A 3-D Metrology System for GMT

Metrology and Control of Large Telescopes,
Green Bank, September 22nd 2016

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2016 GMTO Staff – Pasadena

GMT Founder Institutions

Korea

Astronomy Australia Ltd.

Smithsonian Institution

FAPESP

Sao Paulo, Brazil

HARVARD UNIVERSITY

Texas A&M

Australian National University

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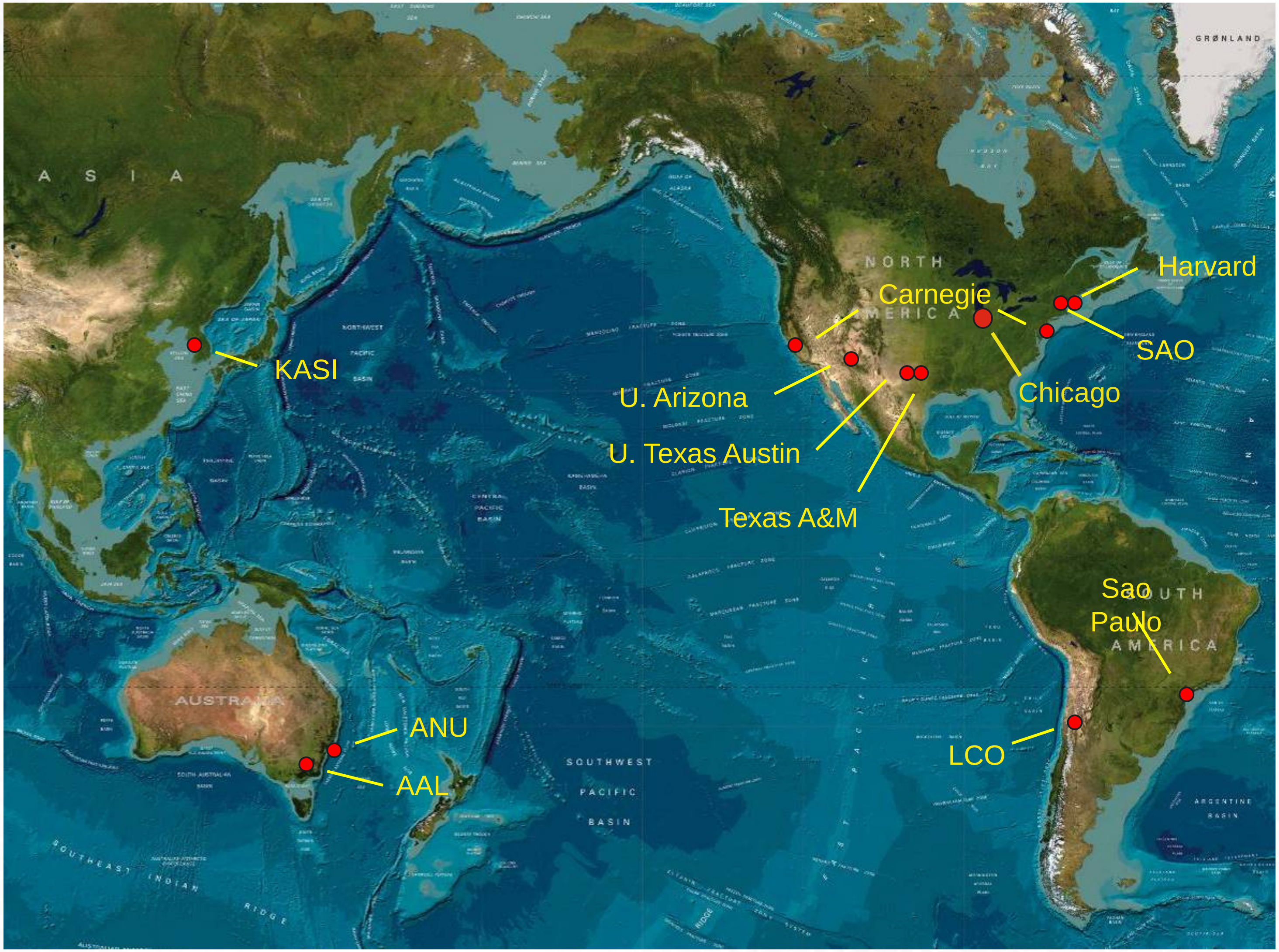
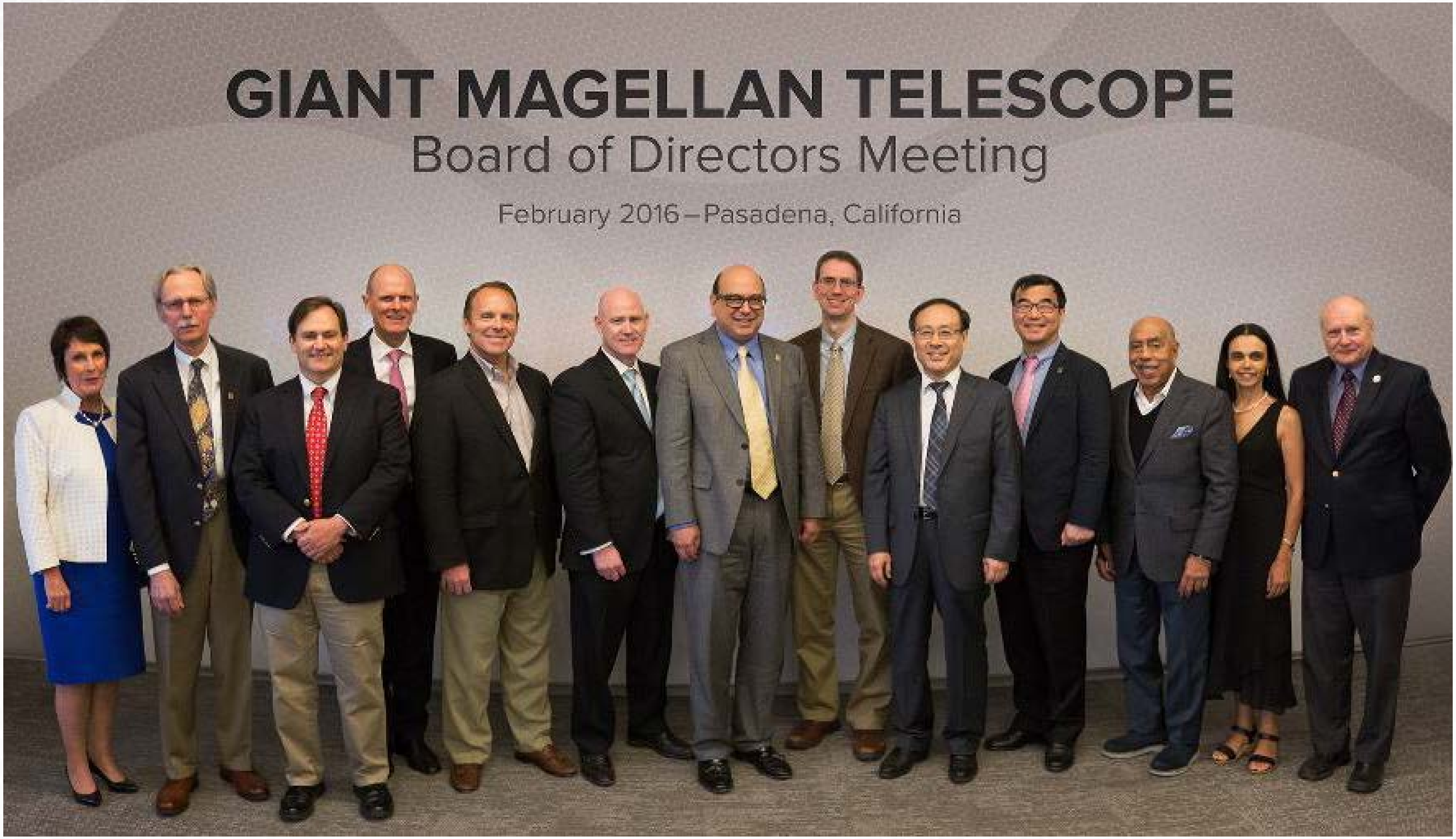
New partners are welcome

GMT Institutions

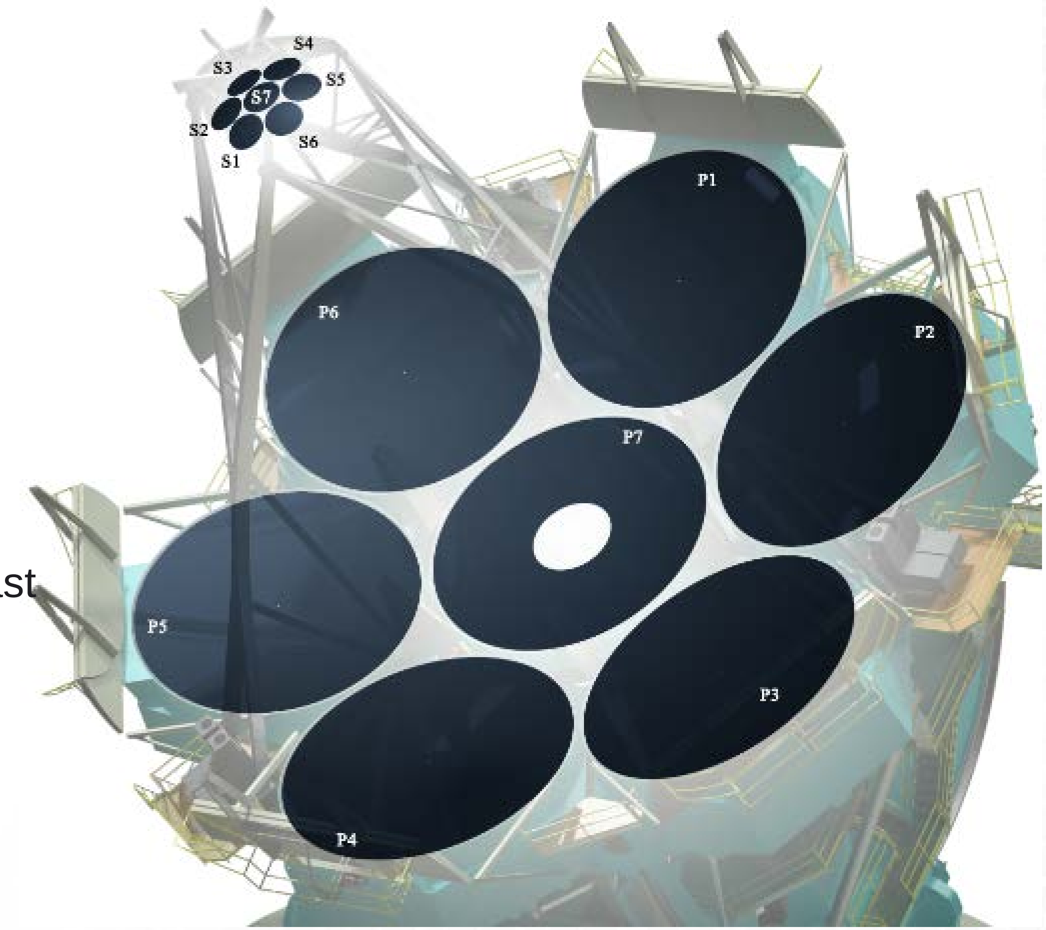


2016 Board of Directors



Telescope Design is Novel

- Doubly segmented design
  - M1 – 8.4m segments
  - M2 – 1.1m segments
  - M1/M2 segments are conjugate
  - Aplanatic Gregorian
  - f/0.7 primary
  - f/8 final focus (1.0 mm/arcsec)
  - High optical throughput
  - PSF Best of ELT's for High Contrast Imaging
- Special challenges
  - Alignment & phasing
  - Wind shake
  - Seismic loads & displacements
  - Compactness (instrument access)

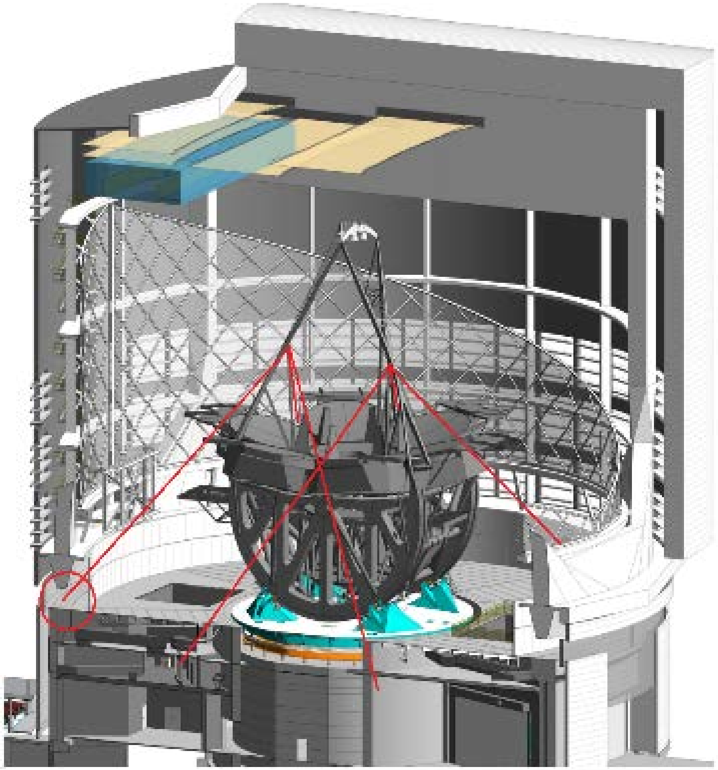


Mirror Casting Sequence – 30 second version!

Polishing Technology Improvements

The Challenge

GMT: A significant jump from the existing generation of optical/IR telescopes:



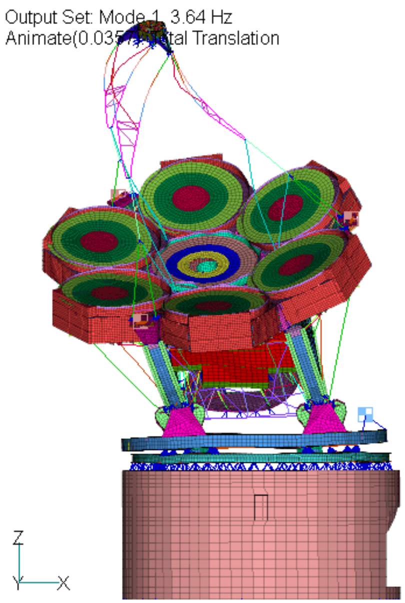
The Challenge

GMT: A significant jump in scale from the existing generation of optical/IR telescopes:

- Structural deflections (new structural scales), thermal, gravity, wind: Toleances driven by NUV observing band.

- Old hat to radio telescope engineers. In an office in Caltech is a wooden model produced by Aden Meinel to demonstrate how radio telescope ideas could aid in the telescope design for ELTs.

1st Lateral

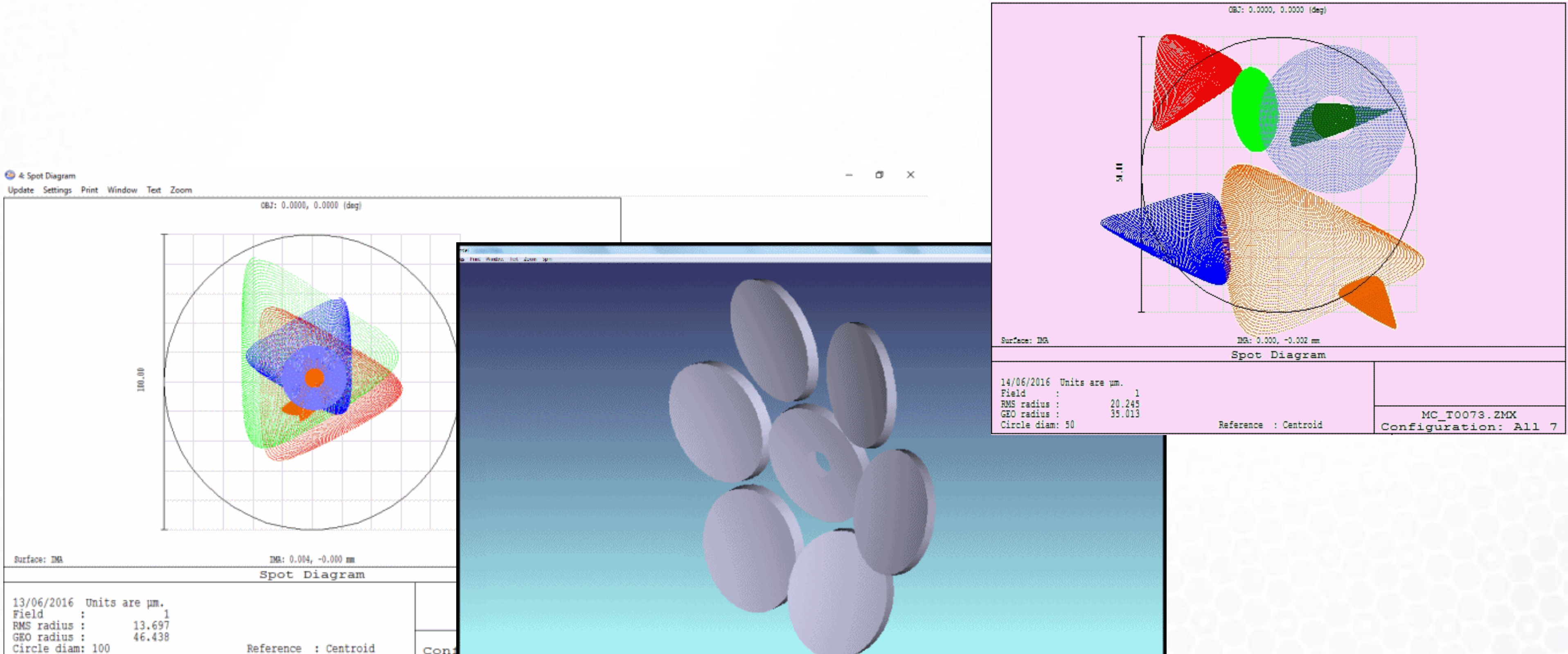


1st Fore-aft

The Challenge

GMT: A significant jump in complexity from the existing generation of optical/IR telescopes:

- Segmentation: GMT has double-segmentation, also a sparser aperture and much larger segments than current segmented telescopes

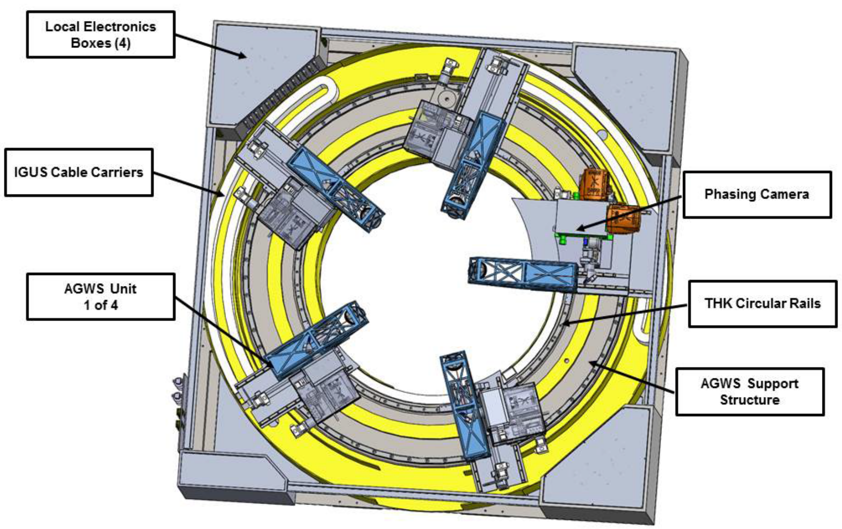


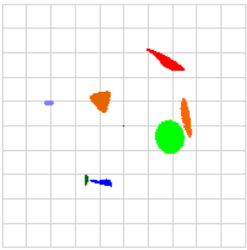
The Challenge

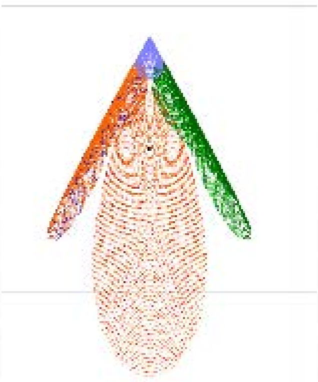
ELT's: A significant tightening of open loop requirements from the existing generation of optical/IR telescopes:

- Routine correction of field-asymmetric aberration with several facility wavefront sensors

Parameter	No Edge Sensors (1σ)	With M1 and M2 Edge Sensors (1σ)
M1 (X, Y)	≤ 75 μm	≤ 50 μm
M1 (Z)	≤ 170 μm	≤ 95 μm
M1 (Rx, Ry)	≤ 0.38 arc seconds	≤ 1.44 arc seconds
M1 (Rz)	≤ 40 arc seconds	N.A.
M2 (X, Y)	≤ 75 μm	≤ 50 μm
M2 (Z)	≤ 170 μm	≤ 95 μm
M2 (Rx, Ry)	≤ 3.0 arc seconds	≤ 3 seconds
M2 (Z)	≤ 330 arc seconds	N.A.

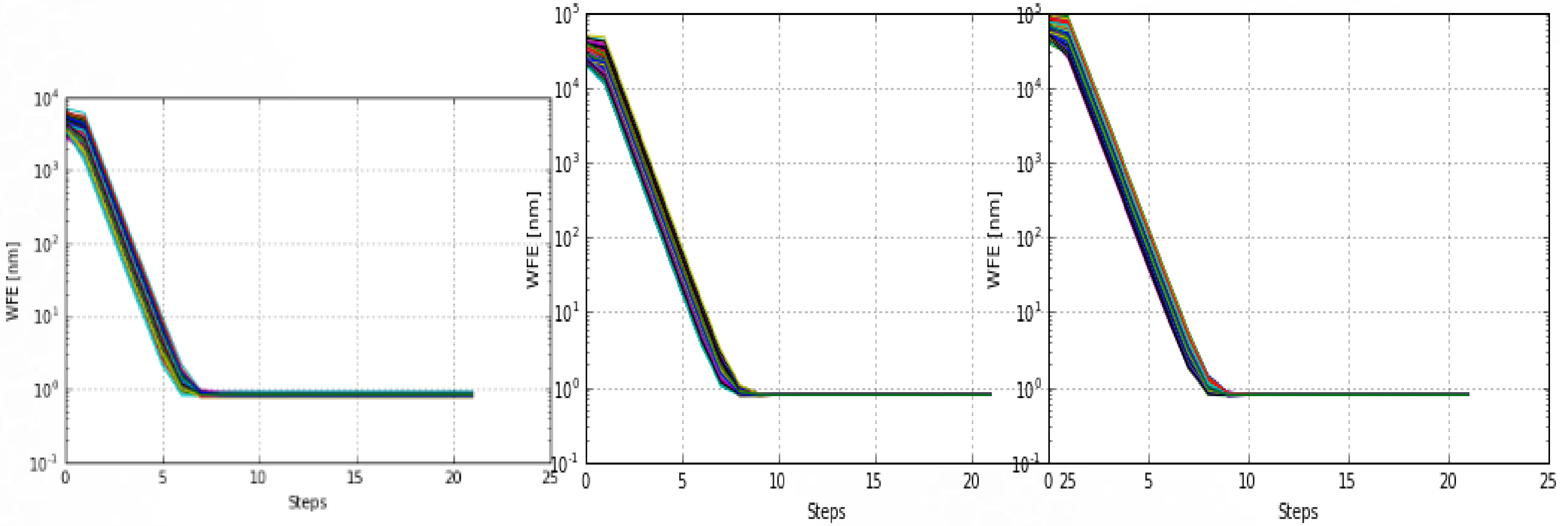






The Challenge

ELT's: A significant increase in absolute cost of lost efficiency from the existing generation of optical/IR telescopes:



	M1 Txyz[micron]	M1 Rxyz[arcsec]	M2 Txyz[micron]	M2 Rxyz[arcsec]
20micron	20	0.982	20	8.250
10micron	10	0.491	10	4.125
5micron	5	0.246	5	2.063

The Challenge

ELT’s: A significant increase in absolute cost of lost efficiency from the existing generation of optical/IR telescopes:

- For GMT a cost per hour of operating time based on production cost + operating cost is > $X0 000/ hour. Other ELT’s publish results significantly higher than this.

- Consider the mean cycle time for the AGWS to converge. Every cycle of mean cycle time consumes ~ 40 hours per year.

Strategy

GMT

General strategic approach to achieve robust and efficient performance: (margin, suppress aberrations at their source, margin, redundancy, margin etc…)

We conclude that relying on AGWS fed with open-loop starting points won't be good enough. Require some sort of metrology system.

The overall strategic approach to the "conflict" of aberration control (fight against entropy), well supported by certain historical works…

telescope alignment project

The art of ~~war~~ is of vital importance to the ~~State.~~ It is a matter of life and death, a road either to safety or to ruin. Hence it is a subject of inquiry which can on no account be neglected.

If you know both yourself and your enemy, you can win numerous (literally, "a hundred") ~~battles~~ without jeopardy.

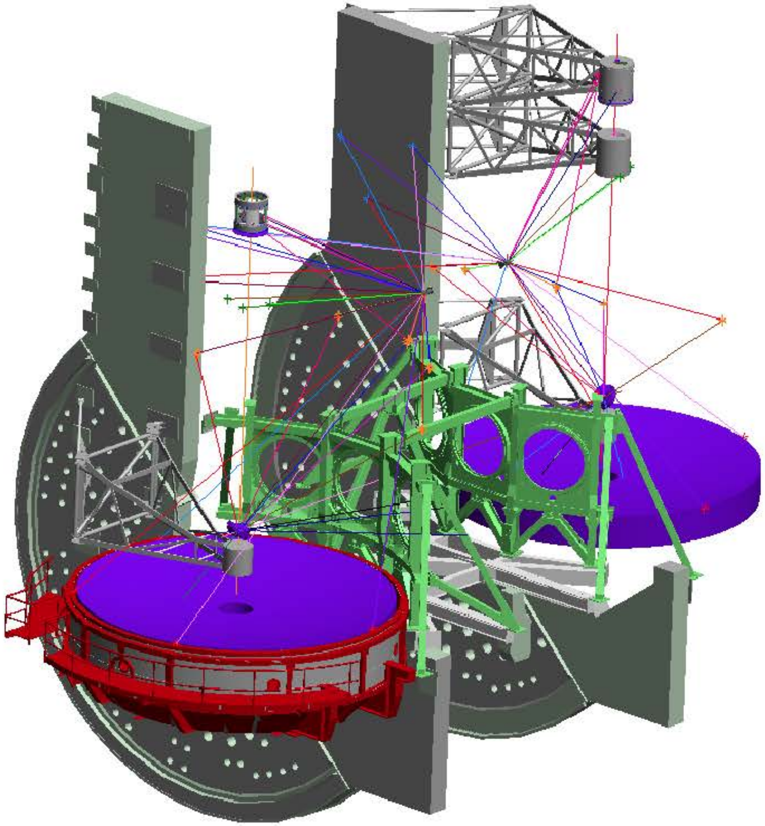
alignment cycles

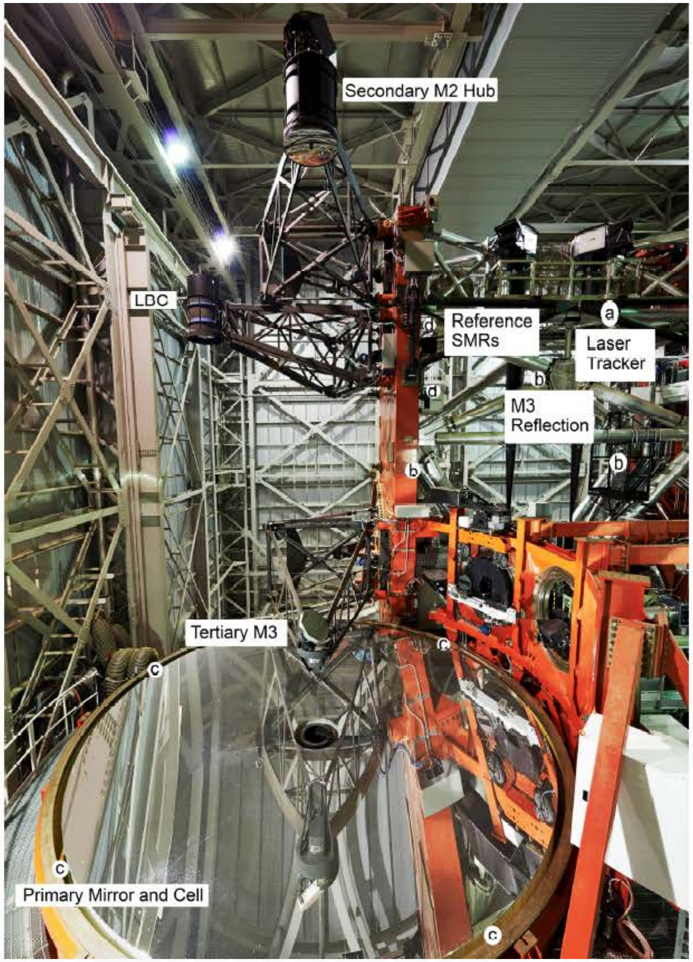
Telescope Alignment Telescope Alignment

2. **Waging ~~War~~ (Chinese: 作戰, 作战)** explains how to understand the economy of ~~warfare~~ and how success requires winning decisive engagements quickly. This section advises that successful ~~military~~ campaigns require limiting the cost of competition and conflict.

Telescope Alignment

Choice of weapons: Laser Tracker Network





Choice of weapons: Laser Tracker Network

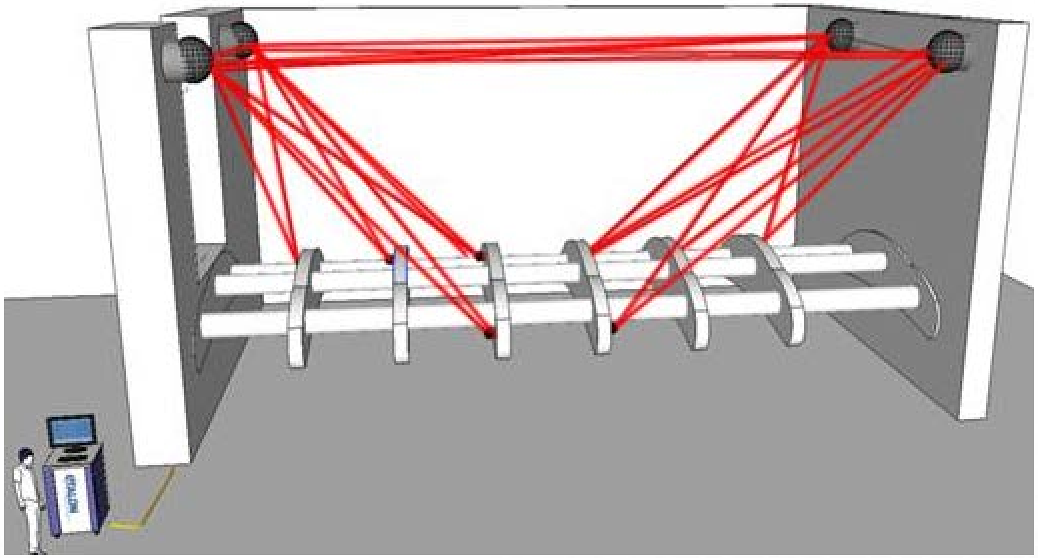
Laser Tracker Network:

Has been applied to telescope alignment but numerous “issues”:

- Multiple trackers required for segmented telescope: bare minimum 8.
- Heat source and stray light source on telescope
- Quirky: they are complex systems with motors, encoders, tracking systems etc., as well as the differential interferometer (IFM) and ADM systems, with everything having to work in harmony for a good result.
- Failure modes often degrade performance before killing it.
- Required spares ~ 2 trackers, total now 10 trackers ~ $1 000 000
- Not been used for prolonged periods, with high I/O, in telescope environment.

Choice of weapons: Optical Truss

- An optical truss based on a network of Absolute Distance Meter beams offers an attractive alternative to Laser Trackers.



Choice of weapons: Optical Truss

A fundamental difference between an optical truss and a laser tracker network:

Truss is “sit and stare”: Passive

Laser trackers are built to move, and have to measure a number of points sequentially: Active

Downsides of active metrology tool:

- moving parts = failure modes
- time taken to measure enough points for object position
- Heat source in telescope environment

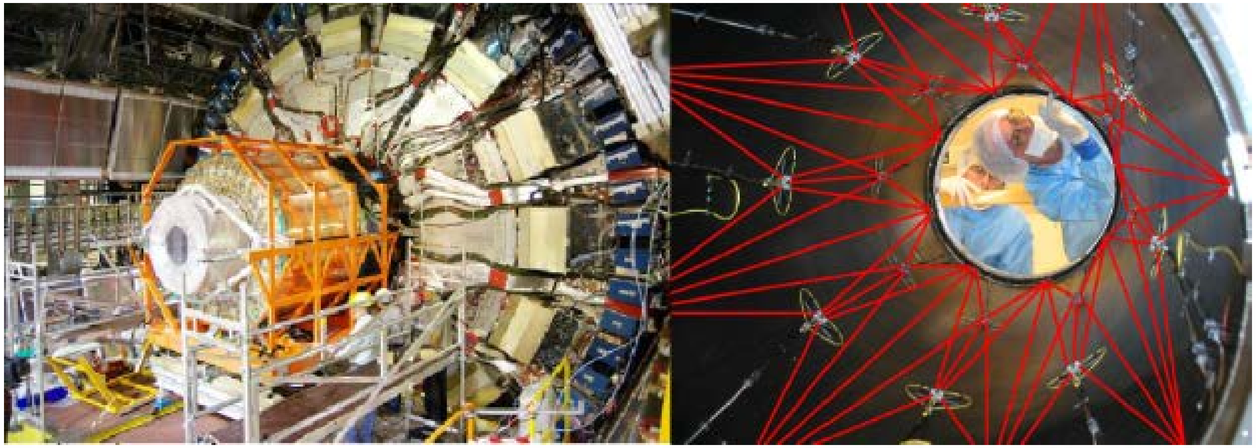
“Passive” metrology is better for a telescope environment

Etalon Ag: Absolute Multiline

- Absolute Distance Meter
- Central unit with up to 800+ independent channels (and extendable)
- Measurement uncertainty (99.7%) : 0.5 µm/m
- Maximum measurement frequency > 500 kHz over up to 2 seconds (with latency).
- Measurement length > 20 m
- Simple measurement channel consisting only of telecom fiber, collimator and triple reflector (no electrical systems at detector)
- Almost unlimited fiber length possible (several kilometers)
- Eye safe infrared radiation
- Metrological traceability by gas absorption cell
- All componentry based on “industry hardened” high I/O telecom equipment.

Etalon Absolute Multiline Technology

- EAMT is a commercialization of a metrology tool developed to meet metrology requirements for the ATLAS detector at CERN.
- In this system more than 800 lines keep detectors aligned within the particle accelerator to <1 microns absolute position error.

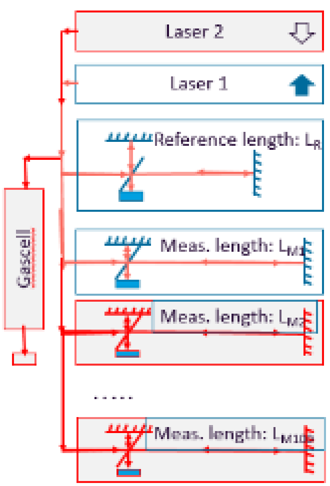


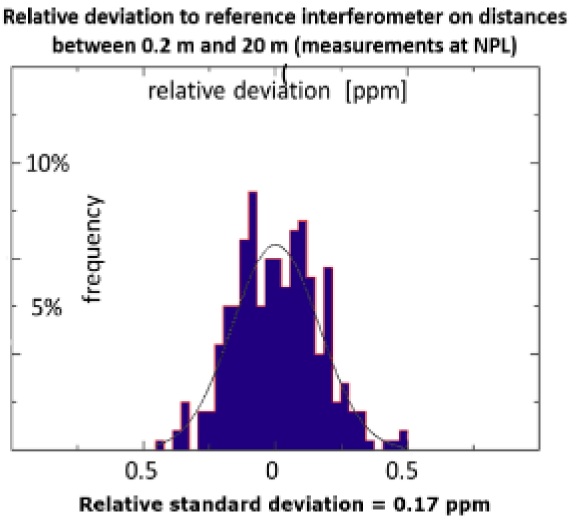
Commercialization: EAMT

- Improvements since the deployment at ATLAS in 2008 have led to new levels of accuracy that now approach theoretical limits.
- Most significantly:

a) the gas calibration cell stabilizes the laser simply and very effectively

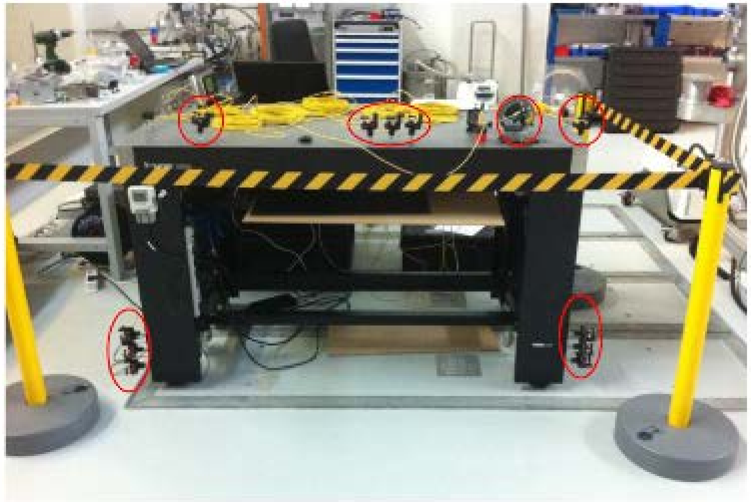
b) The two-beam dynamic scanning takes out target motion during measurement as an error source.





Special Tools: Evaluating EAMT

- Since 2014 ESO and GMTO staff have been investigating the potential of EAMT for ELT alignment.
- This is an example of a good “Beteiligungsgesellschaft”.



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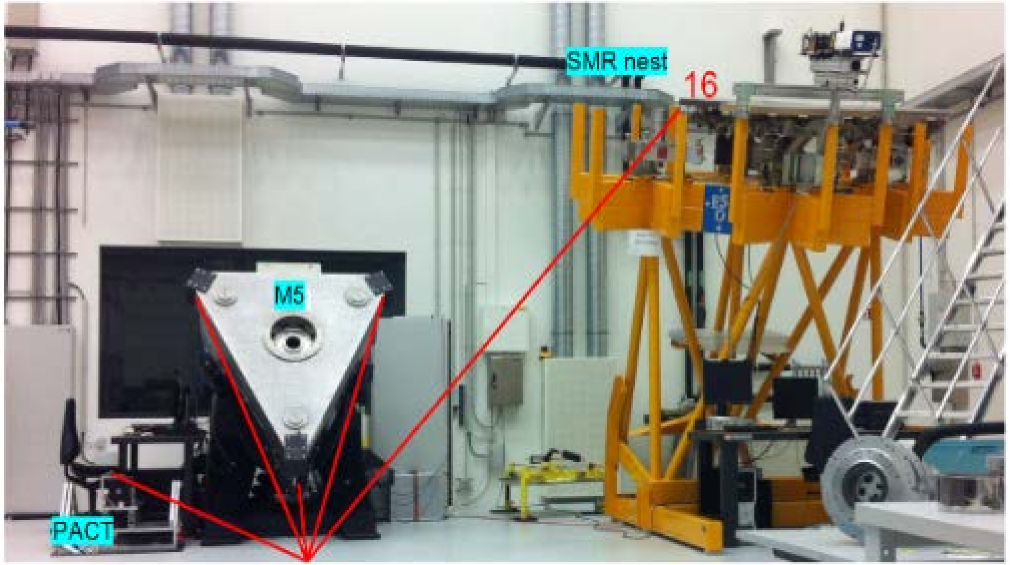
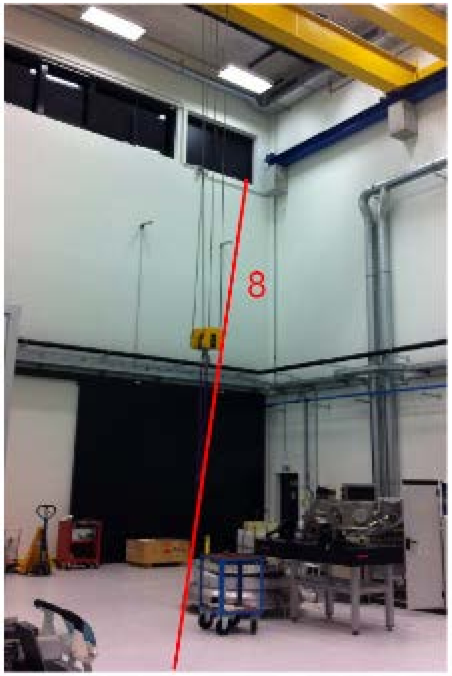


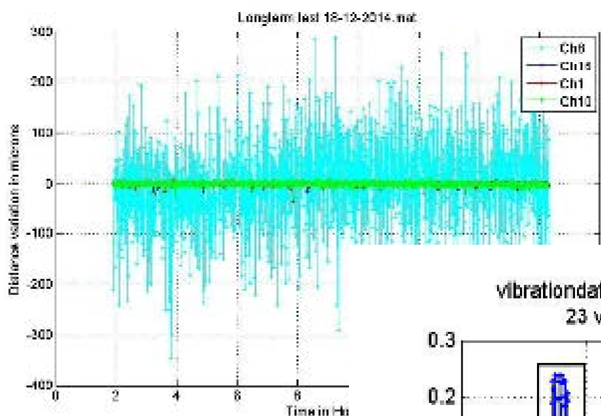


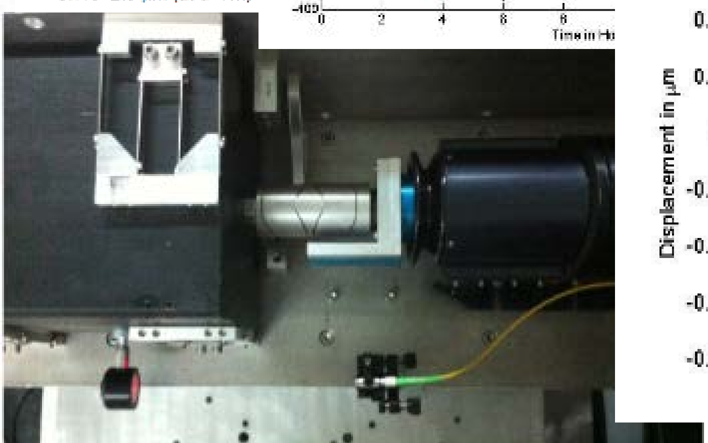
Evaluating EAMT

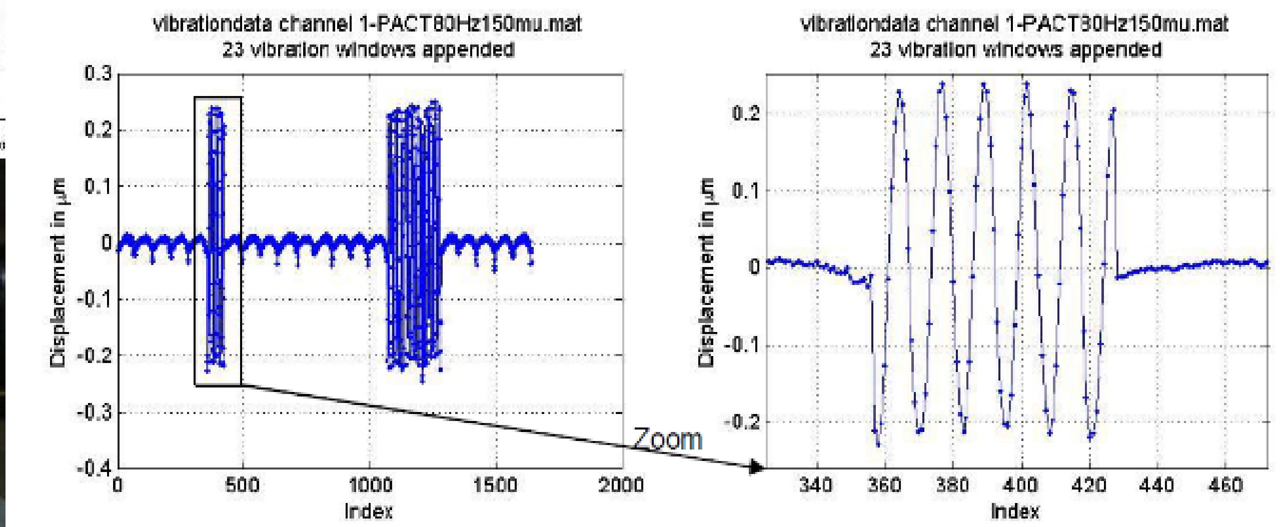
- Some spectacular results, seemingly far exceeding the manufacturers accuracy claims.

- In the expansion of this 80 Hz measurement (sadly not real time) all points on 200 nm amplitude curve at 200 mm range.

- Ch1=2.9 µm (at d~7m)
- Ch3=2.7 µm (at d~7m)
- Ch4=3.8 µm (at d~7m)
- Ch5=3.2 µm (at d~7m)
- Ch6=3.2 µm (at d~7m)
- Ch8=80 µm (at d~19.5m)
- Ch10=2.8 µm (at d~7m)
- Ch11=2.4 µm (at d~7m)
- Ch12=3.4 µm (at d~7m)
- Ch13=3.2 µm (at d~7m)
- Ch14=3.2 µm (at d~7m)
- Ch16=2.5 µm (at d~7m)

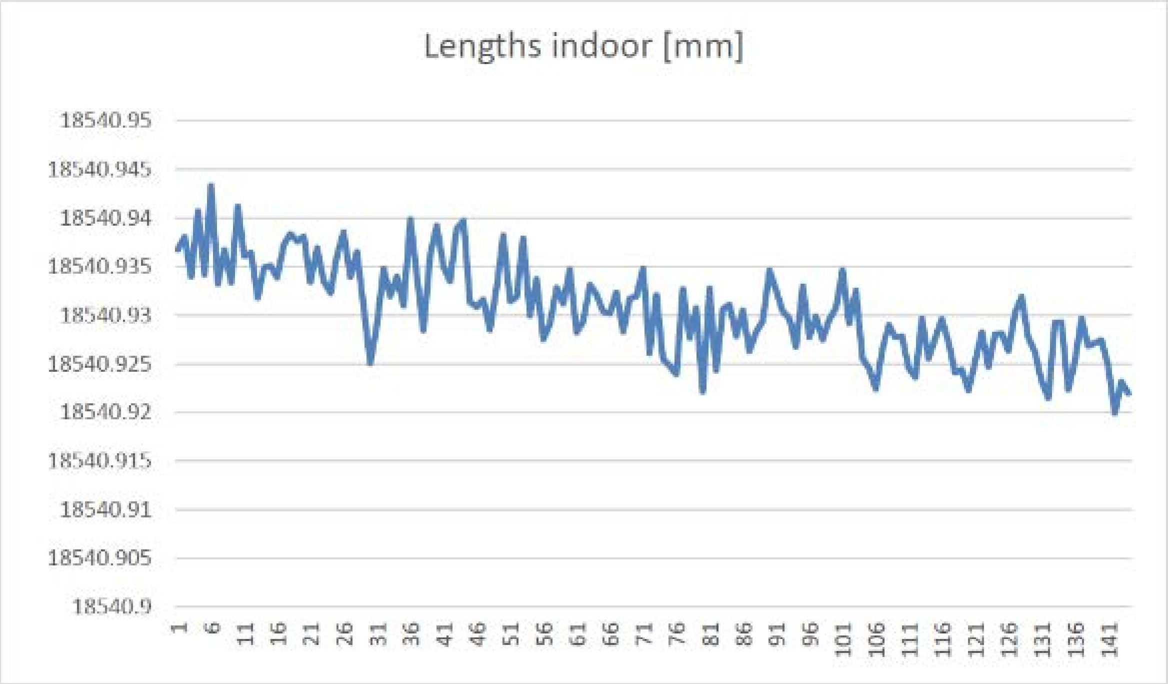






EAMT indoors test 30 minutes over 18.5 m

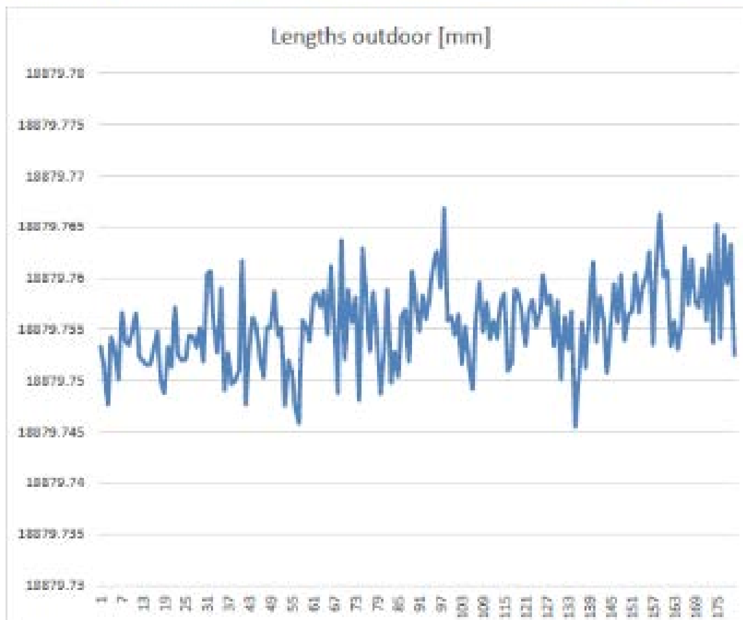
- Subsequent tests have confirmed accuracy and stability on long path measurements



⇨ Standard deviation: s = 5.0 µm

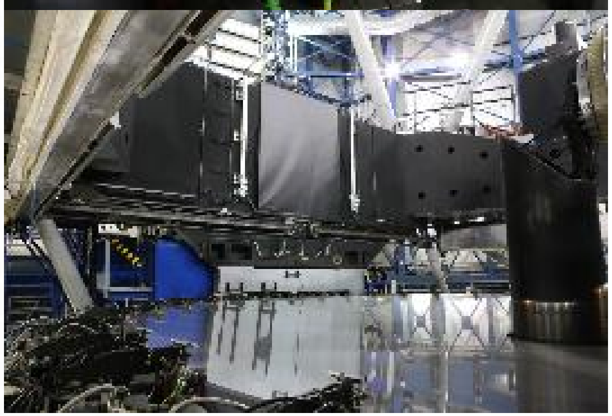
EAMT outdoors test 30 minutes over 18.5 m

Conditions 2: Outdoor, T=0.3-0.7 °C, Standard collimator, Open retro-reflector, 30 min, mild wind

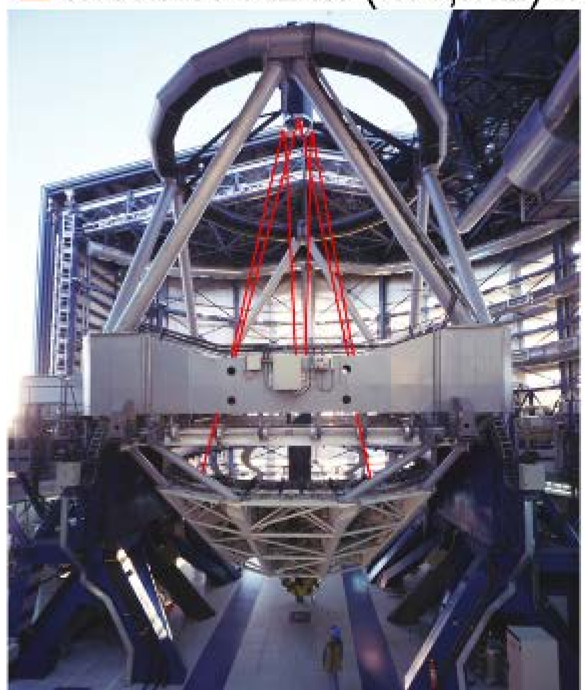


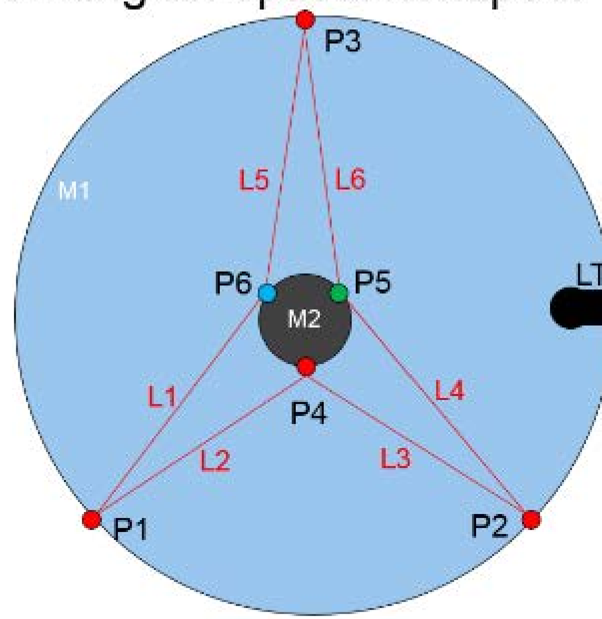
⇨ Standard deviation: s = 4.1 µm

EAMT test on VLT telescope.



- Monitor RBM (M1,M2) by forming an optical hexapod.



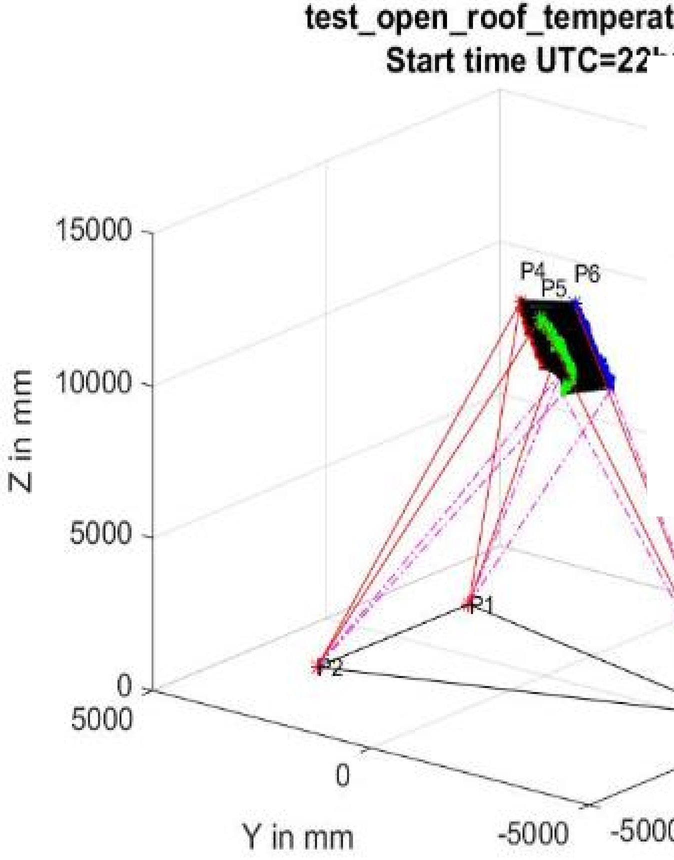


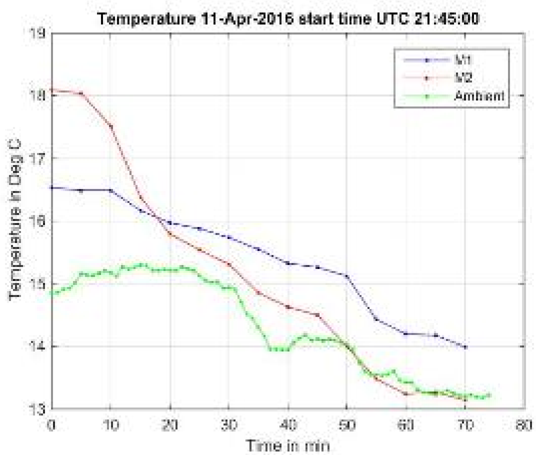
2nd Pacman Workshop 14/6/16

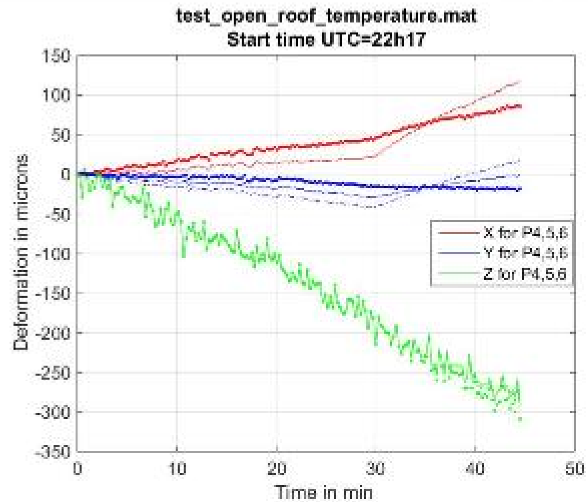
5

EAMT test on VLT telescope.

- Robustness in representative operational conditions: Dome opened, thermalization, wind speed 8 m/s)

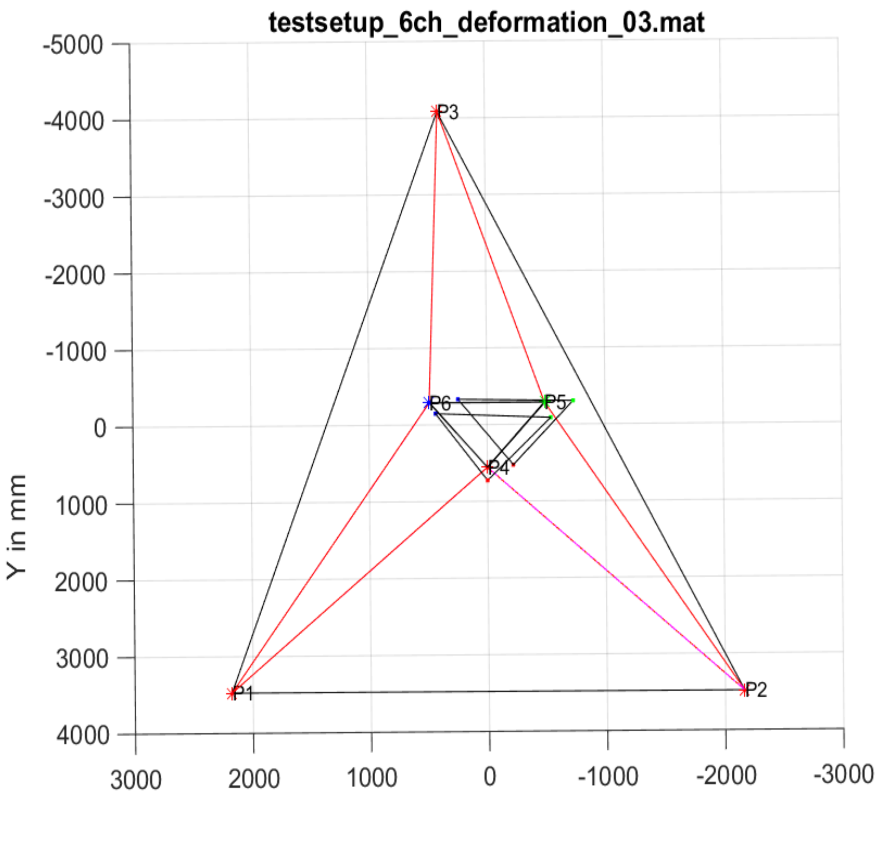


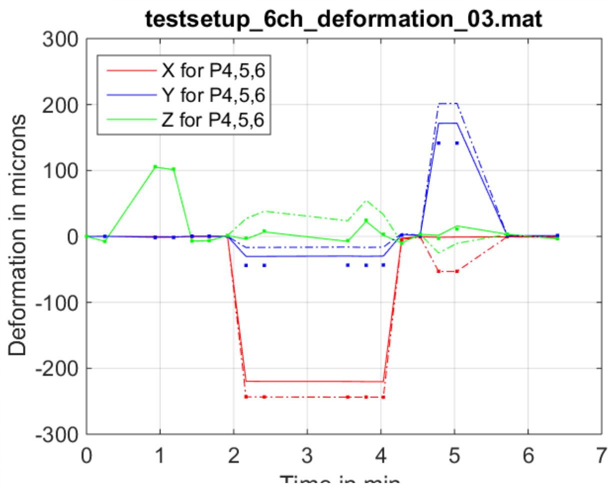


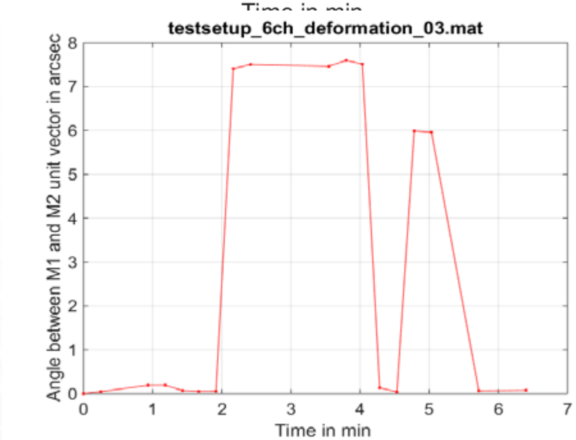


δZ=300 microns.
Steel structure CTE=12ppm/deg at d_{M1M2}=12m, , Expected ΔT=2 degC:
Fits well temperature recording !

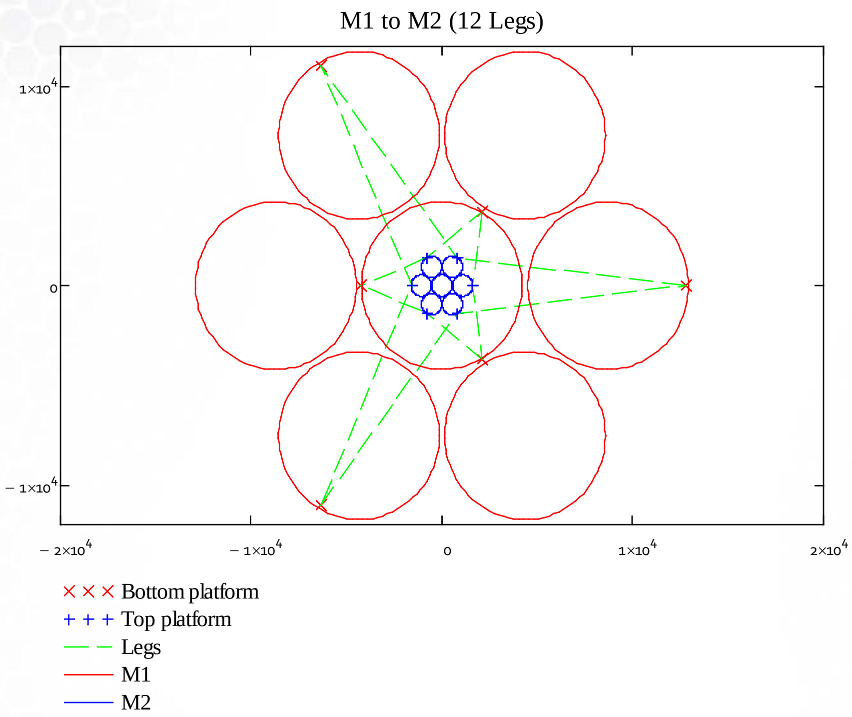
- Response to a small known motion of M2:
  - Δz=+0.1mm $\Delta\varepsilon$, $\Delta\delta$=10as at R_{M2}=4.553m (220μm)

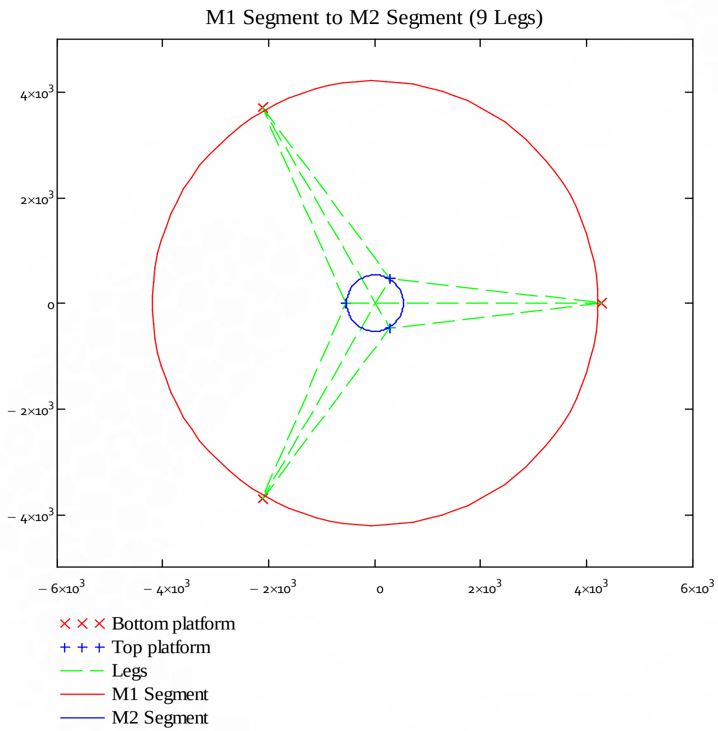






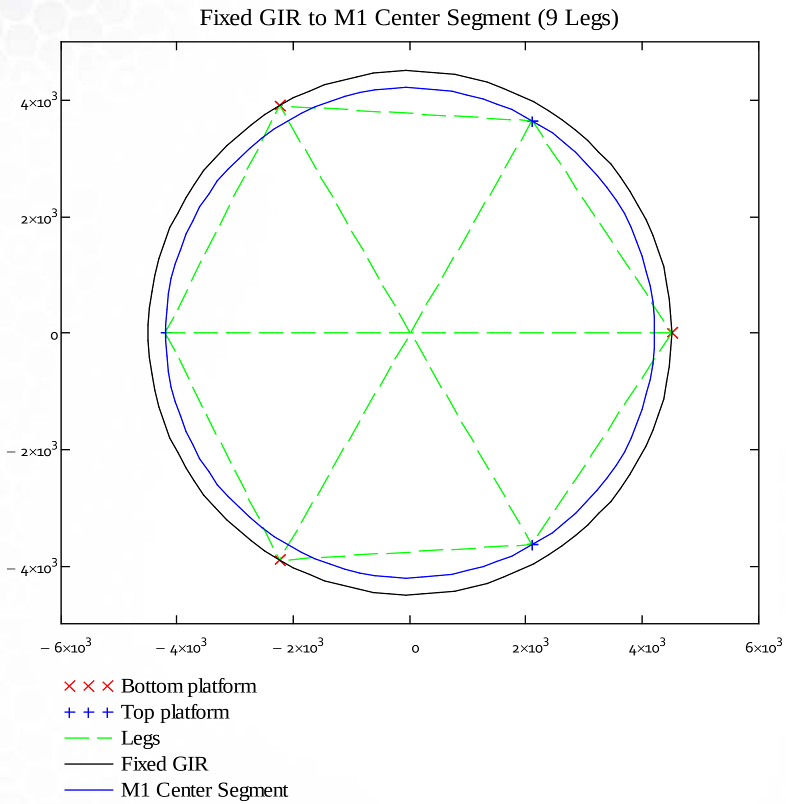
Truss Geometries – M1 to M2

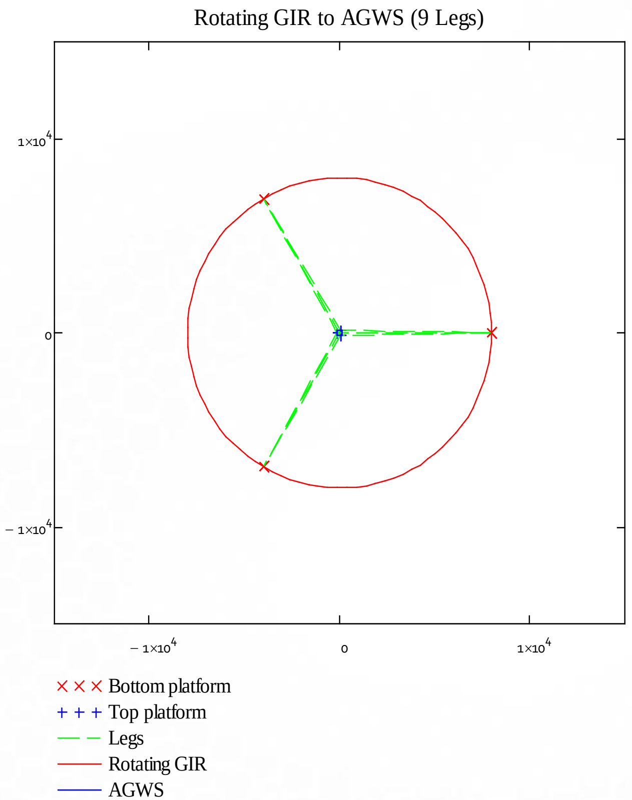




Truss	dX [micron]	dY [micron]	dZ [micron]	dRx [arcsec]	dRy [arcsec]	dRz [arcsec]
M1 to M2 (12 Legs)	4.316	4.296	1.165	0.219	0.217	0.402
M1 Segment to M2 Segment (9 Legs)	8.092	7.989	1.219	0.643	0.632	2.961

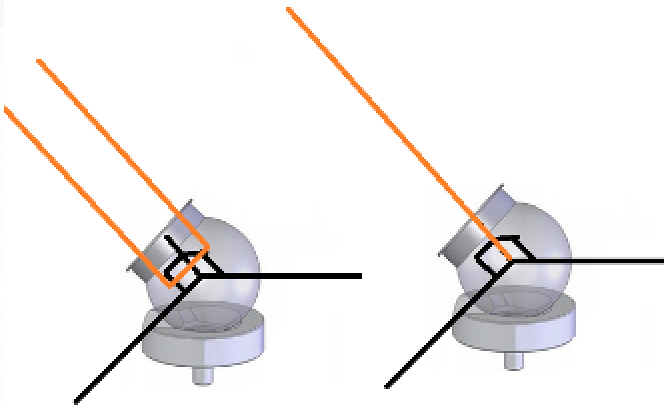
Truss Geometries – GIR to M1 and AGWS

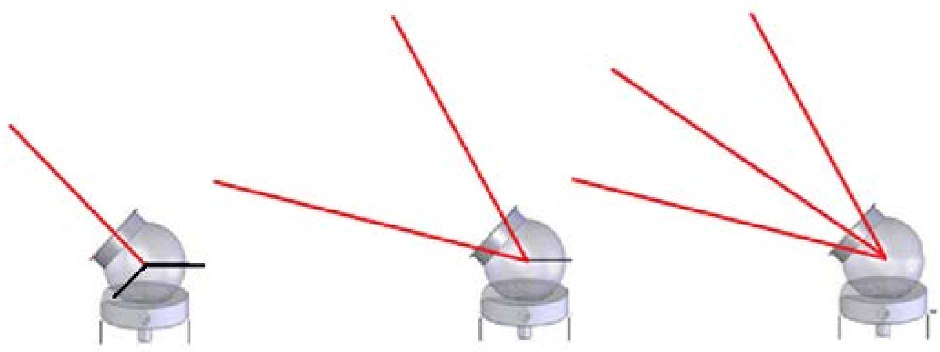




Truss	dX [micron]	dY [micron]	dZ [micron]	dRx [arcsec]	dRy [arcsec]	dRz [arcsec]
Fixed GIR to M1 Center Segment (9 Legs)	1.009	1.02	0.614	0.048	0.047	0.038
Rotating GIR to AGWS (9 Legs)	0.895	0.887	1.009	1.935	1.961	1.201

Special Tools: Optical Truss Geometrical Description.



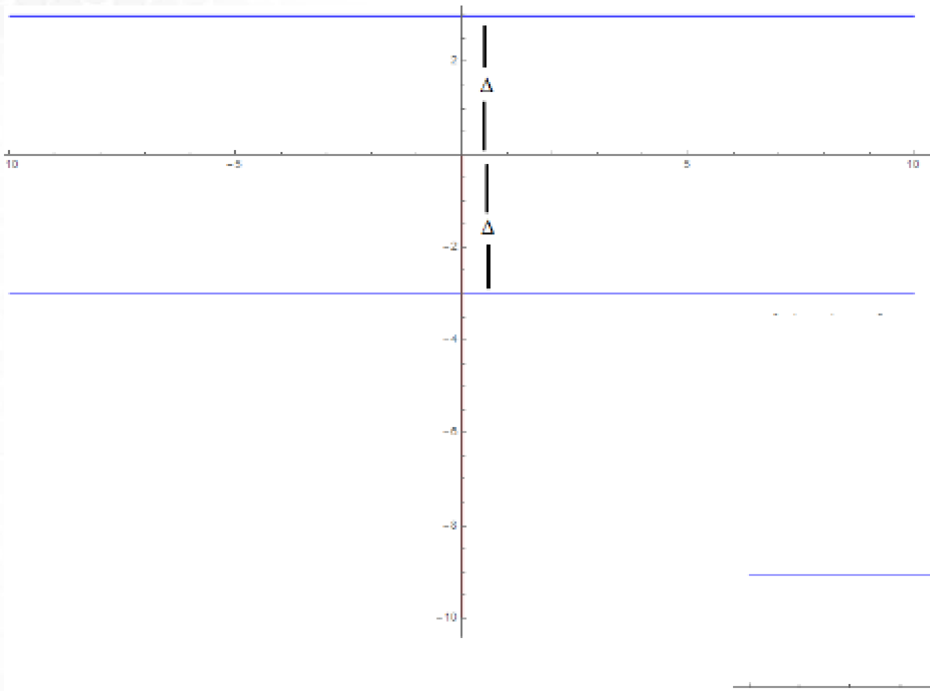


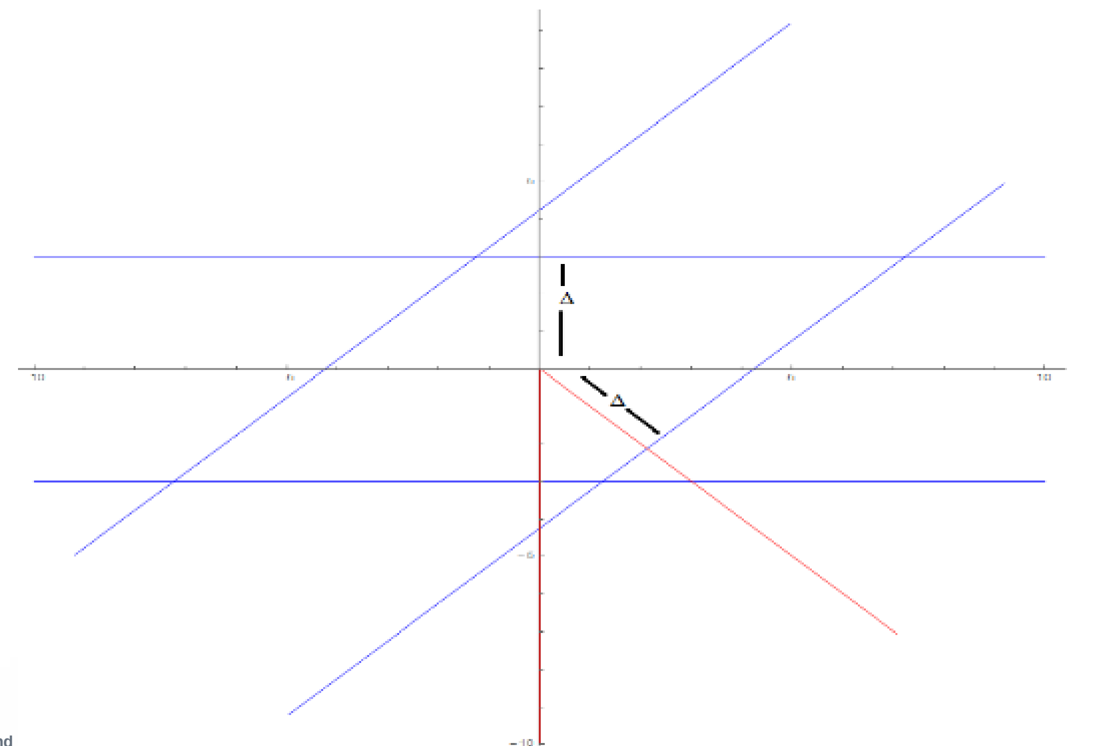
A) Simple Distance Measurement

B) Bilateration; SMR constrained in two dimensions

C) Trilateration; SMR constrained in three dimensions

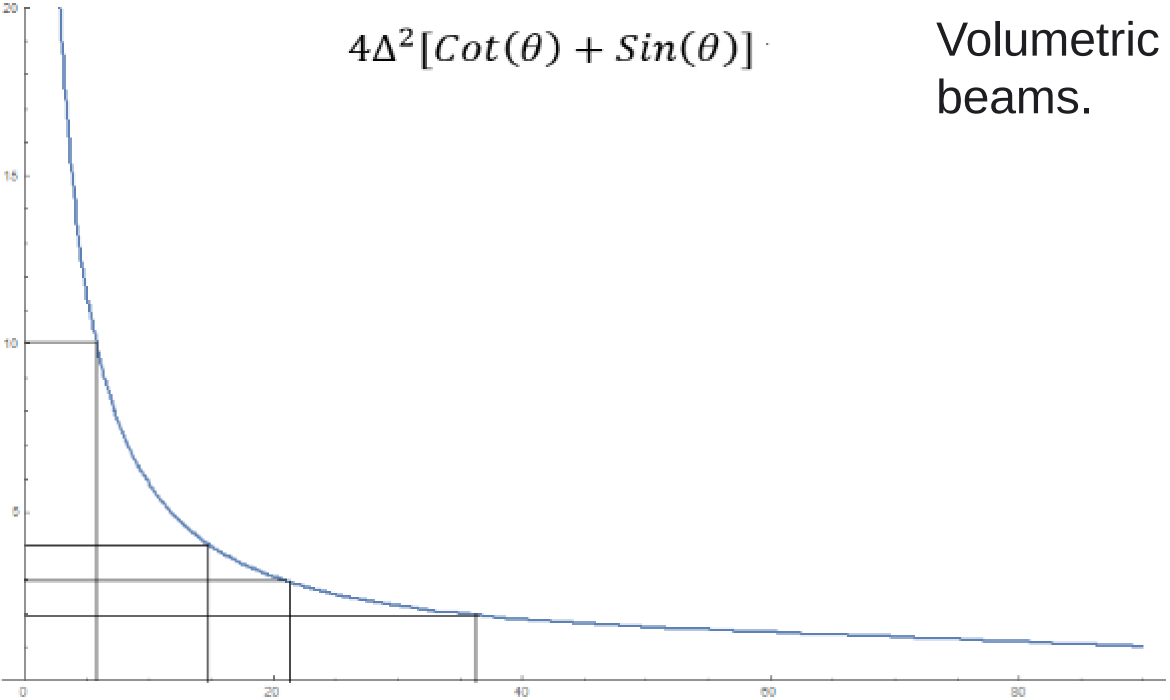
Special Tools: Optical Truss Geometrical Description.



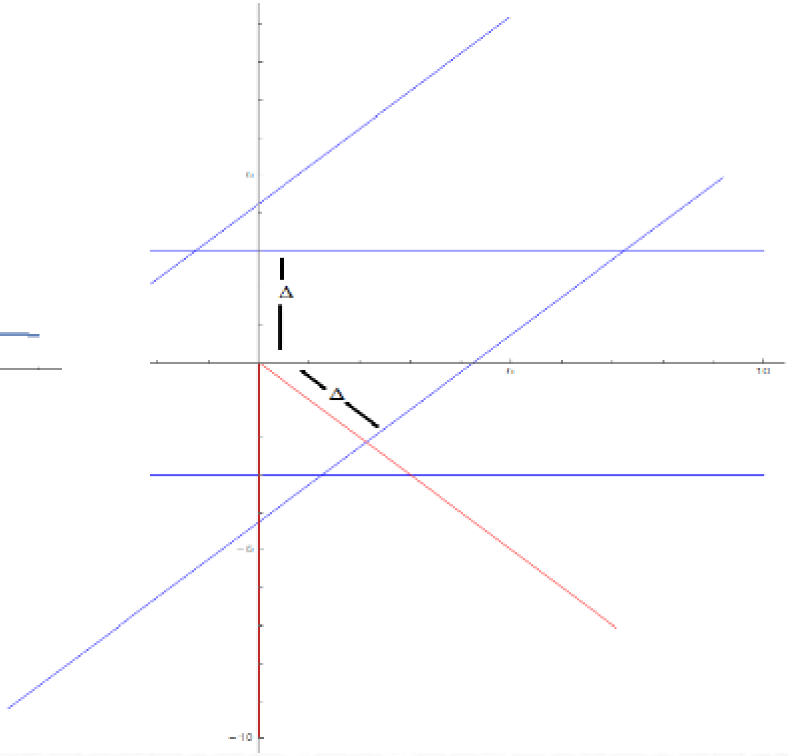


Special Tools: Optical Truss Geometrical Description.

$$4\Delta^2[Cot(\theta) + Sin(\theta)]$$

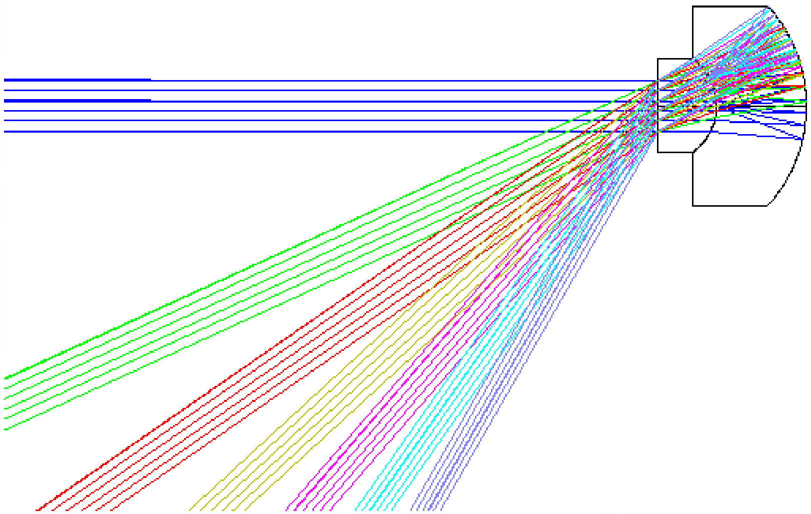


Volumetric uncertainty with AOI of two beams.



This volume of uncertainty for a laser tracker measurement of a retroreflector is ~100 times the volume of uncertainty achieved with 3 EAMT beams on the same retroreflector.

Special Tools: Optical Truss Geometrical Description.



50 mm diameter retroreflector concept based on solid Schmidt of Hendricks. Here no aspheres required, two difference glass types give spherical aberration correction.

Gives 14% return (good for Etalon) and 120 degree field ov view.

Results for quick comparison

Truss	dX [micron]	dY [micron]	dZ [micron]	dRx [arcsec]	dRy [arcsec]	dRz [arcsec]
M1 to M2 (12 Legs)	4.316	4.296	1.165	0.219	0.217	0.402
Fixed GIR to M1 Center Segment (9 Legs)	1.009	1.02	0.614	0.048	0.047	0.038
M1 Segment to M2 Segment (9 Legs)	8.092	7.989	1.219	0.643	0.632	2.961
M1 Segment to PMMS Platform (9 Legs)	6.364	6.443	1.091	1.257	1.238	5.349
M1 to PMMS Platform (9 Legs)	3.583	3.567	1.623	1.836	1.882	2.968
Rotating GIR to AGWS (9 Legs)	0.895	0.887	1.009	1.935	1.961	1.201

Measured Module	# Retros	Max Range (m)	Min Baseline (mm)	RSS Point Error (micron)	Decenter Error (mm)	Angular Error (arcsec)	Standard Zernike Coma (nm)	Focus (nm)	Pointing (arcsec)
WFS Capture							1000	3000	
Reference	6	10.24	1000	74.5	0.012	2.6	0	0	2.6
M1	4	12.08	2275	76.4	0.019	1.7	238	579	3.4
M2 decenter	3	6.63	125	43.3	0.014	23.8*	42	440	0.3
M2 angle	2	12.64	6111	50.8	0.025*	0.9	13	0	0.2
M3 RFBG	2	13.66	5041	54.0	0.027	1.1	0	8	0.1
M3 RCBG	2	14.58	6500	56.8	0.028	0.9	0	9	0.1
M3 RBBG	2	14.57	6474	56.8	0.028	0.9	0	9	0.1
FPIA Capture							2000	3000	
Reference	6	10.24	1000	74.5	0.012	2.6	0	0	2.6
M1	4	12.08	2275	76.4	0.019	1.7	237	583	3.4
LBC	3	6.17	372	43.3	0.014	8.0	104	427	0.7

*For reference only

EAMT results obtained on ~twice distance scale as LBT

Relative accuracies close to what was predicted in geometrical error analysis

(~$\sqrt[3]{100}$ linear error ratio)

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Requirements vs simulations for a TMS

"Crushing" alignment errors

Degree of Freedom	Requirement (1σ)	Design Estimate (1σ)
M1 x,y	≤ 75 μm	1.4 μm
M1 z	≤ 75 μm	0.87 μm
M1 Rx, Ry	≤ 0.375 arcsec	0.068 arcsec
M1 Rz	≤ 0.375 arcsec	0.054 arcsec
M2 x,y	≤ 75 μm	8.2 μm
M2 z	≤ 75 μm	1.5 μm
M2 Rx, Ry	≤ 3 arcsec	0.64 arcsec
M2 Rz	≤ 3 arcsec	3.0 arcsec

Next steps.

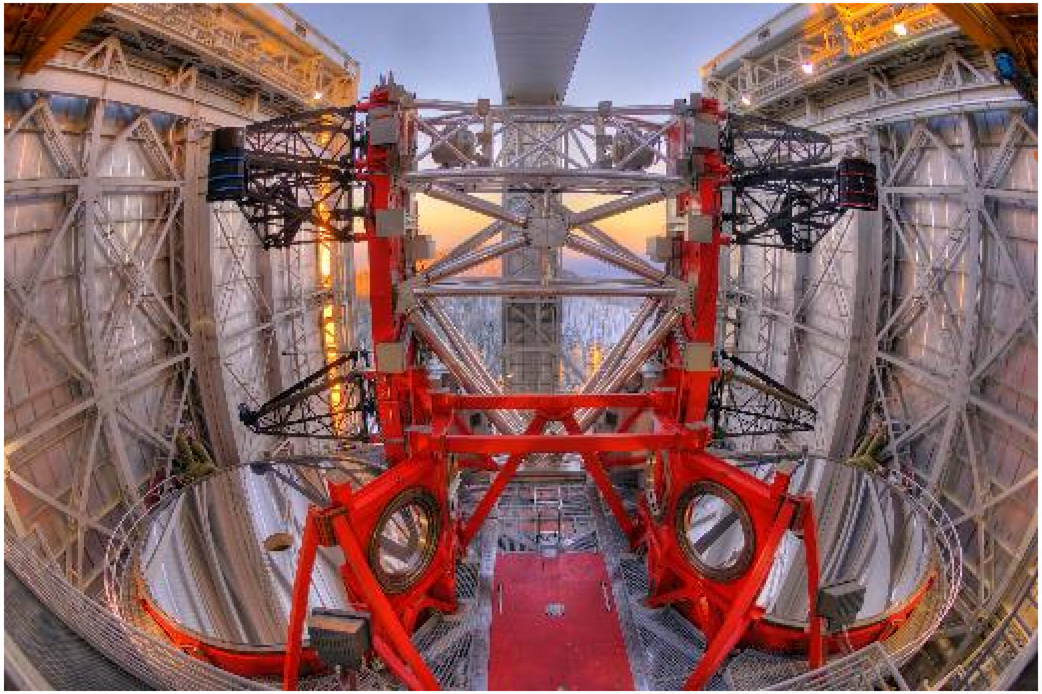
- Develop and refine simulation effort
- Extend teaming development approach to include other projects:

"Multiline ADM Engineering Network"

- Obtain unit .Develop skills, tools, experience of performance. "Boot Camp"
- Tests at Optical Sciences Centre on optical metrology test.
- Learn to "play the instrument". Explore new potentials offered. Dynamic, evolving look-up tables for example (structure grows "muscle memory")…
- Deploy on existing telescope (preferably LBT).
- Become "veterans" before GMT deployment.

Special Tools: Next steps. Get a unit. Put it on a telescope long term.

- Develop skills, tools, experience of performance
- Learn to “play the instrument”.
- Will be also beneficial to the lucky telescope that gets a system like this installed for free for long period (say ~ 1 year)…



Observations from this conference

- Traditionally Radio has been “relatively large and relatively imprecise” (compared to optical telescope requirements).
- In general does not seem to be a large amount of interaction between radio and optical telescope technologists. Of course there is interaction, but could be more.
- Radio pushing to more and more accuracy.
- Optical pushing towards large and larger aperture/structures.
- Our common ground is increasing. Seems like there is growing potential for fruitful information/technique exchange.

Movie