NANO MANUFACTURING AND METROLOGY FOR GIANT OPTO-MECHANICAL IMAGING MACHINES

2018 International Conference on Nanomanufacturing

Brunel University London, UK

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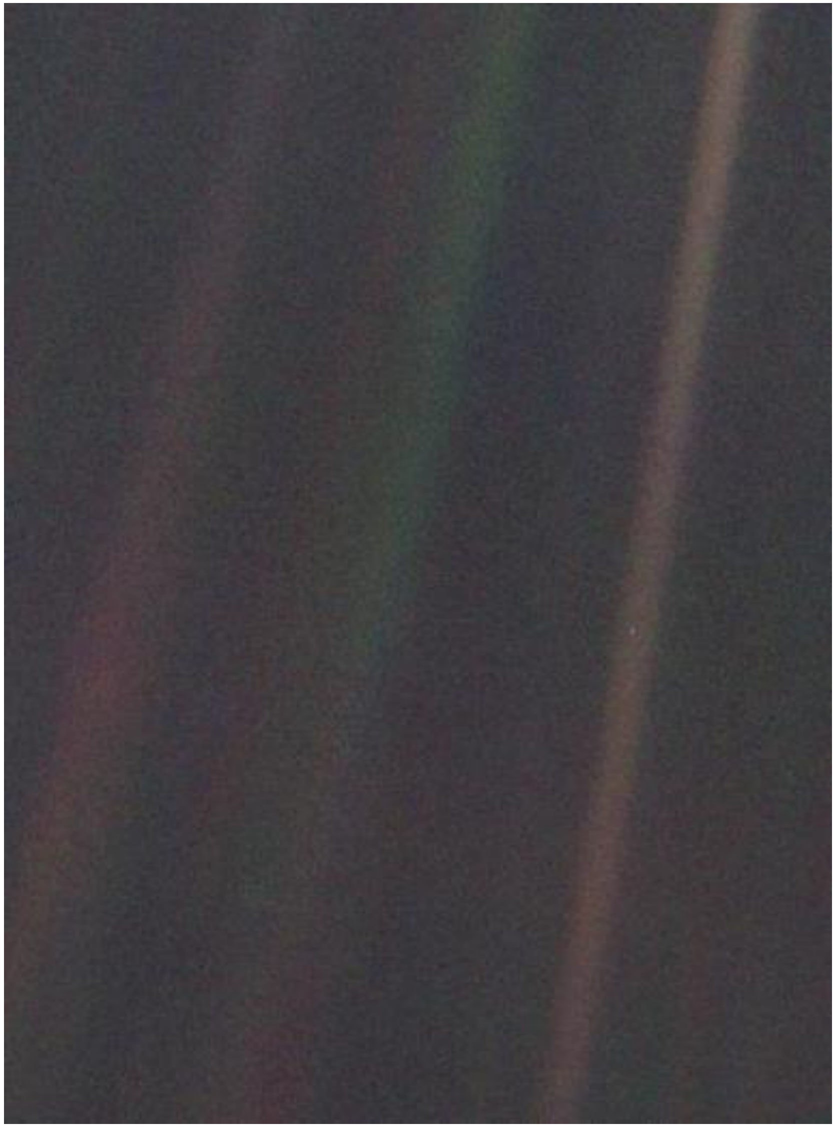
OUR FIRST GROUP PHOTO IN 1990

DO YOU REMEMBER?

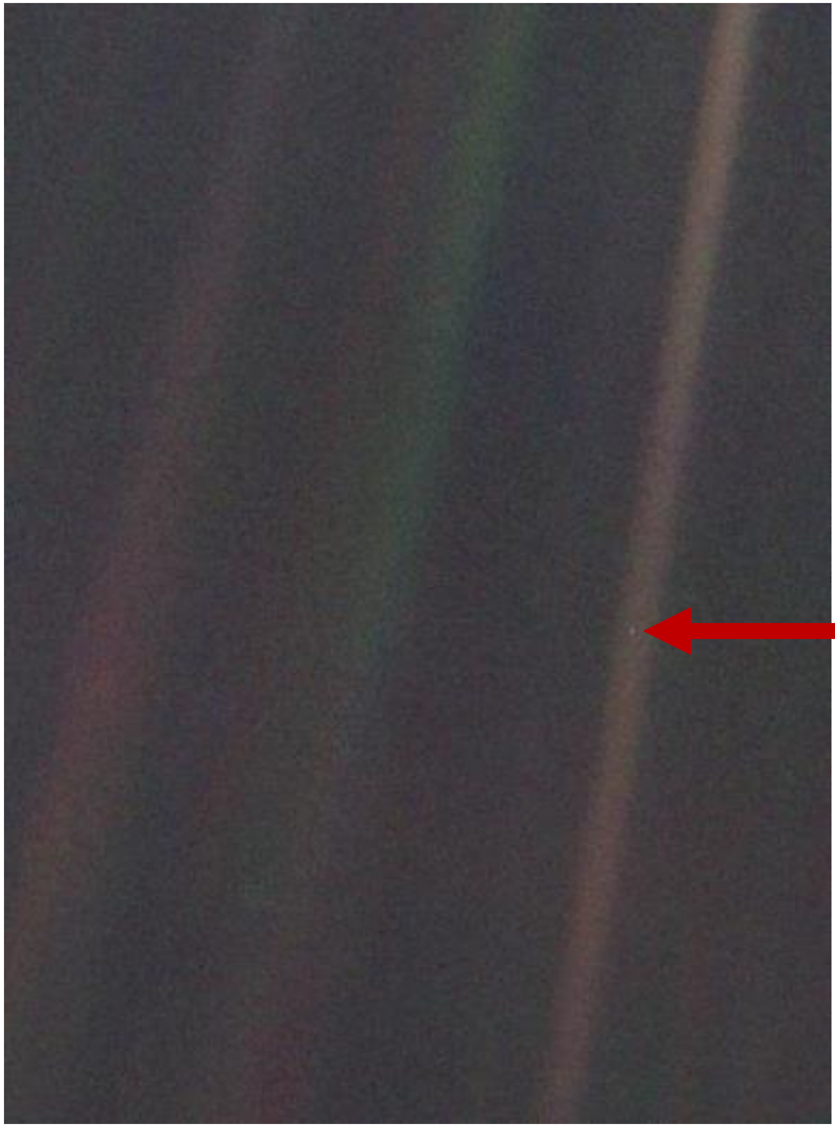


https://photojournal.jpl.nasa.gov/catalog/PIA00452

Photo Credit: NASA/JPL

PALE BLUE DOT

IN 0.12 PIXEL BY VOYAGER 1 FROM 4 BILLION MILES FROM US



Dae Wook the kid at the elementary school and "you" also.

https://photojournal.jpl.nasa.gov/catalog/PIA00452

Photo Credit: NASA/JPL

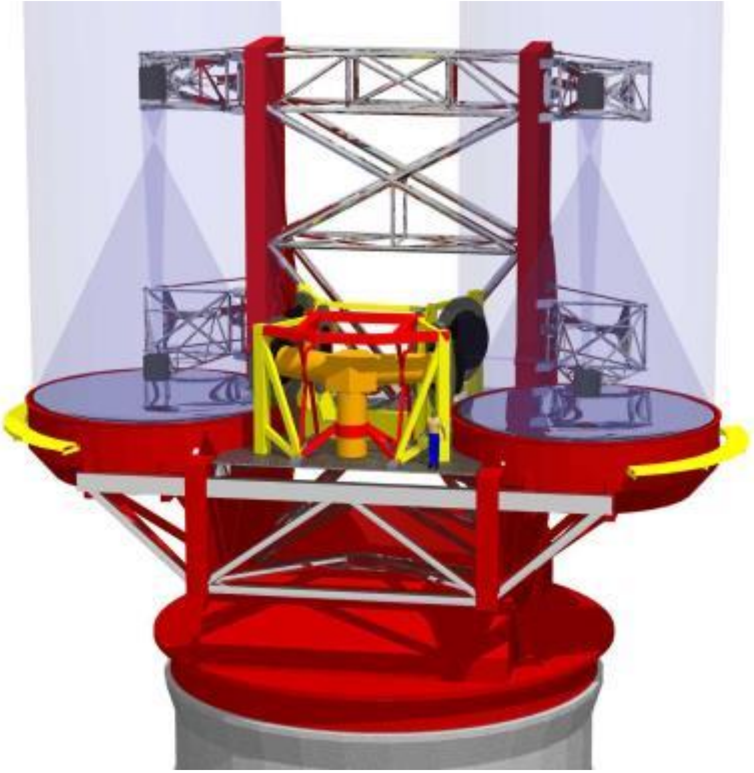
LARGE BINOCULAR TELESCOPE

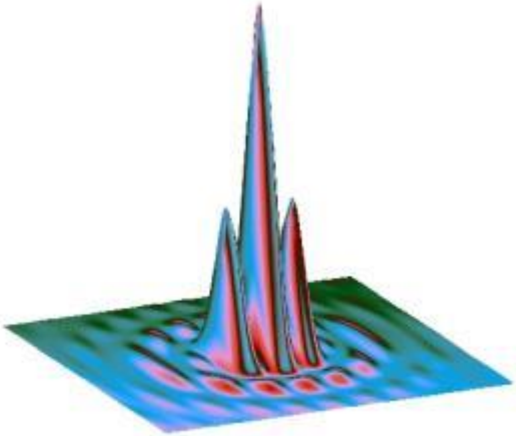
TWO 8.4M PRIMARY MIRRORS ON A SINGLE STRUCTURE

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

Image from LBT office

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.

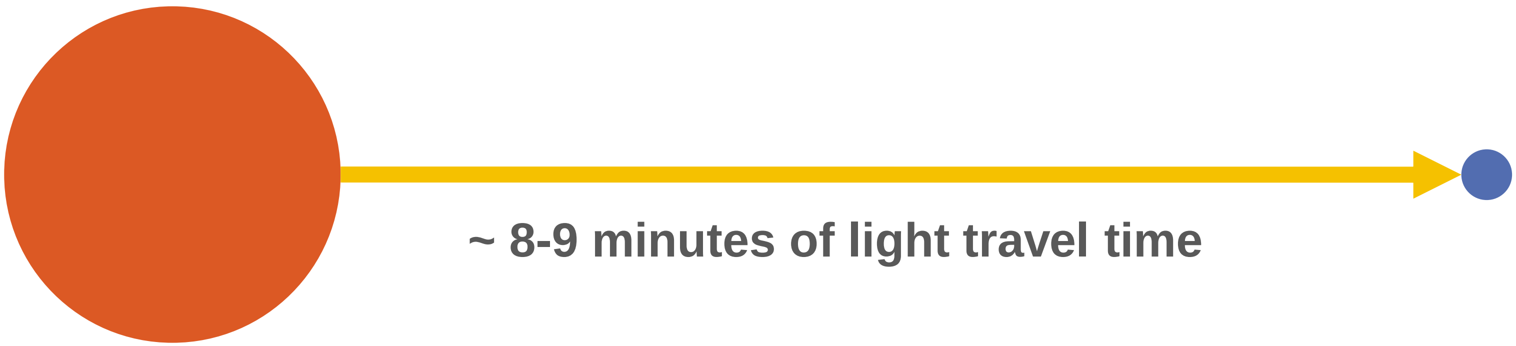
http://www.lbto.org/

THE OPTO-MECHNICAL TIME MACHINES

LOOKING AT THE DYNAMIC UNIVERSE

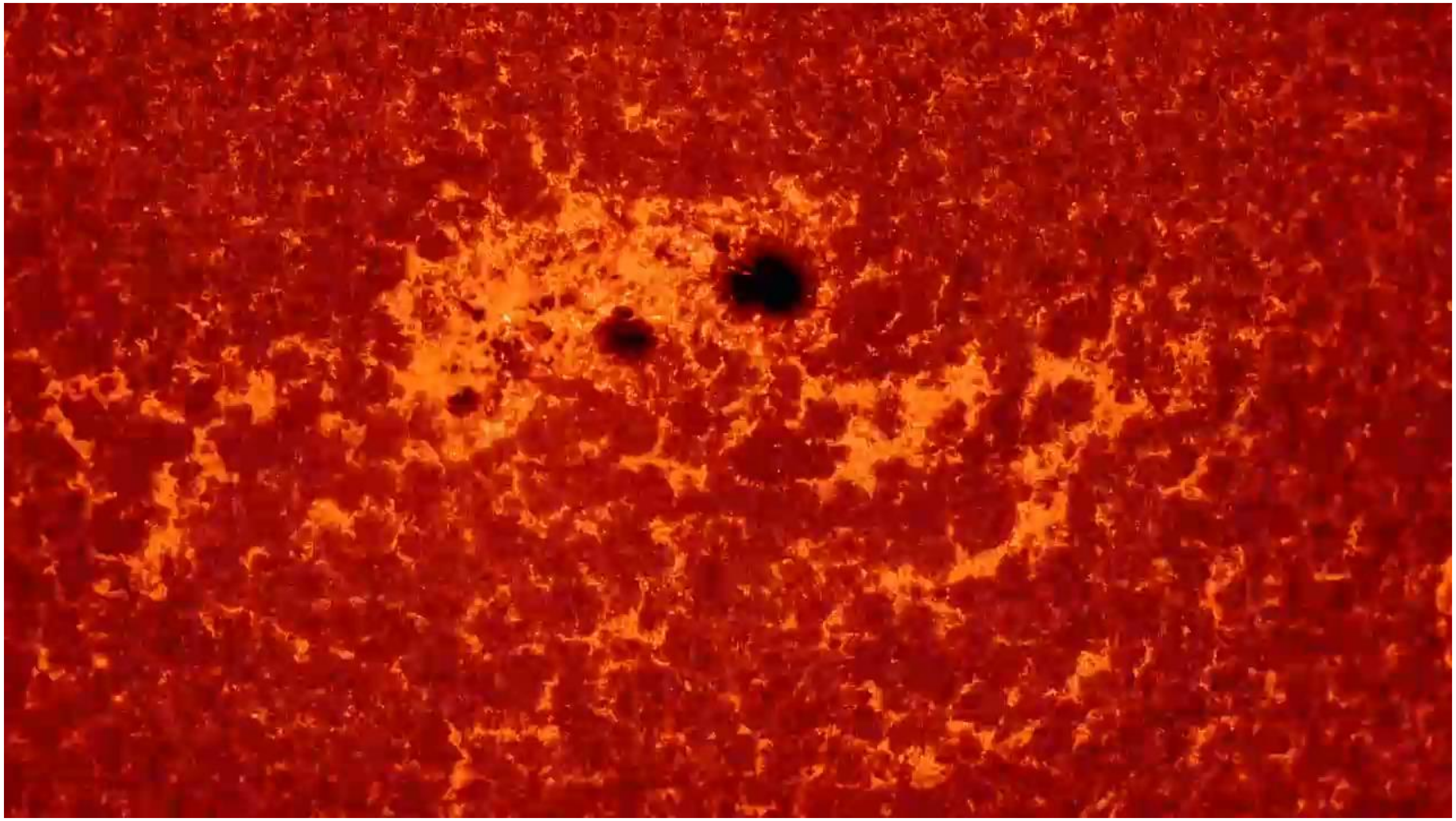
TIME TRAVEL

YOU CAN DO IT.



Yes, we are looking at the past of Sun. If you see deeper in space, you are looking at the past of the Universe.

SUN
SOLAR ASTRONOMY



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

It is the closest and brightest star in the sky.

http://svs.gsfc.nasa.gov/vis/a010000/a011100/a011136/

GIANT MICROSCOPE
DKIST USING 4.2M PRIMARY MIRROR

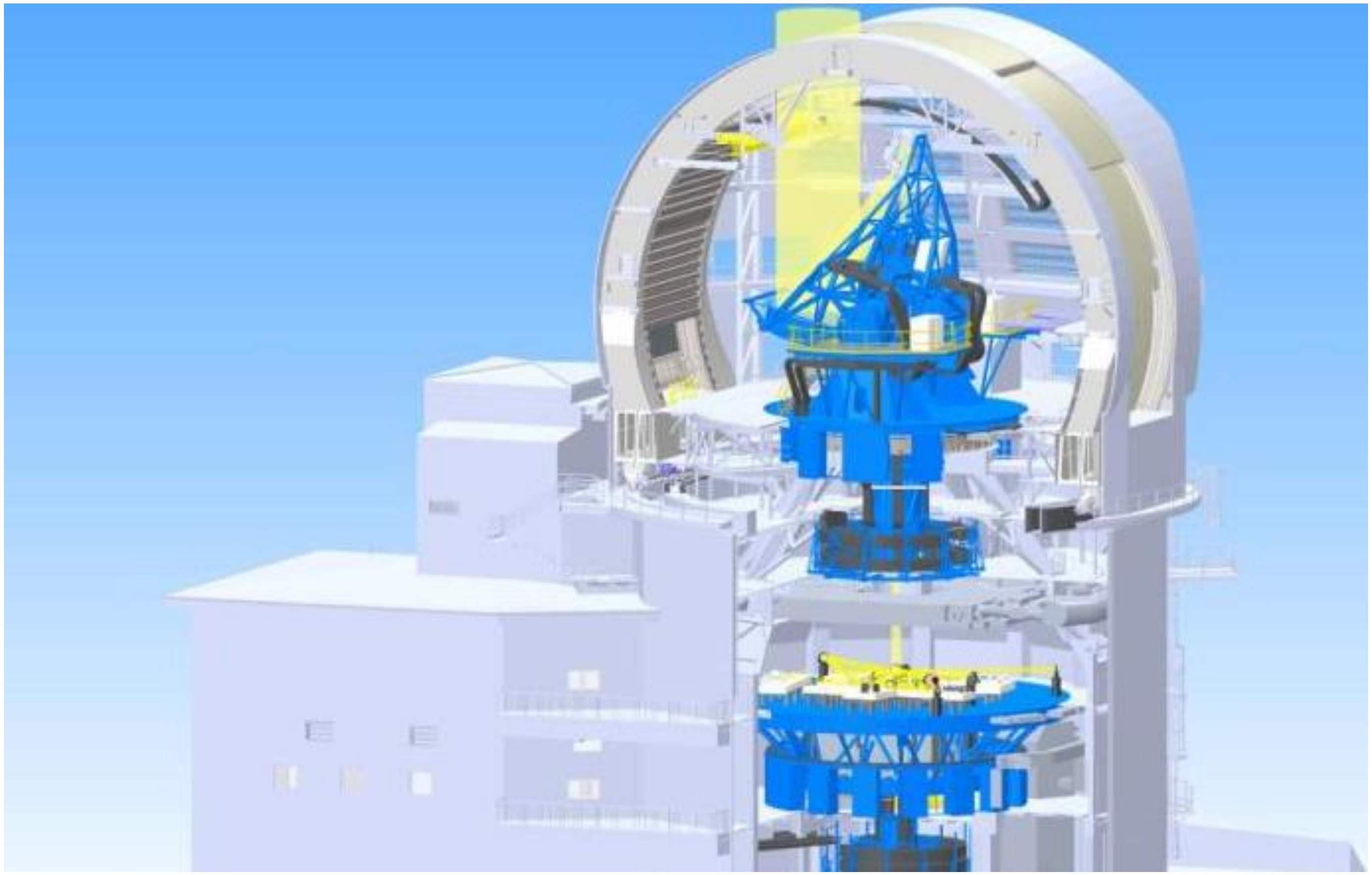


Image from atst.nso.edu

It is imaging the extend object, Sun.

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

Off-axis optical design to control stray light issues

GIANT ACTION-CAM

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

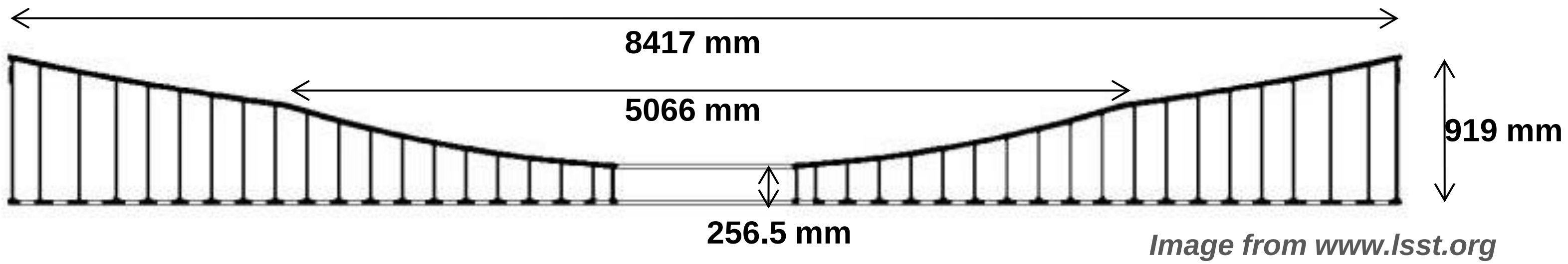


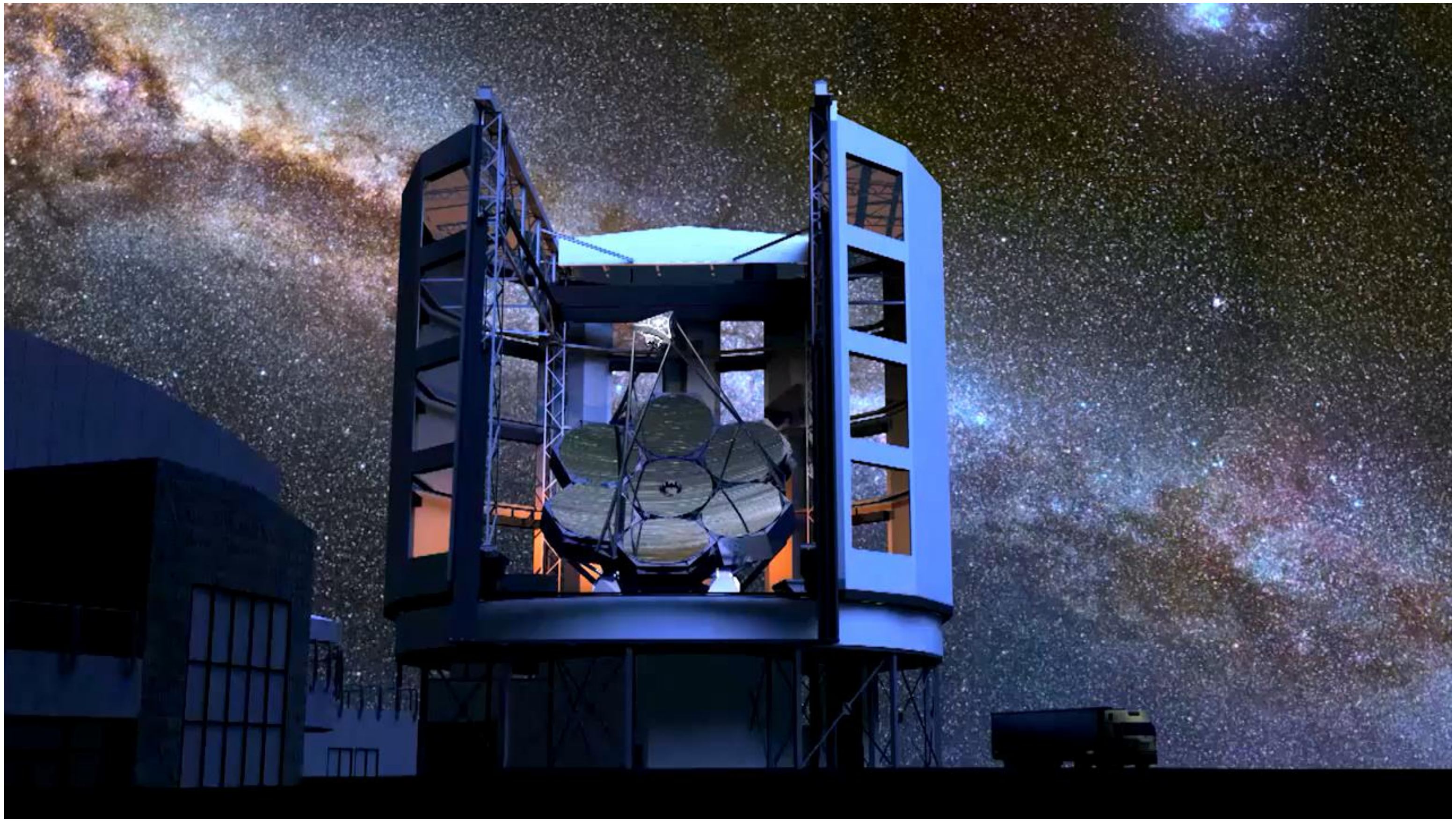
Image from www.lsst.org

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).

GIANT DSLR CAMERA

GMT, 24.5M PRIMARY USING SEVEN 8.4M SEGMENTS



The ultimate telescope which defines a new category called 'Extremely Large Telescope' for 13 billion years time travel.

10X resolution compared to the Hubble Space Telescope.

Image from www.gmto.org

THREE CHALLENGES

TO BUILD THE ~1,000 TONS OPTO-MECHANICAL MACHINE

1. FREEFORM DESIGN

KP12 / 12M RADIO TELESCOPE
FOR MM TO SUB-MM WAVE OBSERVATION

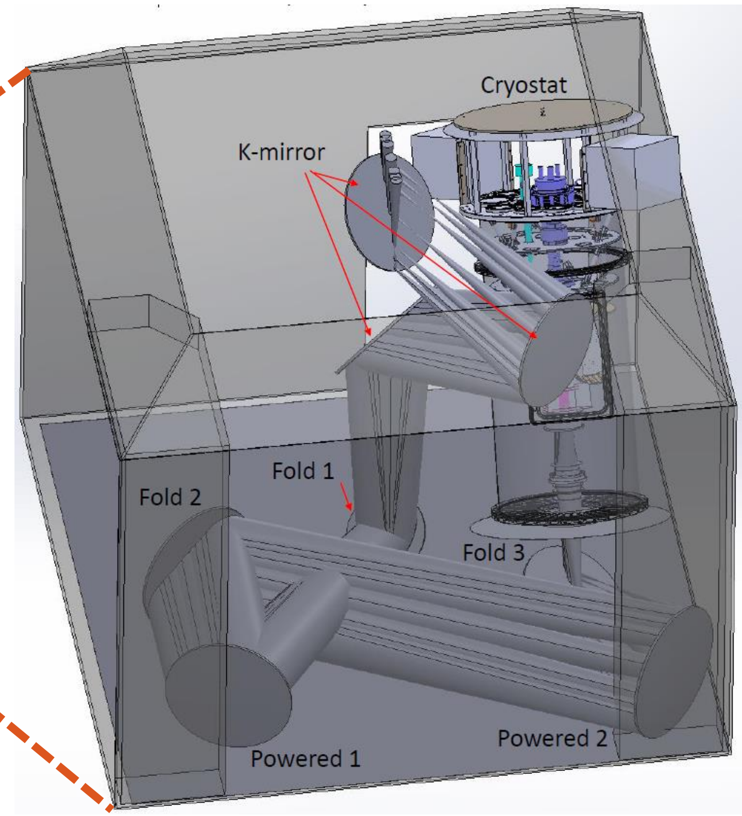
The European ALMA Prototype Antenna

KP12: mm or sub-mm (i.e., Terahertz) wavelength camera.

Photo by Thomas Folkers

MAIN INSTRUMENT CAMERA

FREEFORM OPTICAL DESIGN INCLUDING K-MIRROR

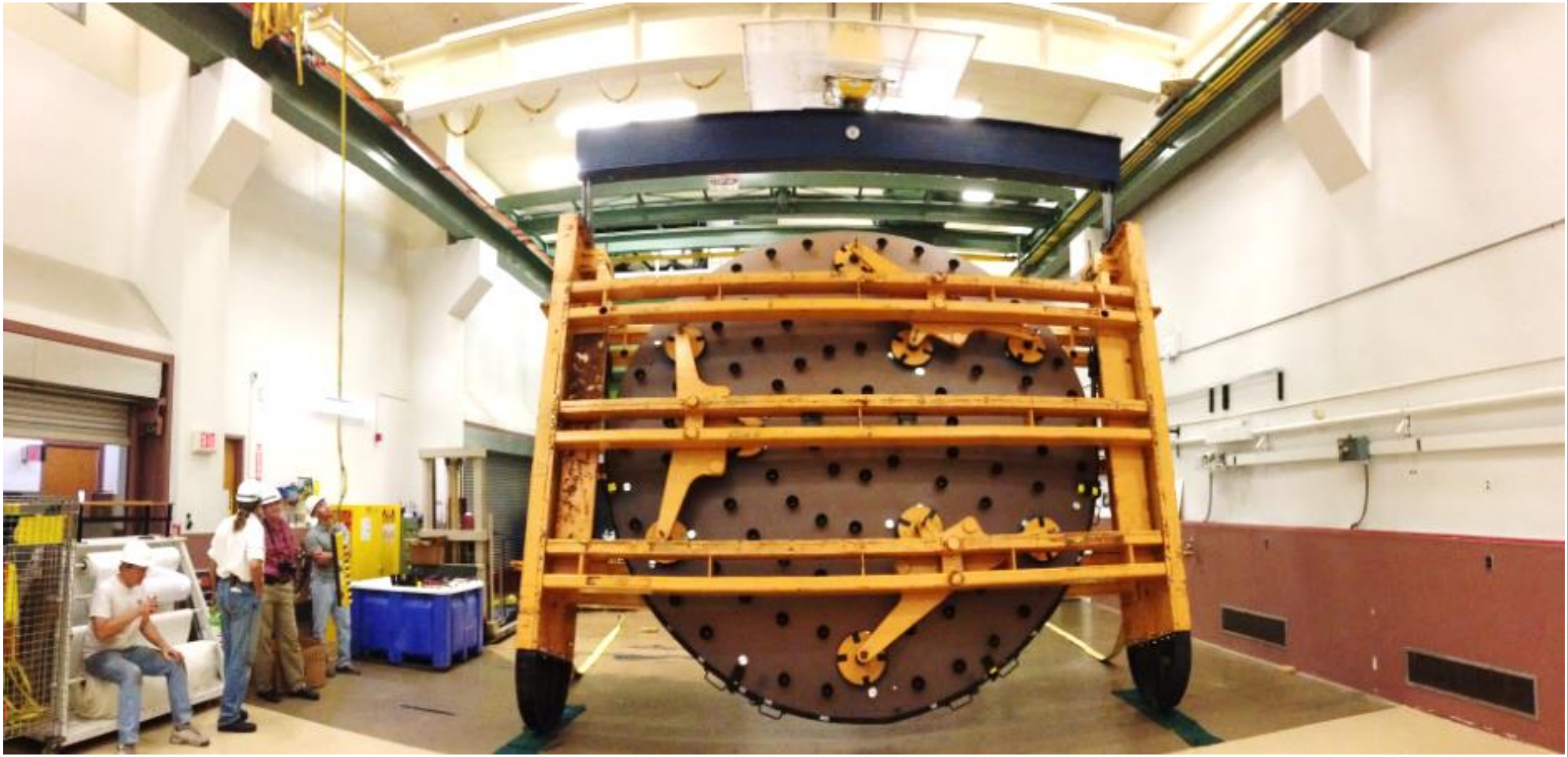


Multiple freeform optical surfaces to achieve a good field performance

K-Mirror in order to de-rotate the rotating image

2. FABRICATION

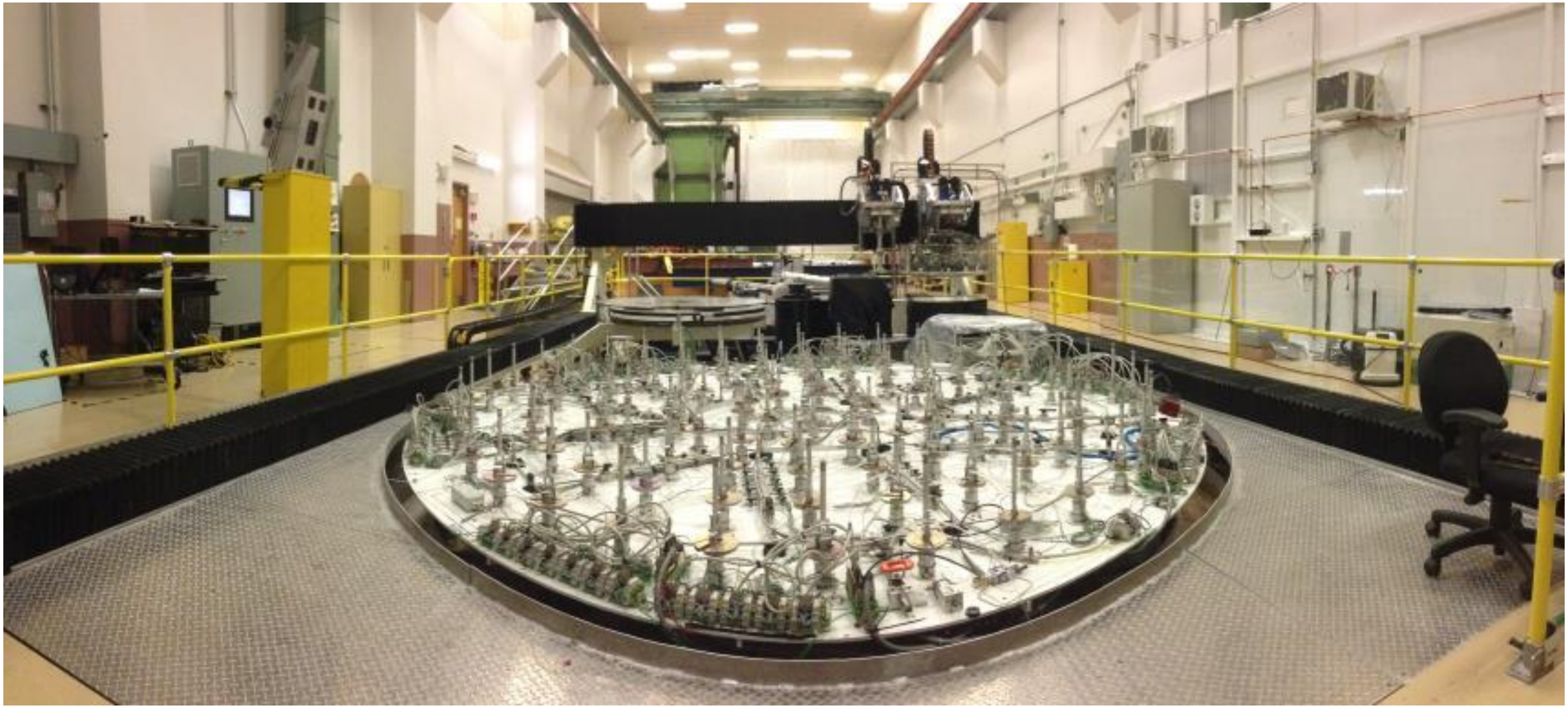
PRIMARY MIRROR
4.2M ZERODUR OFF-AXIS MIRROR



4.2m SCHOTT Zerodur mirror blank w/ near 0 CTE

118 hydraulic supporting fixtures on the back side of the blank

HYDRAULIC SUPPORT
FOR FABRICATION AND TESTING

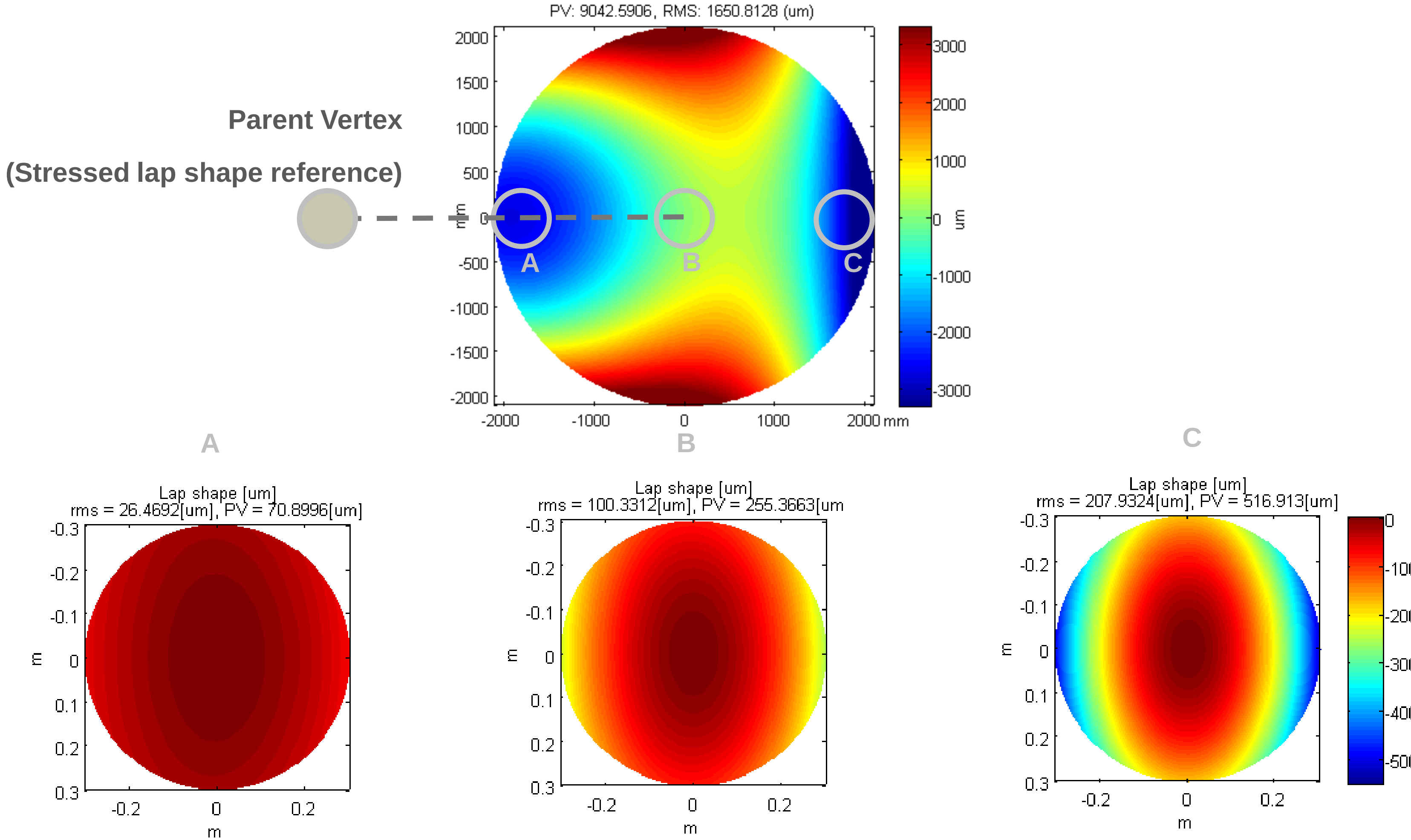


118 hydraulic supports to mount the thin (aspect ratio ~ 50) flexible mirror

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

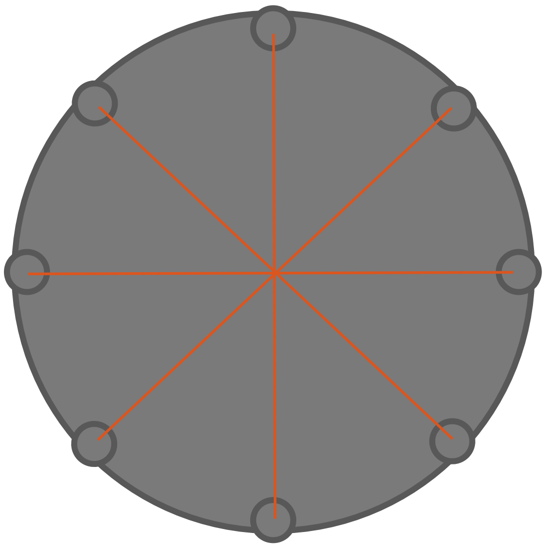
ACTIVE SHAPE CONTROL

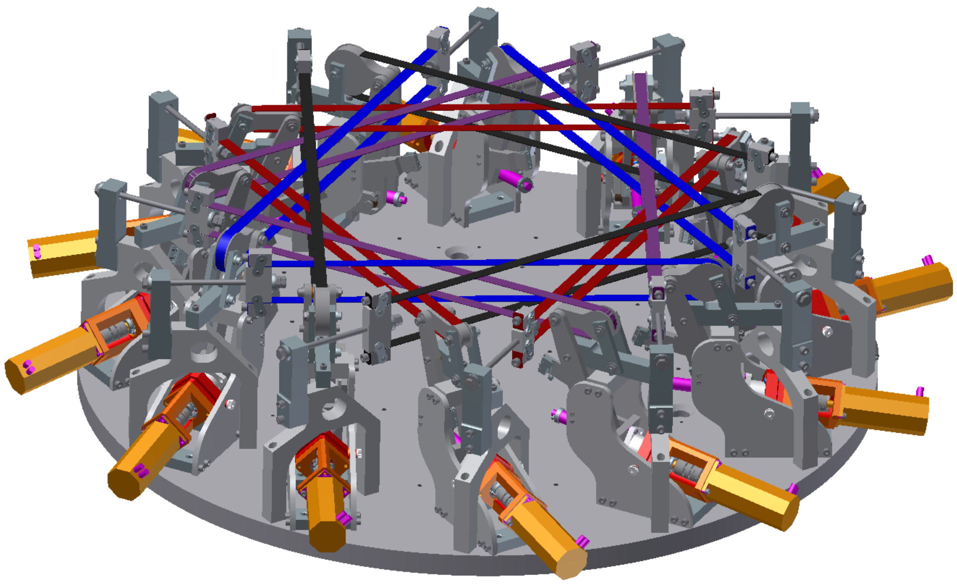
0.6M STRESSED LAP ON 4.2M DKIST PRIMARY



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

ACTIVE SOLUTION
STRESSED LAP



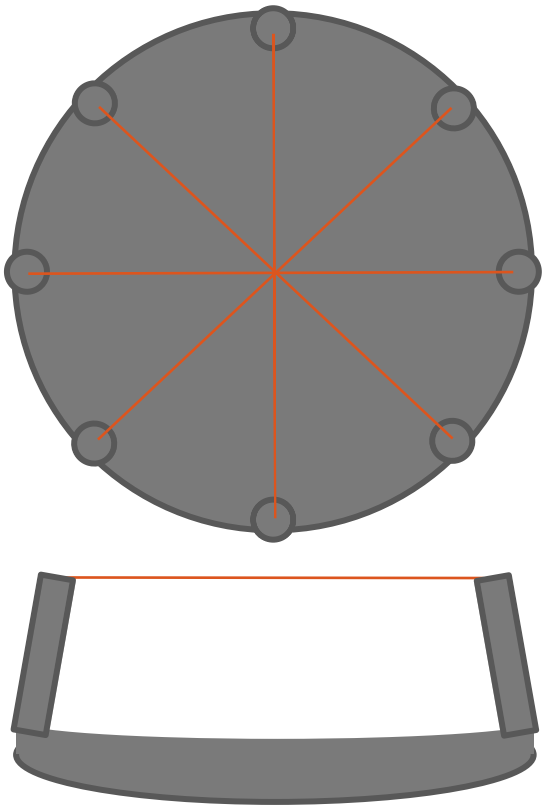


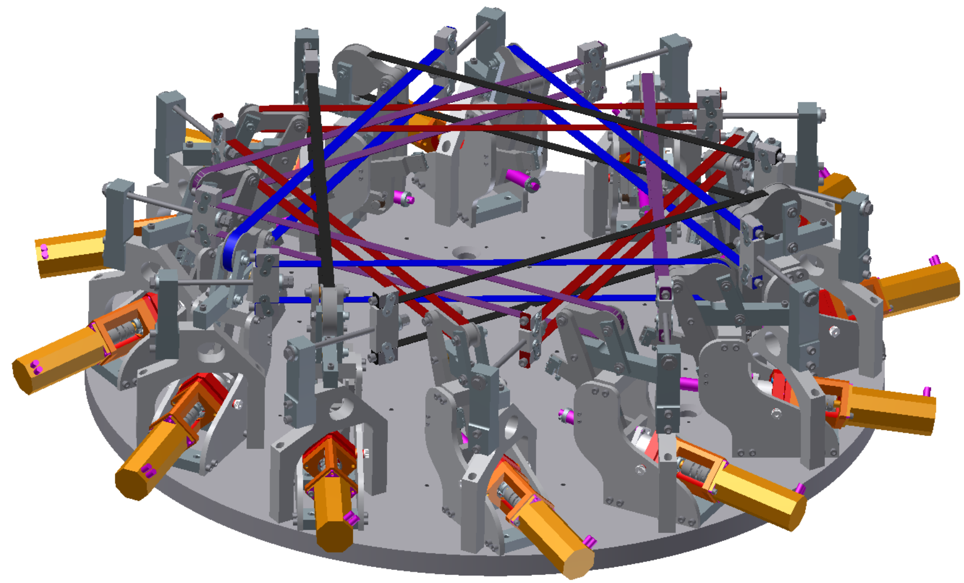
0.6 - 1.2 m Stressed lap is updating its shape (Zernike 4-10) at ~100 Hz to maintain its local fit between the lap and the workpiece.

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
STRESSED LAP





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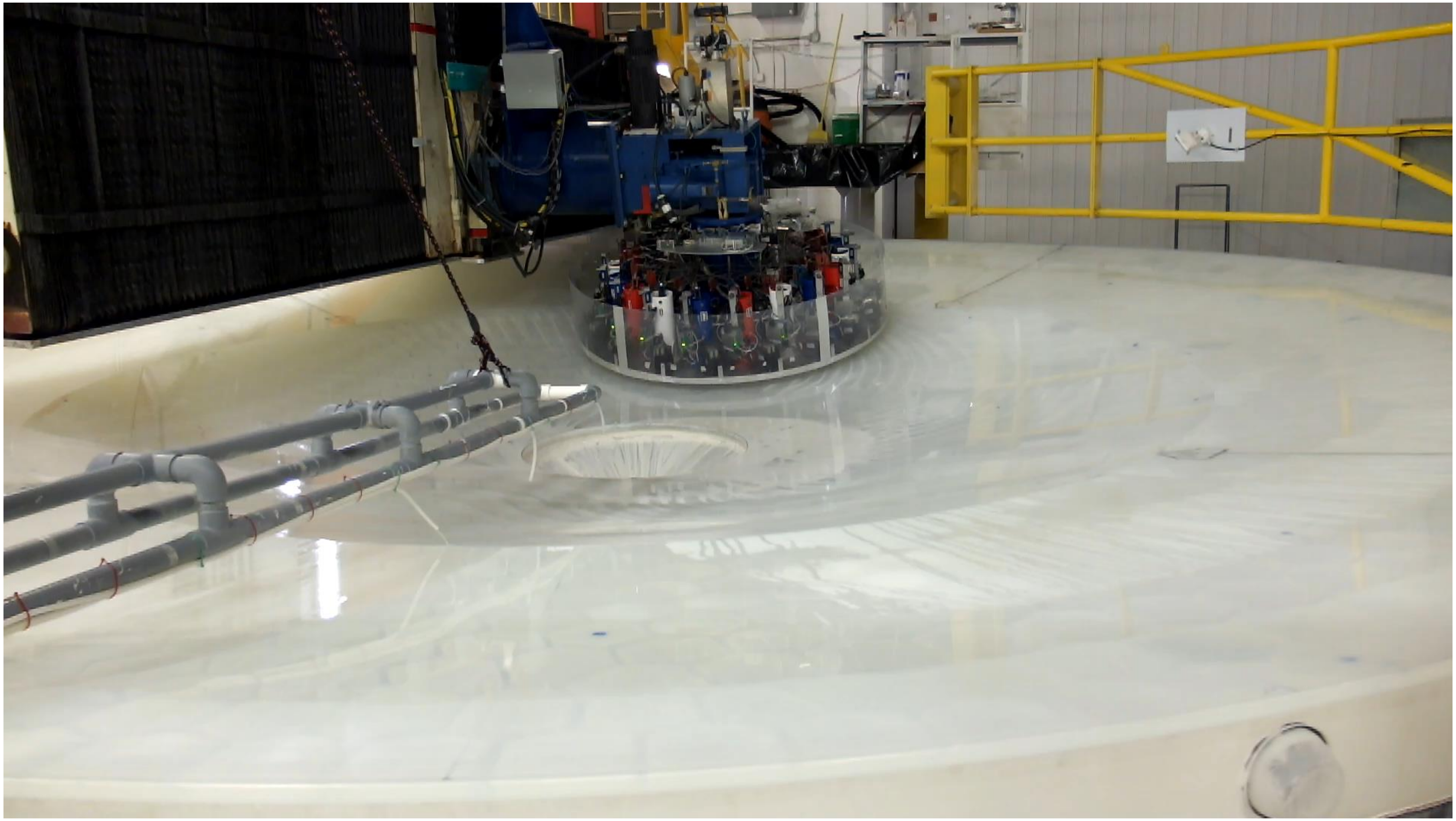
D. W. Kim et al., "Advanced Technology Solar Telescope 4.2 m Off-axis Primary Mirror Fabrication," in Classical Optics 2014, OTh2B.3

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

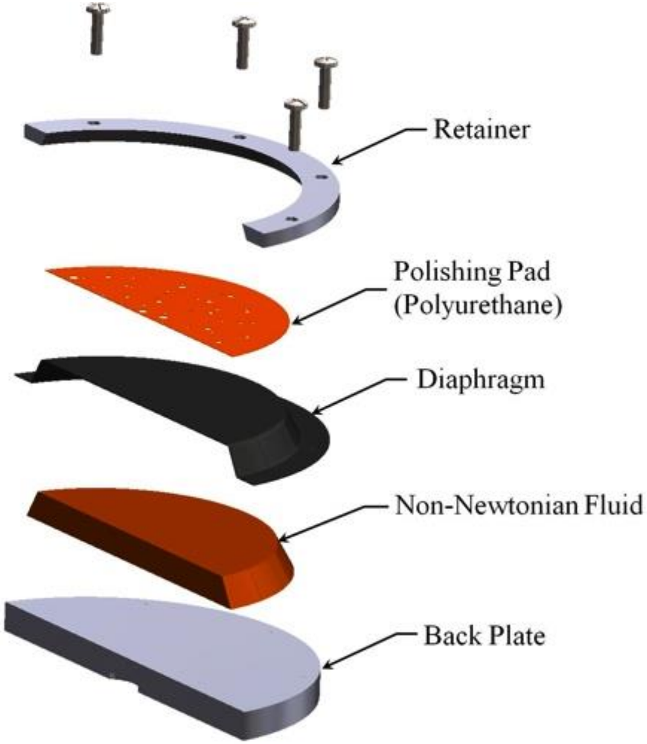
https://www.youtube.com/watch?v=f2XQ97XHjVw

Non-Newtonian Fluid is not like water-or-ice.

It is like water-and-ice.

PASSIVE SOLUTION (~$500.00)

RIGID CONFORMAL LAP USING SILLY PUTTY



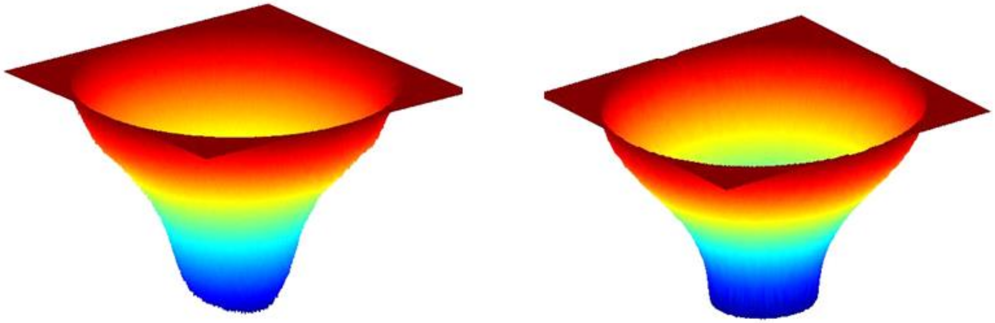
3D schematic Rigid Conformal lap structure (exploded and cut in half).

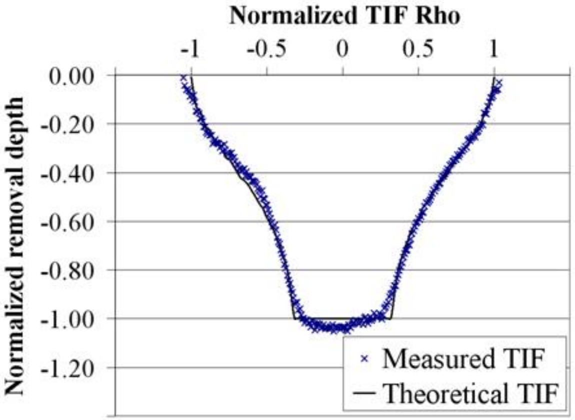
D. W. Kim and J. H. Burge, "Rigid conformal polishing tool using non-linear visco-elastic effect," Opt. Express. 18, 2242-2257 (2010)

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

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)

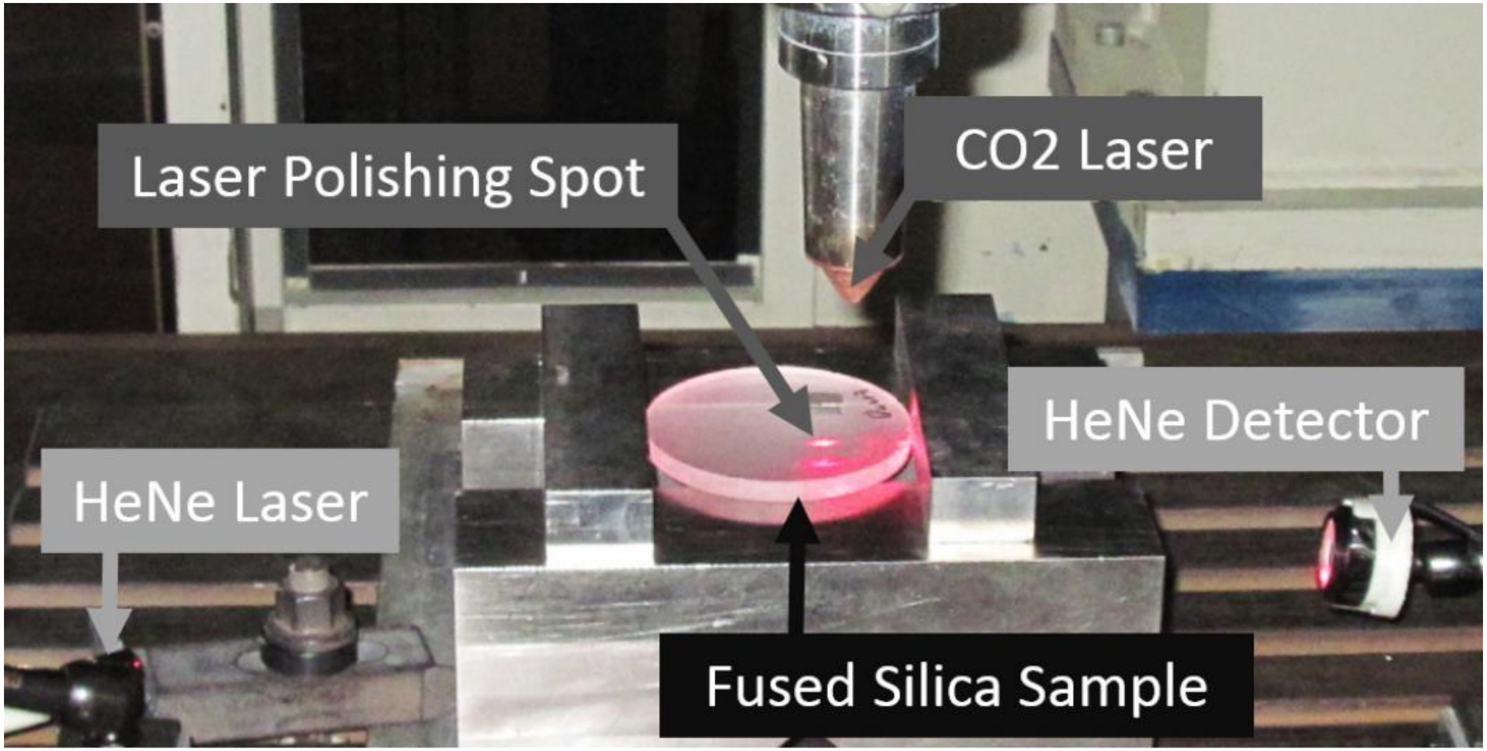
PASSIVELY SHAPE CONTROLLED LAP

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)

CLOSED-LOOP LASER POLISHING

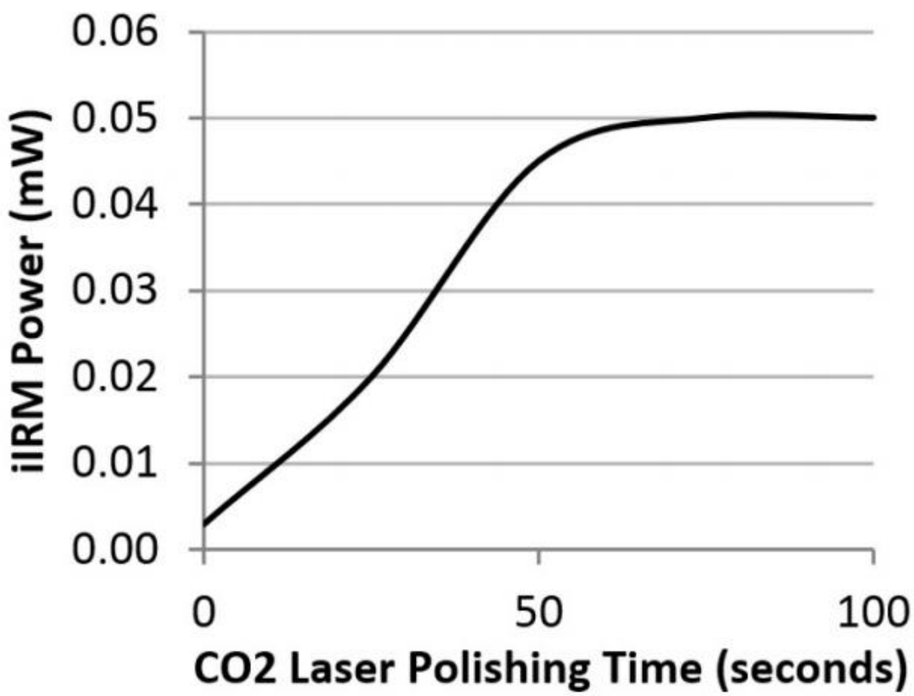
VIA IN-PROCESS METROLOGY

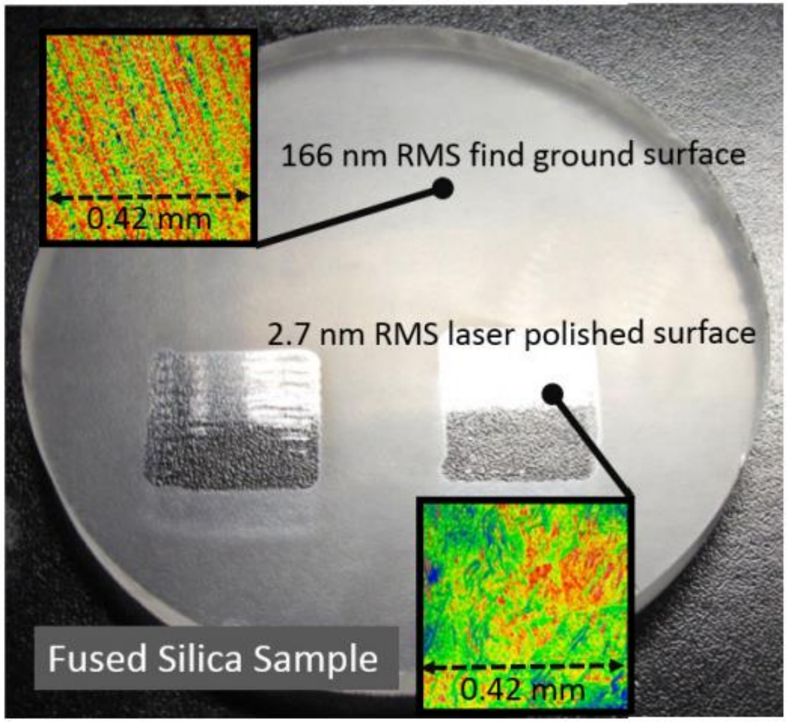


While the Fused Silica sample is locally laser polished, the local surface roughness within the laser footprint is being monitored by detecting the intensity of a HeNe laser reflected right in the collocating CO_2 laser footprint zone.

CLOSED-LOOP LASER POLISHING

YOU KNOW WHEN YOU HAVE ARRIVED YOUR DESTINATION.

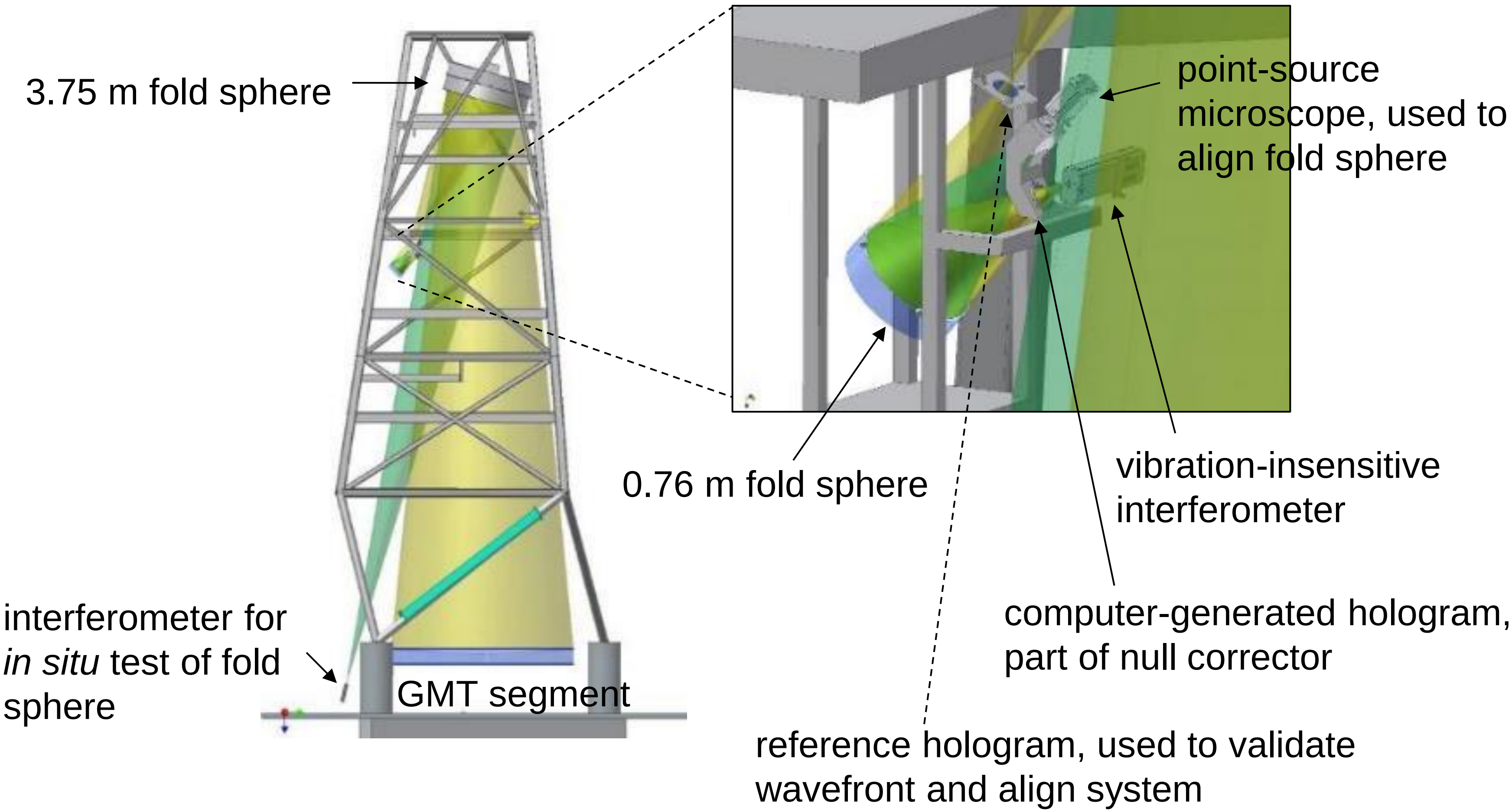




Oliver Faehnle, Rolf Rascher, Christian Vogt, and Dae Wook Kim, "Closed-loop laser polishing using in-process surface finish metrology," Appl. Opt. 57, 834-838 (2018)

3. METROLOGY

GMT INTERFEROMETRIC TEST
USING COMPUTER GENERATED HOLOGRAM



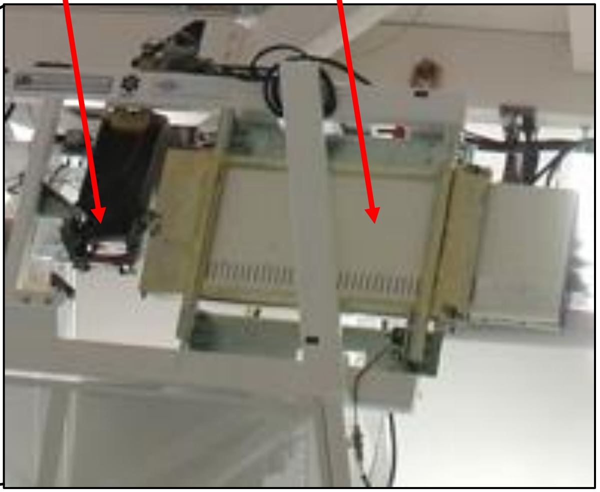
PRINCIPAL OPTICAL TEST IN TOWER

SITTING IN THE AIR

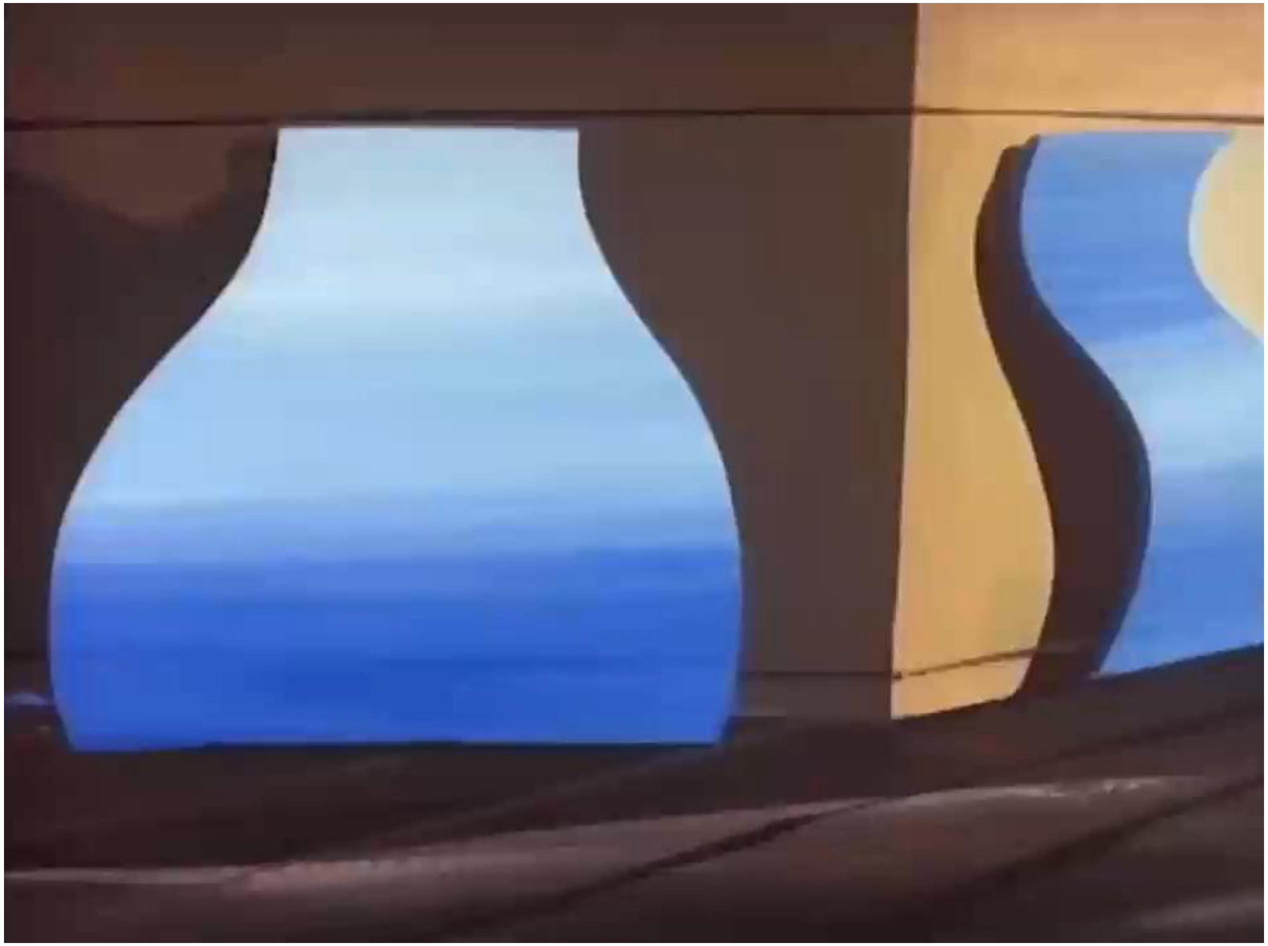
3.75 m spherical mirror
23 m above GMT segment

CGH

Vibration-insensitive
interferometer



FREEFORM MIRROR
IS NOT ONLY FUN, BUT ALSO USEFUL!



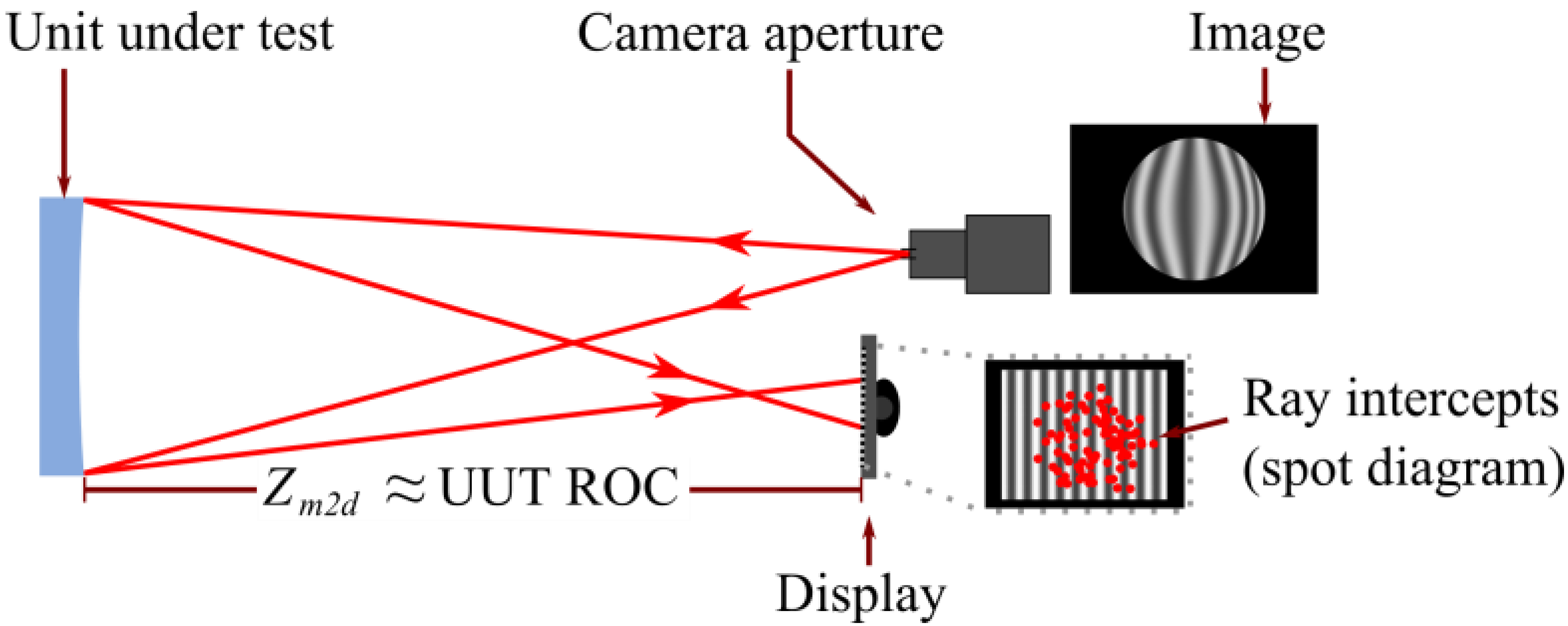
Scooby Doo! Funny Mirror Boomerang

FREEFORM CHICKEN DEFLECTOMETRY

“HAPPY-CHICKS” RESTAURANT IN AUSTIN

Located “next” to the SPIE Astronomical Telescope + Instrumentation Conference in Austin, Texas, 2018

SCOTS
SOFTWARE CONFIGURABLE OPTICAL TEST SYSTEM

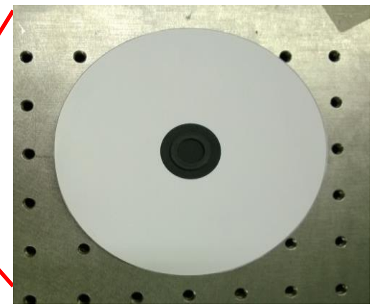
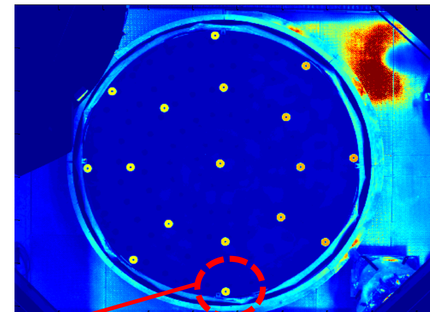


Advanced deflectometry system measuring surface slope with both high precision and large dynamic range.

Figure by Alex Maldonado

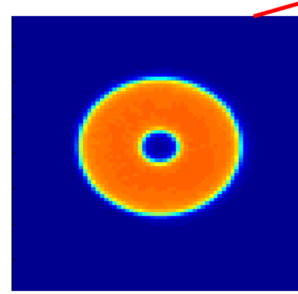
Peng Su, et al., "Software configurable optical test system: a computerized reverse Hartmann test," Applied Optics, Vol. 49, Issue 23, pp. 4404-4412 (2010)

MAPPING FOR LOW-ORDER SHAPE
DISTORTION CORRECTION TO INTEGRATE CORRECTLY

Fiducials on the mirror

Illustration showing how the SMR sits on the fiducial target.



Fiducial image captured by SCOTS camera

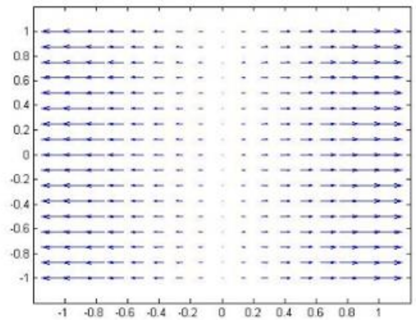
- Measure fiducials with laser tracker
- Find in camera image
- Orthogonal mapping (S/T) polynomial fit removes distortion/keystone

Andrew Lowman, et al., "Measurement of Large On-Axis and Off-Axis Mirrors using Software Configurable Optical Test System (SCOTS)," Astronomical SPIE Conference, Austin, USA (2018)

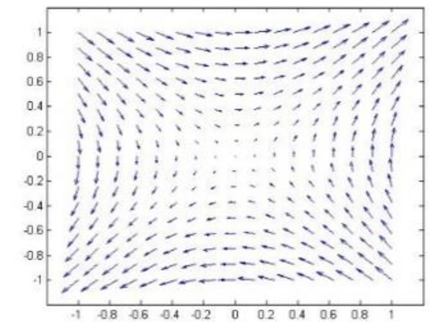
MODAL SLOPE DATA PROCESSING

GRADIENT VECTOR G-POLYNOMIAL

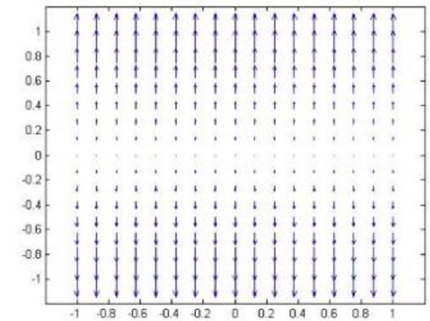
***G*$_3$**



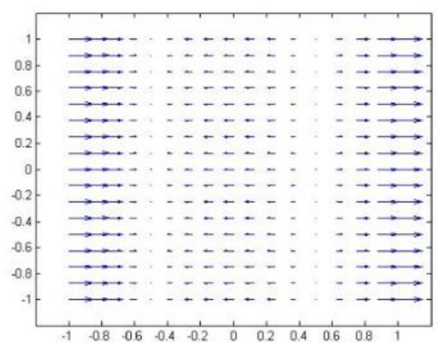
***G*$_4$**



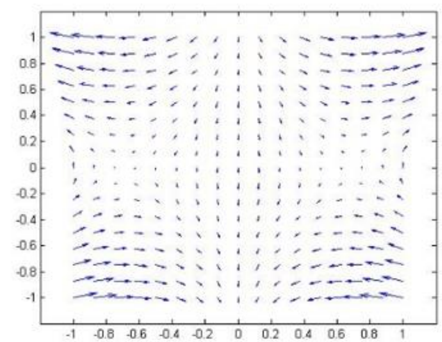
***G*$_5$**



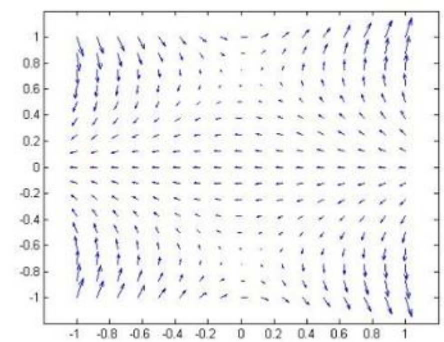
***G*$_6$**



***G*$_7$**



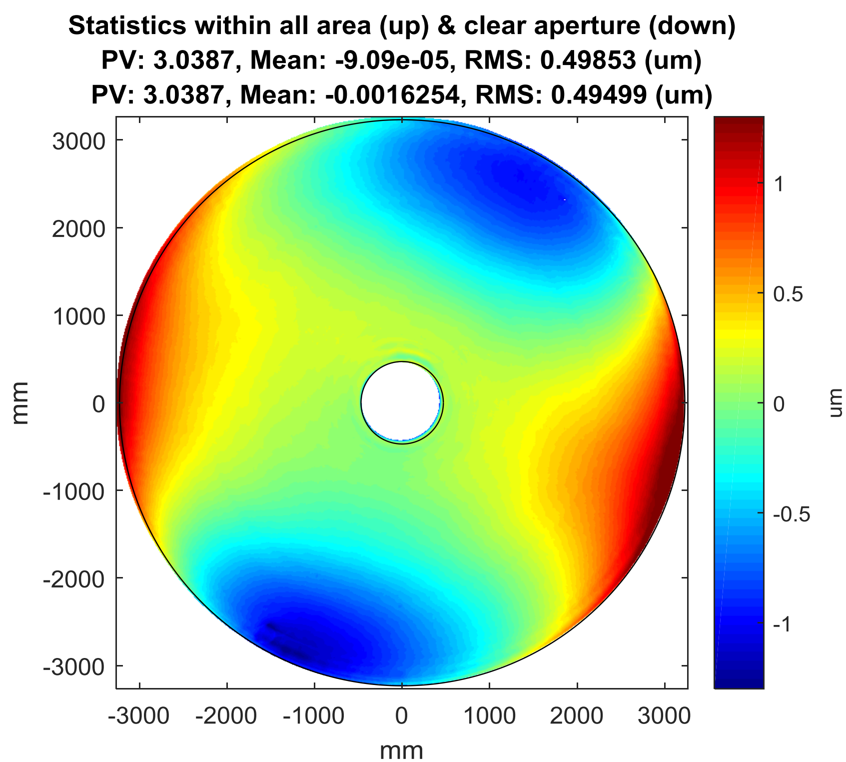
***G*$_8$**

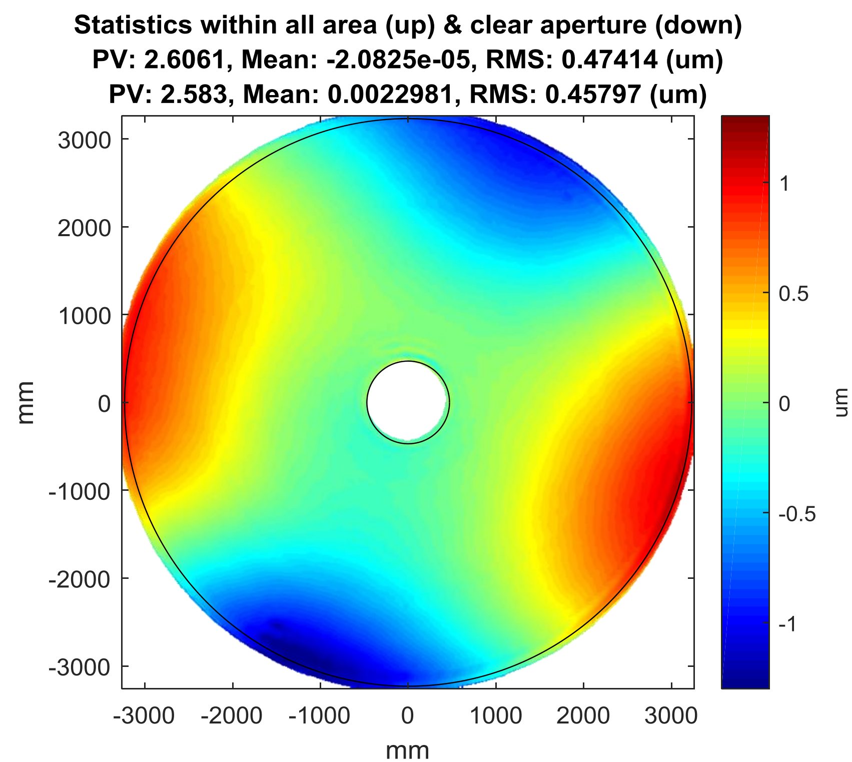


Maham Aftab, et al., "Modal Data Processing for High Resolution Deflectometry," IJPEM, In Press (2018)

MEASUREMENT OF 6.5 M MIRROR

UP TO POWER AND COMA TERMS REMOVED

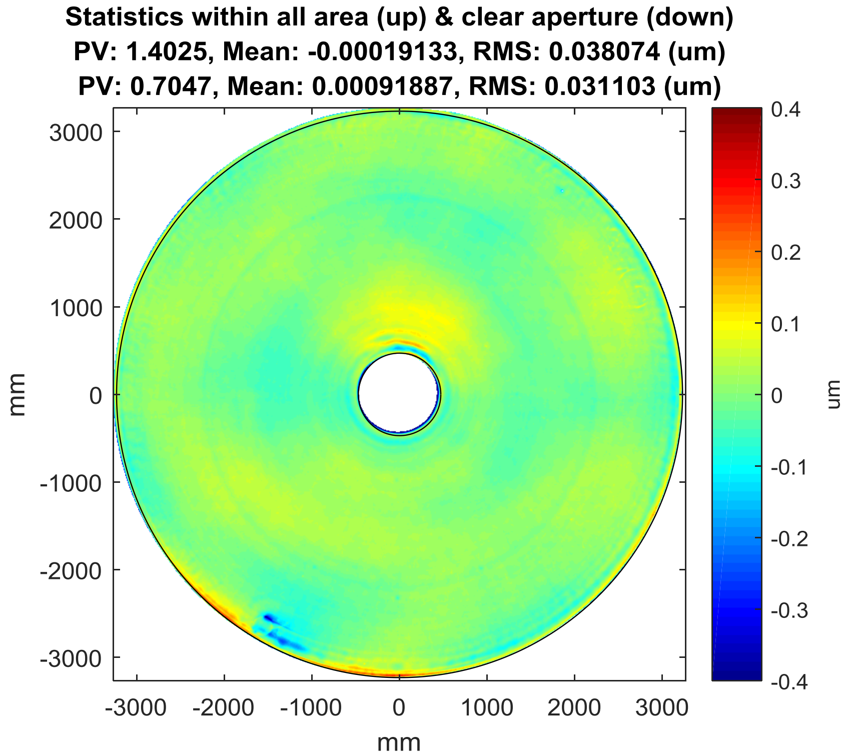


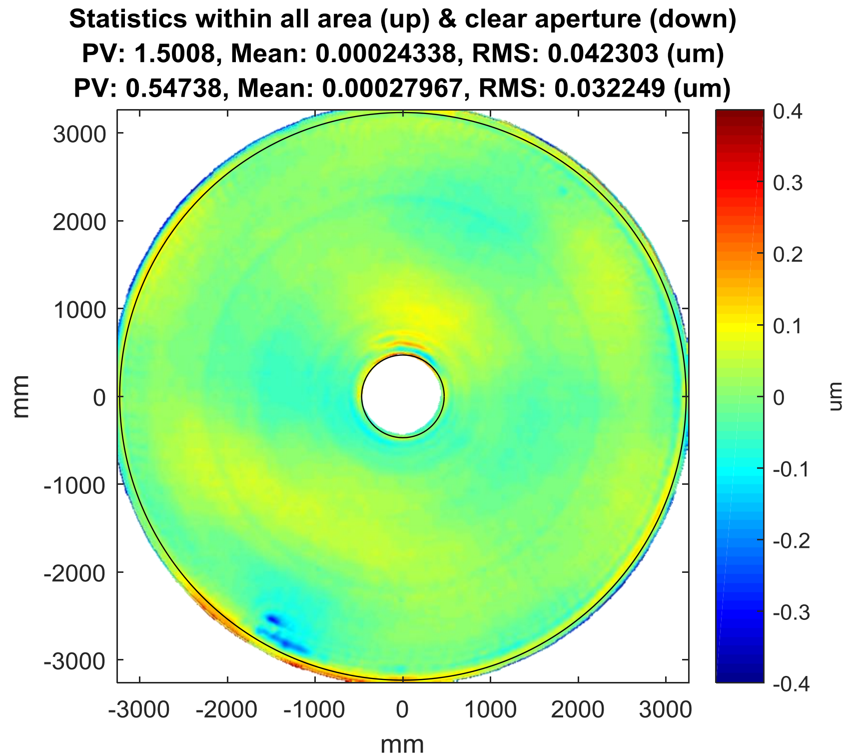


SCOTS **Interferometry**

Andrew Lowman, et al., "Measurement of Large On-Axis and Off-Axis Mirrors using Software Configurable Optical Test System (SCOTS)," Astronomical SPIE Conference, Austin, USA (2018)

MEASUREMENT OF 6.5 M MIRROR
UP TO ZERNIKE 12 TERMS REMOVED



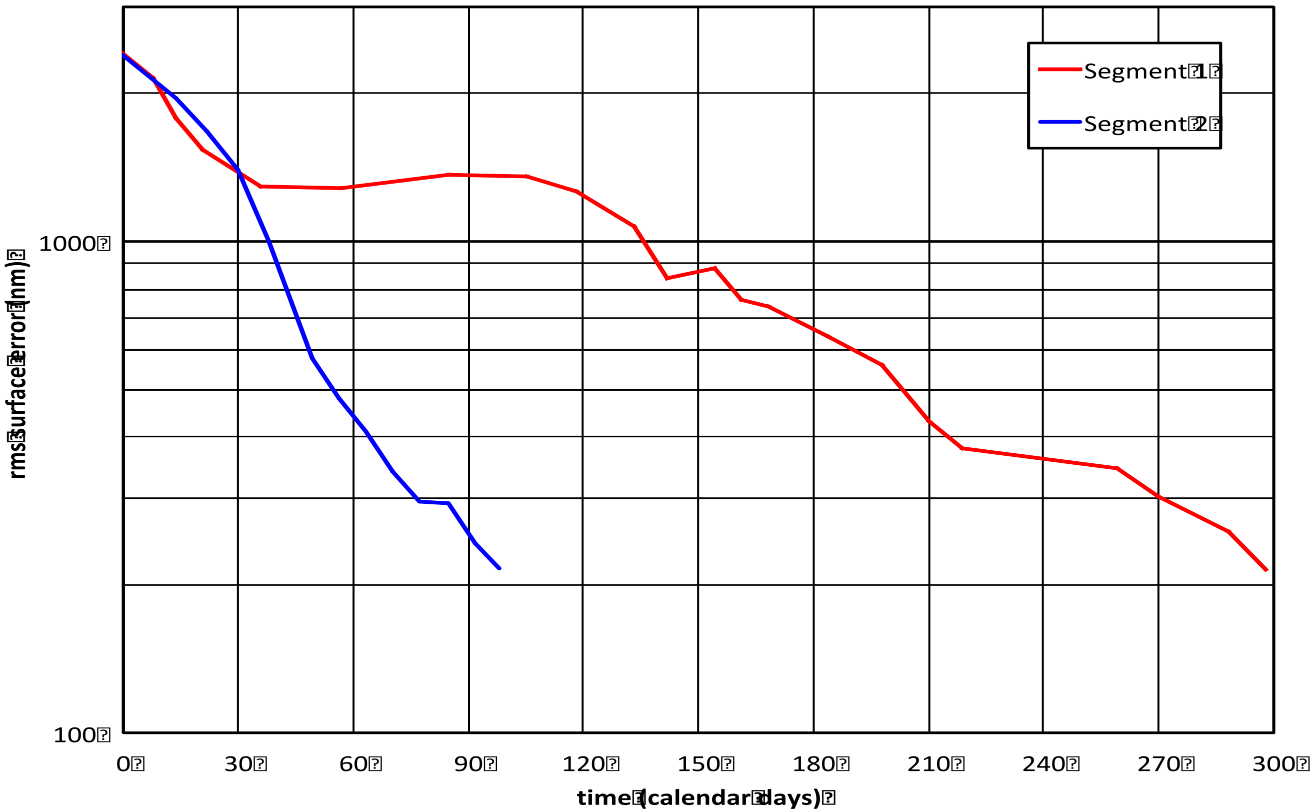


SCOTS **Interferometry**

Andrew Lowman, et al., "Measurement of Large On-Axis and Off-Axis Mirrors using Software Configurable Optical Test System (SCOTS)," Astronomical SPIE Conference, Austin, USA (2018)

CONVERGENCE PLOT

COMPARING 8.4 M GMT SEGMENT 1 AND 2

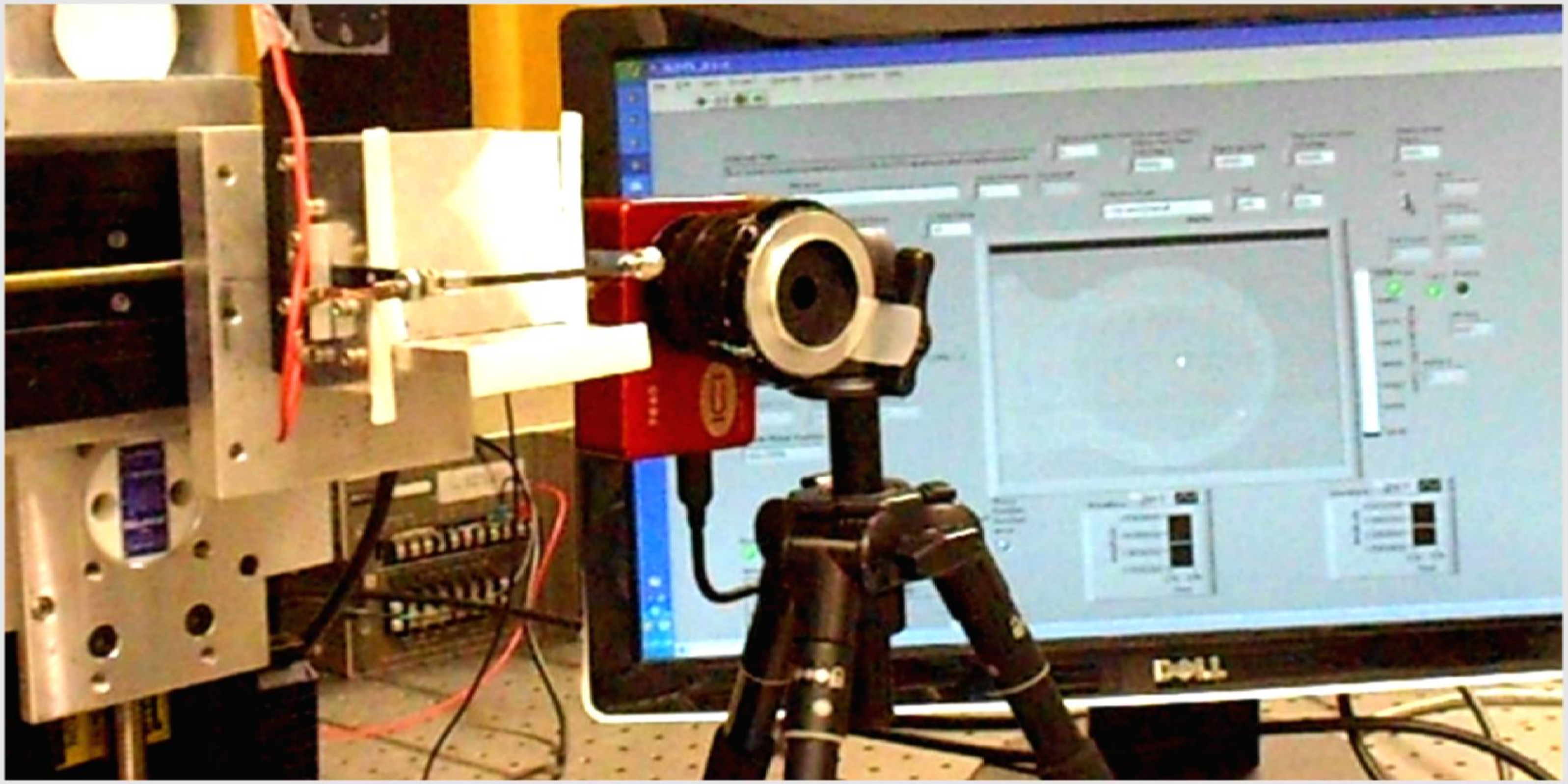


Improvement for Segment 2 is 3× faster.

Metric is same for both mirrors: rms surface error after active-optics correction using 11 bending modes.

Hubert Martin, et al., "Manufacture of primary mirror segments for the Giant Magellan Telescope," Astronomical SPIE Conference, Austin, USA (2018)

IR DEFLECTOMETRY
FOR FREEFORM PART METROLOGY



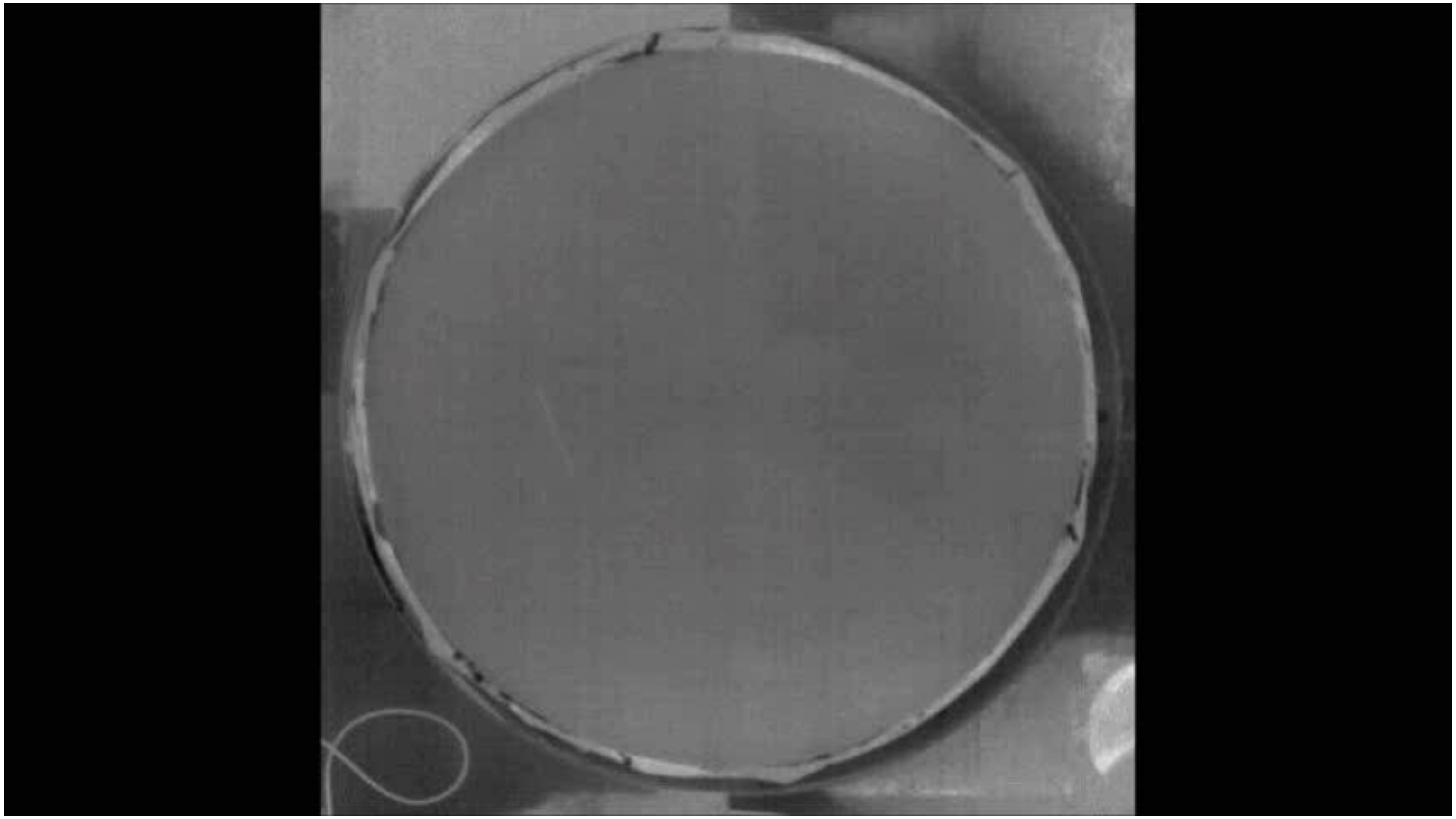
DEMO: Table-top SLOTS is measuring a sphere

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

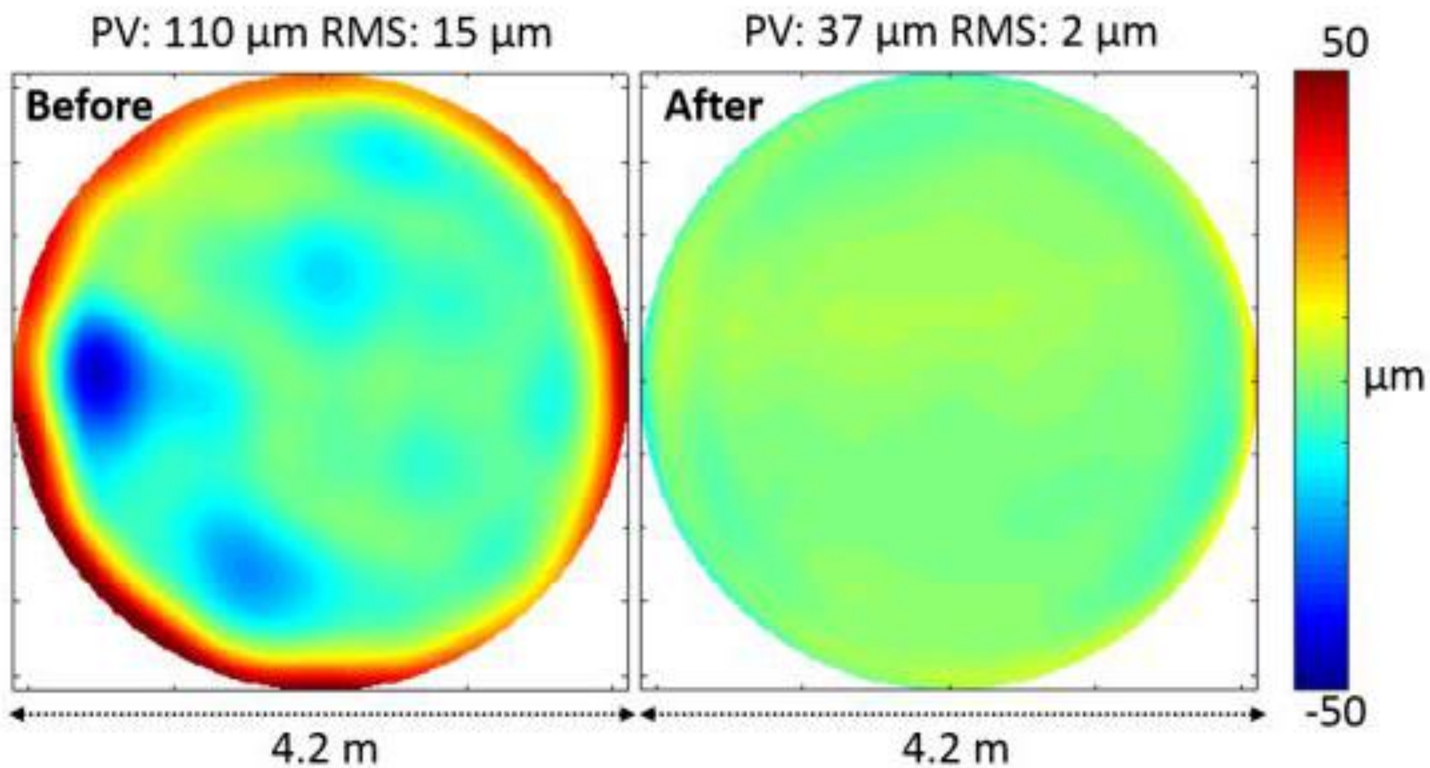
UNIQUE SOLUTION TO GUIDE FINE GRINDING PROCESS



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)

RAPID FINE GRINDING RESULT
MEASURED BY SLOTS

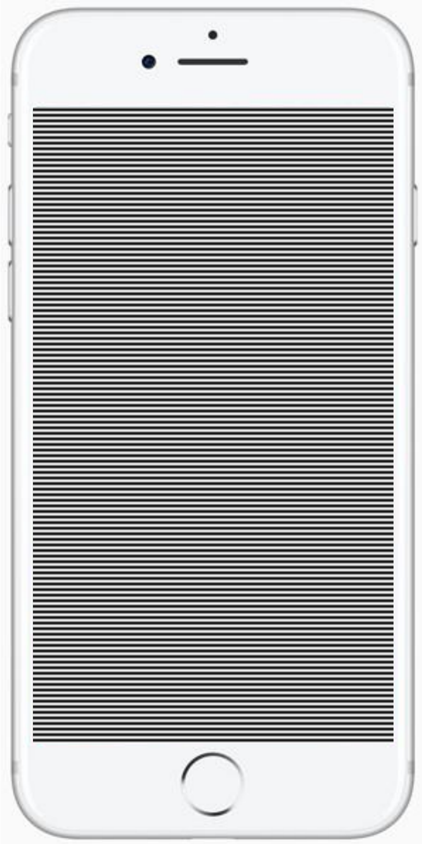


DKIST primary mirror surface shape error (from the ideal shape) changes from 15µm to 2µm RMS between 3 successive fine grinding runs using 25µm Aluminum Oxide grits (surface shape measured by SLOTS).

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)

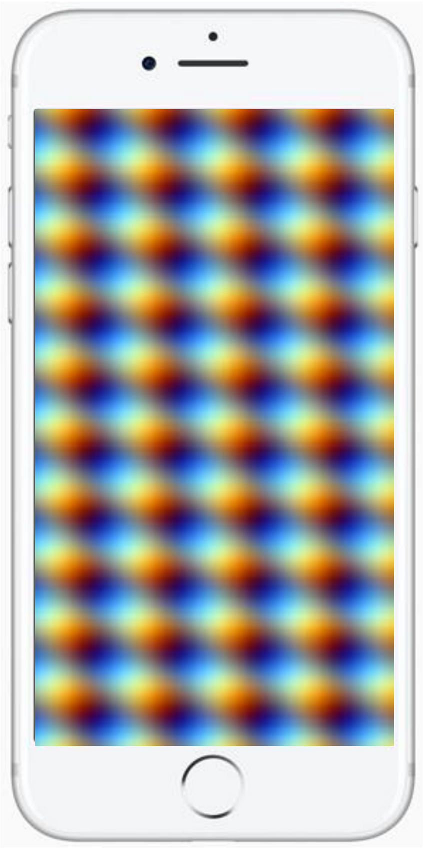
DYNAMIC TECHNOLOGY

YOU CAN MEASURE THE MOTION.



This monochromatic pattern movie (time-domain modulated) approach is not fast enough.

MULTIPLEXING
THREE COLORS IN TWO DIRECTIONS

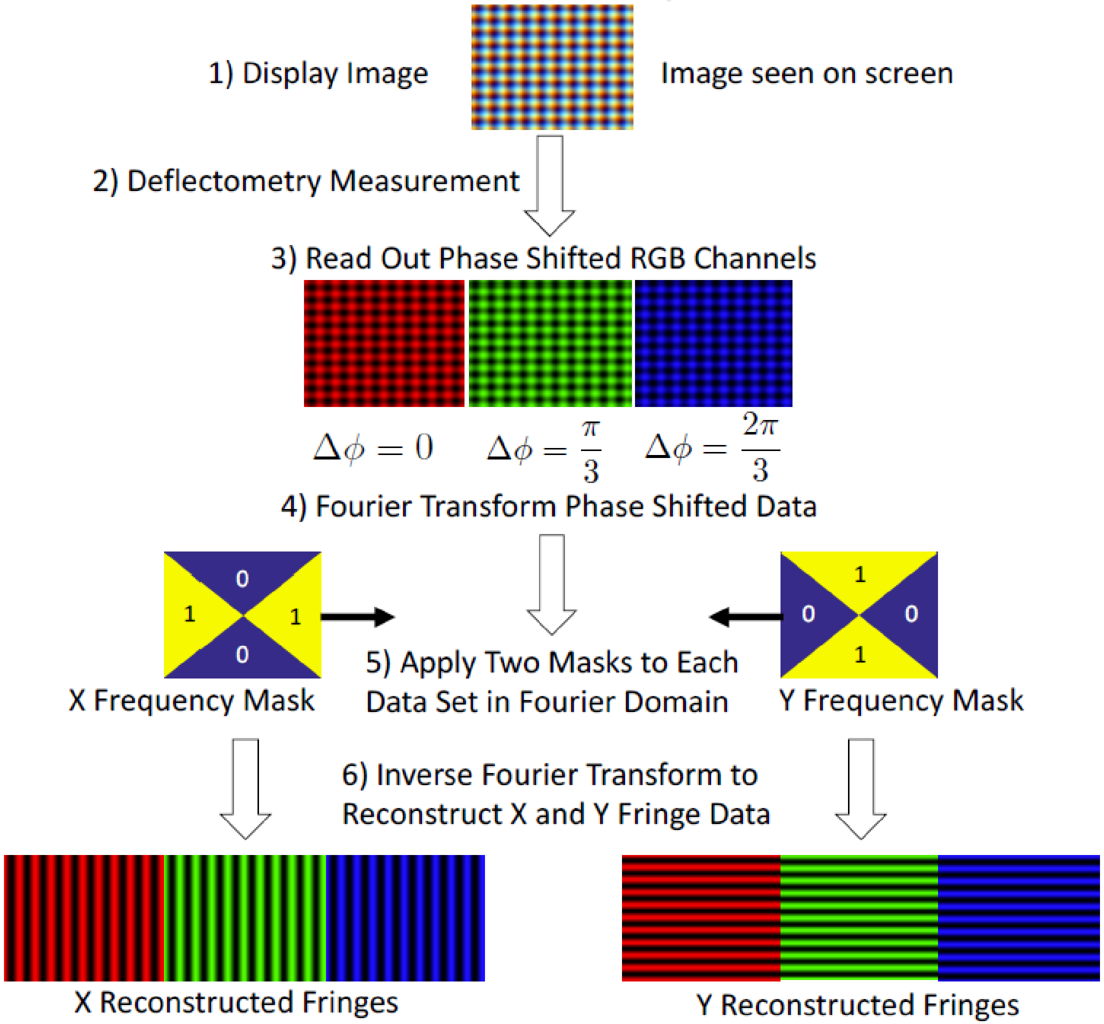


This colorful-yet-fixed pattern is not a movie anymore, but it can measure a moving surface.

DATA PROCESSING

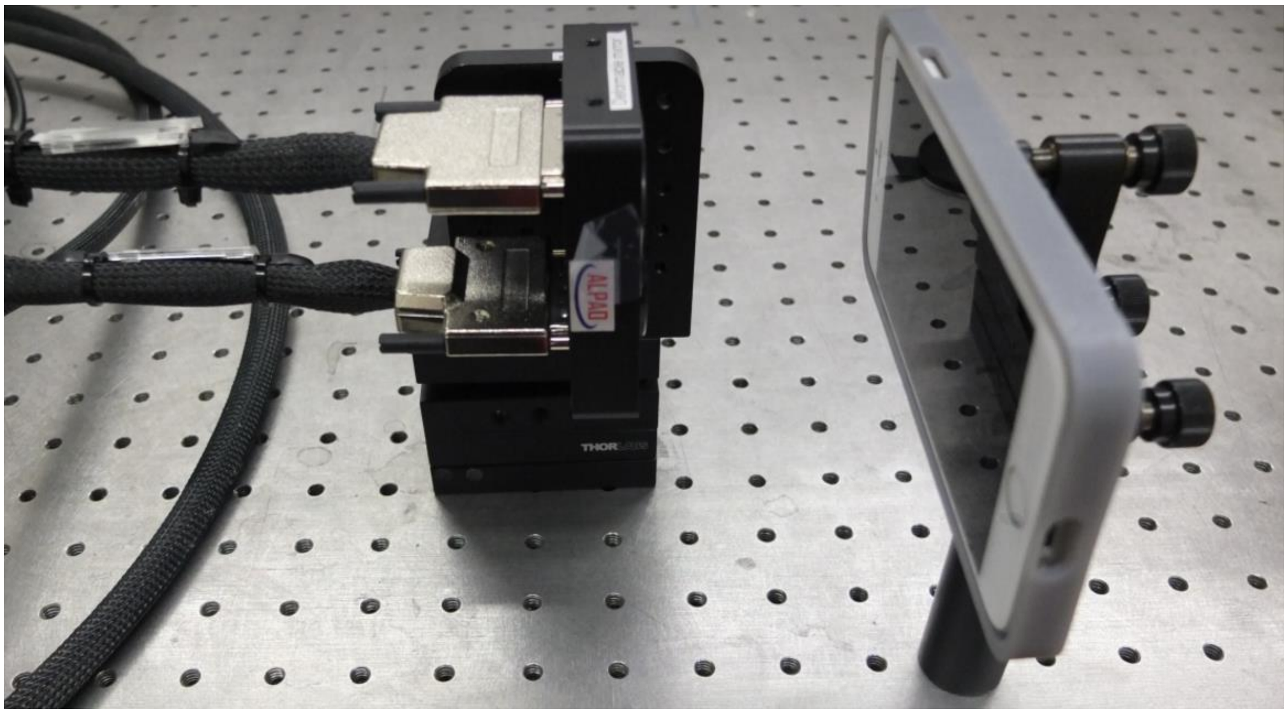
THREE COLORS IN TWO DIRECTIONS

Instantaneous Deflectometry Data Flow



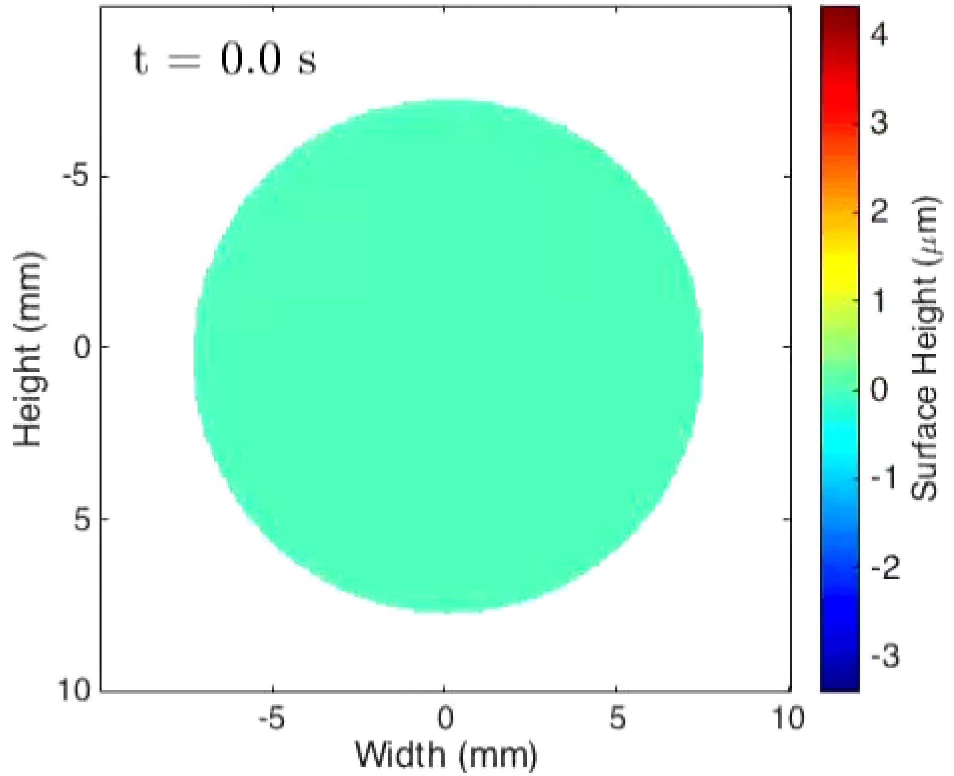
DYNAMIC DEFLECTOMETRY

MEASURING A DEFORMABLE MIRROR USING IPHONE



iPhone in a 3D printed mount (right) looking at an ALPAO Deformable Mirror (left) changing its shape in a Trefoil mode with ~ 7 µm peak-to-valley.

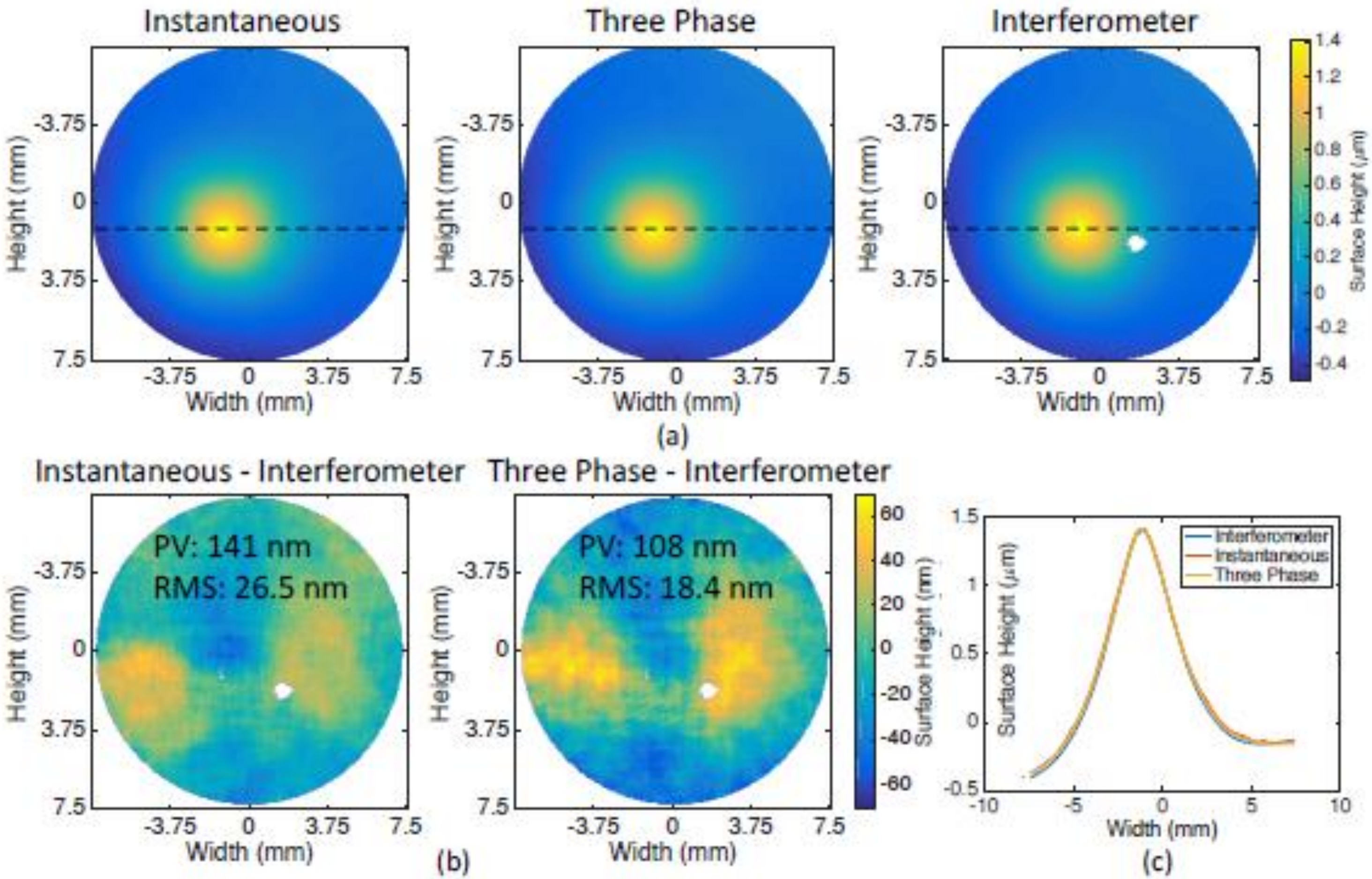
DYNAMIC DEFLECTOMETRY
MEASURING A CONTINUOUSLY VARYING SURFACE



Deformable mirror was "continuously" driven to change its shape in a Trefoil mode with ~ 7 μm peak-to-valley.

I. Trumper, H. Choi and D. W. Kim, "Instantaneous phase shifting deflectometry," Opt. Express. Accepted & under a production process (2016)

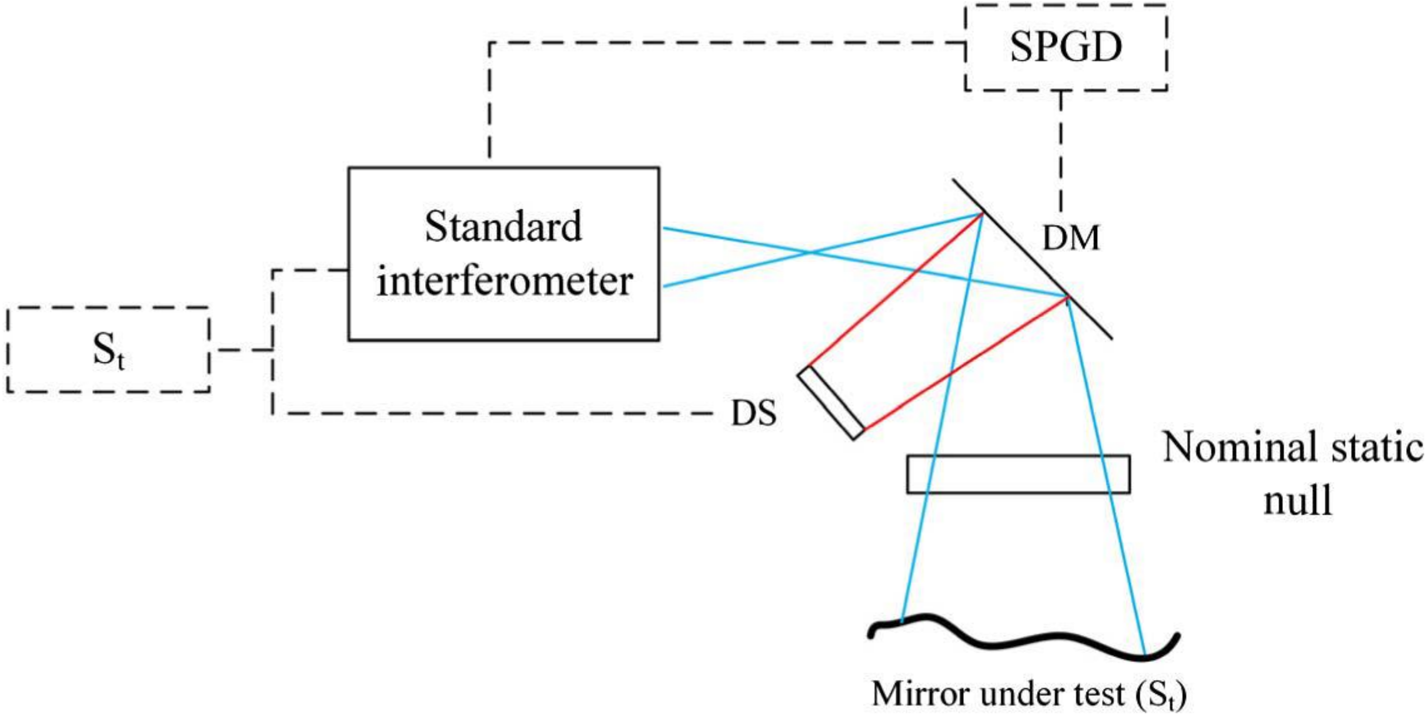
DYNAMIC DEFLECTOMETRY
COMPARISON WITH OTHER TECHNIQUES



I. Trumper, H. Choi and D. W. Kim, "Instantaneous phase shifting deflectometry," Opt. Express (2016)

ADAPTIVE INTERFEROMETRY
FOR UNKNOWN FREEFORM OPTICS MEASUREMENT

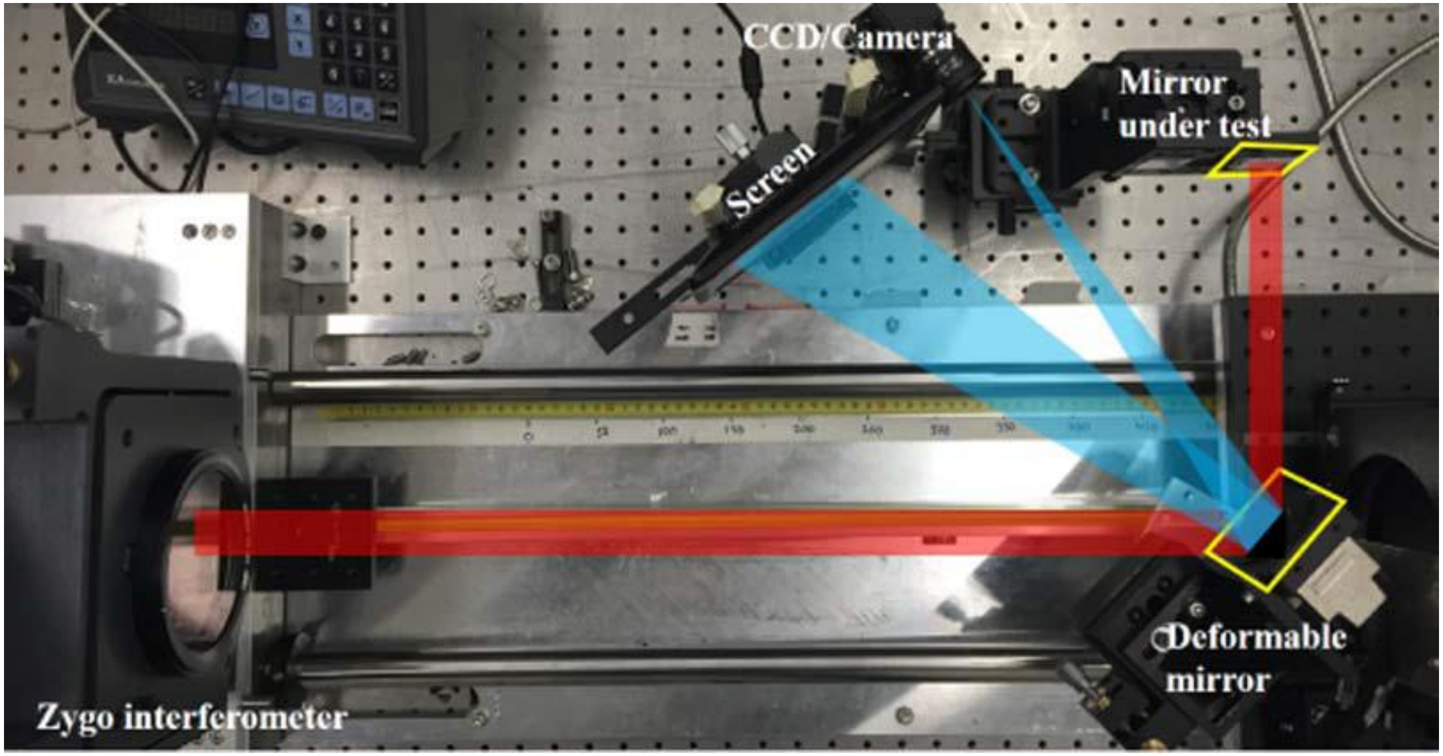
Stochastic Parallel Gradient Descent



Leveraging Deformable Mirror (DM) and Deflectometry technology for a precision in-process metrology system

Lei Huang, Heejoo Choi, Wenchuan Zhao, Logan R. Graves, and Dae Wook Kim, "Adaptive interferometric null testing for unknown freeform optics metrology," Opt. Lett. 41, 5539-5542 (2016)

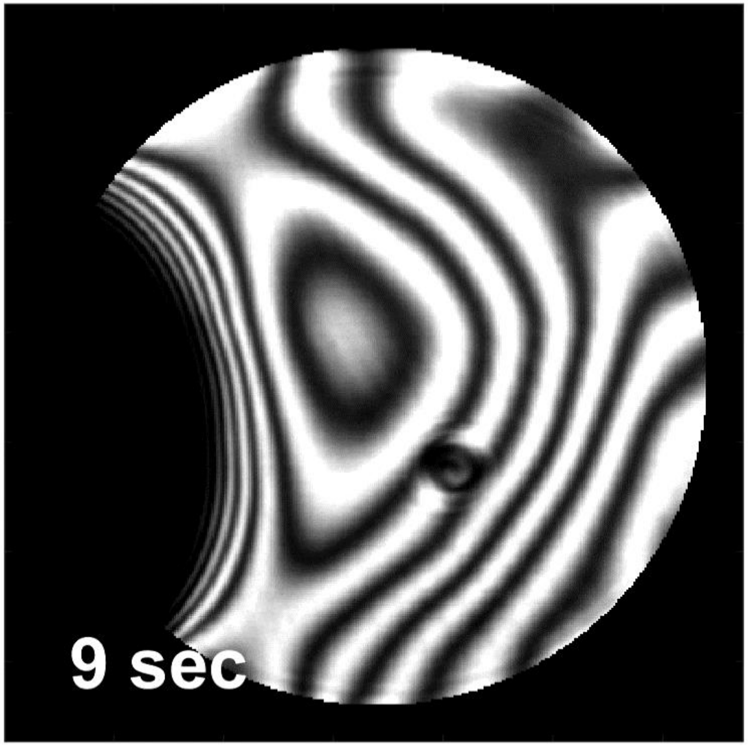
ADAPTIVE INTERFEROMETRY
USING COMMERCIAL INTERFEROMETER



Demonstrator using Zygo interferometer, Deformable Mirror (DM) and Deflectometry system

Lei Huang, Heejoo Choi, Wenchuan Zhao, Logan R. Graves, and Dae Wook Kim, "Adaptive interferometric null testing for unknown freeform optics metrology," Opt. Lett. 41, 5539-5542 (2016)

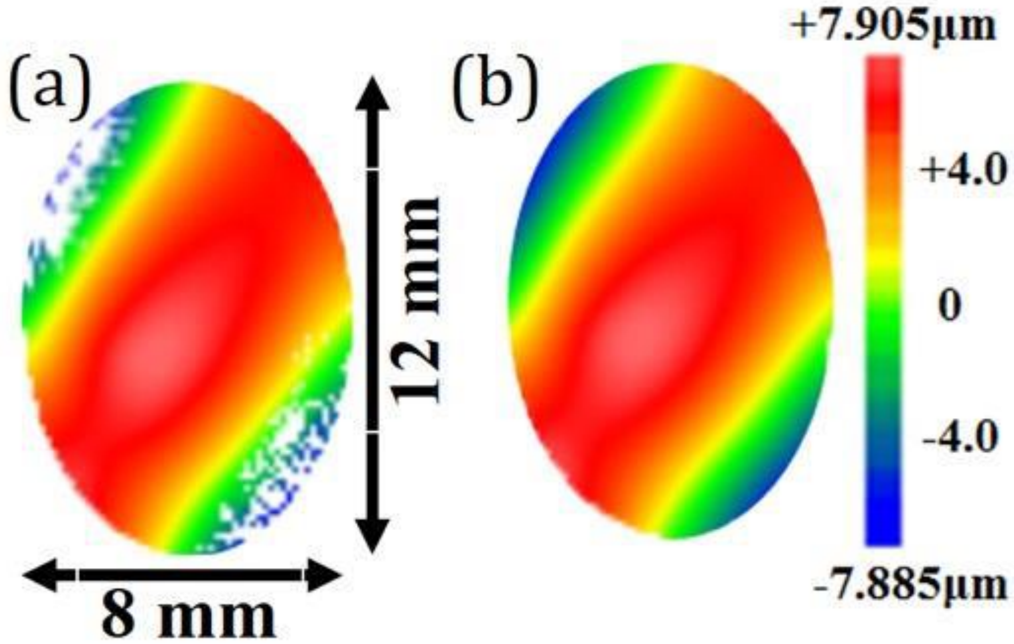
ADAPTIVE NULL FRINGE SEARCHING
FOR UNKNOWN FREEFORM OPTICS MEASUREMENT



Stochastic Parallel Gradient Descent (SPGD) - guided fringe restoration process

MEASURING UN-MEASURABLES

COMPARISON WITH STANDARD INTERFEROMETRY



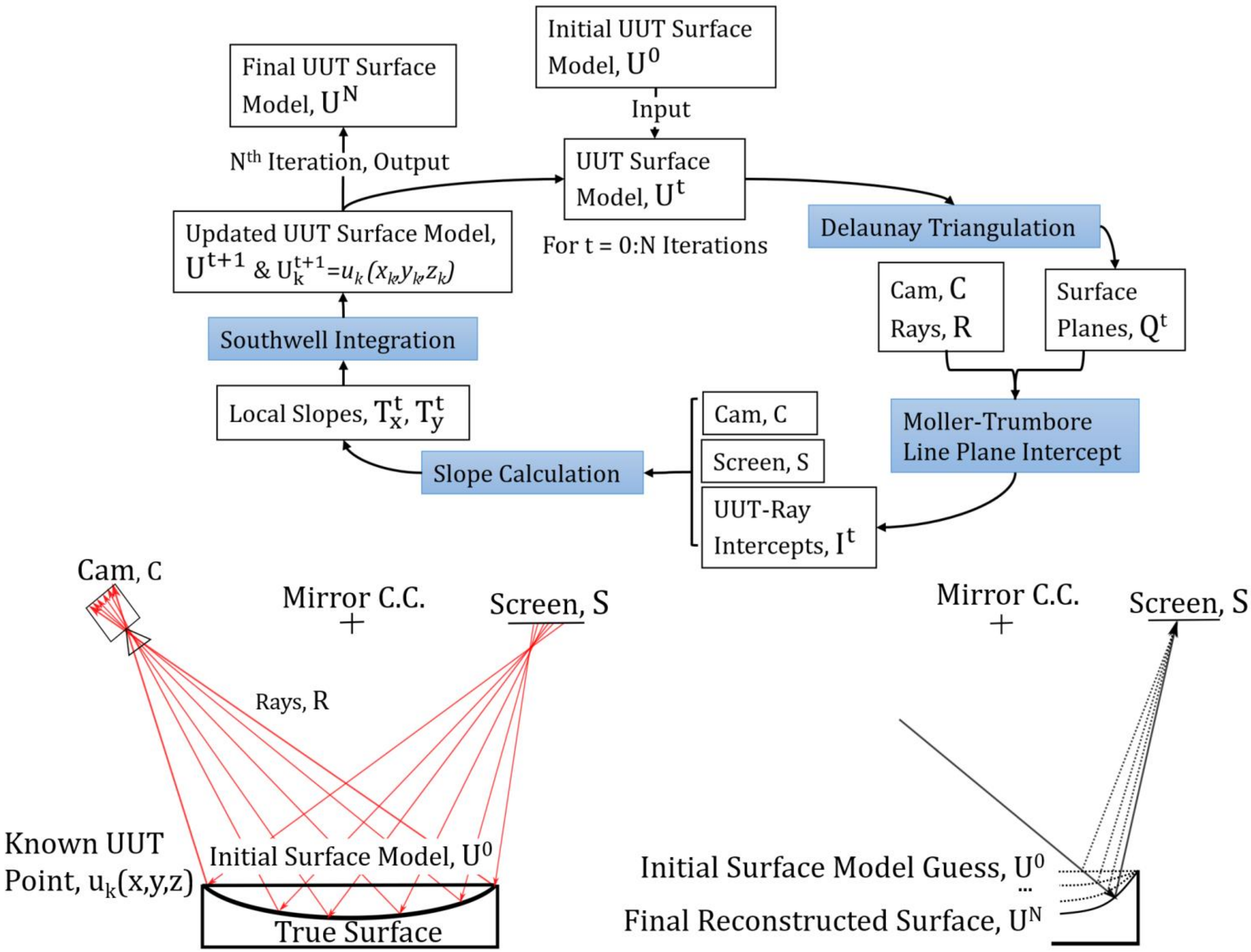
(a) Standard interferometry with limited dynamic range.

(b) Dynamic interferometry with adaptable dynamic range.

Lei Huang, Heejoo Choi, Wenchuan Zhao, Logan R. Graves, and Dae Wook Kim, "Adaptive interferometric null testing for unknown freeform optics metrology," Opt. Lett. 41, 5539-5542 (2016)

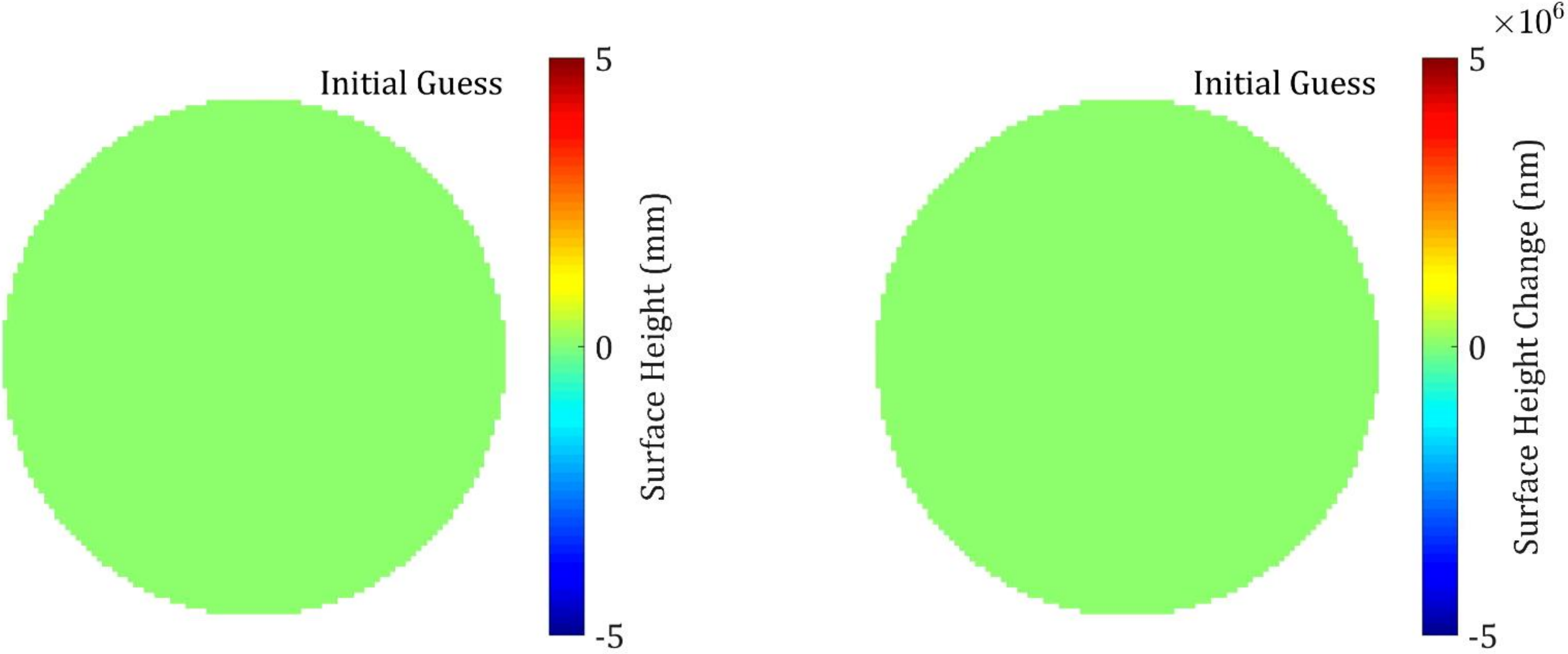
MODEL-FREE FREEFORM METROLOGY

ITERATIVE SOLUTION



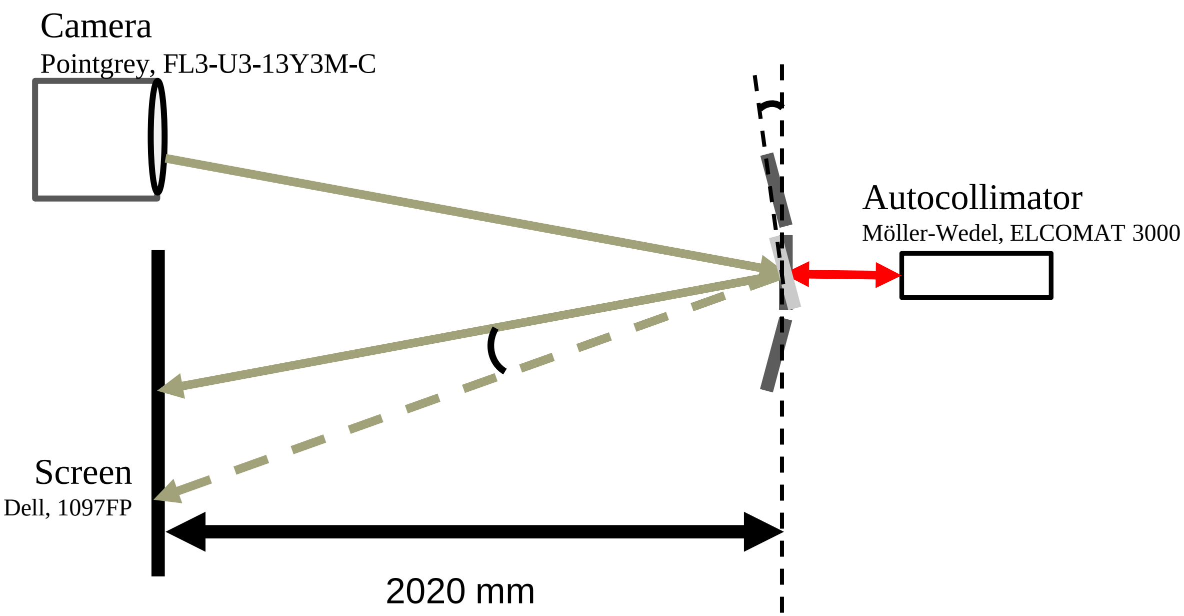
MODEL-FREE FREEFORM METROLOGY

ITERATIVE SOLUTION



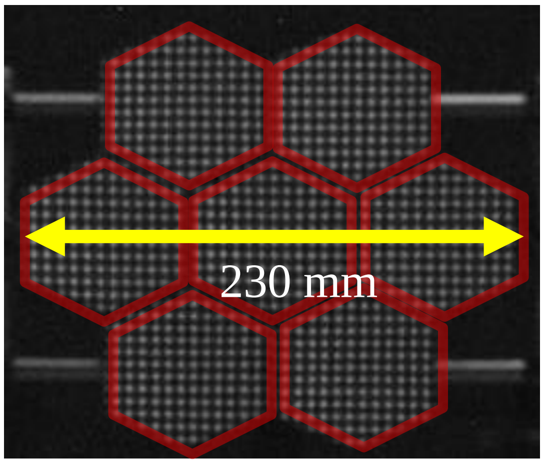
Logan R. Graves, Heejoo Choi, Wenchuan Zhao, Chang Jin Oh, Peng Su, Tianquan Su, and Dae Wook Kim, "Model-free deflectometry for freeform optics measurement using an iterative reconstruction technique," Opt. Lett. 43, 2110-2113 (2018).

SMOTS
SIMULTANEOUS MULTI-SEG. MIR. ORIENTATION TEST SYSTEM



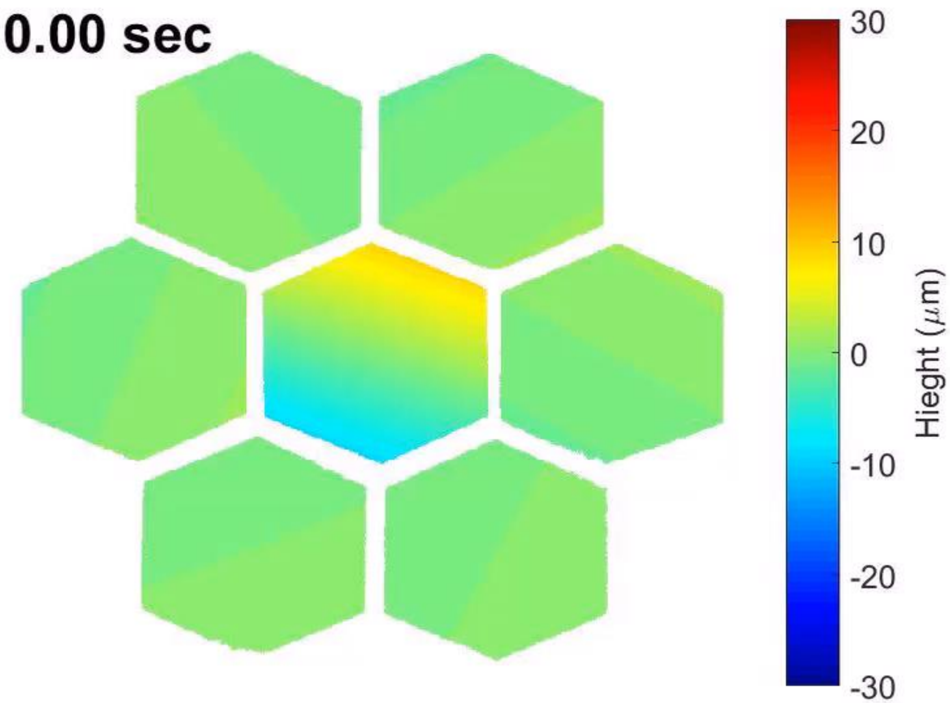
Angular resolution: 0.5 μrad

Target mirror



Heejoo Choi, Isaac Trumper, Matthew Dubin, Wenchuan Zhao, and Dae Wook Kim, Opt. Express25, 18152-18164 (2017)

SMOTS
TEST RESULTS SHOWING THE REAL-TIME CAPABILITY



Measurement capability
Updating rate : ~ 15 Hz
RMS error: 0.8 μrad

Calculation condition
CPU : Intel Xeon CPU E3-155Mv5, 2.80 GHz
RAM : 64GB, DDR4 2133MHz SDRAM

Heejoo Choi, Isaac Trumper, Matthew Dubin, Wenchuan Zhao, and Dae Wook Kim, Opt. Express25, 18152-18164 (2017)

METROLOGY IS ENABLING THE TIME MACHINES.

GMT SEGMENT 1 TO 3

YES, MORE IS COMING.

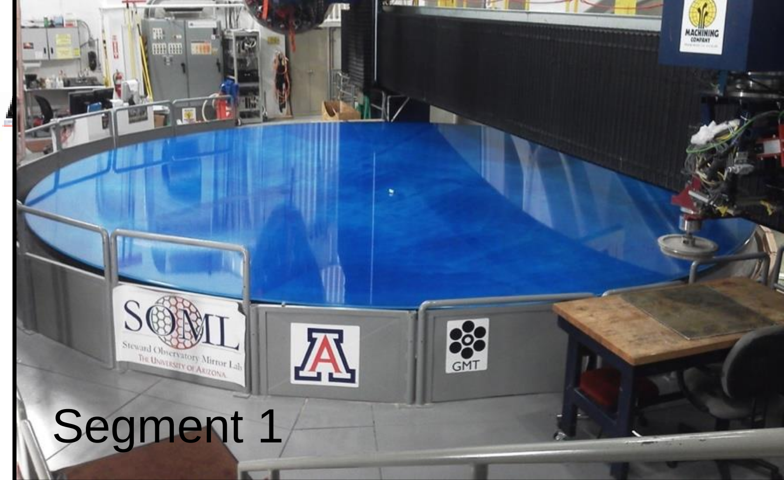
Segment 1 (off-axis) was completed in August 2012.

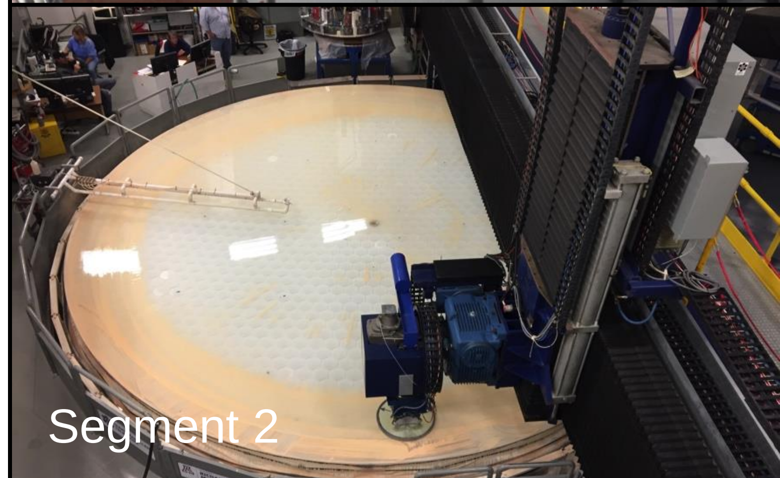
- 18 nm rms surface after simulated active optics
- Its completion demonstrated the essential manufacturing technology.

Segment 2 (off-axis) is being polished.

- Excellent progress to date, with improved methods and equipment for fabrication and testing

Segment 3 (off-axis) is having optical surface diamond-generated.





Hubert Martin, et al., "Manufacture of primary mirror segments for the Giant Magellan Telescope," Astronomical SPIE Conference, Austin, USA (2018)

GMT SEGMENT 4 TO 7

YES, MORE IS COMING.

Segment 4 (center segment) was cast in September 2015.

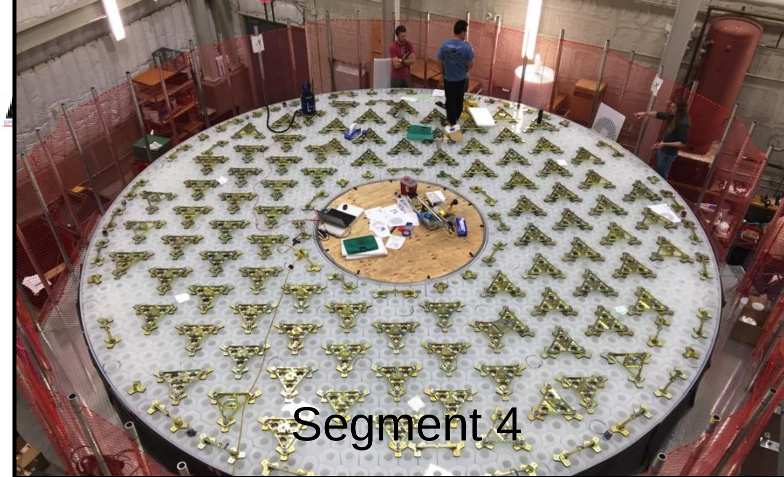
- Rear surface has been ground and polished.
- Loadspreaders are being attached.

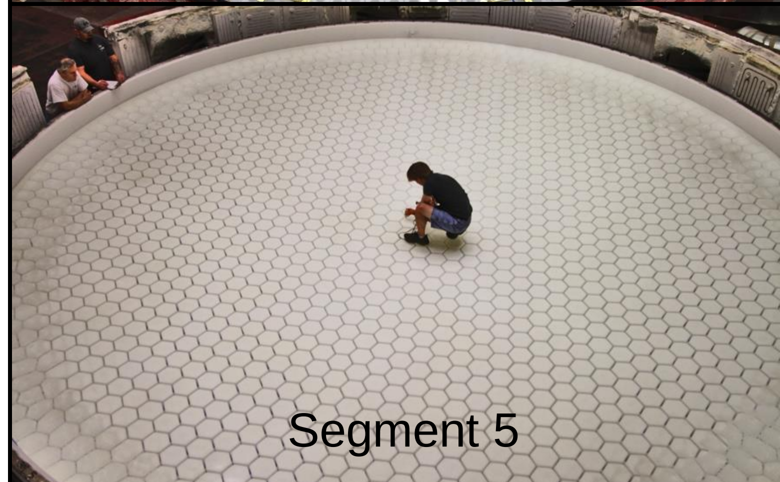
Segment 5 (off-axis) was cast in November 2017.

- Ready for rear surface processing

Glass was purchased for Segments 6 and 7 (off-axis).

- 2×20 tons of Ohara E6 low-expansion borosilicate
- The best material that can be cast in a complex structure





Hubert Martin, et al., "Manufacture of primary mirror segments for the Giant Magellan Telescope," Astronomical SPIE Conference, Austin, USA (2018)

CONCLUDING REMARKS

SIMPLE MOTIVATIONS

NOTHING IS EASY.

WHY DO WE DO THIS?

I AM SIMPLY CURIOUS!
AS A SCIENTIST

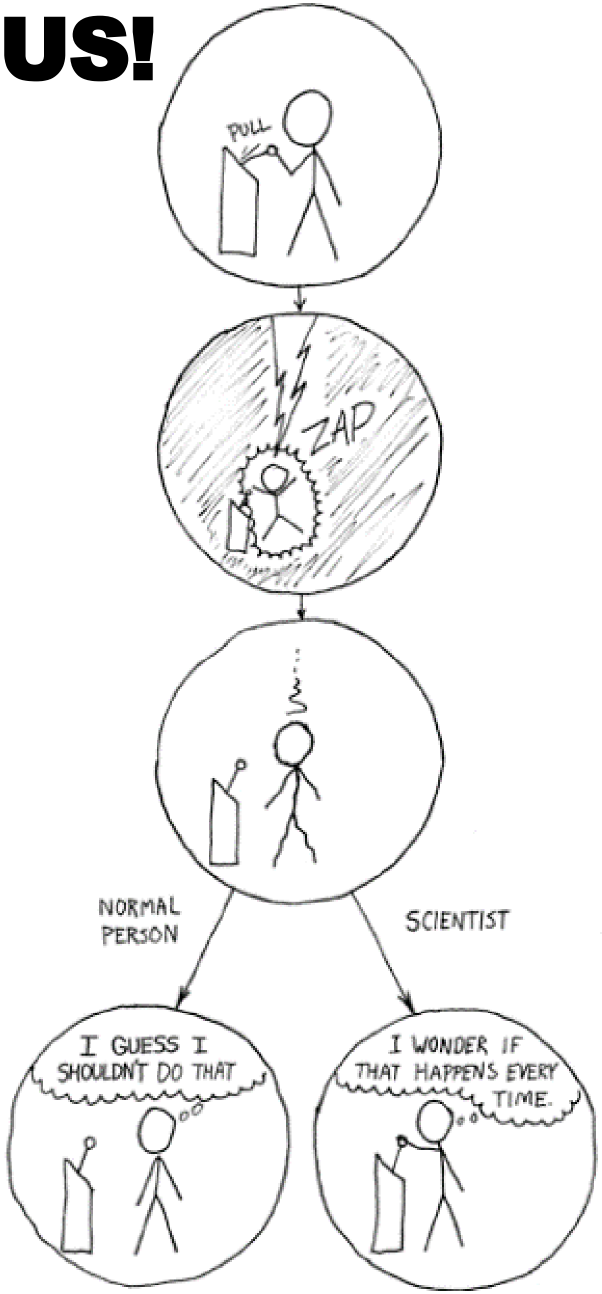
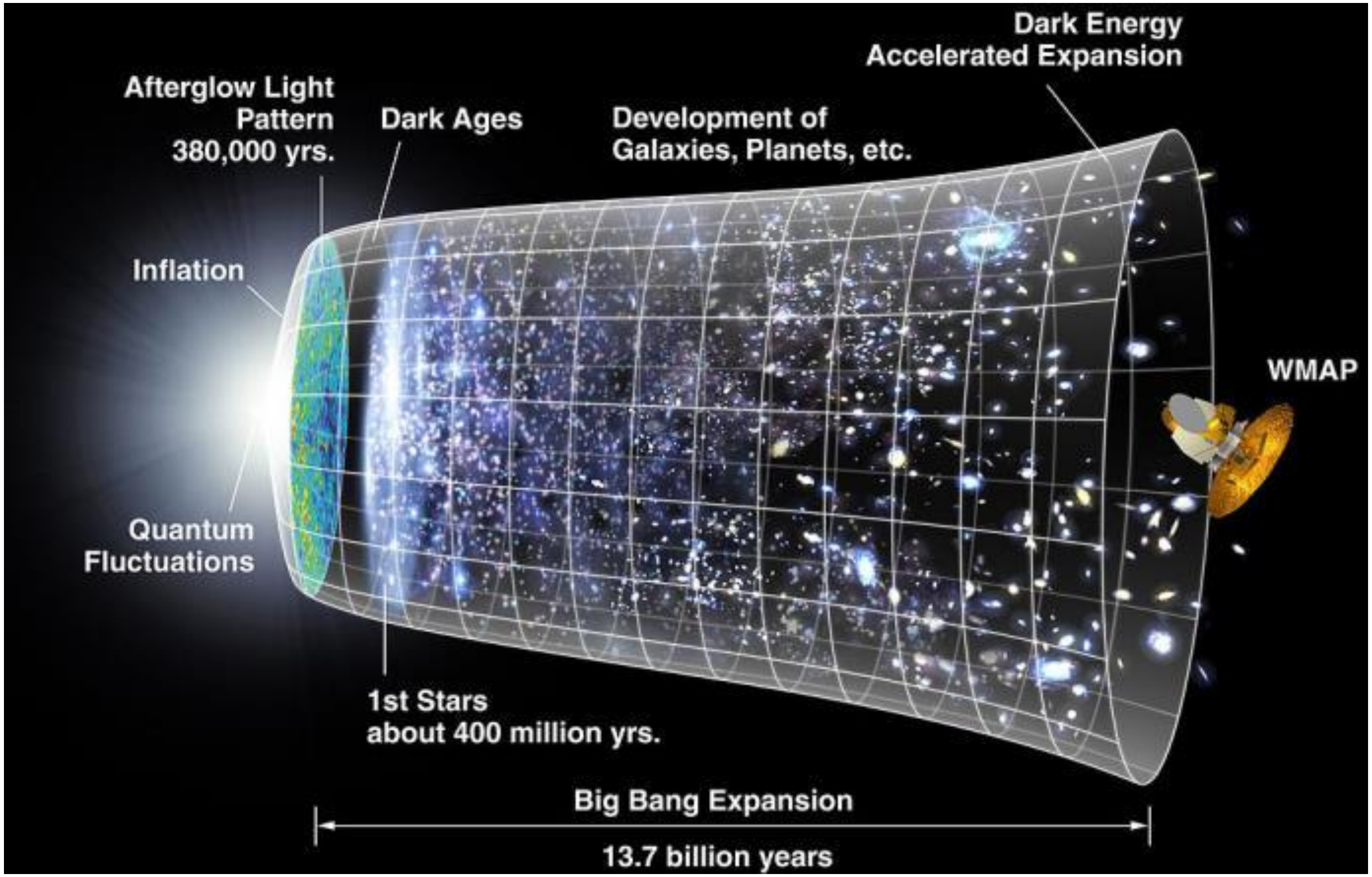


Image from http://xkcd.com/242/

DISCOVERY

EXPECTING SOMETHING WE DON'T KNOW AT THE MOMENT



It will be just like the first detection of Einstein's gravitational wave by LIGO team in 2016.

ACKNOWLEDGMENT

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This material is based in part upon work supported by AURA through the National Science Foundation under Scientific Program Order No. 10 as issued for support of the Giant Segmented Mirror Telescope for the United States Astronomical Community, in accordance with Proposal No. AST-0443999 submitted by AURA.

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