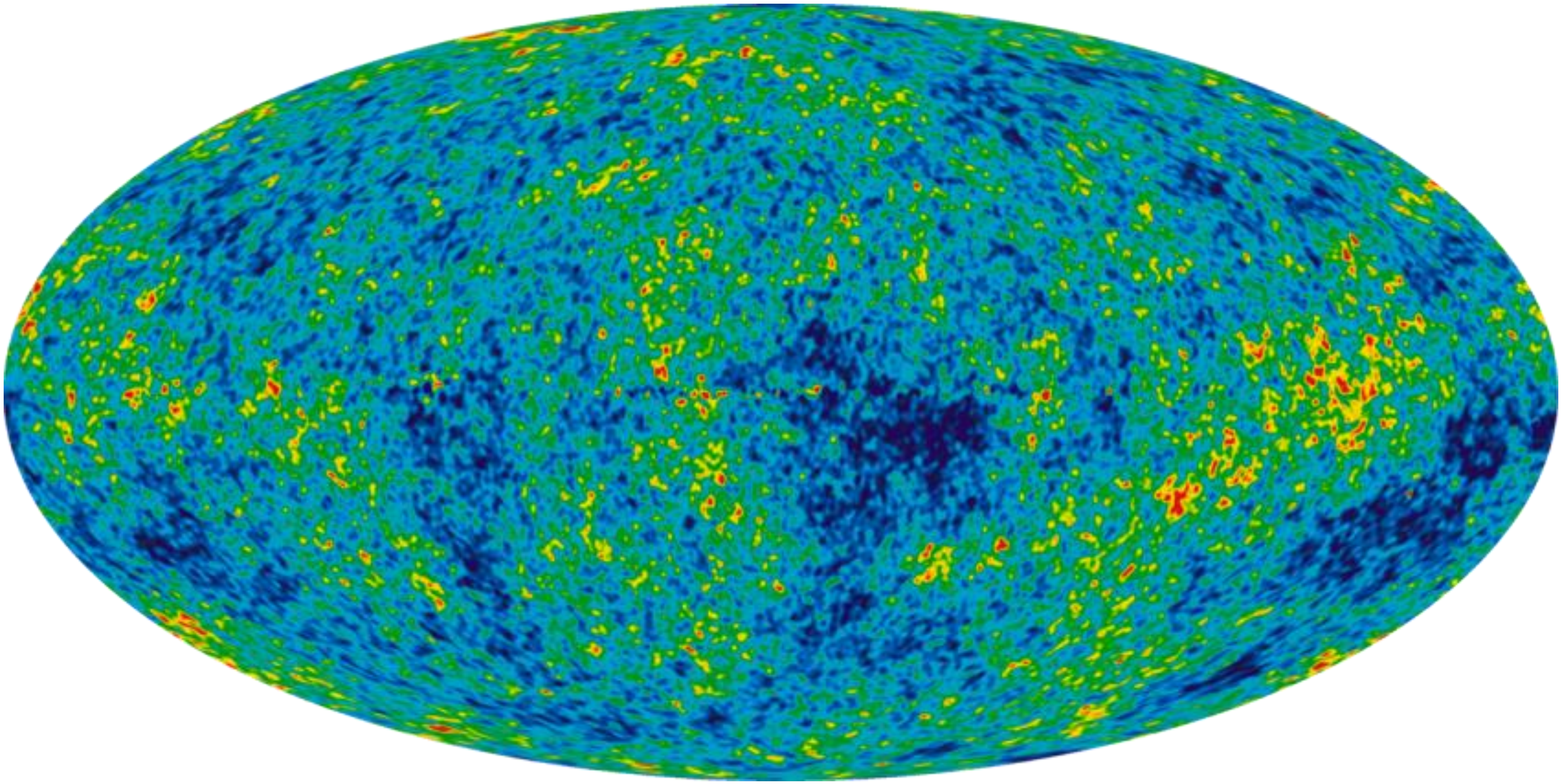
The ultimate telescope which defines a new category called 'Extremely Large Telescope.'

Image from www.gmto.org

10X resolution compared to the Hubble Space Telescope.

2. WHOLE UNIVERSE

SURVEY ASTRONOMY: ALL-SKY MAP



~2.7K Cosmic microwave background: 9 years of WMAP (Wilkinson Microwave Anisotropy Probe) data

Image from http://en.wikipedia.org/wiki/Cosmic_microwave_background

GIANT CAMCORDER

LSST, 3.5 BY 3.5 DEGREE FOV W/ 3200 MEGAPIXEL CAMERA

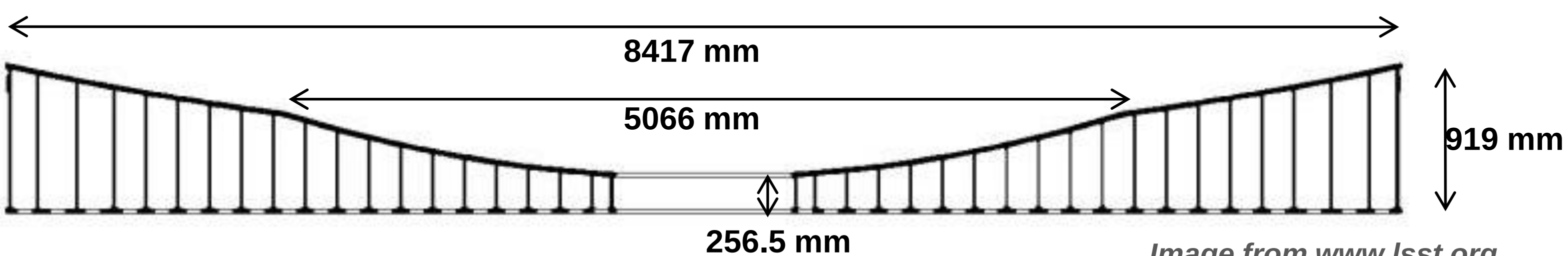
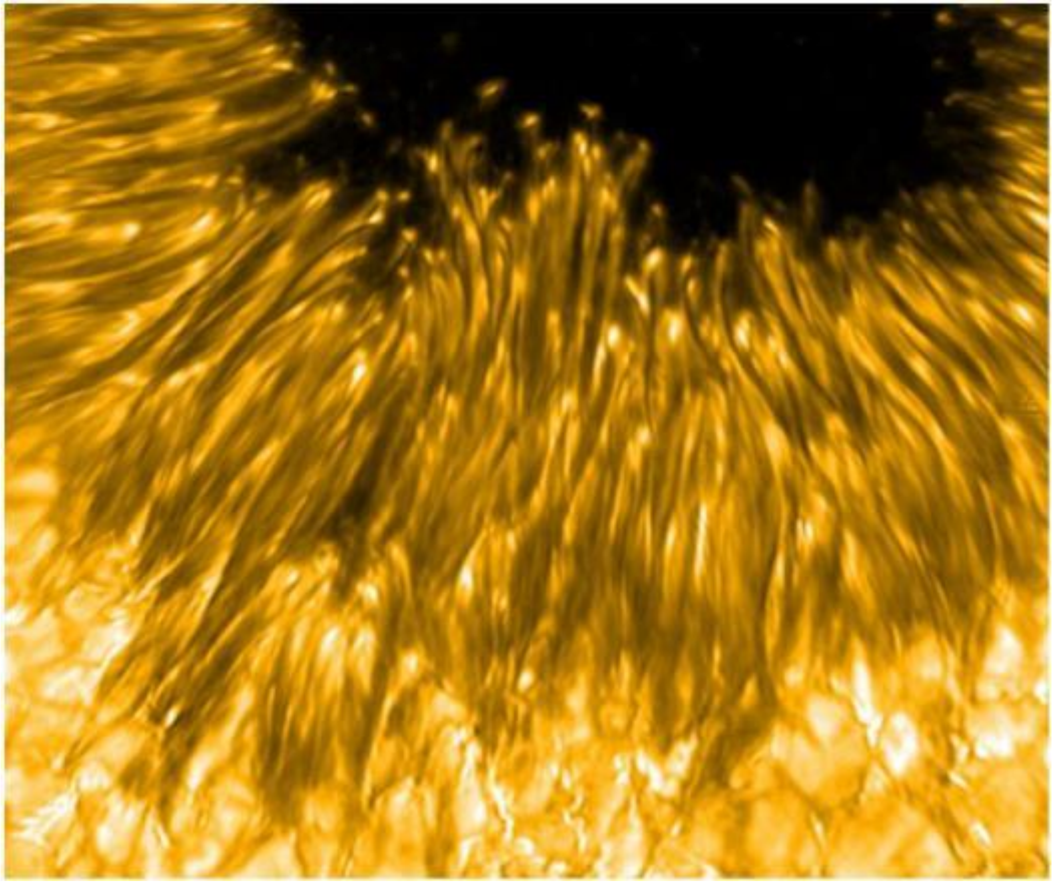


Image from www.lsst.org

Monolithic 8.4 m primary-tertiary (on a single substrate)

Synoptic means "looking at all aspects" including 6 colors, billions of object, and time (video camera).

3. SUN
SOLAR ASTRONOMY



Sunspot fine structure (Solar scientists want ~20km resolution.)

It is the closest and brightest star in the sky.

Image from http://atst.nso.edu/node/387

GIANT MICROSCOPE
DKIST USING 4.2M PRIMARY MIRROR

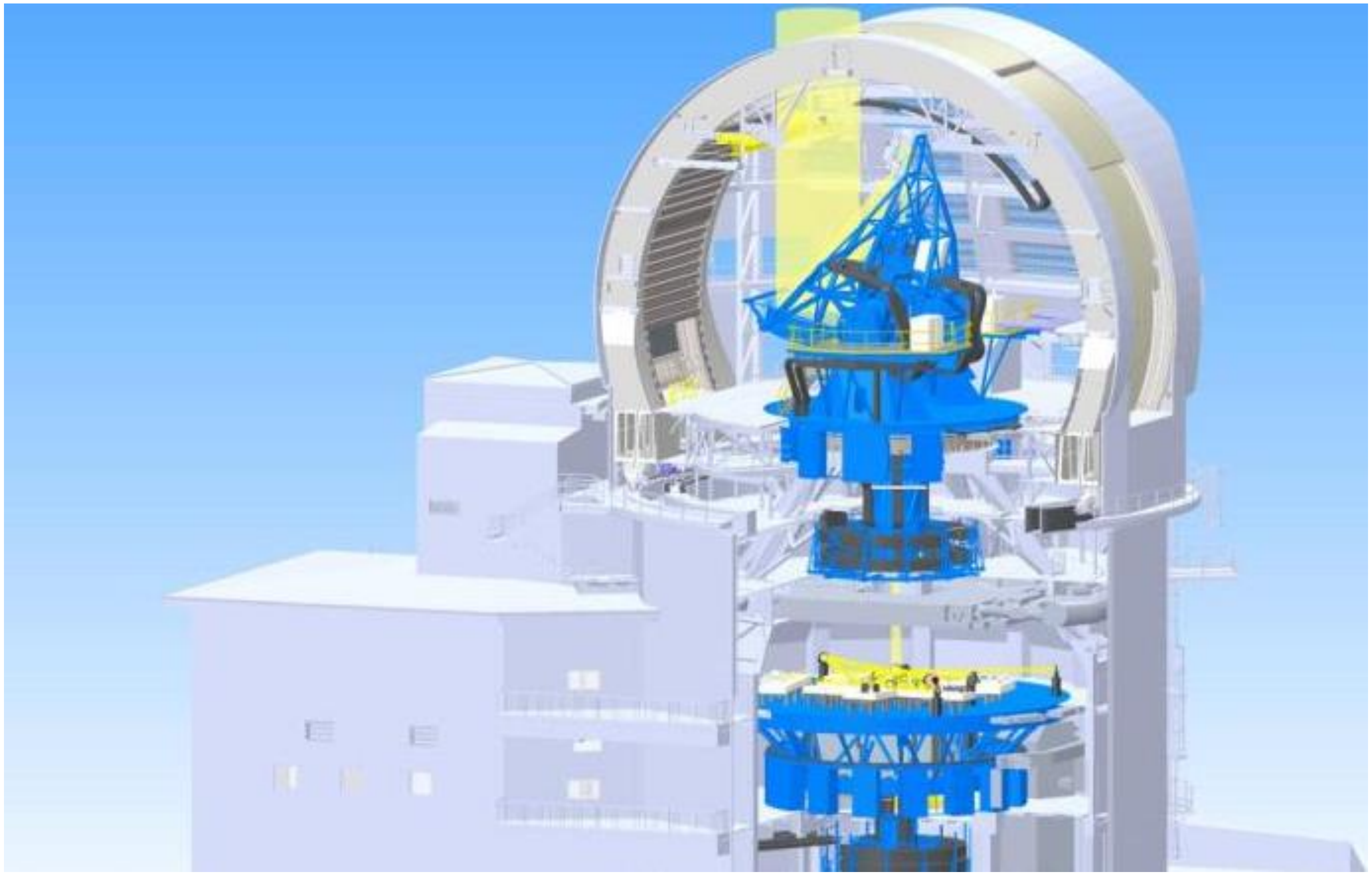


Image from atst.nso.edu

It is imaging the extend object, Sun.

Sunspot fine structure (Solar scientists want ~20km resolution.)

Off-axis optical design to control stray light issues

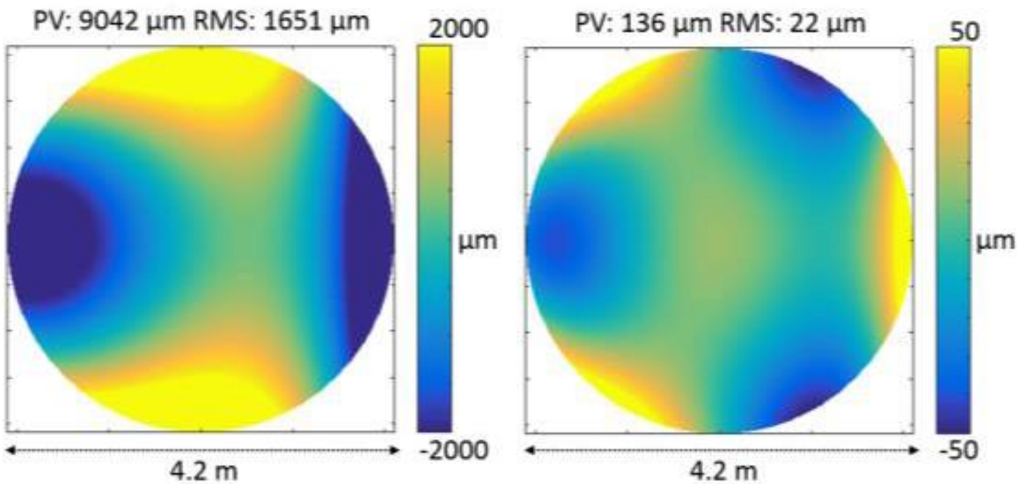
CHALLENGES

MANUFACTURING OF
NEXT GENERATION OPTICAL SYSTEMS
UTILIZING FREEFORM OPTICS

DKIST PRIMARY MIRROR

4.2M DIAMETER OFF-AXIS PARABOLIC MIRROR

Optical parameter	Value	Note
Radius of curvature	16 m	
Conic constant	-1	Parabola
Off-axis distance	4 m	Distance from the parent vertex
Mirror diameter	4.2 m	
Aspheric departure	~9 mm	Peak-to-valley departure

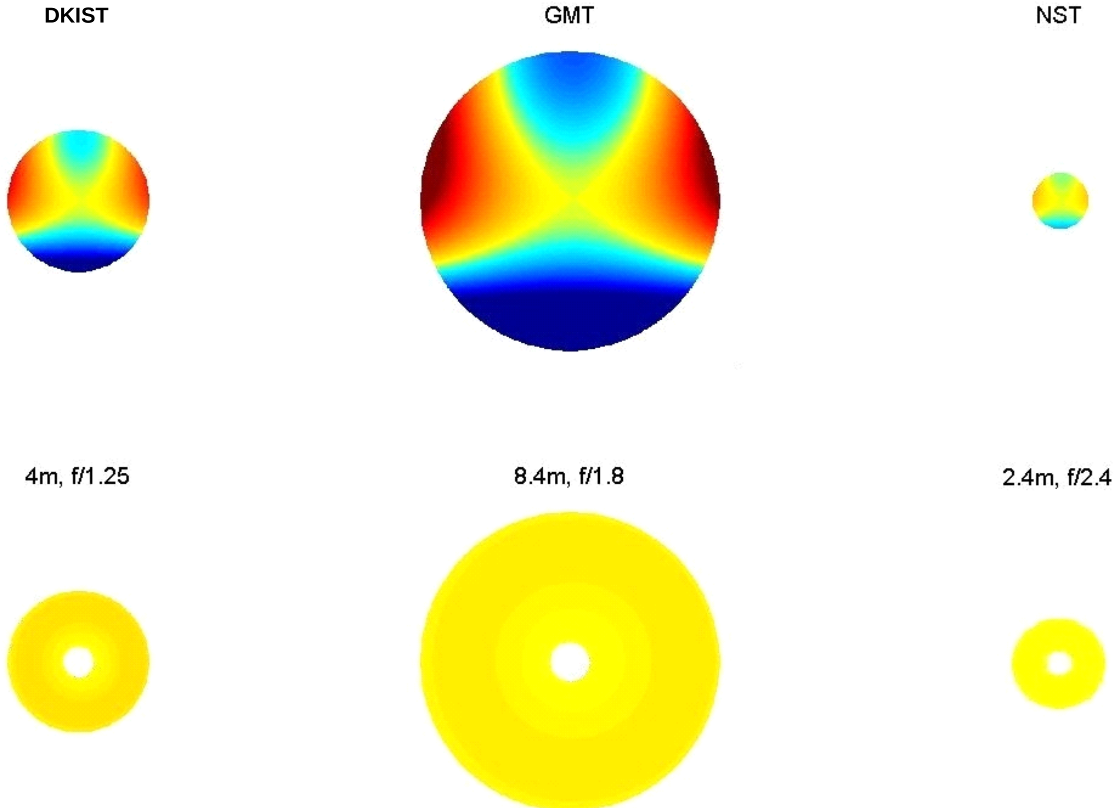


Freeform departure of the DKIST primary mirror (left) and high order shape after subtracting the first 8 standard Zernike terms (right).

Dae Wook Kim, Peng Su, Chang Jin Oh, and James H. Burge, "Extremely Large Freeform Optics Manufacturing and Testing," CLEO-PR, Optical Society of America (2015)

LARGE FREE-FORM OPTICS

ASPHERIC DEPARTURE FROM BEST FIT SPHERE



GMT primary mirror has more than 13 mm aspheric departure from its best fit sphere.

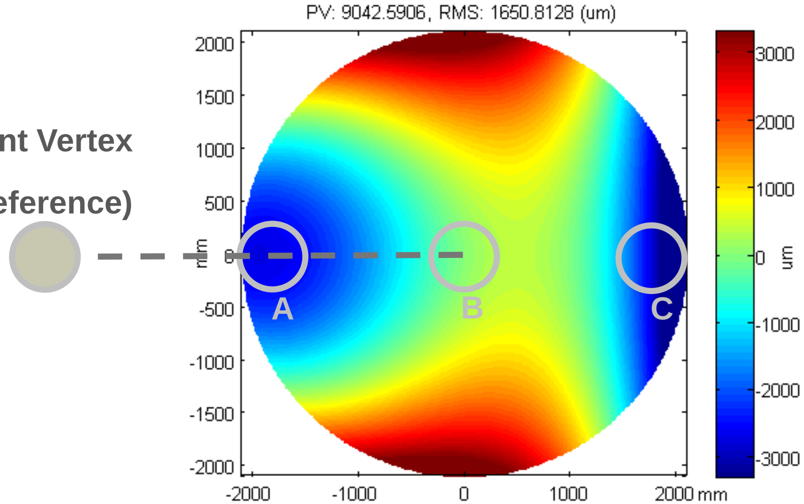
The local curvature and shape keep changing, so that it becomes a freeform fabrication issue.

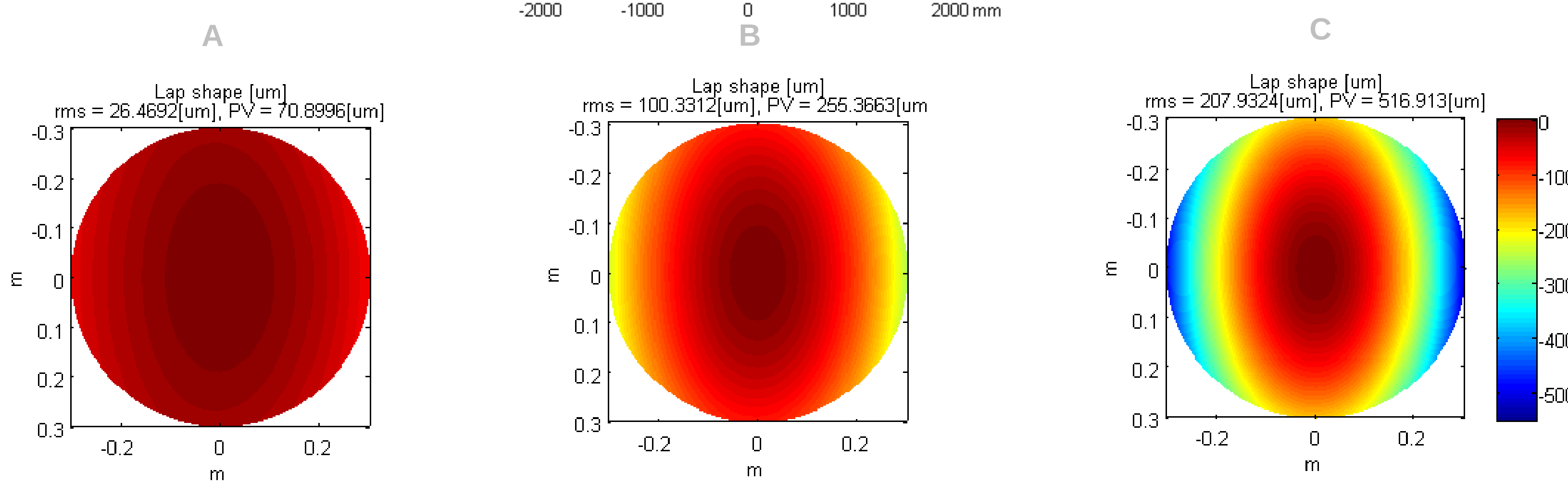
ACTIVE SHAPE CONTROL

0.6M STRESSED LAP ON 4.2M DKIST PRIMARY

Parent Vertex

(Stressed lap shape reference)





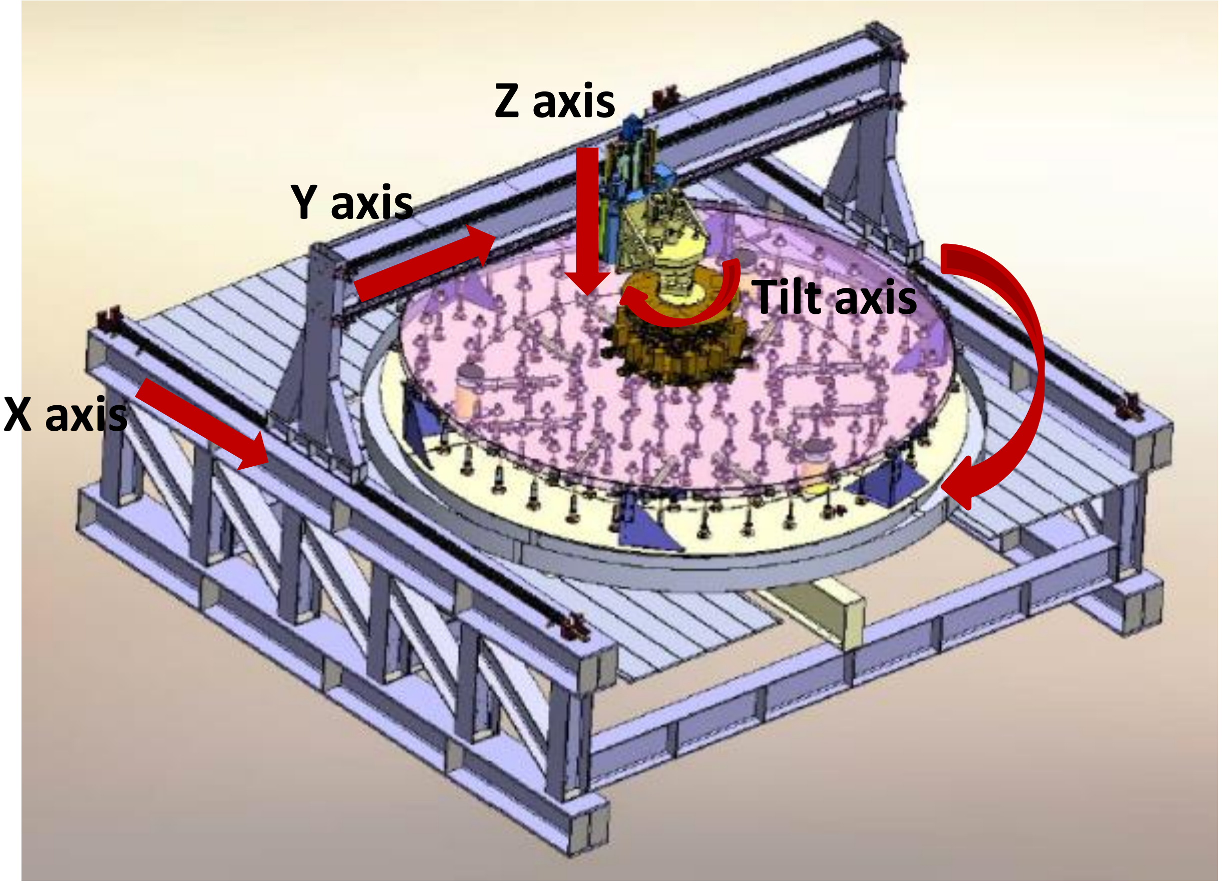
D. W. Kim et al., "Advanced Technology Solar Telescope 4.2 m Off-axis Primary Mirror Fabrication," in Classical Optics 2014, OTh2B.3

TWO ESSENTIAL TECHNOLOGIES

FABRICATION AND METROLOGY

1. FABRICATION

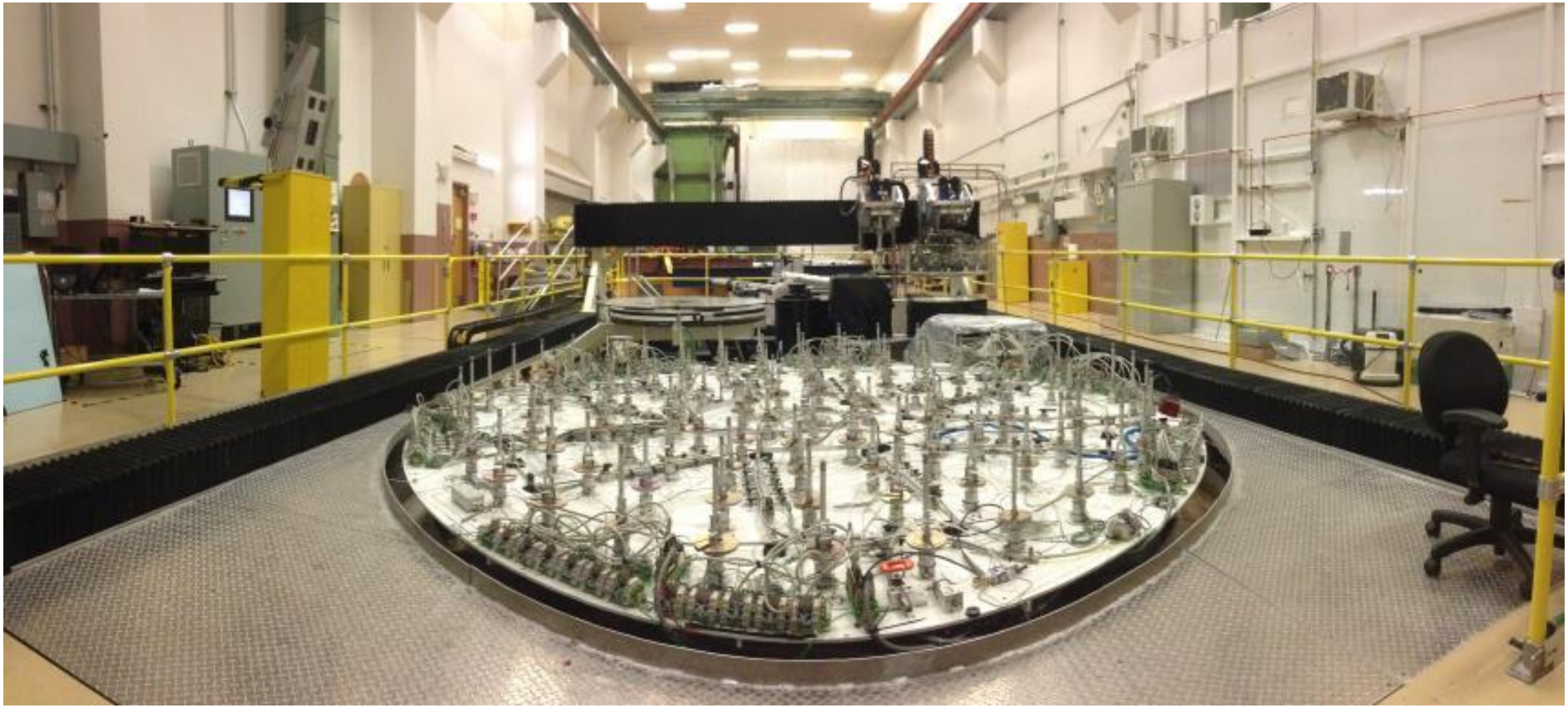
CCPM – COMPUTER CONTROLLED POLISHING MACHINE
5 AXIS PRECISION MACHINE



All axis are fully computer controlled during the fabrication process.

The tool follows the local normal of the optics using tilt axis.

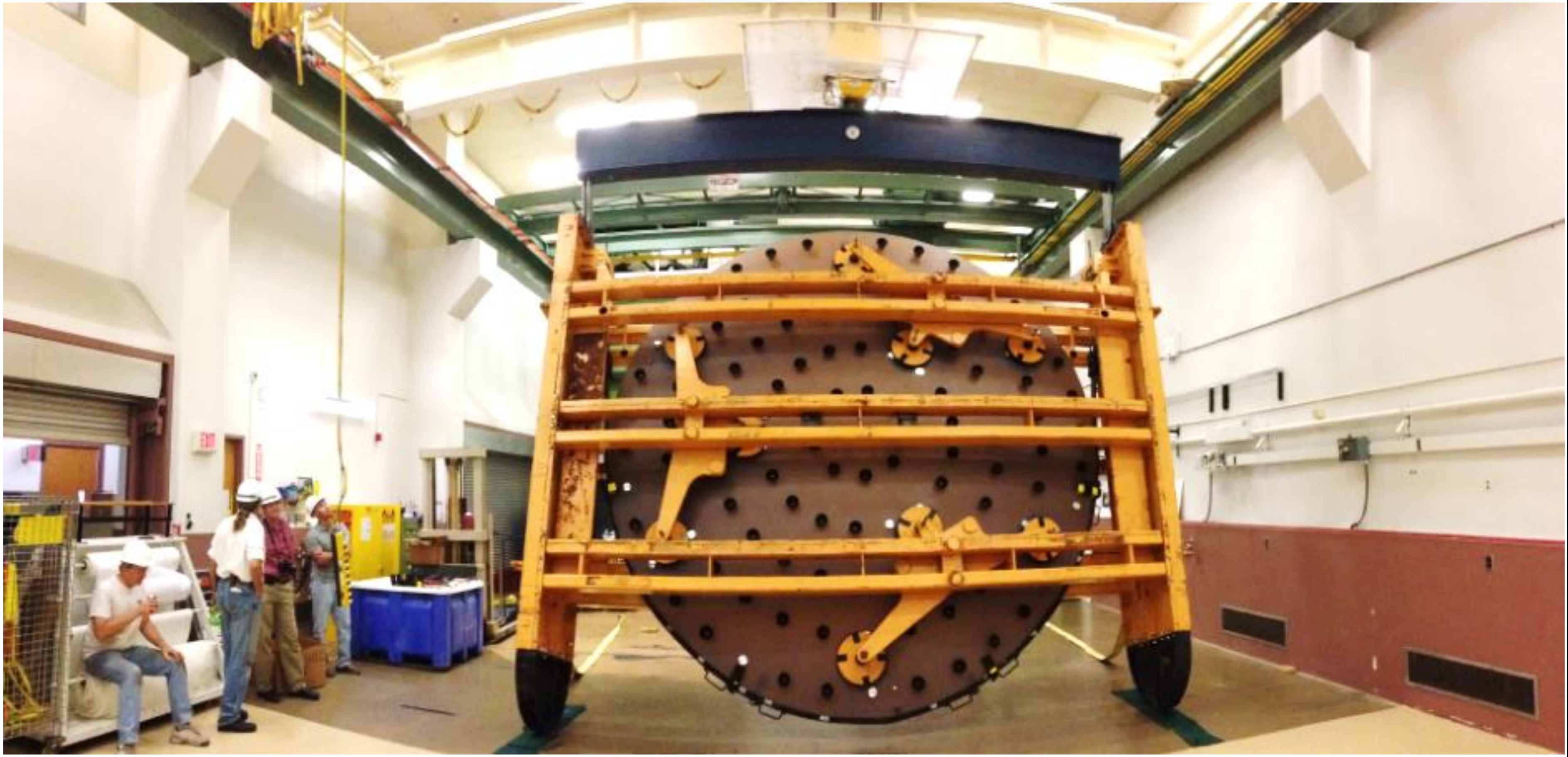
HYDRAULIC SUPPORT
FOR FABRICATION AND TESTING



118 hydraulic supports to mount the thin (aspect ratio ~ 50) flexible mirror

About 30 mirror bending modes are used for active optics correction.

PRIMARY MIRROR
4.2M ZERODUR OFF-AXIS MIRROR

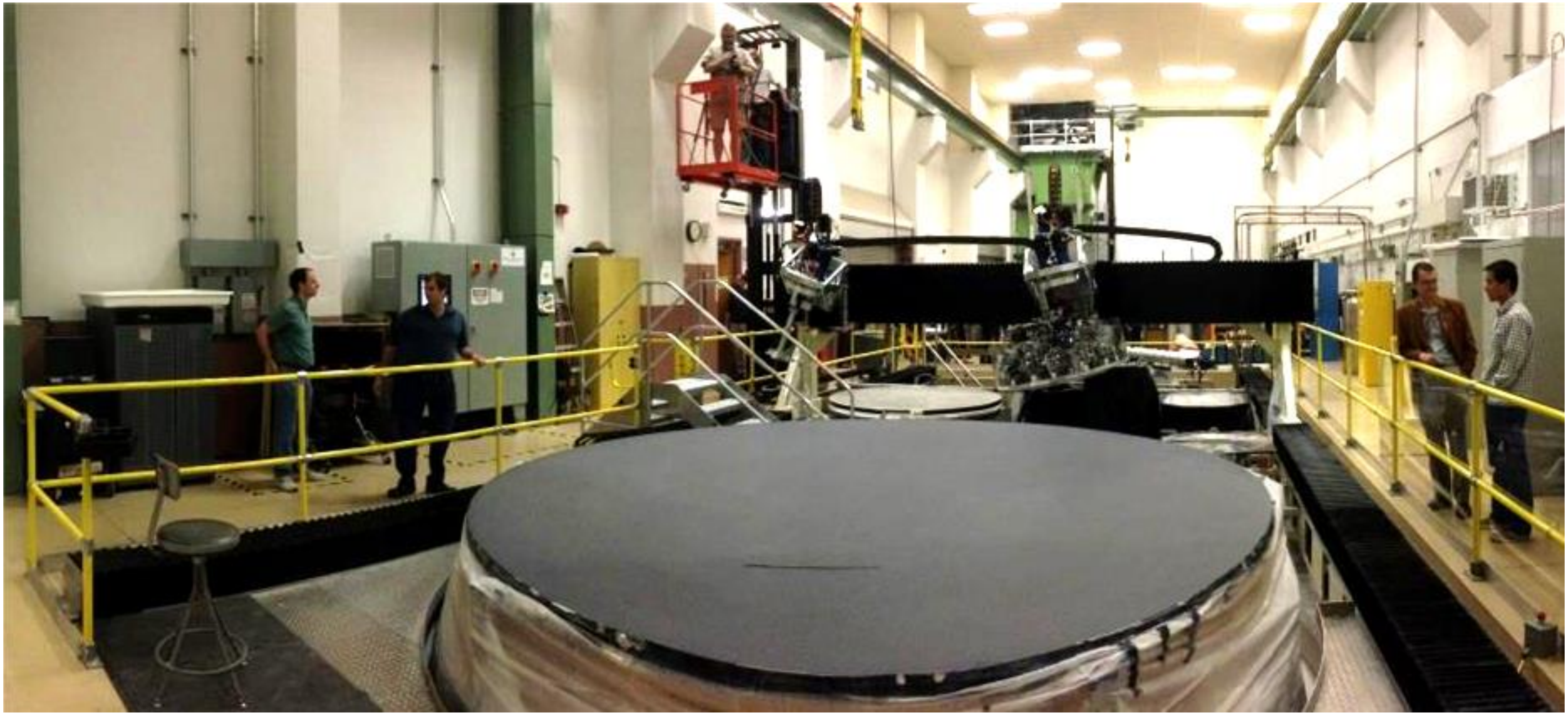


4.2m SCHOTT Zerodur mirror blank w/ near 0 CTE

118 hydraulic supporting fixtures on the back side of the blank

DKIST PRIMARY ON CCPM

4.2M ZERODUR OFF-AXIS MIRROR

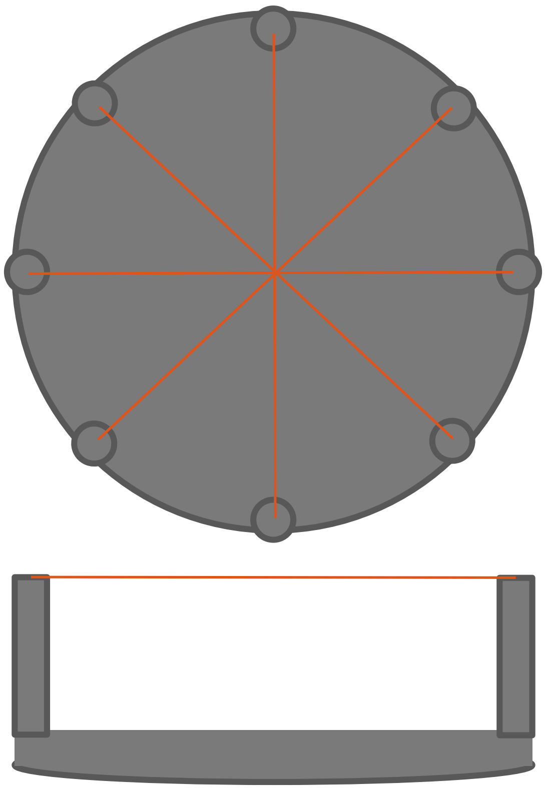


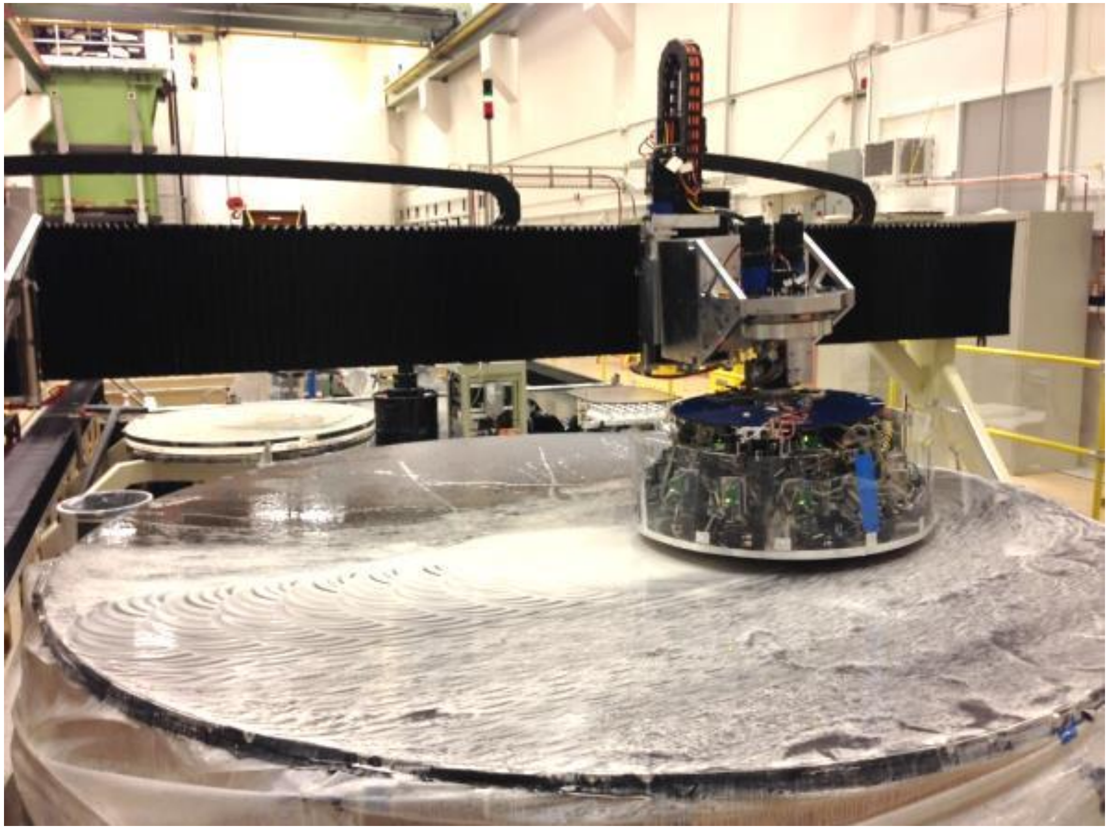
Radius of curvature: 16m (Conic constant: -1)

Off-axis distance (from parent vertex): 4m

ACTIVE SOLUTION (~$1.5M)

STRESSED LAP ON THE 4.2M DKIST PRIMARY MIRROR





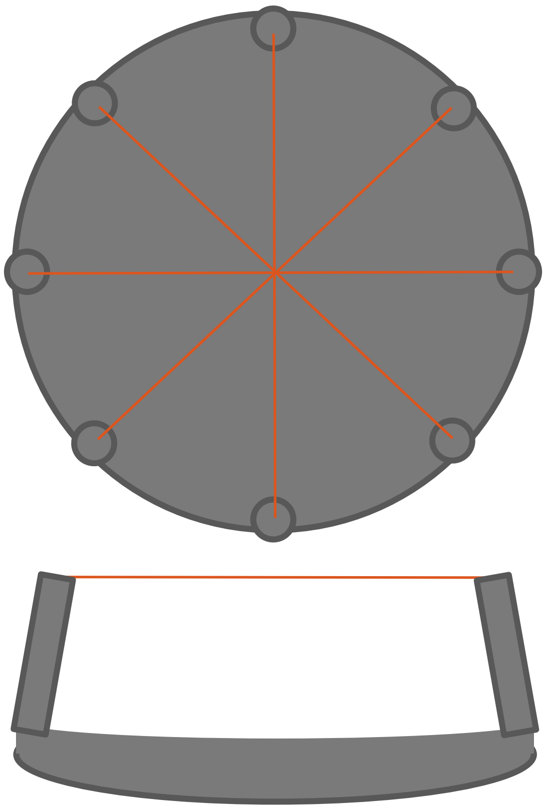
0.6m Stressed lap is updating its shape (Zernike 4-10) at ~100 Hz to maintain its local fit between the lap and the workpiece.

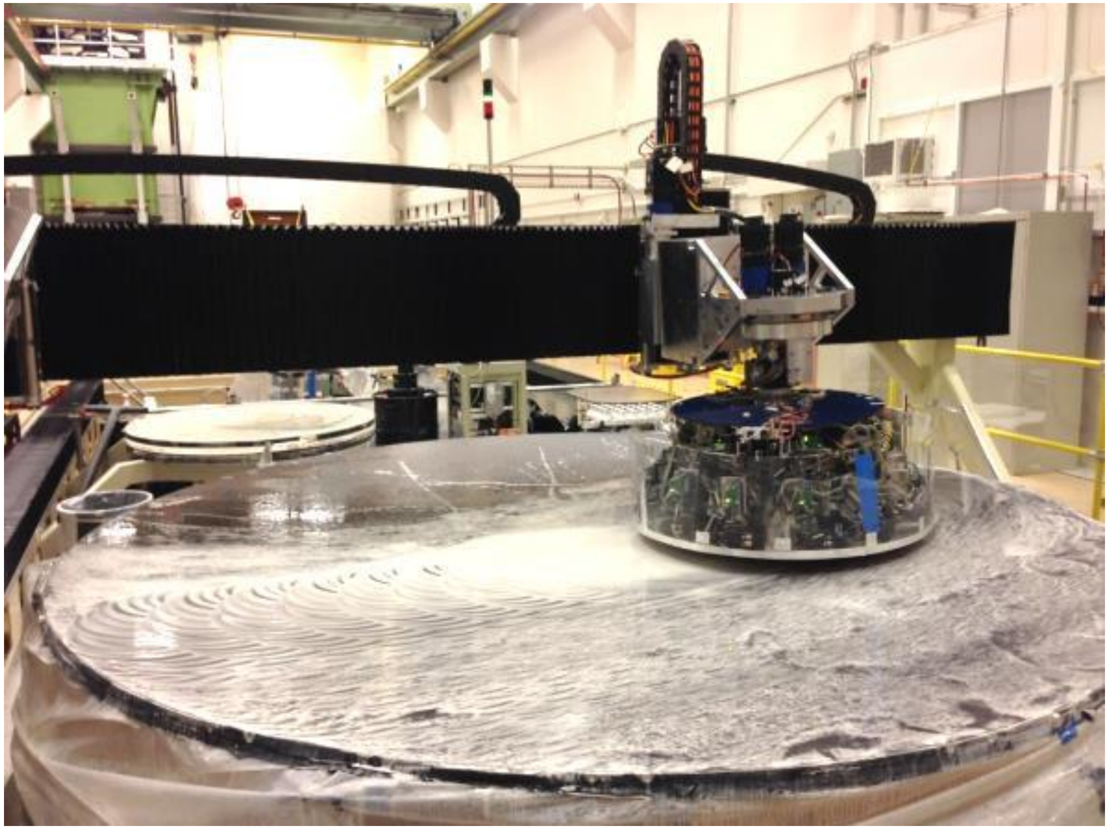
D. W. Kim et al., "Advanced Technology Solar Telescope 4.2 m Off-axis Primary Mirror Fabrication," in Classical Optics 2014, OTh2B.3

S. West et al., “Development and results for Stressed-lap polishing of large telescope mirrors,” OTh2B.4

ACTIVE SOLUTION (~$1.5M)

STRESSED LAP ON THE 4.2M DKIST PRIMARY MIRROR





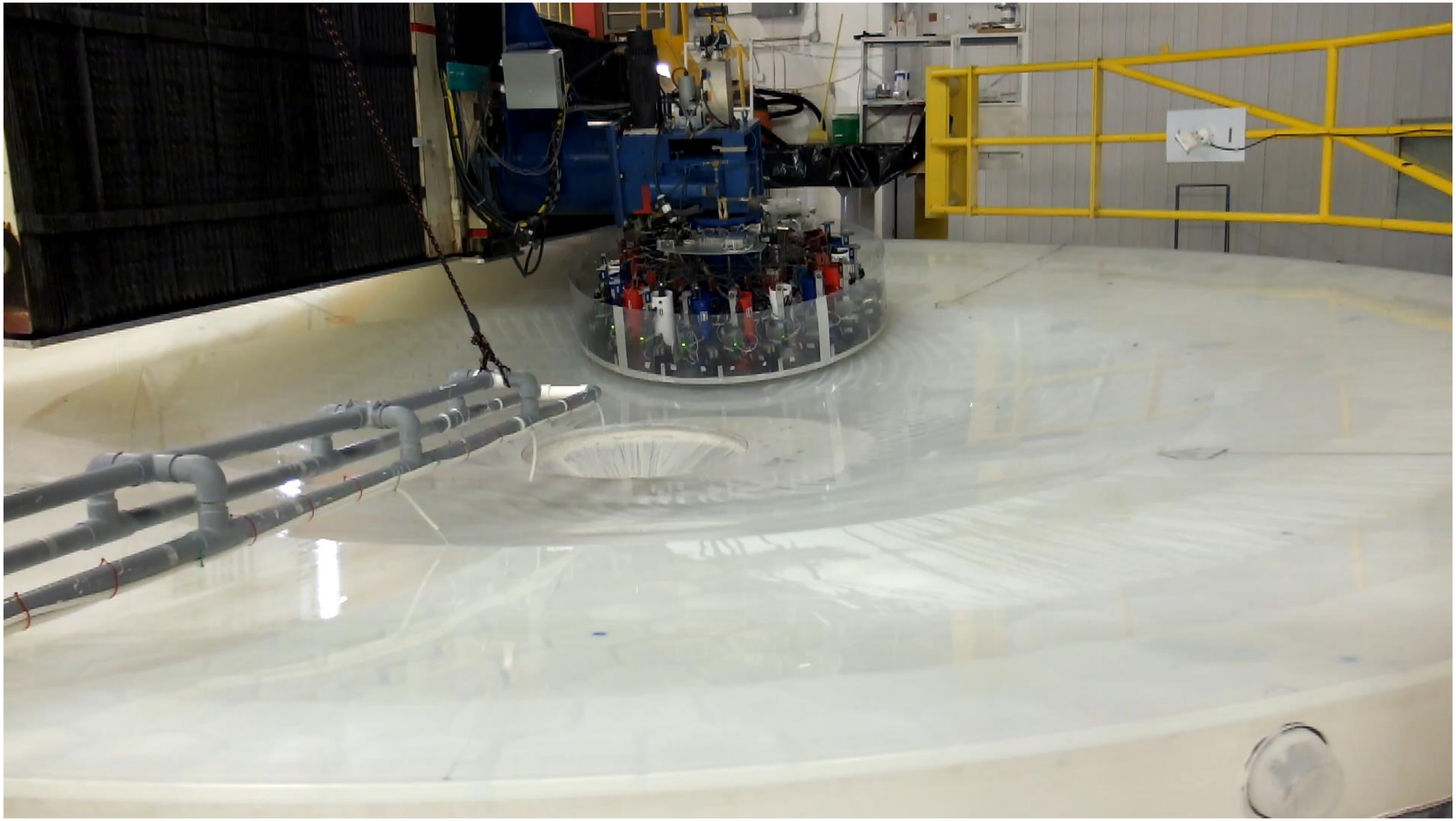
0.6m Stressed lap is updating its shape (Zernike 4-10) at ~100 Hz to maintain its local fit between the lap and the workpiece.

D. W. Kim et al., "Advanced Technology Solar Telescope 4.2 m Off-axis Primary Mirror Fabrication," in Classical Optics 2014, OTh2B.3

S. West et al., "Development and results for Stressed-lap polishing of large telescope mirrors," OTh2B.4

ACTIVELY SHAPE CONTROLLED LAP

1.2M STRESSED LAP ON 8.4M LSST PRIMARY-TERTIARY



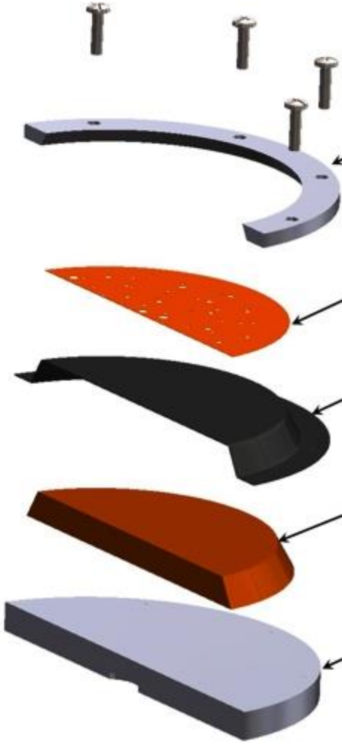
WALKING ON THE WATER

SWIMMING POOL FILLED WITH CORNSTARCH AND WATER

https://www.youtube.com/watch?v=f2XQ97XHjVw

PASSIVE SOLUTION (~$500.00)

RIGID CONFORMAL LAP USING SILLY PUTTY



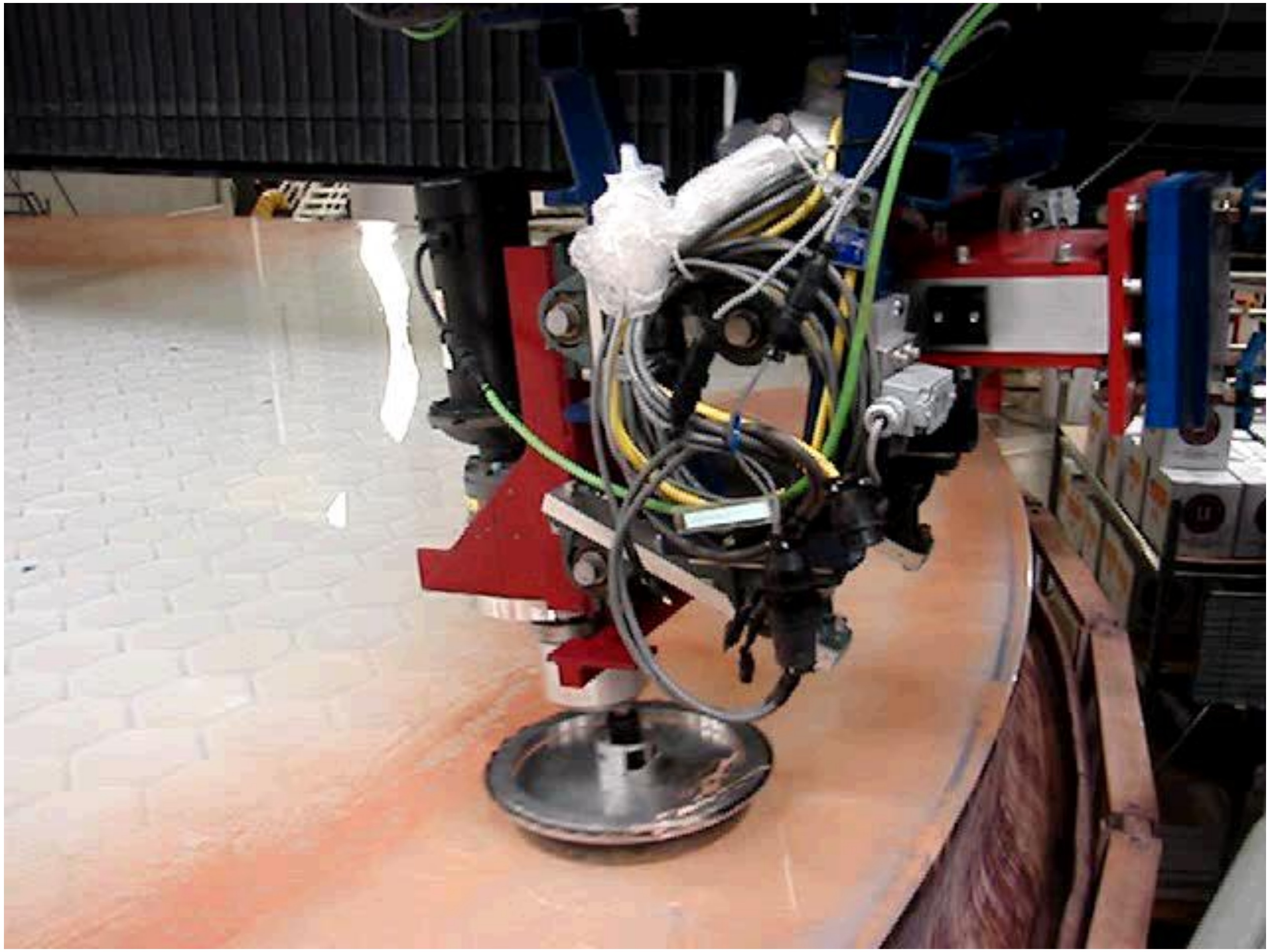
3D schematic Rigid Conformal lap structure (exploded and cut in half).

D. W. Kim and J. H. Burge, "Rigid conformal polishing tool using non-linear visco-elastic effect," Opt. Express. 18, 2242-2257 (2010)

http://www.crayola.com/products/original-silly-putty-product/

PASSIVELY SHAPE CONTROLLED LAP

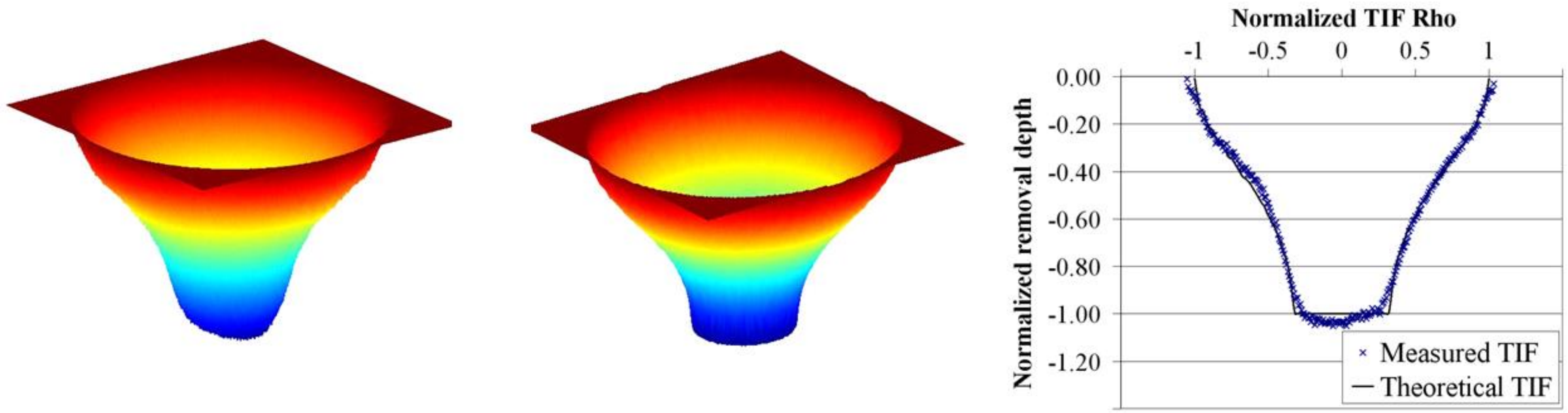
RC LAP ON THE 8.4M GMT PRIMARY SEGMENT



D. W. Kim and J. H. Burge, "Rigid conformal polishing tool using non-linear visco-elastic effect," Opt. Express. 18, 2242-2257 (2010)

TIF CALIBRATION

PERFORMANCE OF THE ADVANCED CCOS PROCESS



TIFs using the RC lap with an orbital tool motion: measured 3D TIF (left), theoretical 3D TIF (middle), and radial profiles of them (right).

Preston's coefficient *κ* is calibrated to fit the theoretical TIF to the measured one.

$$\Delta z(x,y) = \kappa \cdot P(x,y) \cdot V_T(x,y) \cdot \Delta t(x,y)$$

D. W. Kim and J. H. Burge, "Rigid conformal polishing tool using non-linear visco-elastic effect," Opt. Express. 18, 2242-2257 (2010)

2. METROLOGY

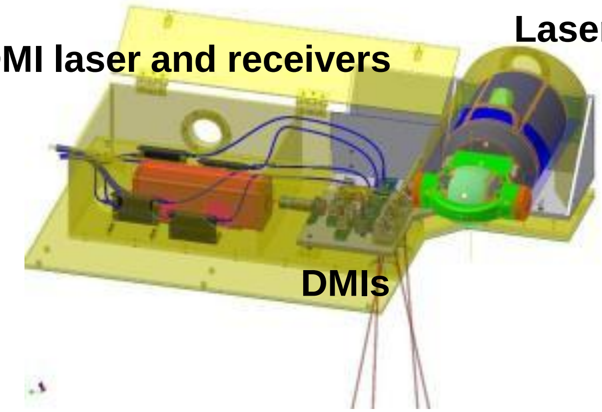
LASER TRACKER
INTERFEROMETRIC / TIME OF FLIGHT MEASUREMENT

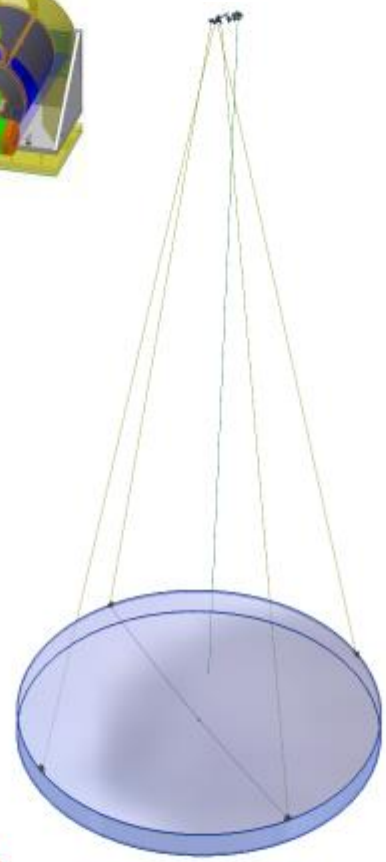
Large working distance (tens of meters)

Accuracy up to 15μm (typical angle at 2m)

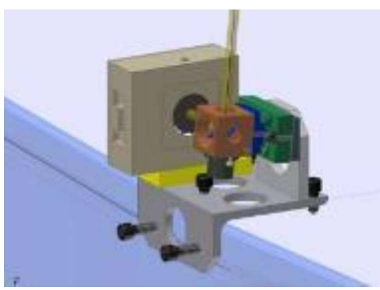
data from http://www.faro.com/

LASER TRACKER PLUS
LOW ORDER SURFACE SHAPE MEASUREMENT





SMR positioner (automated)



Retroreflector for DMI: 4 places at edge of segment

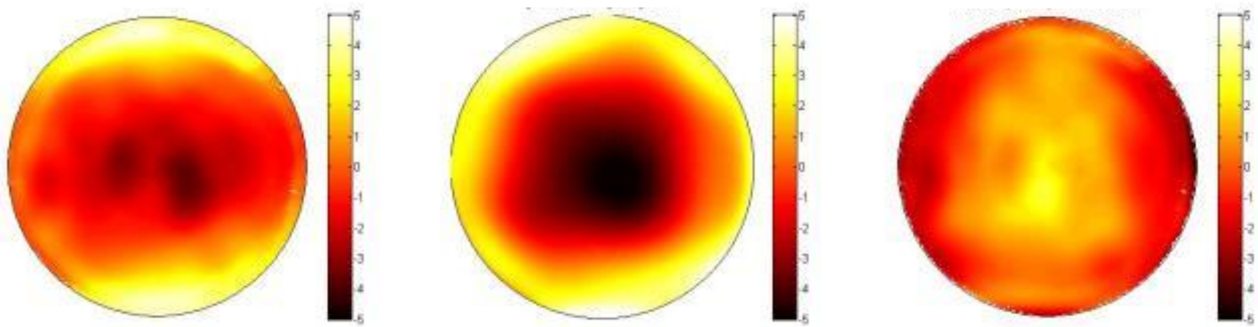
Laser tracker and 4 DMI (distance-measuring interferometers)

Tom L. Zobrist ; James H. Burge ; Hubert M. Martin; Accuracy of laser tracker measurements of the GMT 8.4 m off-axis mirror segments. Proc. SPIE 7739, 77390S (July 19, 2010)

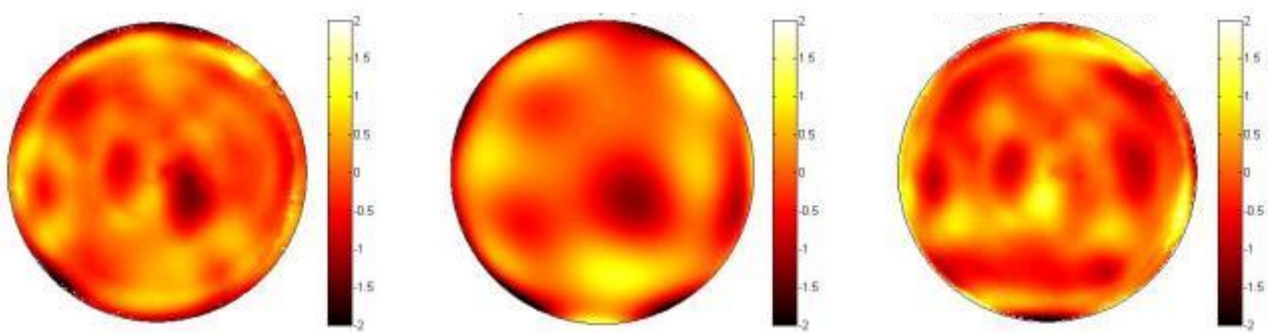
MEASUREMENT W/ LT+

COMPARISON BETWEEN INTERFEROMETRIC VS. LT+ DATA

Principal test | **Laser Tracker Plus** | **Difference**



all aberrations included 2.0 µm rms | **all aberrations included 2.6 µm rms** | **all aberrations included 1.3 µm rms**

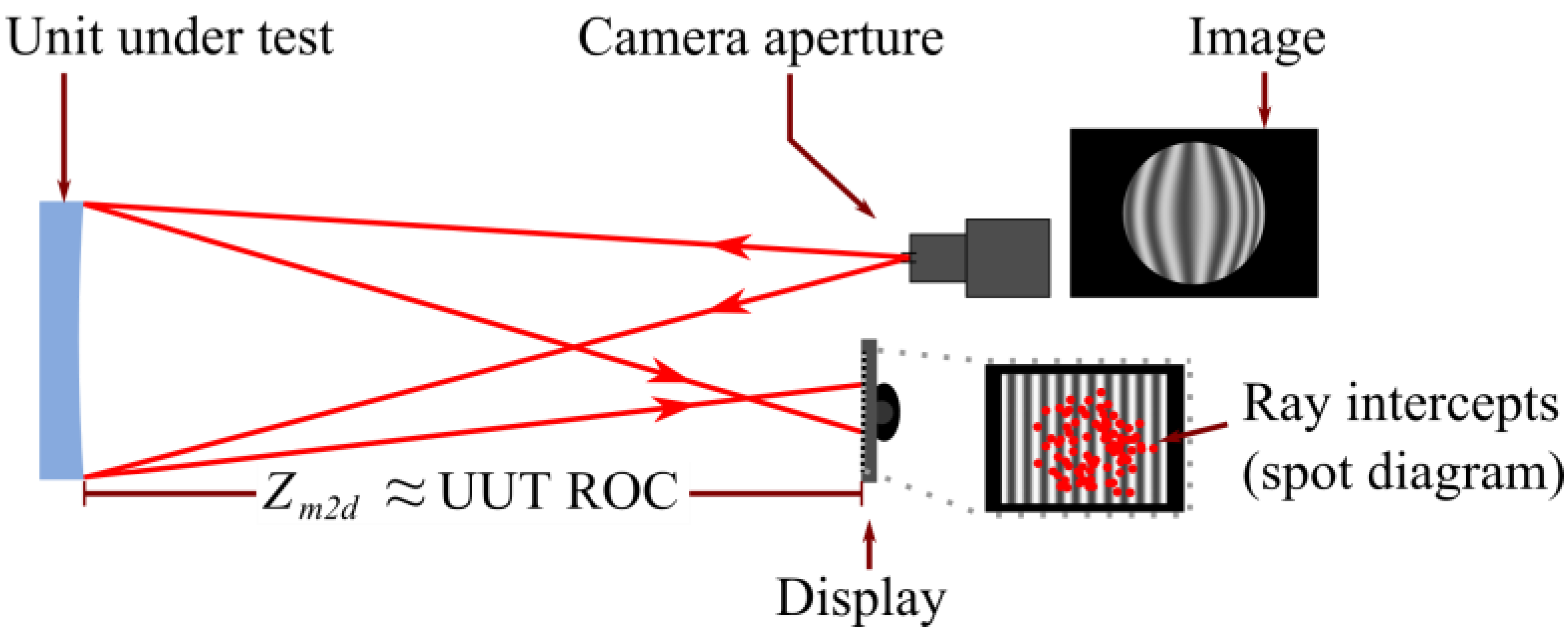


focus & astig subtracted 0.44 µm rms | **focus & astig subtracted 0.53 µm rms** | **focus & astig subtracted 0.48 µm rms**

LT+ map is polynomial fit to 256 measured points (0.5 m spacing).

H. M. Martin, R. G. Allen, J. H. Burge, D. W. Kim, J. S. Kingsley, M. T. Tuell, S. C. West, C. Zhao and T. Zobrist, "Fabrication and testing of the first 8.4 m off-axis segment for the Giant Magellan Telescope," Proc. SPIE 7739, (2010)

SCOTS
SOFTWARE CONFIGURABLE OPTICAL TEST SYSTEM



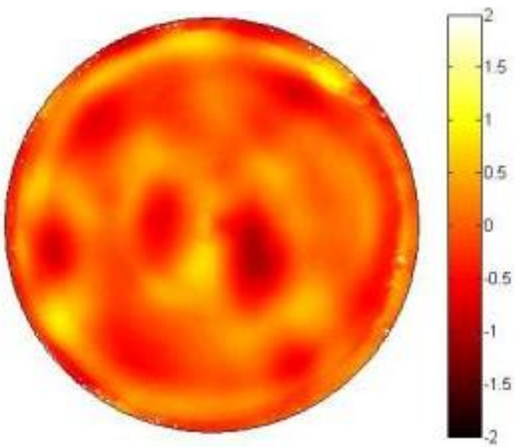
Advanced deflectometry system measuring surface slope with both high precision and large dynamic range.

Figure by Alex Maldonado

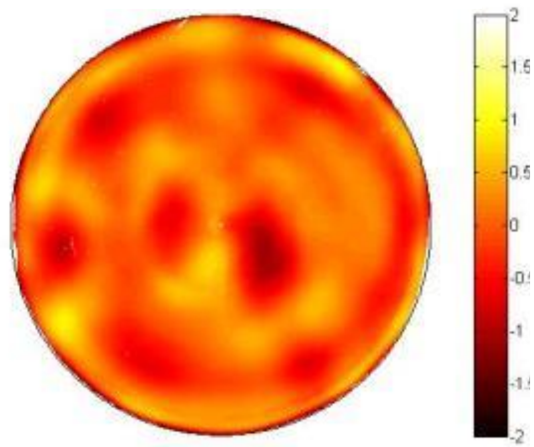
Peng Su, et al., "Software configurable optical test system: a computerized reverse Hartmann test," Applied Optics, Vol. 49, Issue 23, pp. 4404-4412 (2010)

MEASUREMENT W/ SCOTS

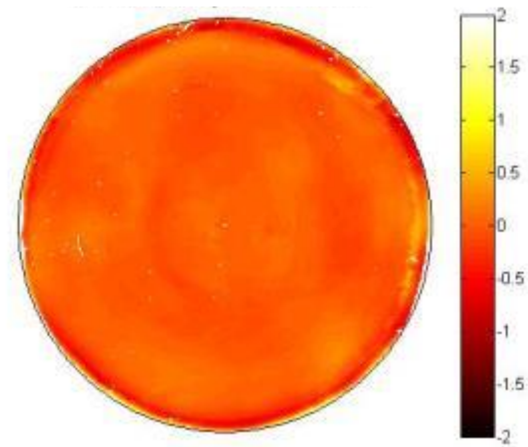
COMPARISON BETWEEN INTERFEROMETRIC VS. SCOTS DATA



Interferometric test
21 polynomials subtracted
0.32 μm rms



SCOTS
21 polynomials subtracted
0.35 μm rms



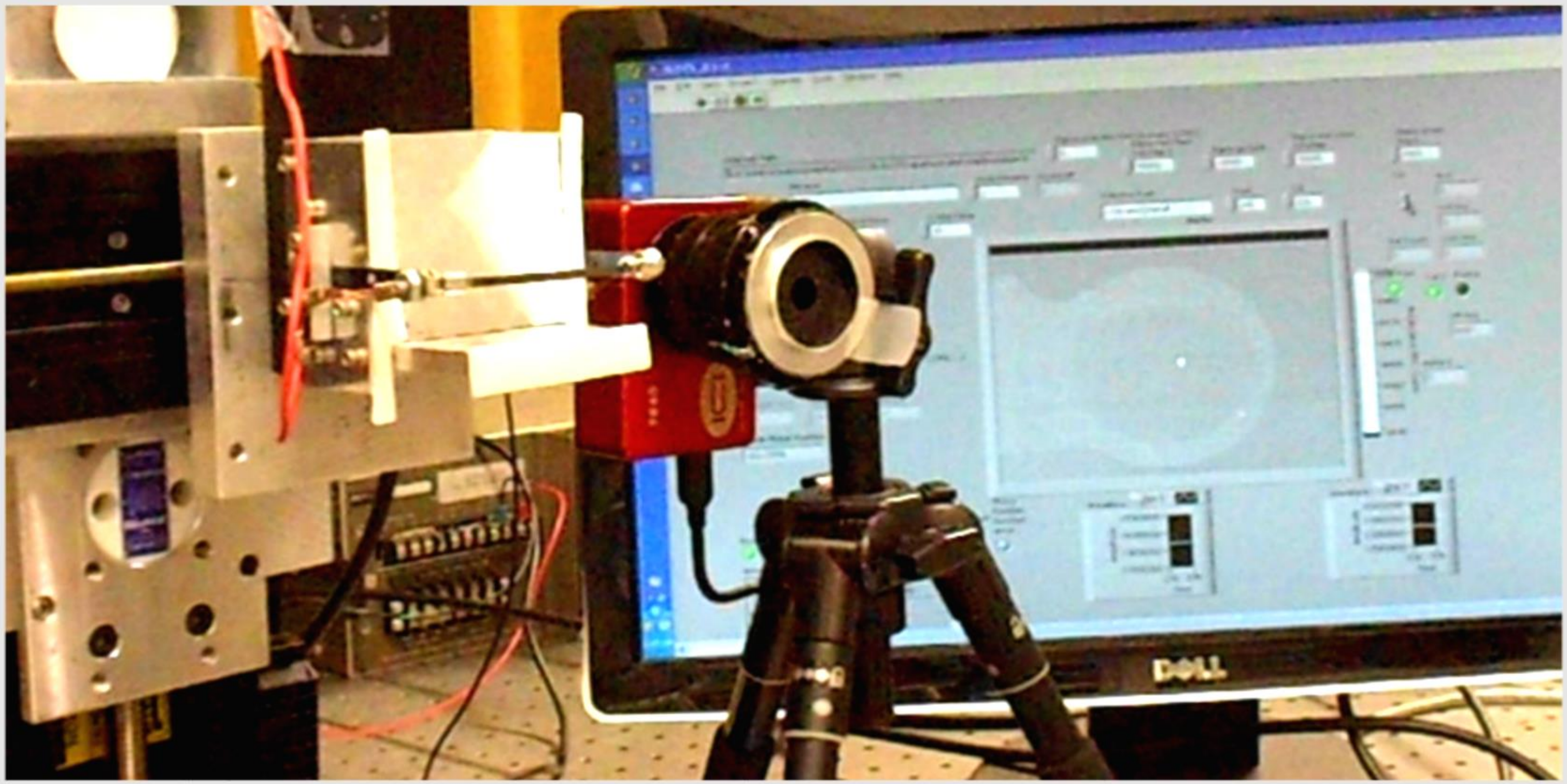
difference
0.16 μm rms

SCOTS ignores 21 low-order polynomials, so same polynomials are subtracted from principal test.

Excellent agreement. Much of difference is error in interferometric test at edge of segment.

H. M. Martin, R. G. Allen, J. H. Burge, D. W. Kim, J. S. Kingsley, M. T. Tuell, S. C. West, C. Zhao and T. Zobrist, "Fabrication and testing of the first 8.4 m off-axis segment for the Giant Magellan Telescope," Proc. SPIE 7739, (2010)

IR DEFLECTOMETRY
FOR FREEFORM PART METROLOGY



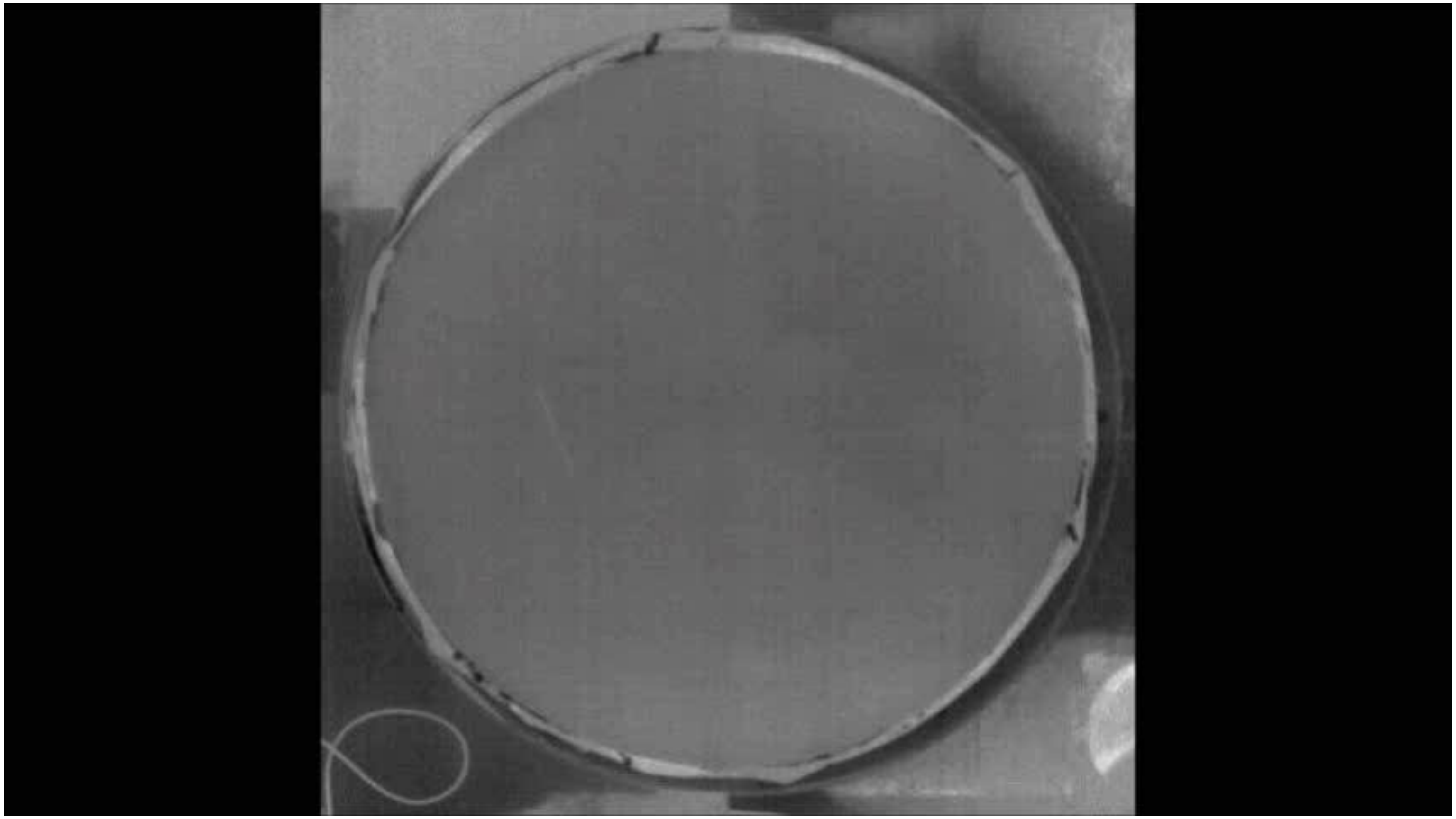
DEMO: Table-top SLOTS is measuring a sphere

Tianquan Su, et al., "Measuring rough optical surfaces using scanning long-wave optical test system. 1. Principle and implementation," Applied Optics, Vol. 52, Issue 29, pp. 7117-7126 (2013)

Dae Wook Kim, Tianquan Su, Peng Su, Chang Jin Oh, Logan Graves, and James H. Burge, "Accurate and rapid IR metrology for the manufacturing of freeform optics," SPIE Newsroom, DOI: 10.1117/2.1201506.006015 (July 6, 2015)

SLOTS FOR 4.2M ATST MIRROR

UNIQUE SOLUTION TO GUIDE FINE GRINDING PROCESS

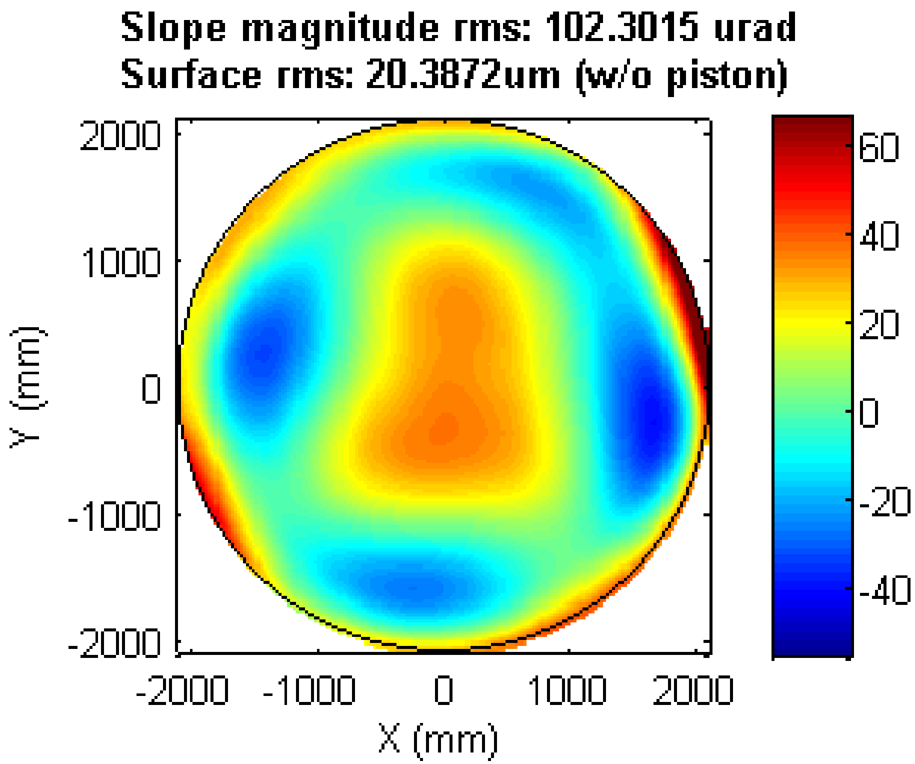


Vertical and horizontal line (~300º C hot wire emitting ~10um wavelength) scanning is being made.

Dae Wook Kim, Tianquan Su, Peng Su, Chang Jin Oh, Logan Graves, and James H. Burge, "Accurate and rapid IR metrology for the manufacturing of freeform optics," SPIE Newsroom, DOI: 10.1117/2.1201506.006015 (July 6, 2015)

MEASUREMENT W/ SLOTS

12 MICRON GRIT GROUND 4.2M DKIST OFF-AXIS MIRROR



The measured DKIST surface map demonstrates the excellent measuring capability of SLOTS for the ground surface.

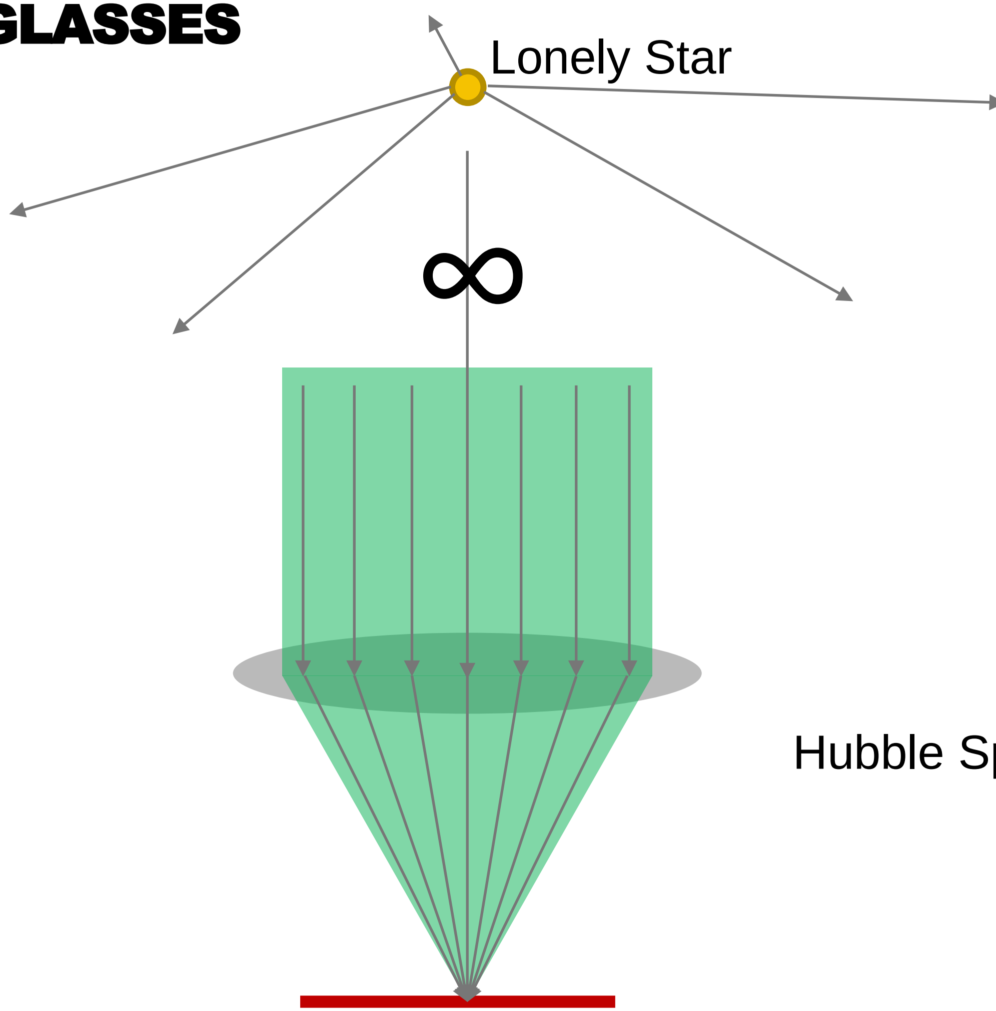
High spatial resolution (e.g. 353 pixels across the 4.2m diameter) with dynamic range measuring >100μm range.

Dae Wook Kim, Chang Jin Oh, Peng Su, and James H. Burge, "Advanced Technology Solar Telescope 4.2 m Off-axis Primary Mirror Fabrication," in Optical Fabrication and Testing (OF&T) (Optical Society of America), OTh2B.3 (2014)

GIANTS OFTEN WEAR VERY SPECIAL EYEGLASSES.

ADAPTIVE OPTICS

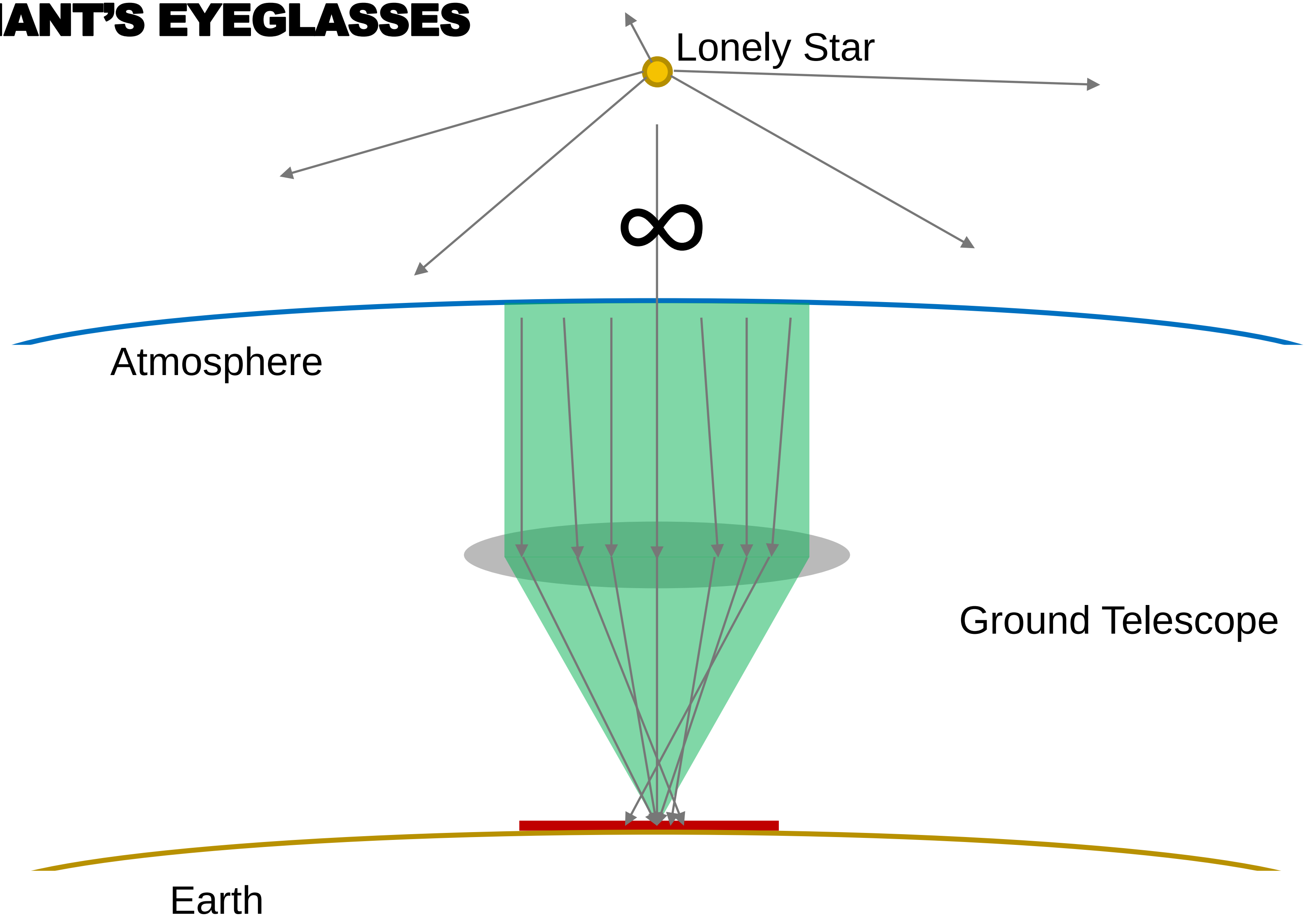
GIANT'S EYEGLASSES



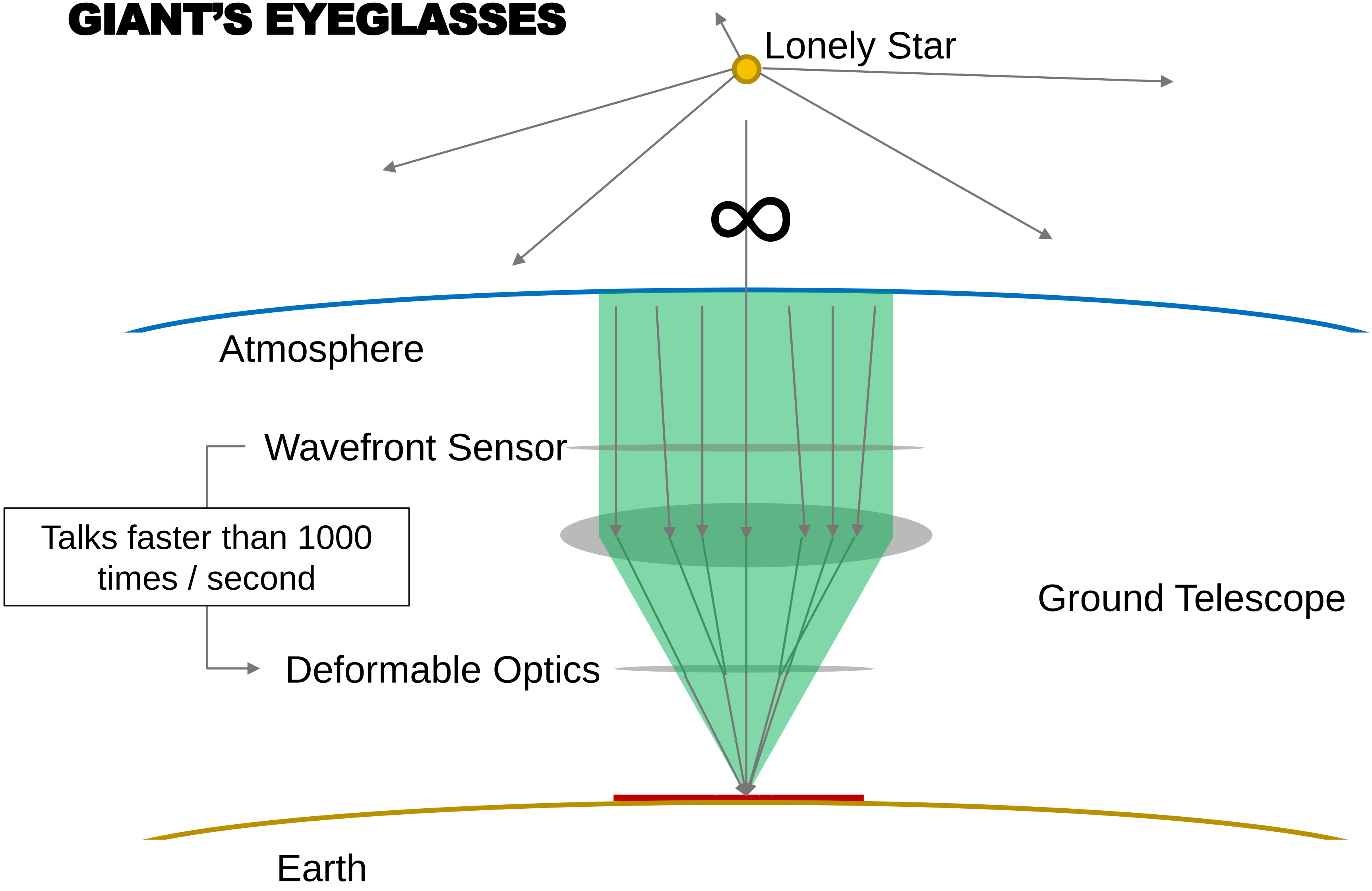
Hubble Space Telescope

ADAPTIVE OPTICS

GIANT'S EYEGLASSES

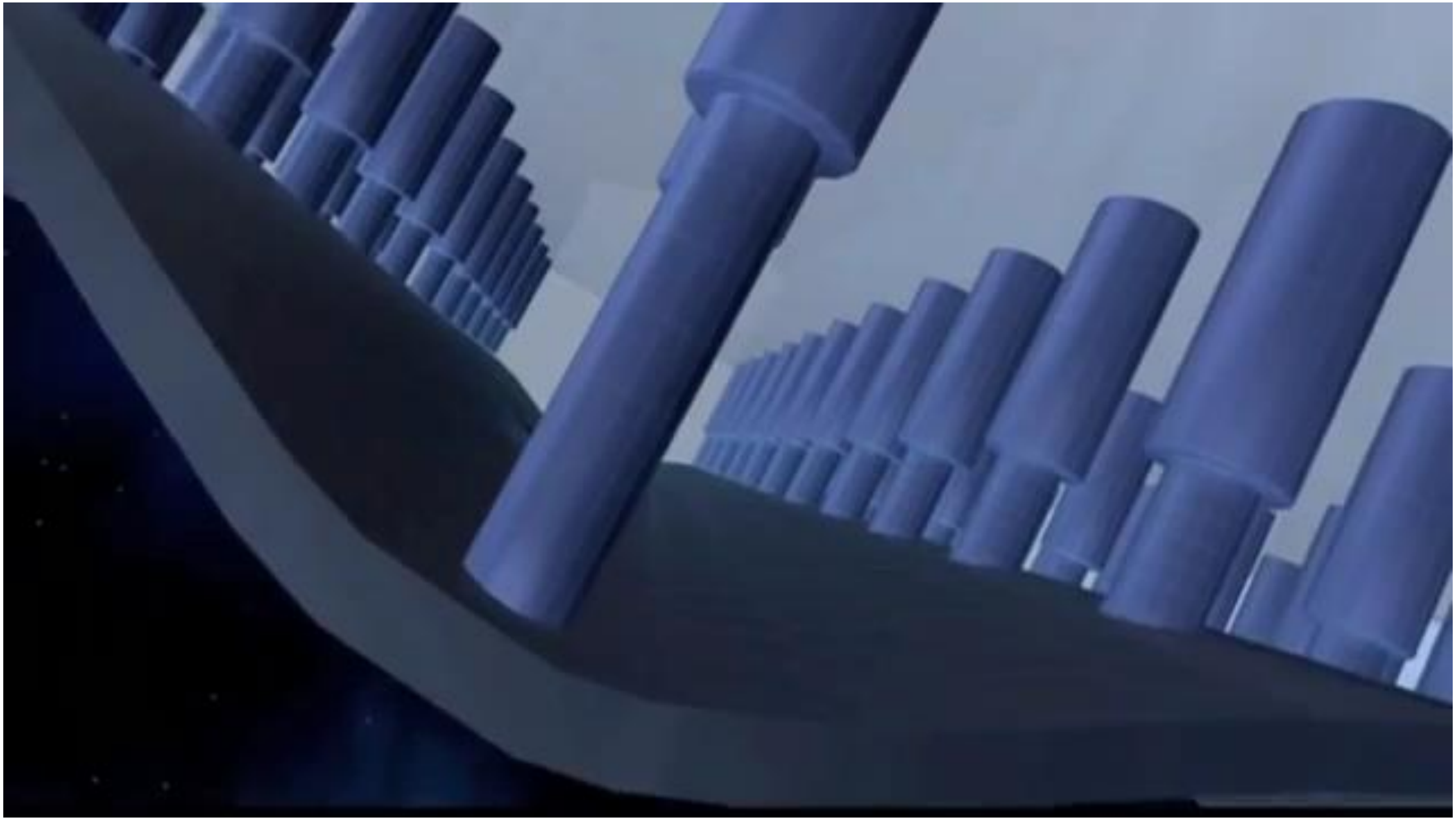


ADAPTIVE OPTICS
GIANT'S EYEGLASSES



LBT ADAPTIVE OPTICS

SECONDARY ADAPTIVE OPTICS IN ACTION

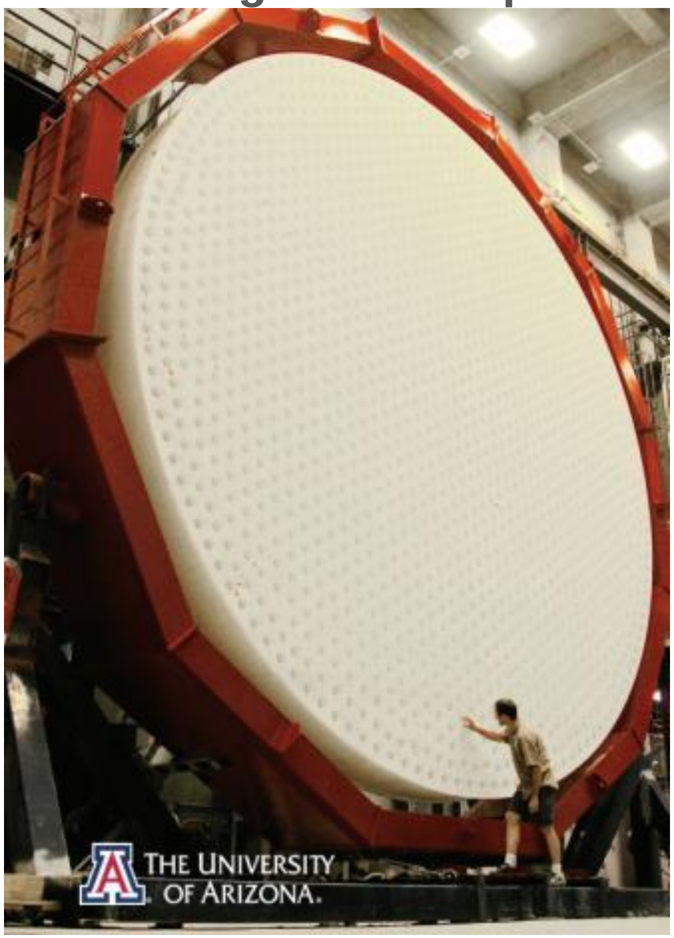


THREE GIANTS ARE RAPIDLY AND TRULY COMING.

STEWARD OBSERVATORY

RICHARD F. CARIS MIRROR LAB (RFCML)

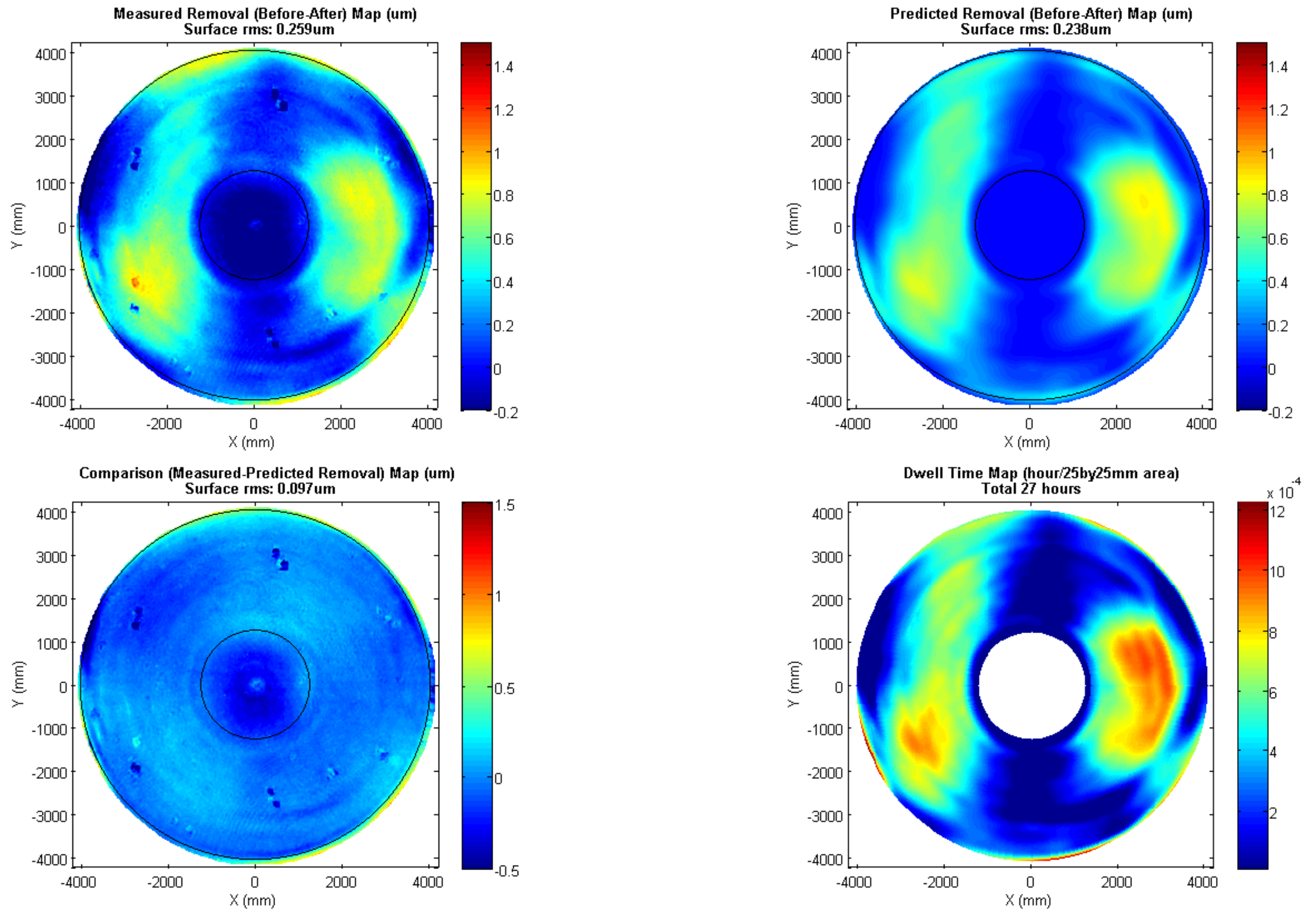
The world largest 8.4m optics manufacturing capability



H. M. Martin, R. G. Allen, J. H. Burge, D. W. Kim, J. S. Kingsley, M. T. Tuell, S. C. West, C. Zhao and T. Zobrist, "Fabrication and testing of the first 8.4 m off-axis segment for the Giant Magellan Telescope," Proc. SPIE 7739, (2010)

POLISHING/FIGURING RUN

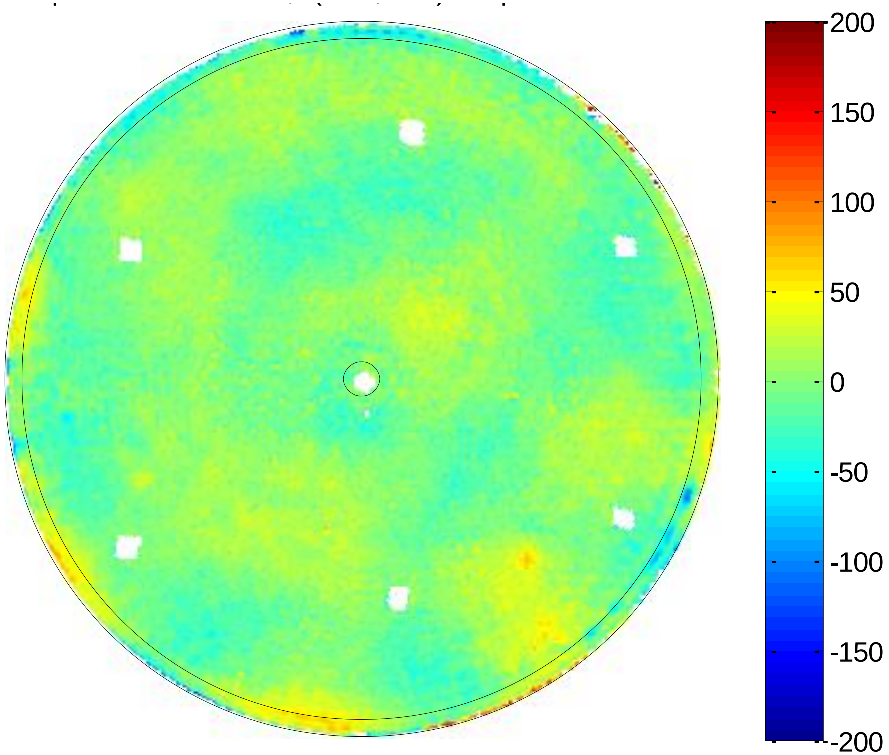
8.4M GMT OFF-AXIS SEGMENT

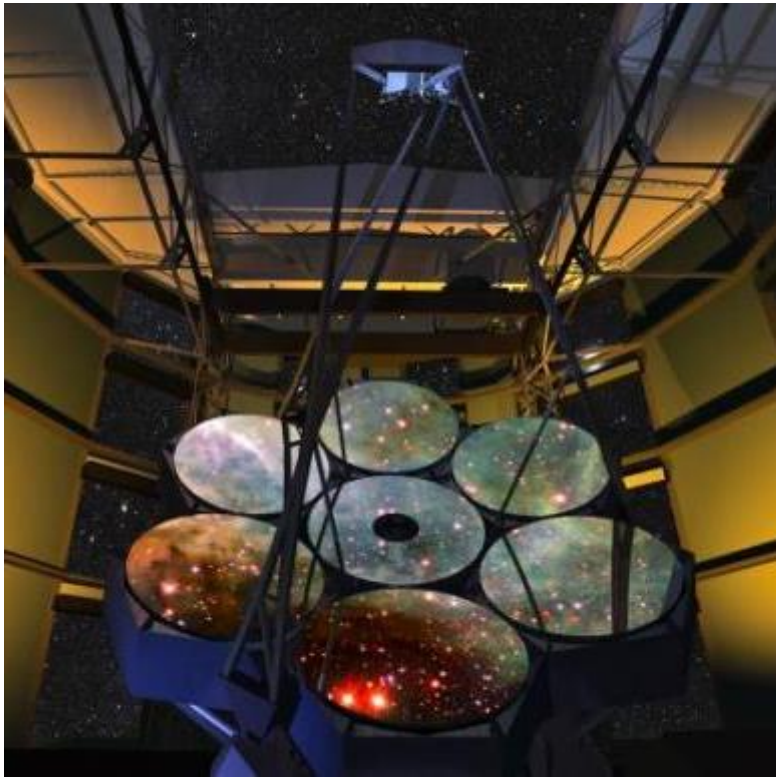


Difference (bottom left) between the measured removal map (top left) and the predicted removal map (top right) after the 27 hour CCOS run using a 250mm RC lap on the 8.4m GMT off-axis segment.

GMT SEGMENT 1 OUT OF 7

HUMAN'S 1ST 8.4M OFF-AXIS SEGMENT GOT COMPLETED.





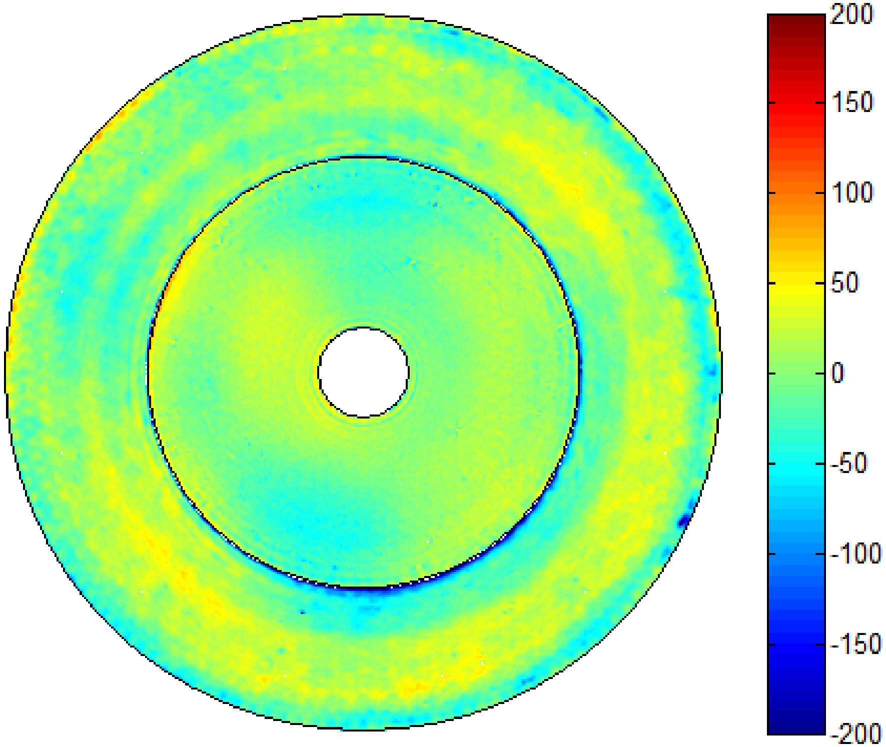
18nm RMS (after bending modes subtraction) over the full aperture.

H. martin, et al, "Production of 8.4 m segments for the Giant Magellan Telescope," in Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II, Proc. 8450 SPIE (2012)

http://www.gmto.org

LSST M1-M3

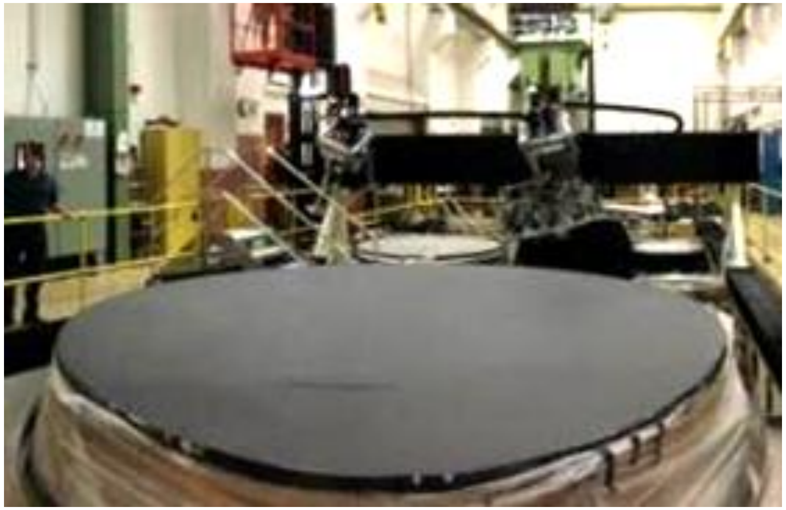
HUMAN'S 1ST 8.4M HYBRID OPTICS GOT COMPLETED IN 2015.



It meets the given structure function specification.

<~30nm RMS (after bending modes subtraction) for both M1 and M3 surface shape.

4.2M DKIST FINE GRINDING RUN
USING 0.6M STRESSED LAP & 0.3M LAP WITH CERAMIC TILES



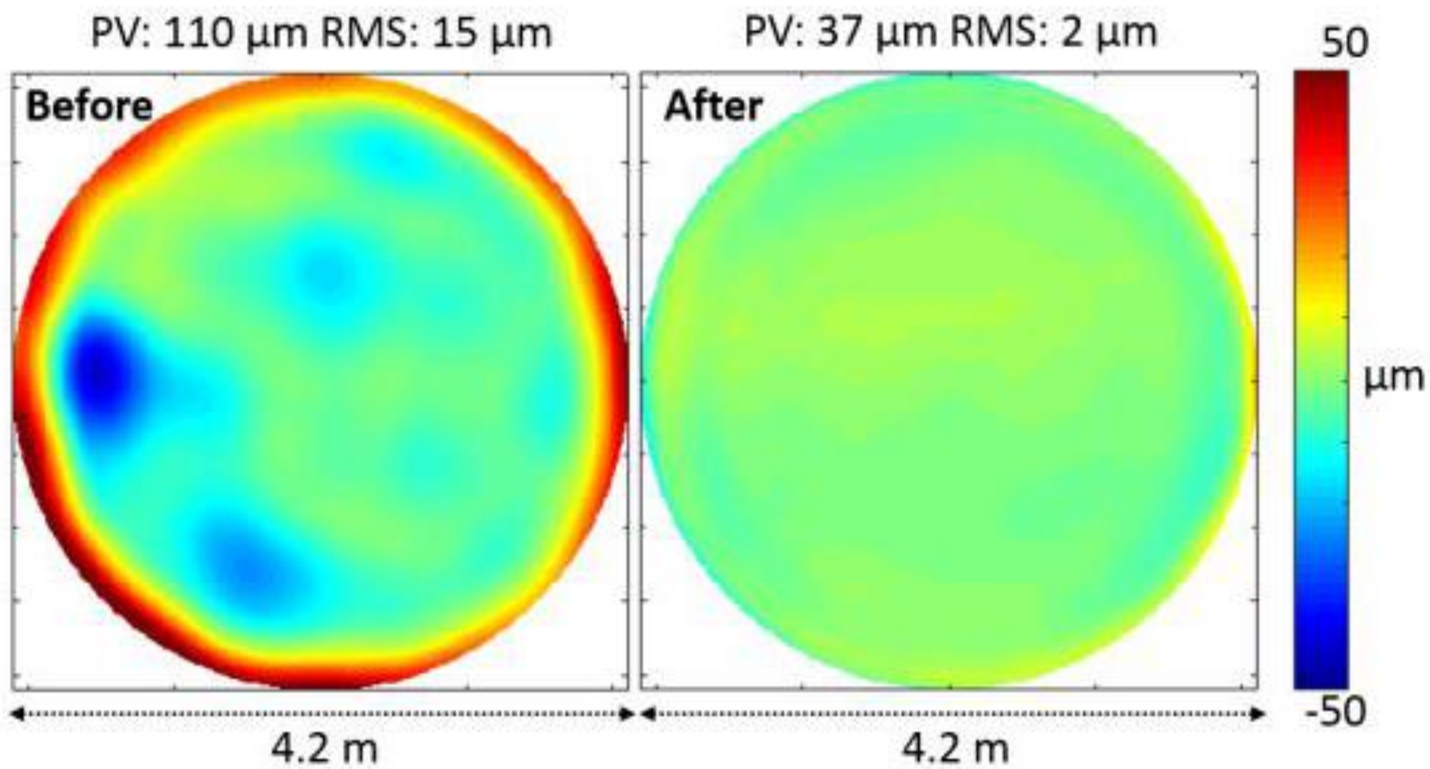
Fabrication parameter	Value	Note
Loose abrasive grit size	25 µm	Aluminum Oxide
Polishing pressure	0.3 psi	
Tool sizes	300 – 600 mm	Circular tool diameter
Orbital stroke speed	30 rpm	
Orbital stroke radius	75 – 150 mm	[4]
Preston's constant	~794 µm/psi(m/sec)hour	Calibrated from measurement
Mirror aspect ratio	~50	Mirror diameter / thickness

A series of fine grinding runs have been performed using 25 µm loose abrasive grits.

Detailed fabrication parameters are listed in the Table.

Dae Wook Kim, Peng Su, Chang Jin Oh, and James H. Burge, "Extremely Large Freeform Optics Manufacturing and Testing," CLEO-PR, Optical Society of America (2015)

RAPID FINE GRINDING RESULT
MEASURED BY SLOTS

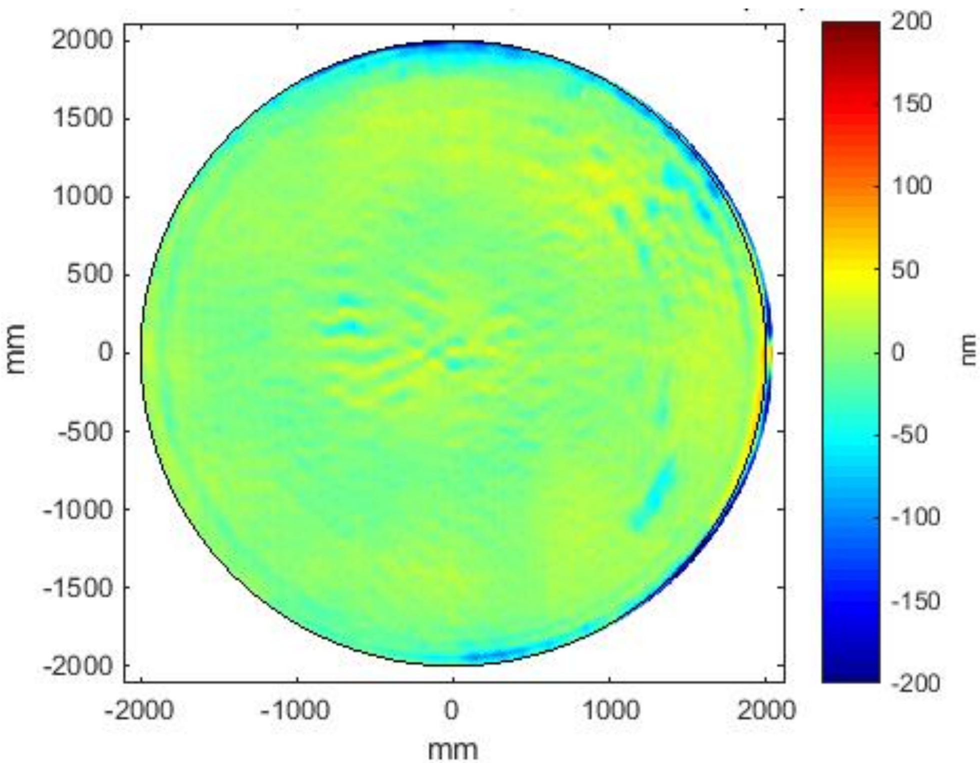


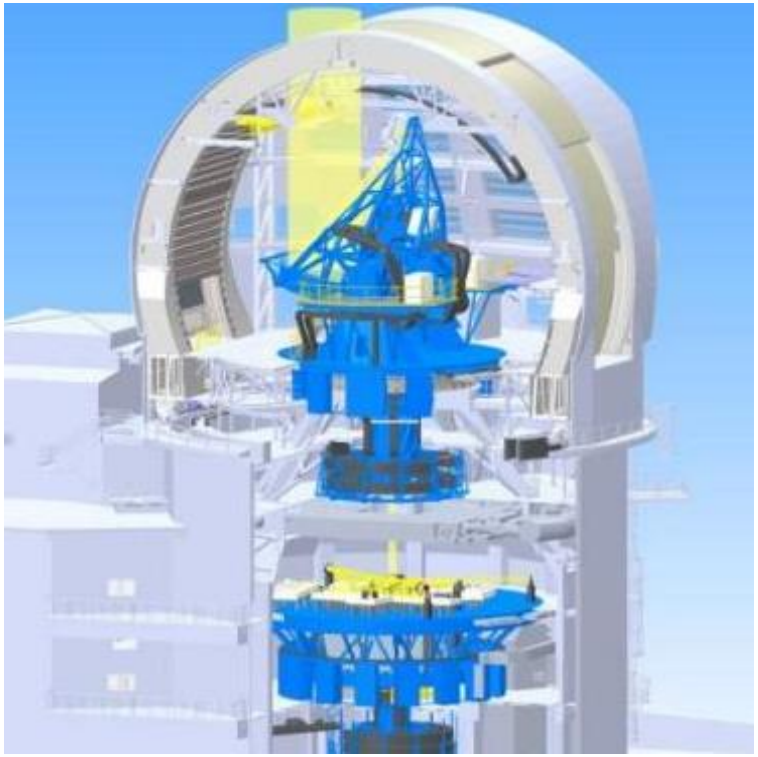
DKIST primary mirror surface shape error (from the ideal shape) changes from 15µm to 2µm RMS between 3 successive fine grinding runs using 25µm Aluminum Oxide grits (surface shape measured by SLOTS).

Dae Wook Kim, Peng Su, Chang Jin Oh, and James H. Burge, "Extremely Large Freeform Optics Manufacturing and Testing," CLEO-PR, Optical Society of America (2015)

DKIST 4.2M PRIMARY MIRROR

WORLD LARGEST MICROSCOPE OPTIC COMPLETED IN 2015

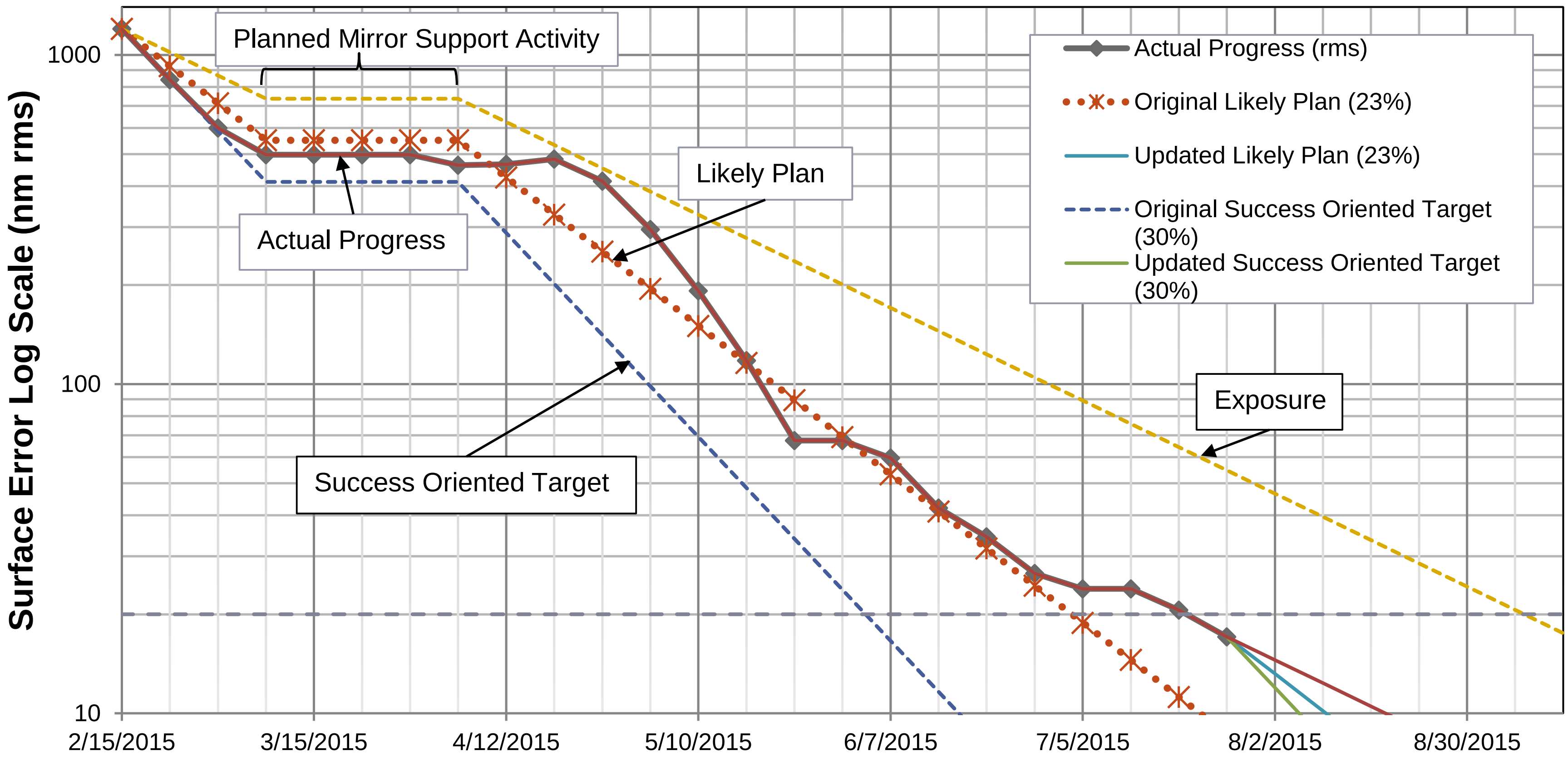




<~20nm RMS (after 30 bending modes subtracted) optical surface over the clear aperture

Image from atst.nso.edu

CONTROLLING THE FUTURE
BY PREDICTING THE FUTURE



The "expected" convergence of residual surface error of DKIST 4.2m primary mirror was simulated and predicted in Feb. 2015.

Six month later, we arrived at the "predicted" destination.

FINAL NOTES

SOME DEEP MOTIVATIONS

DESTINY

AS A SCIENTIST AND ENGINEER

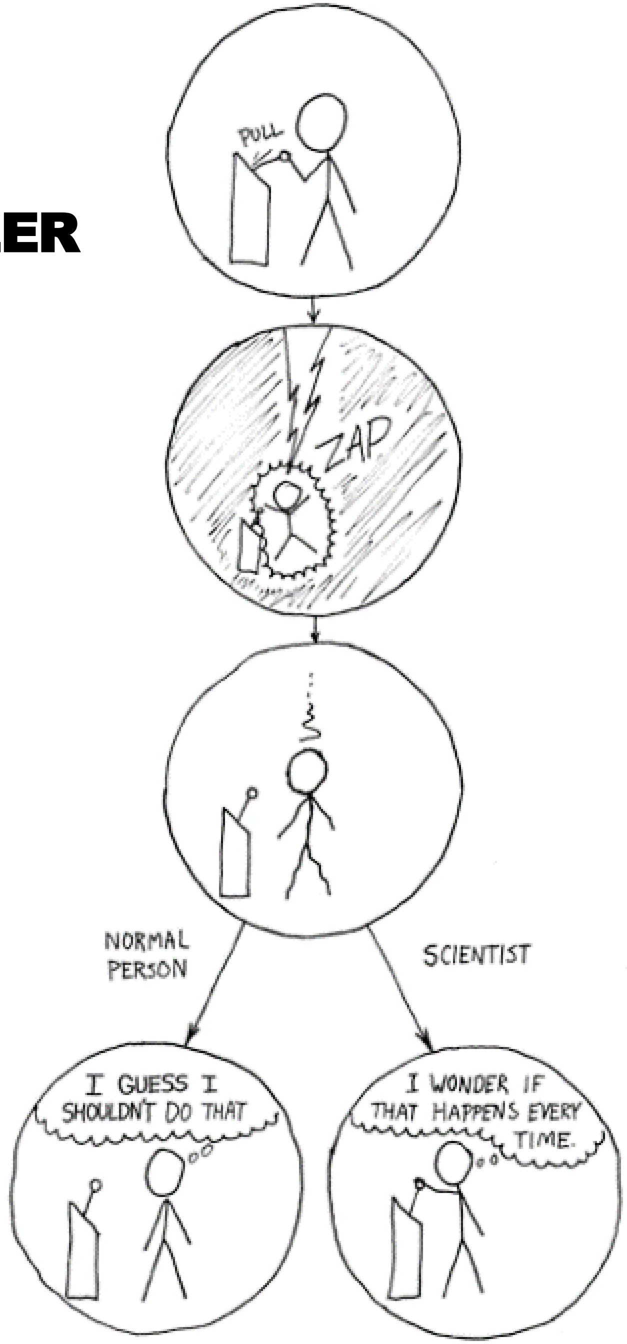
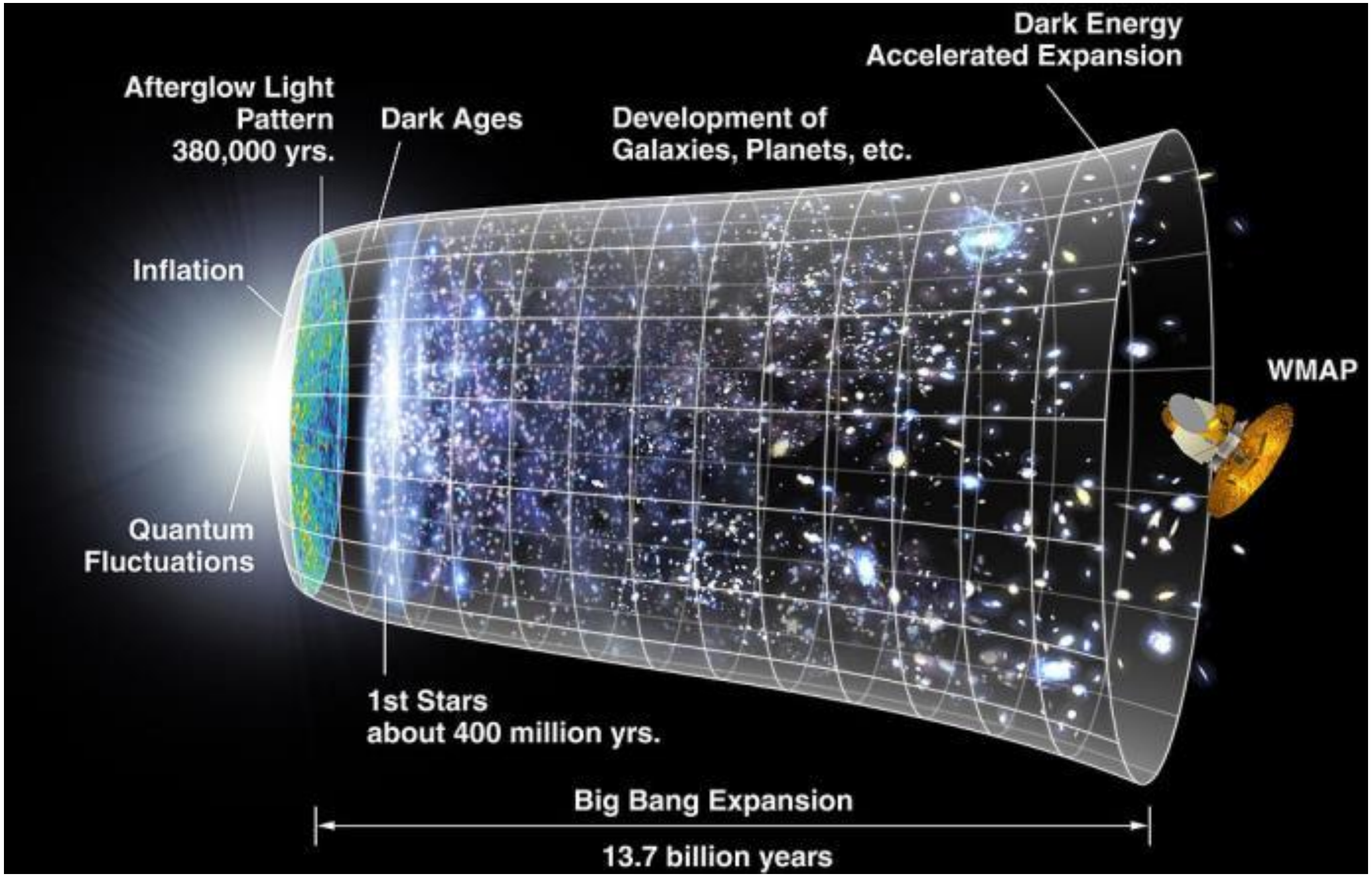


Image from http://xkcd.com/242/

DISCOVERY

EXPECTING SOMETHING WE DON'T KNOW AT THE MOMENT



NEXT GENERATIONS

WHO WILL LOVE AND APPRECIATE WHAT WE DO TODAY.

I wish, one day, Aiden and Daniel will bring their kids to their dream places.

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