Measurement and Control of Large Telescope Surfaces CCAT example

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http://www.ccatobservatory.org

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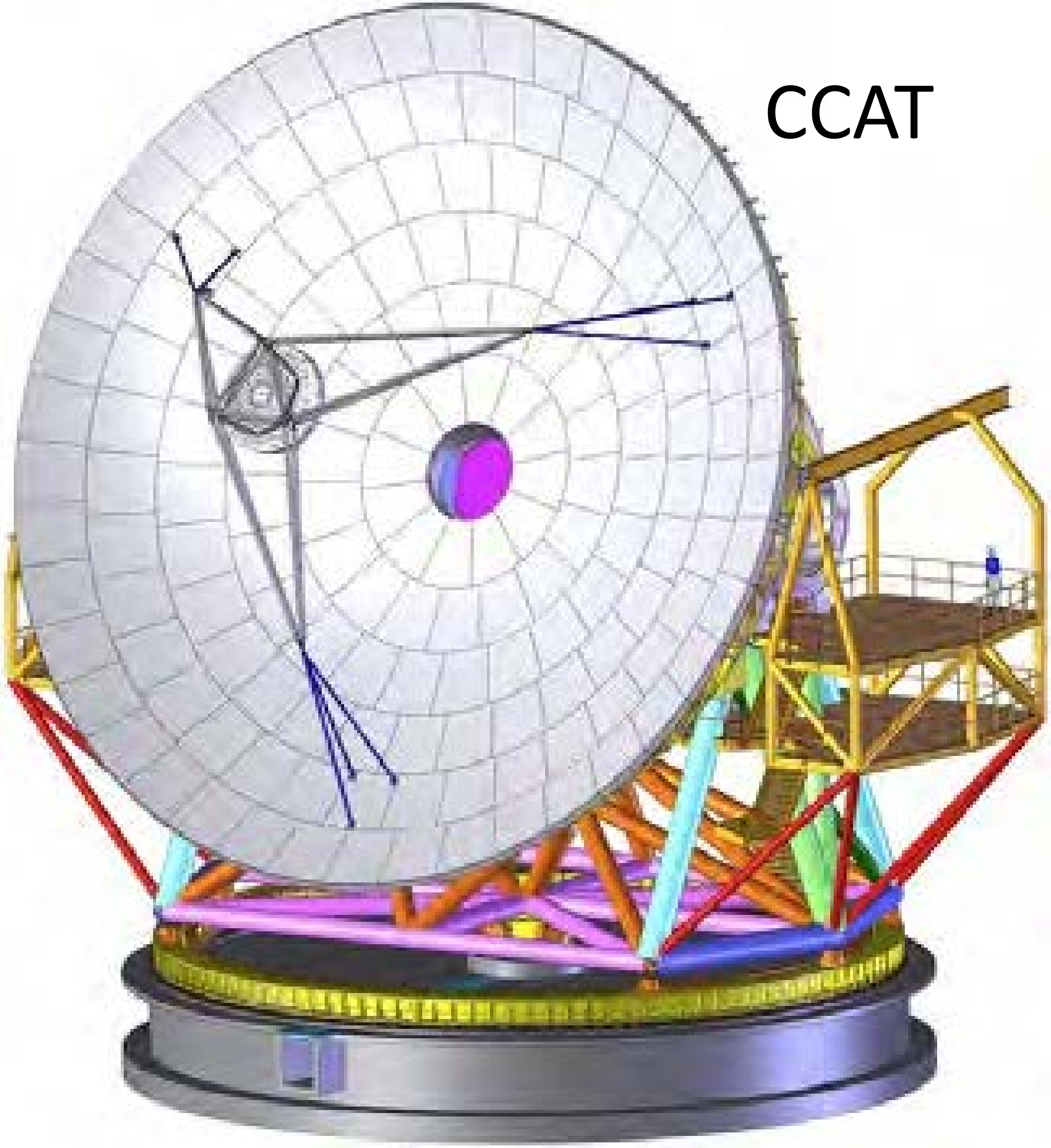


CCAT

25 m dia telescope on Cerro Chajnantor, 5612 m

Observe up to 350 μm
=> 12 μm RMS

CFRP primary support structure

162 compound segments, CFRP subframe with 16 machined Aluminum tiles

Active surface

In an enclosure, never sees the sun or high winds

Segments are critical

CCAT

- Only 9 μm RMS allocated to primary
- Segments < 4 μm
- Want largest possible segment to minimize parts count
- Segments also serve as the reference for any closed loop control using edge sensors (like ULE segments on large optical telescopes)
- => 2 m x 2 m compound segments, CFRP subframe and machined Aluminum tiles

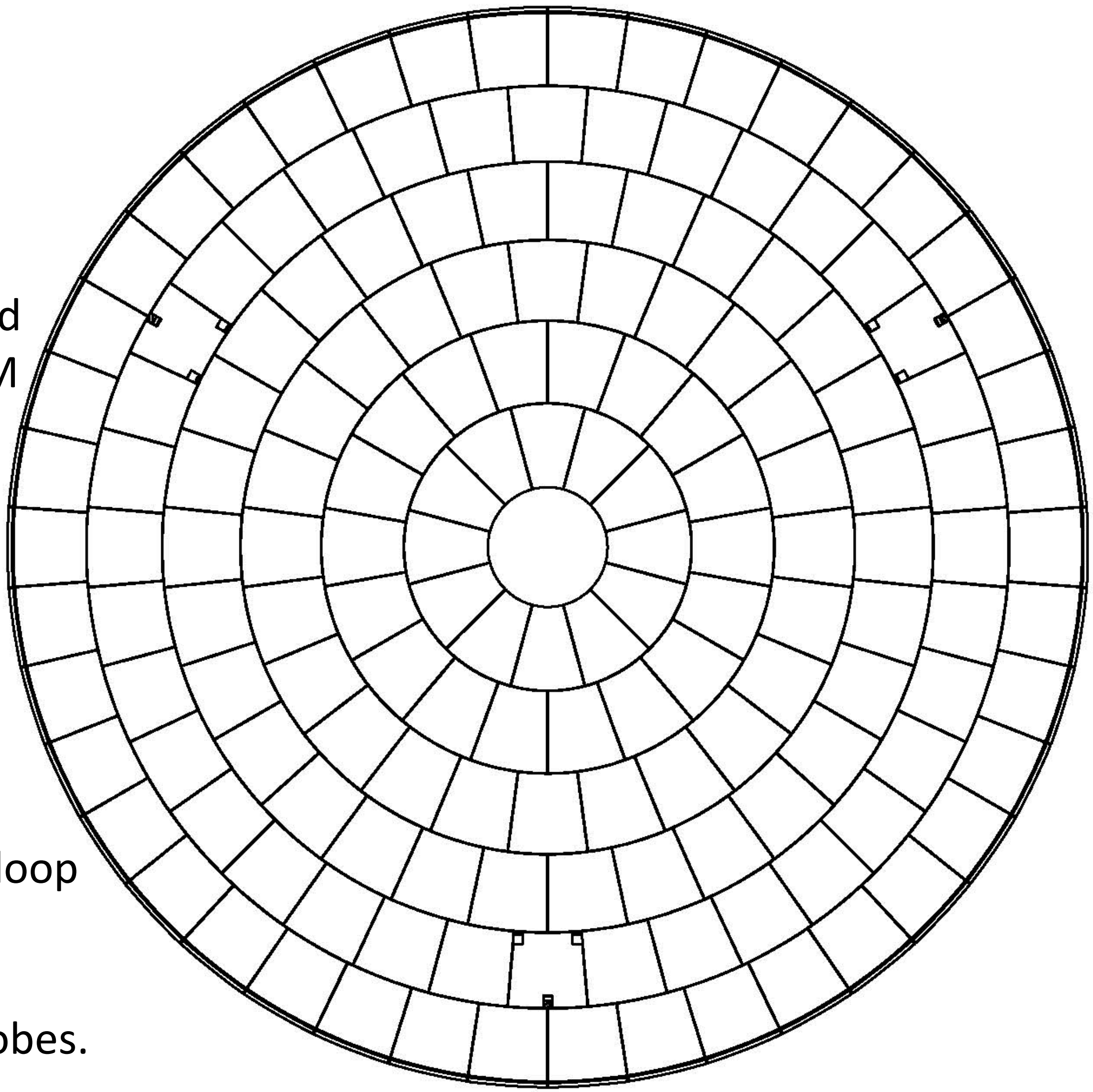
Segment configuration

162 segments in 5 rings

Segments fit in 2m x 2m box

Can be measured in standard CMM

No fold lines to improve closed-loop control.
Also decreases diffraction sidelobes.

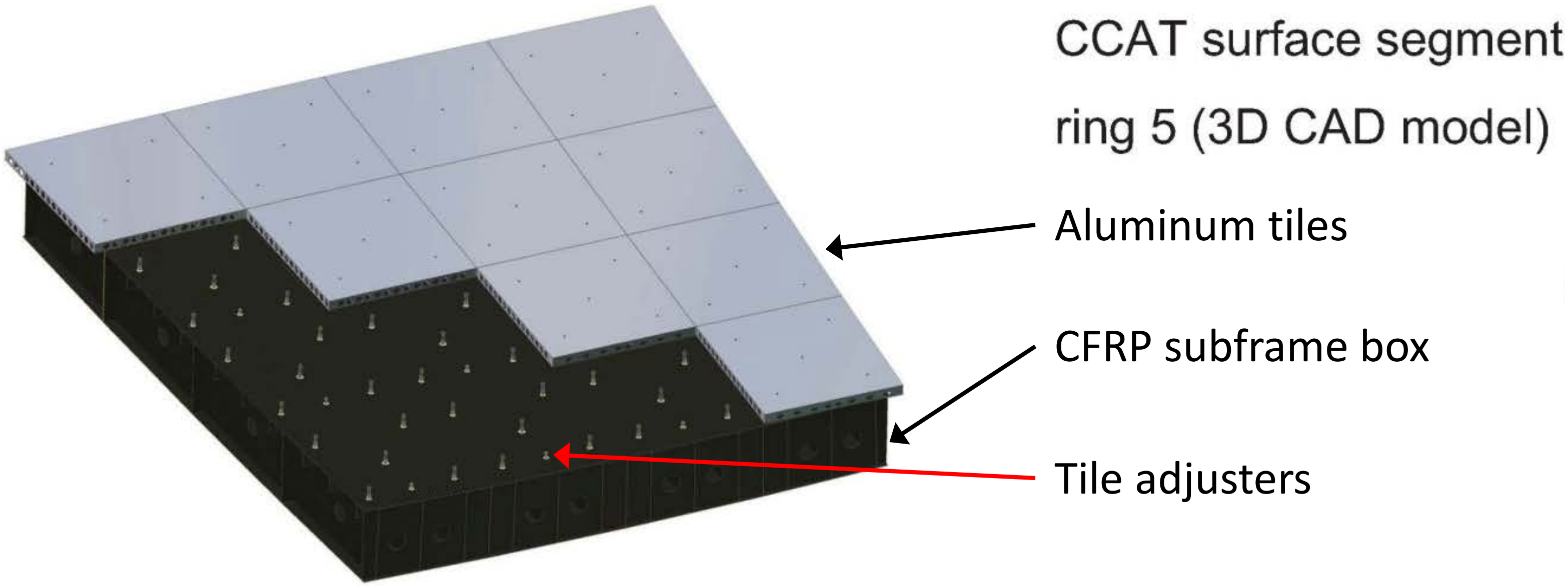


Each segment supported by three actuators

Goal of open loop control for gravity distortions

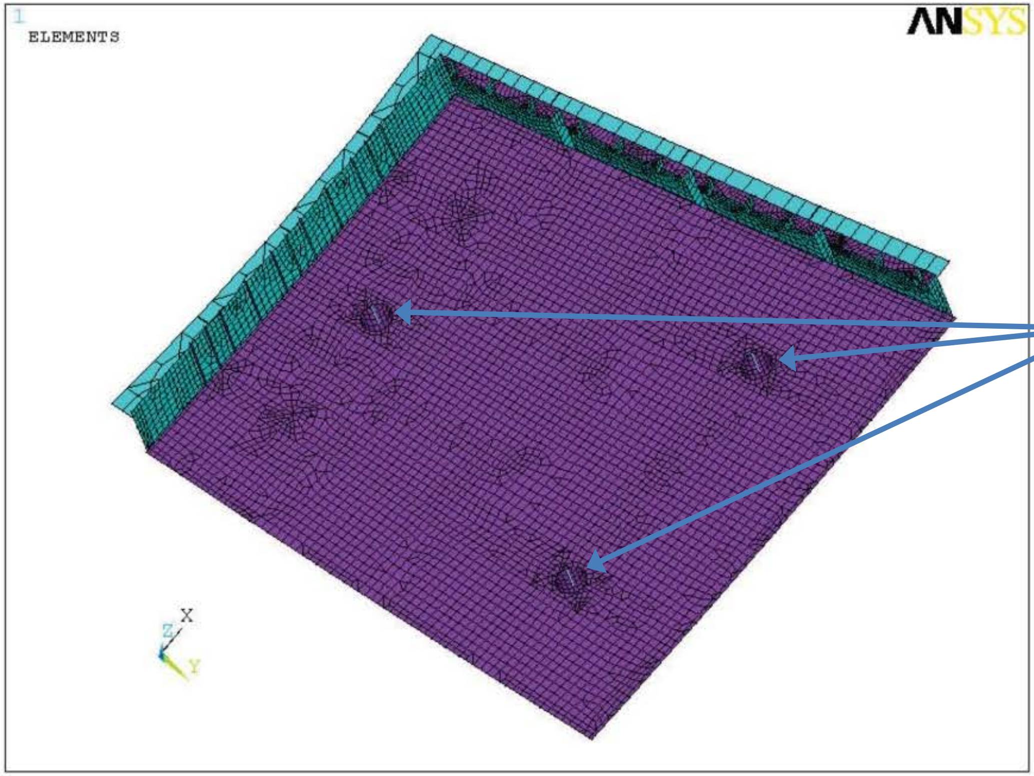
Plan for edge sensors and closed control if necessary

2. CFRP Subframe



VERTEX ANTENNENTECHNIK

2. CFRP Subframe - FE Model



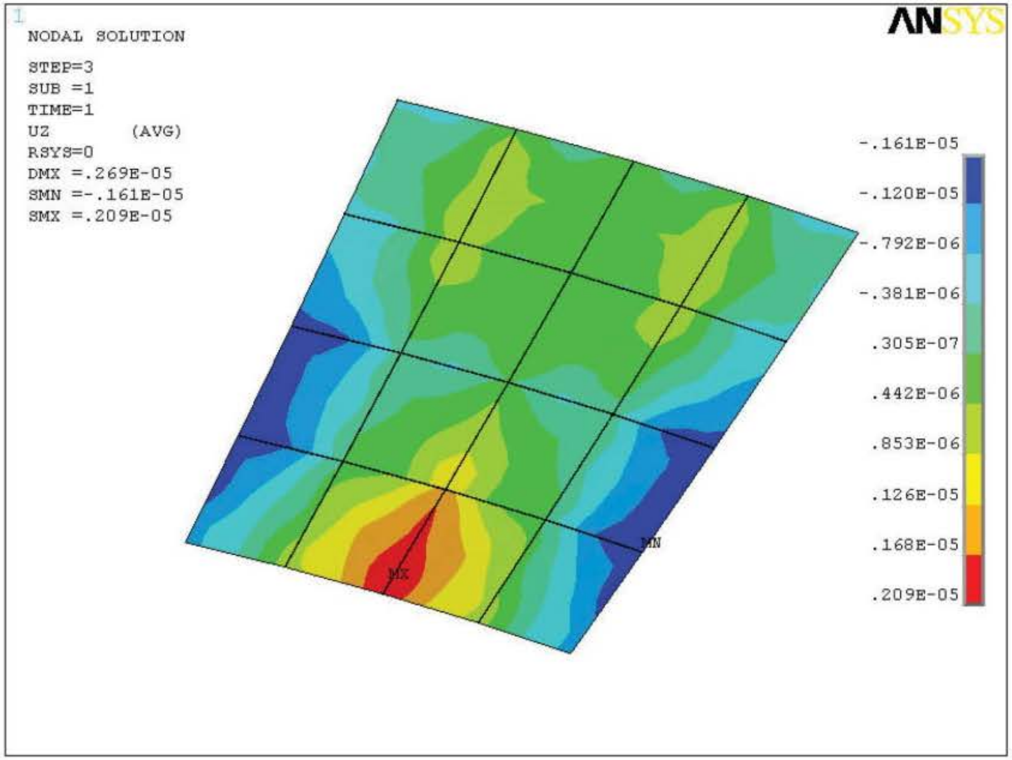
<u>segment (ring 5) rear view</u>

FE model including:

- double curved CFRP subframe
- actuator connection (subframe)
- panel adjusters (xy, x, z)
- aluminum tiles

total segment weight as modeled:
66.9 kg (19.4 kg/m^2)

2. CFRP Subframe - Exemplary Displacement Plots (K63712 prepregs)



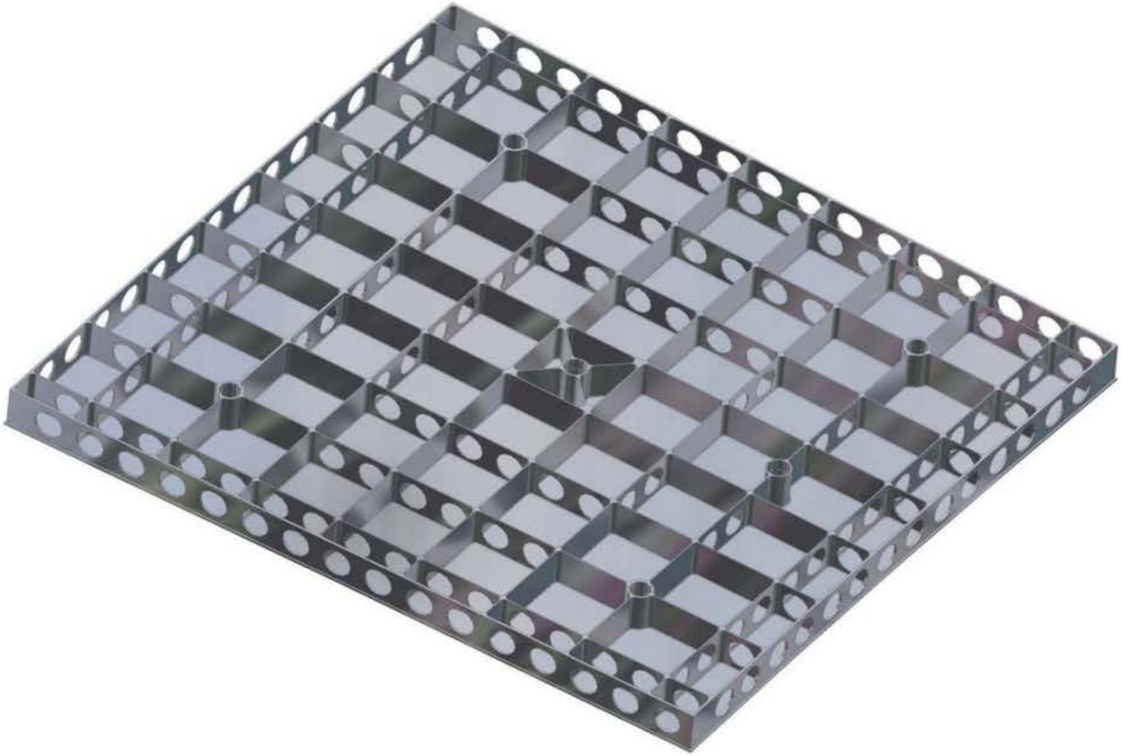
LC3: gravity along zq (actuator axis)

normal-to-surface best-fit dev. [m]

rms surface error = 0.7 µm (001110)

VERTEX ANTENNENTECHNIK

4. Aluminum Panels (tiles)



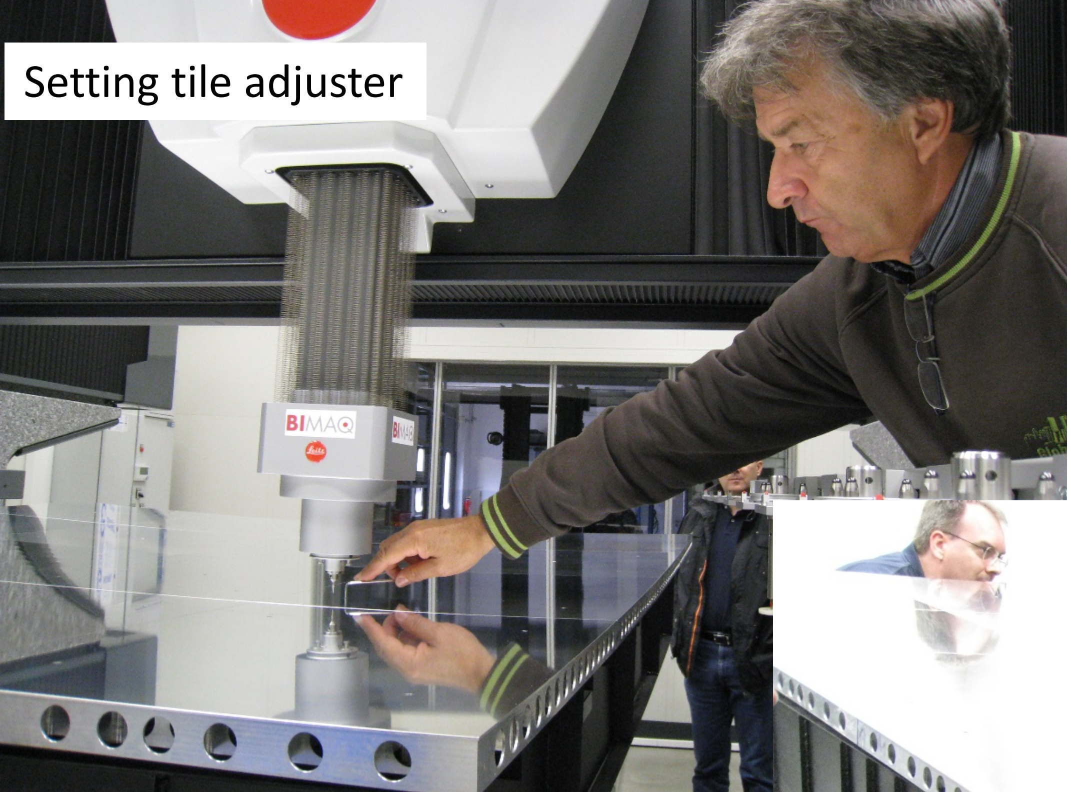
3D CAD model of largest panel of segment ring 5

Panel areal weight ≈ 6.7 kg/m^2

5. Surface Error Budget (K63712 fiber prepregs)

Error Source	Surface Error	Source
gravity, 20° EL to 90° EL	0.8 µm	FEA, active
ambient temp. change 20 K	0.7 µm	FEA, passive
temp gradient dDT/dz = 1 K	0.3 µm	FEA, passive
wind 1 m/s	< 0.1 µm	FEA, passive
flexure heating dT= 1 K	< 0.1 µm	FEA, passive
1 mm actuator stroke	0.8 µm	FEA, active
panels	3.0 µm	best manufactured to date
adjustment	2.0 µm	estimate
others	1.0 µm	estimate
Total (RSS)	**4.0 µm**	Spec.(CCAT) : rms!≤ 3.8 µm

Ring 5 segment

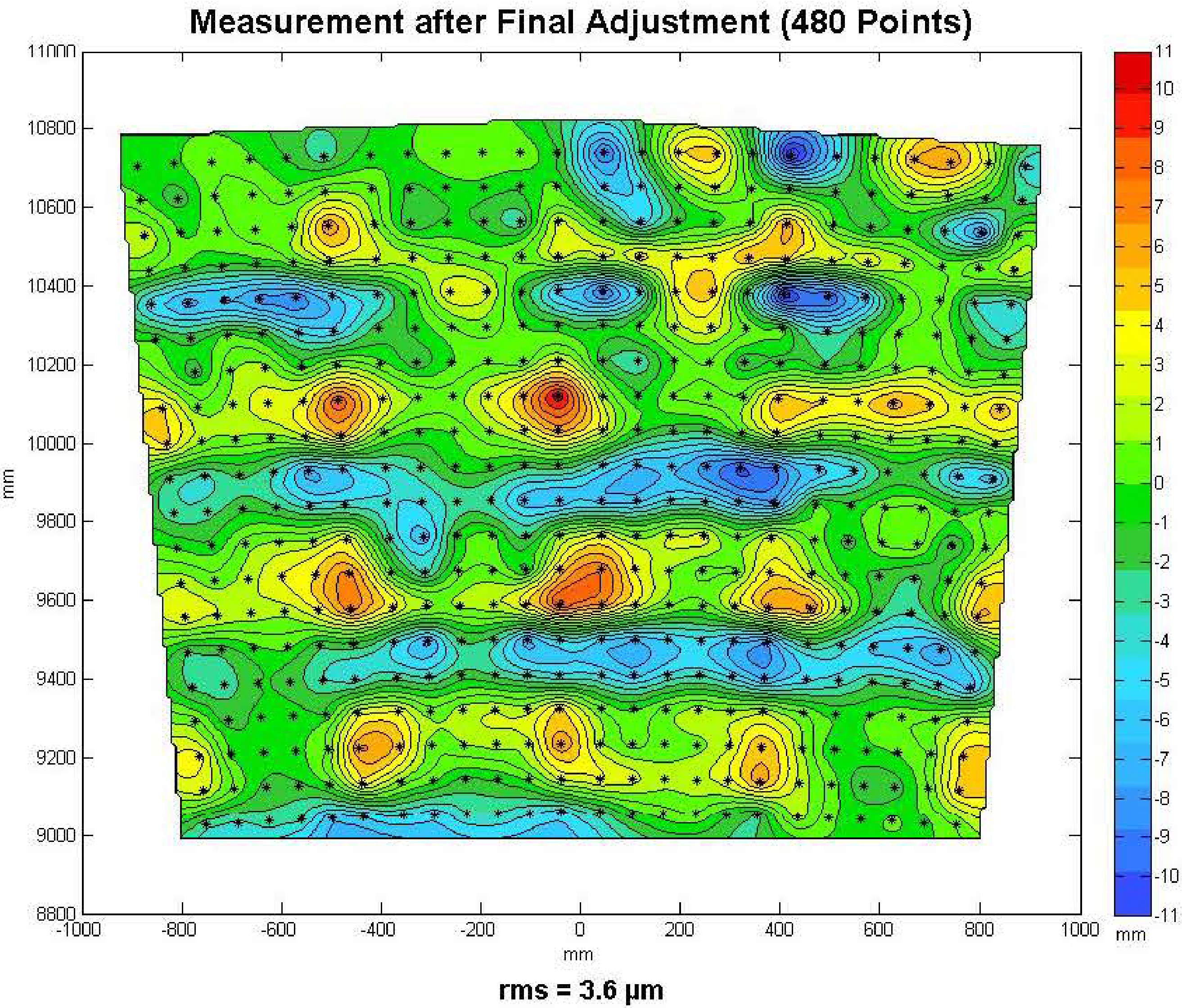


Setting tile adjuster

Weight 60 kg

Leitz 2m x 2m CMM in Bremen

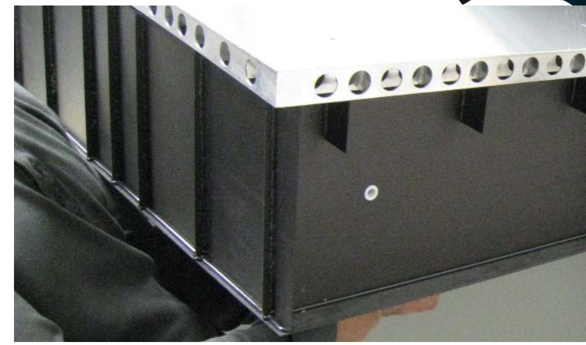
Ring 5 segment measurement

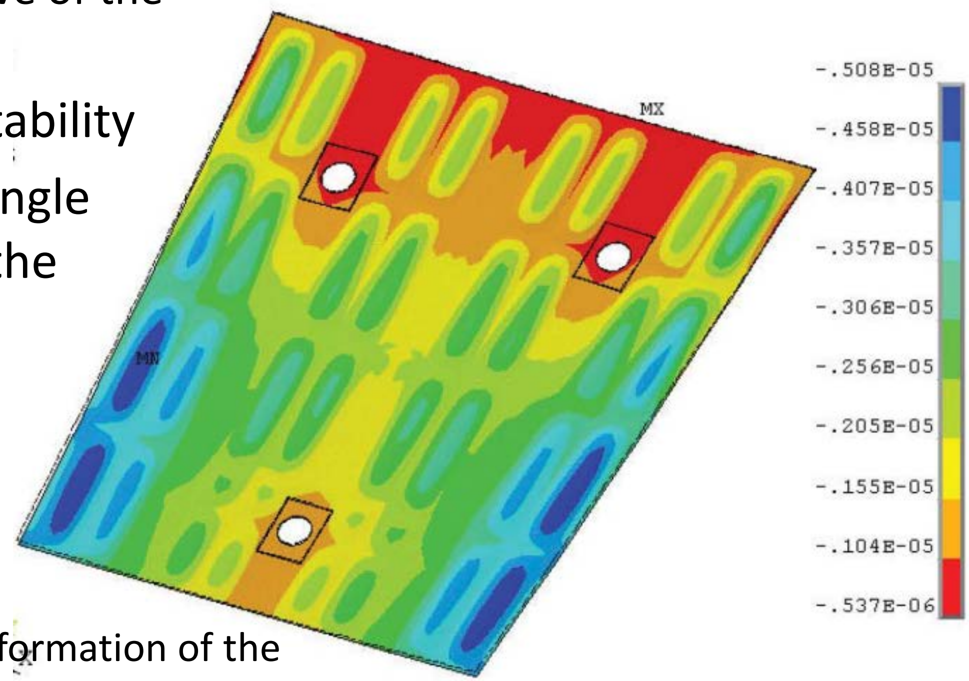


Rms = 1.1 μm at the 80 tile adjusters

Closed-loop control of segment actuators

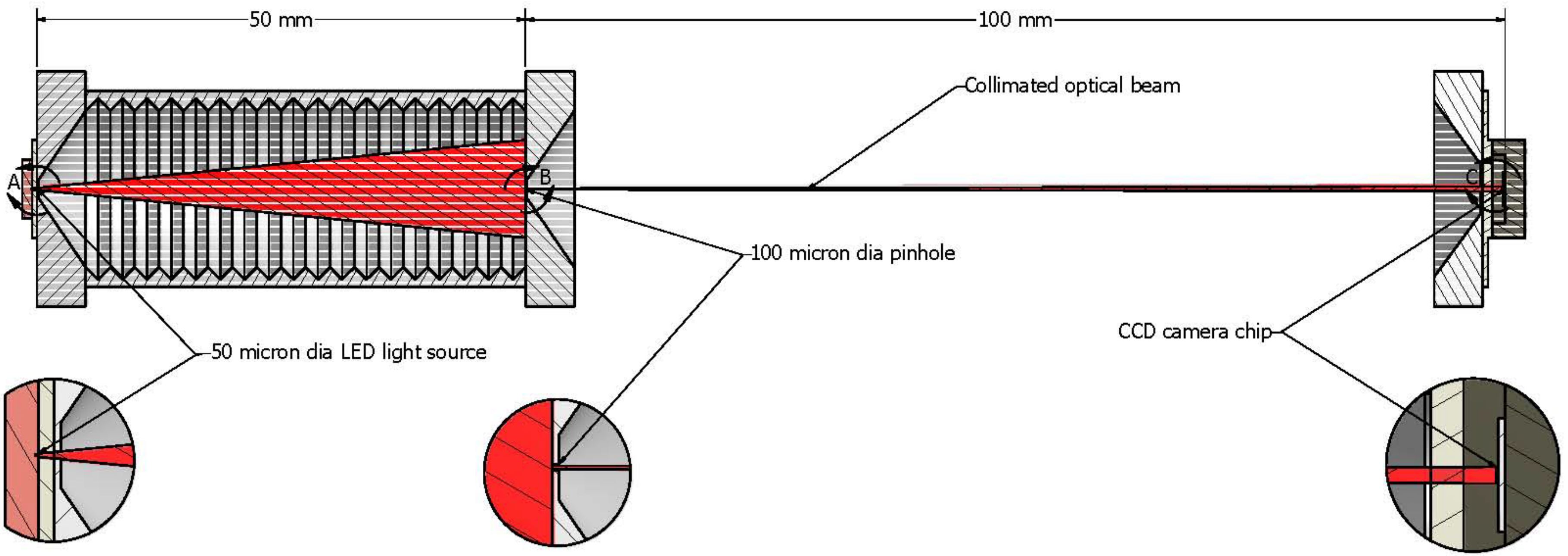
- Difficulties
  - Full wavefront measurements will be infrequent
  - CFRP sub-frames are not as stiff nor as stable as ULE glass
  - Segment edges are not representative of the whole segment
- Edge sensors need good long term stability
- Measuring more than just dihedral angle and piston displacements improves the surface control





Gravity deformation of the subframe backs side

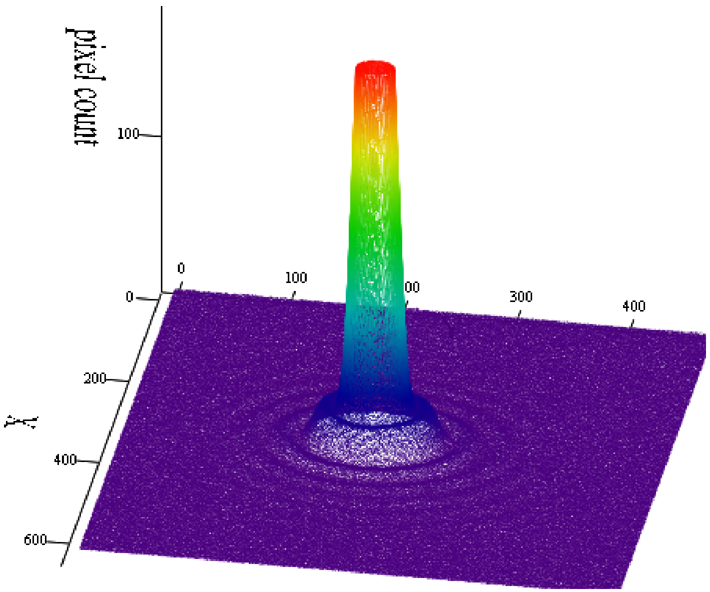
Imaging Displacement Sensor (IDS)



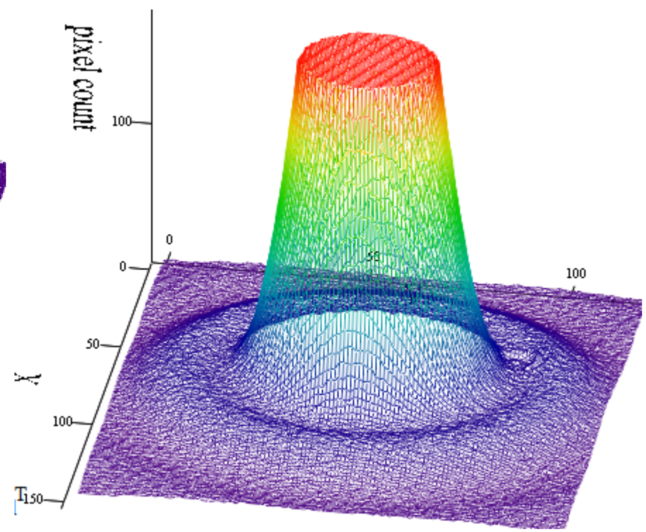
- Measures lateral displacements at a distance
- Exploit the precision lithography used for CCD or CMOS camera chips
- One device measures displacements in X and Y
- Inexpensive components, LED and standard monochrome VGA CCD
- Very simple and stable
- Single frame image centroiding error <1/100th of a pixel
  - Averaging multiple frames < 1/1000th of a pixel

Large saturated spot on CCD

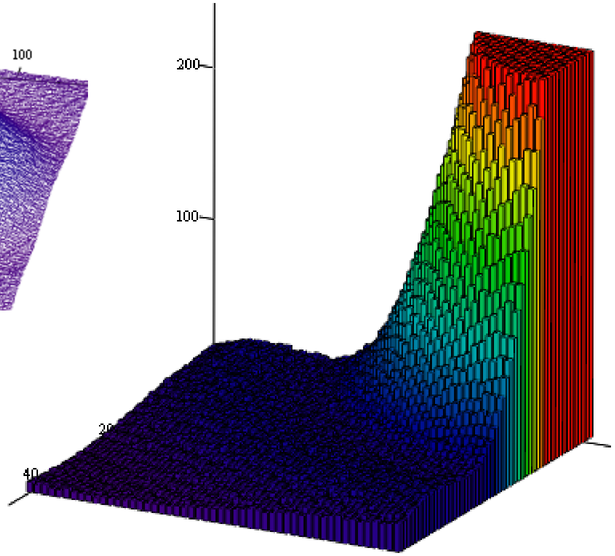
Full image, 640x480



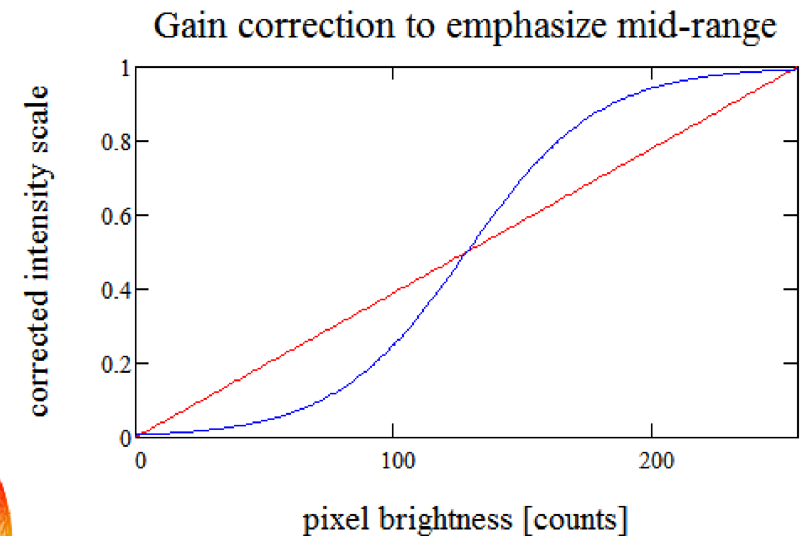
Zoom in on spot



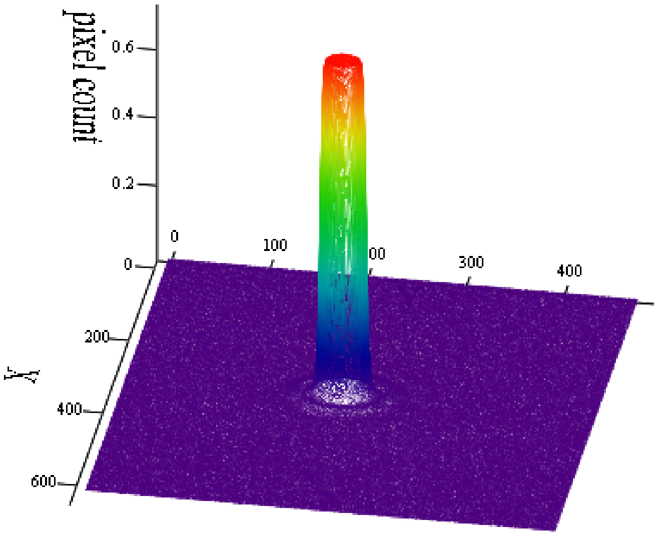
50x50 pixels

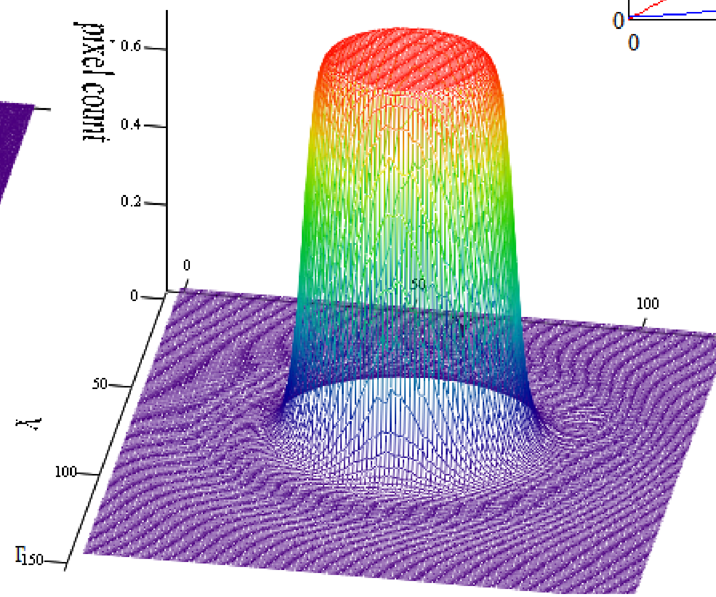


Apply gain correction to emphasize middle range



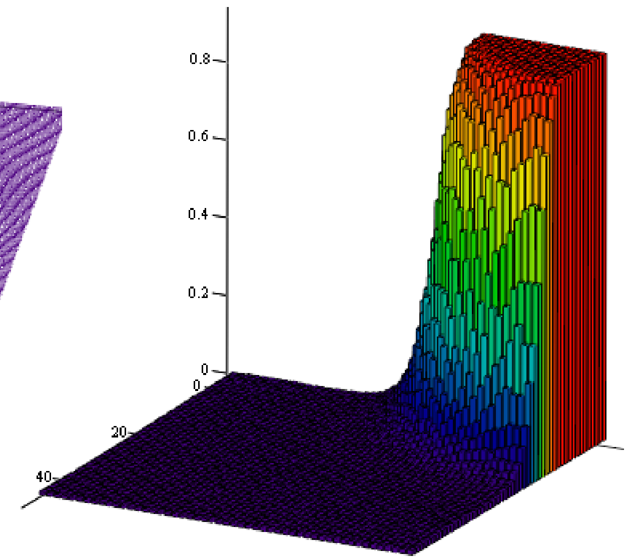
Full image, 640x480





Zoom in on spot

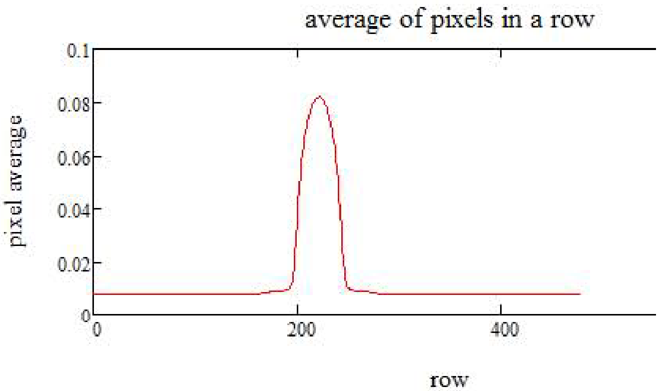
50x50 pixels

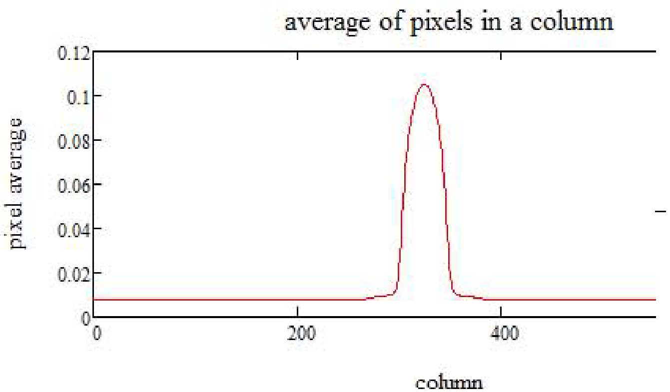


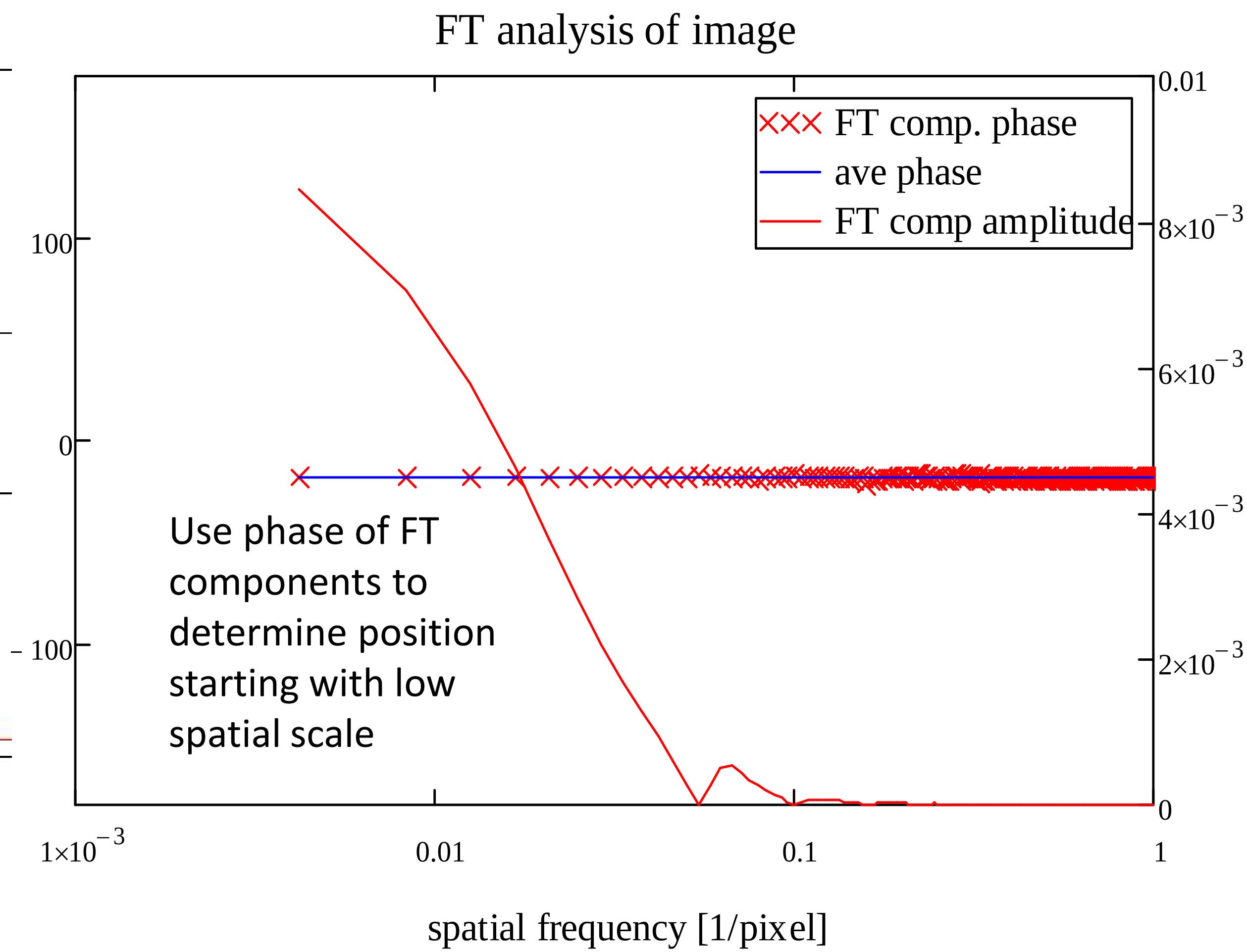
Centroid algorithm

Calculate row and column averages and Fourier Transform to determine the centroid.

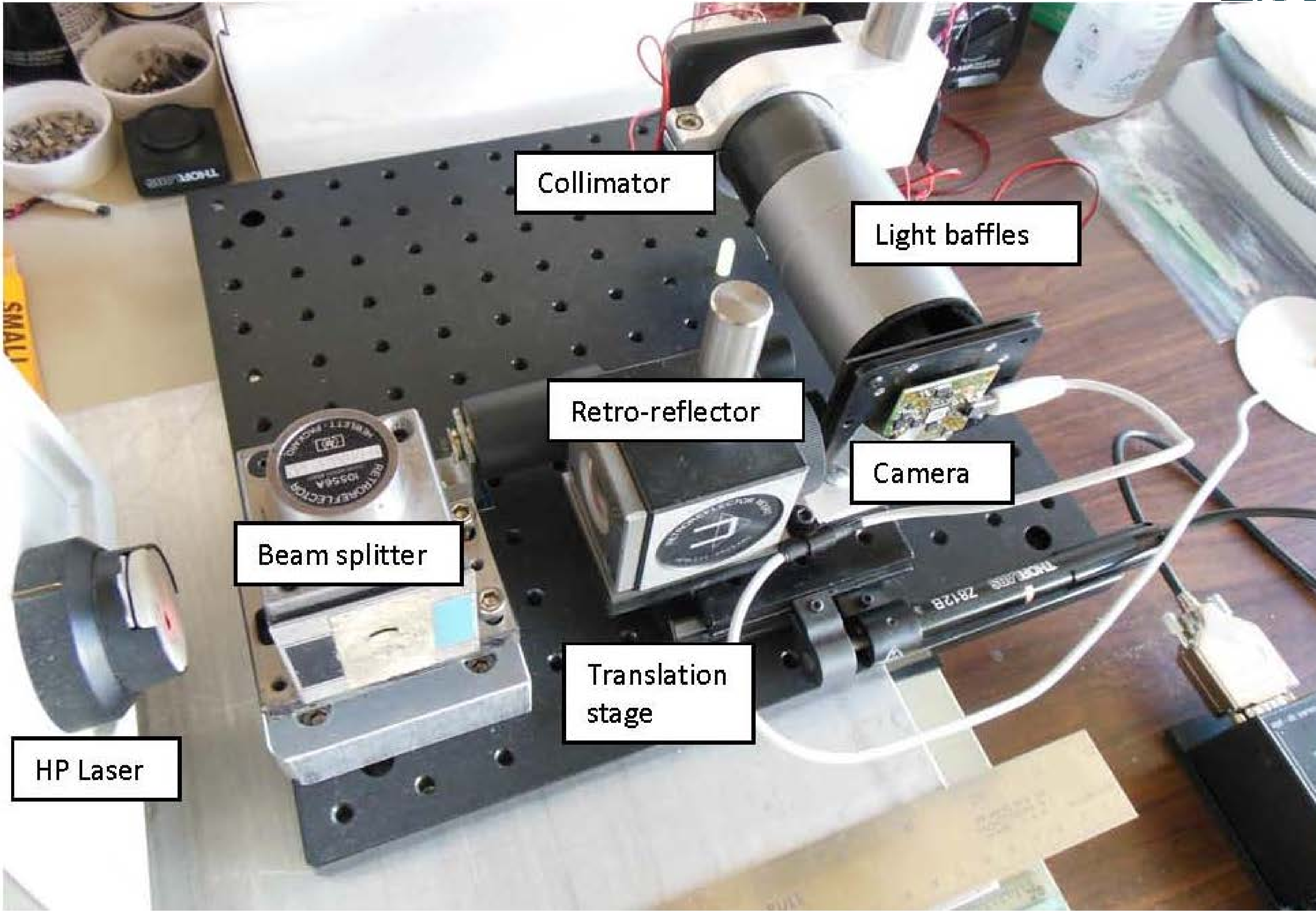
Use the phase of the lowest FT components to resolve ambiguity of the phase for the higher components. Find position from amplitude weighted averages of the phases.



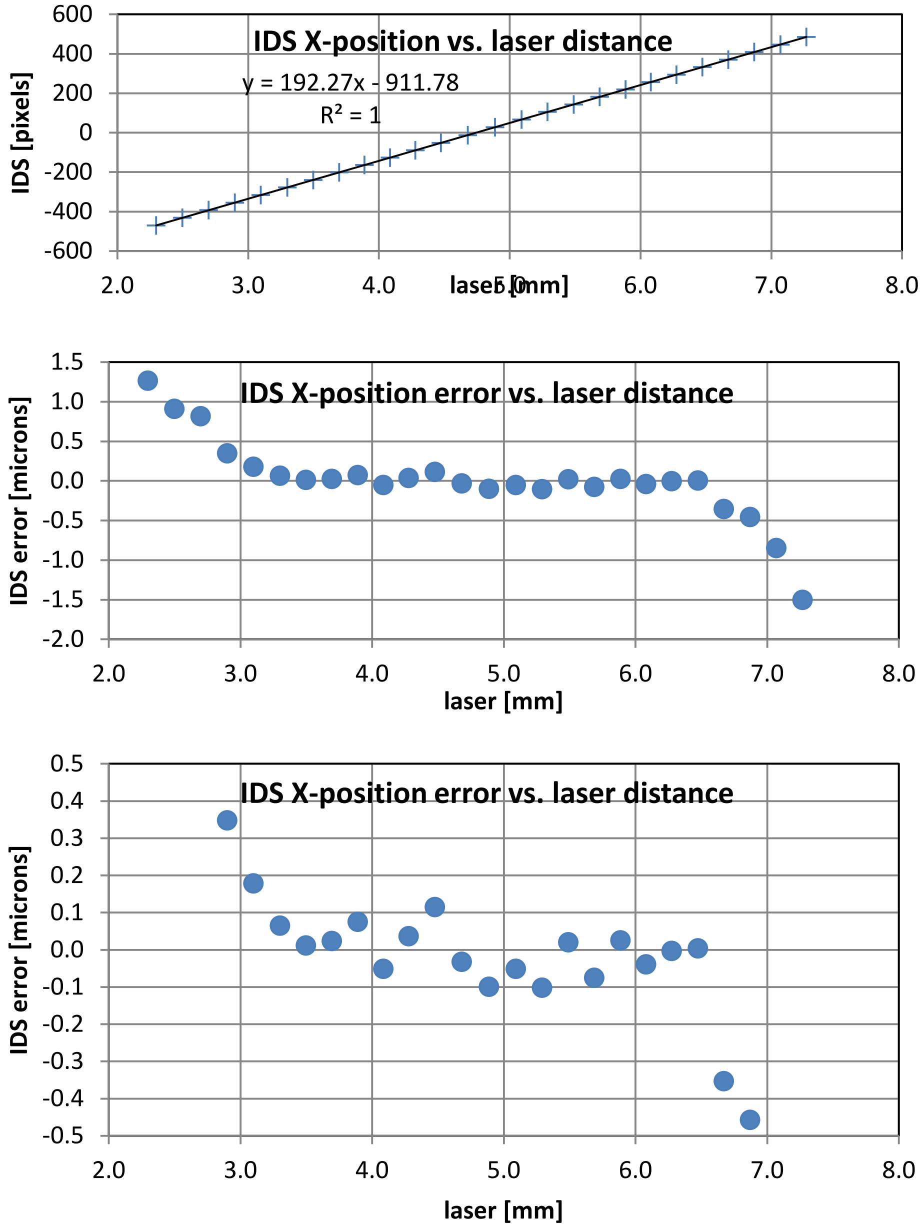




Linearity measurement setup



X-position linearity



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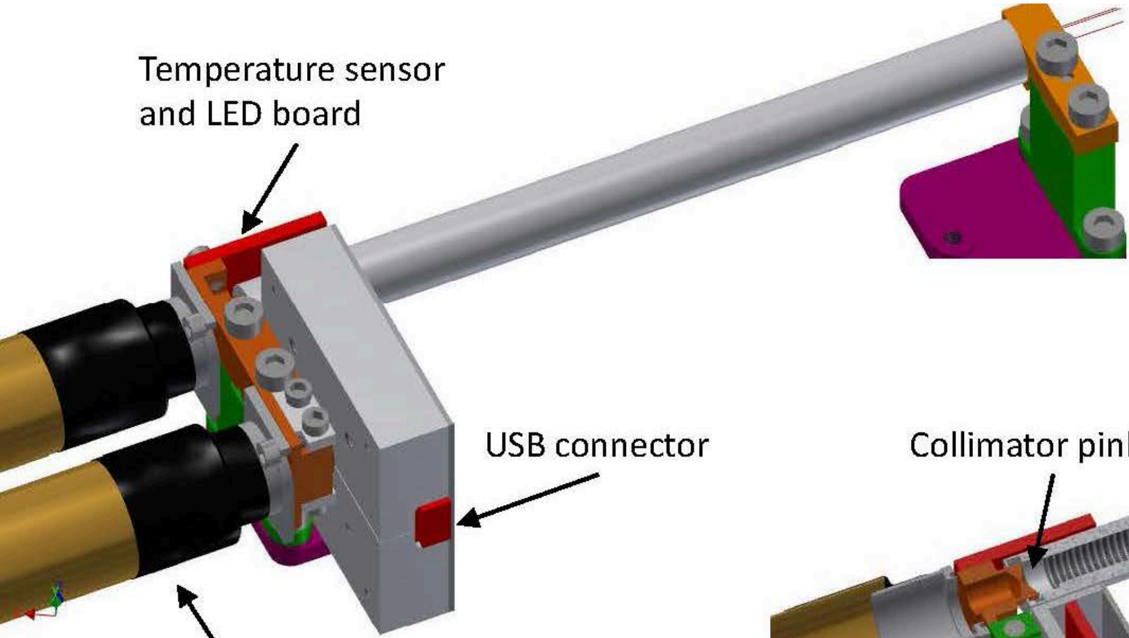
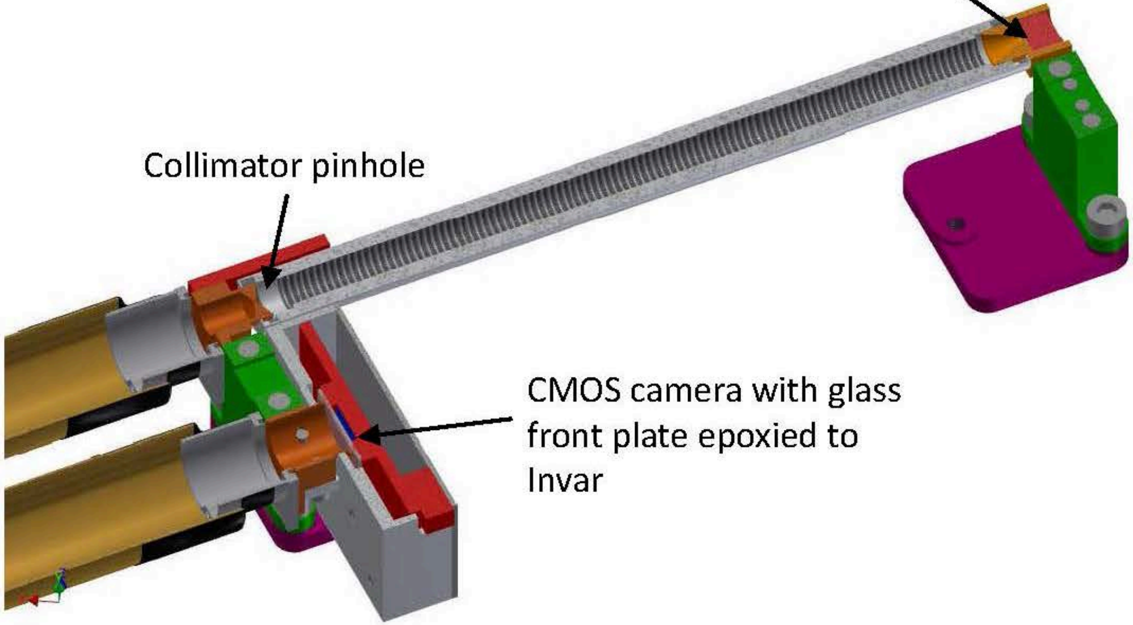
Nominal 5.2 mm pixel gives 192.30 pixels/mm

No calibration required

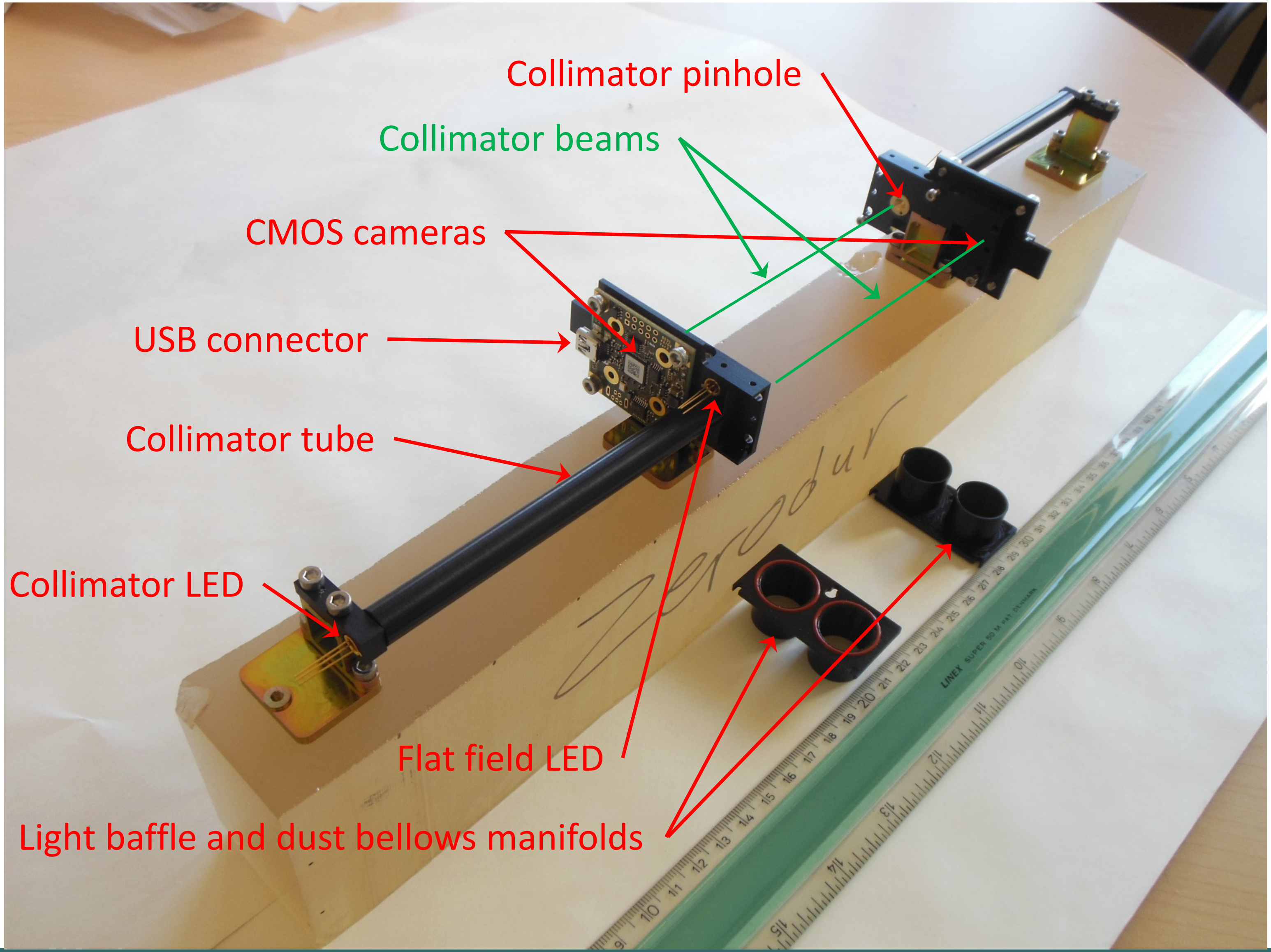
IDS design model

Purple, green and orange are Invar
Gray is aluminum

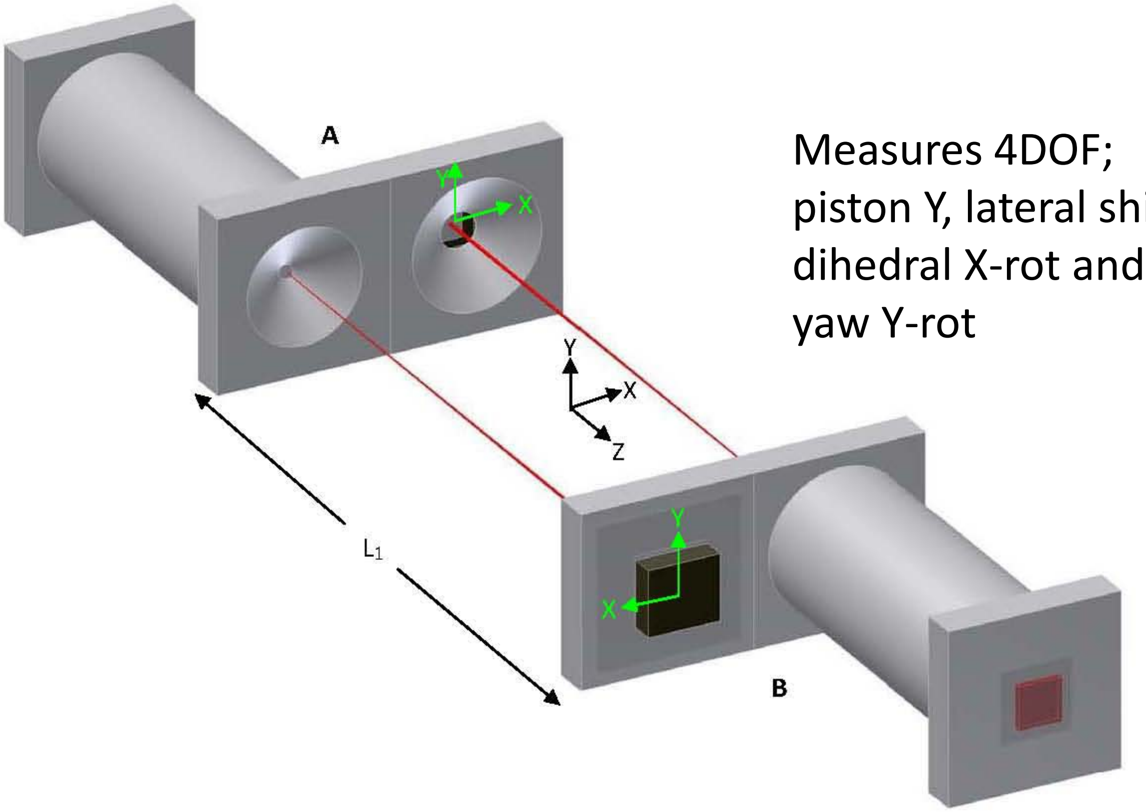




Pair of IDS modules

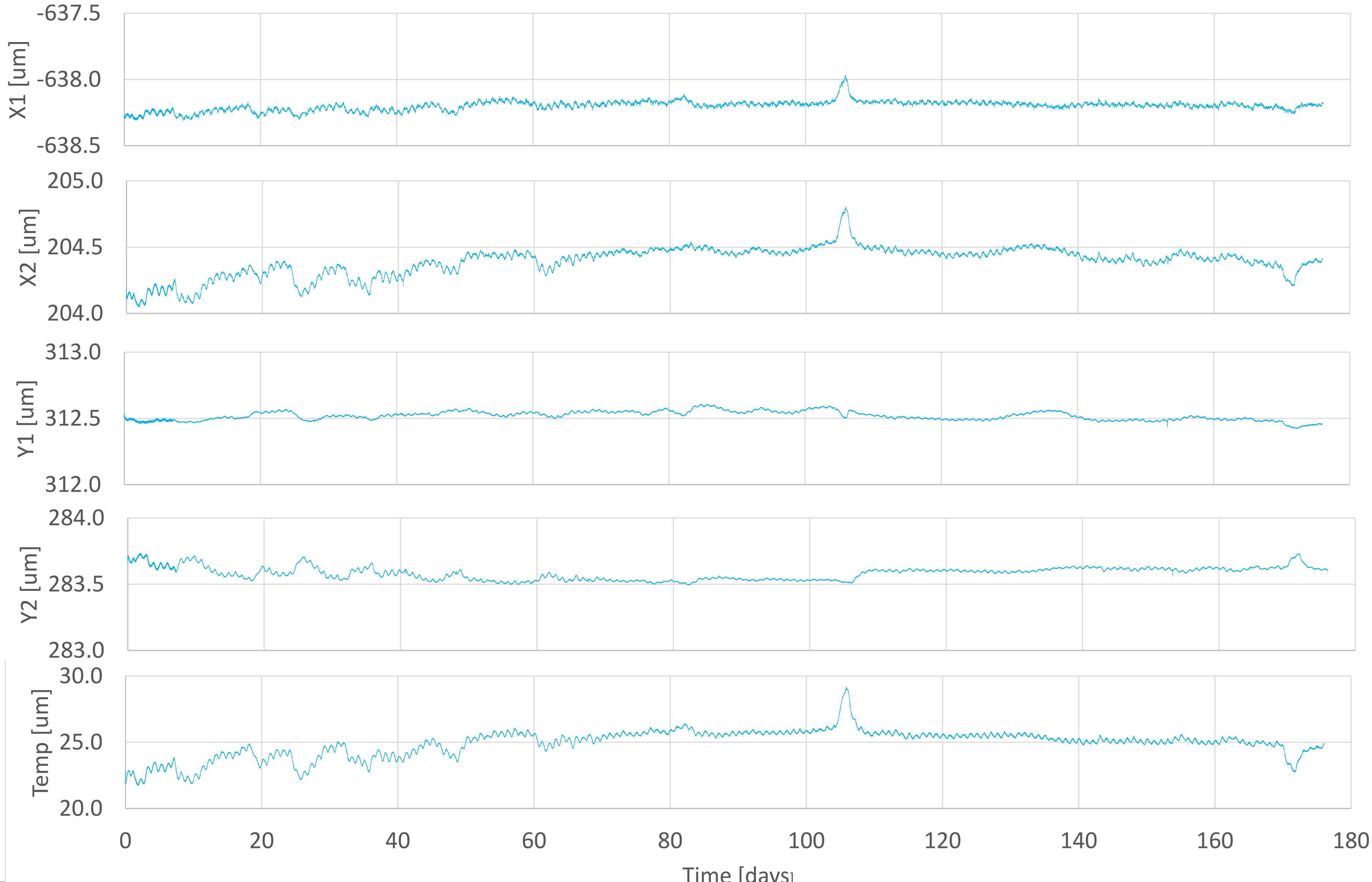


Pair of IDS modules

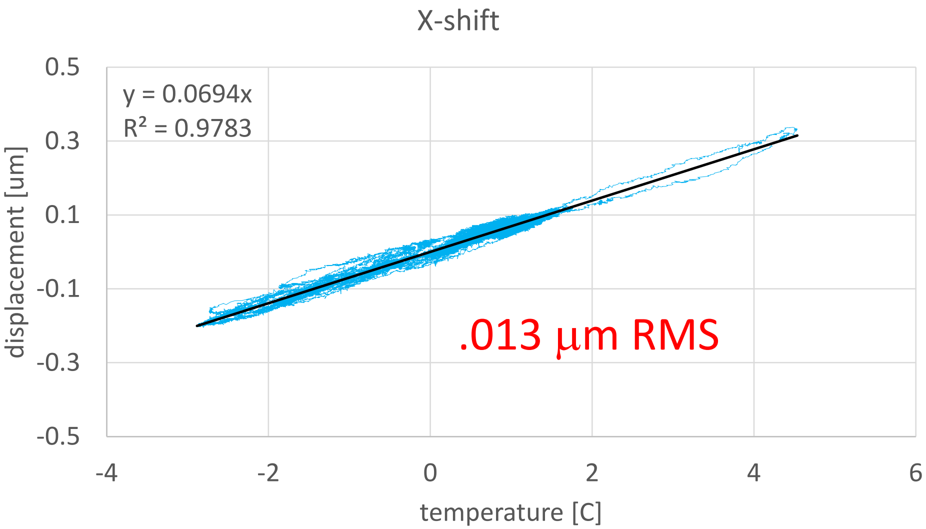


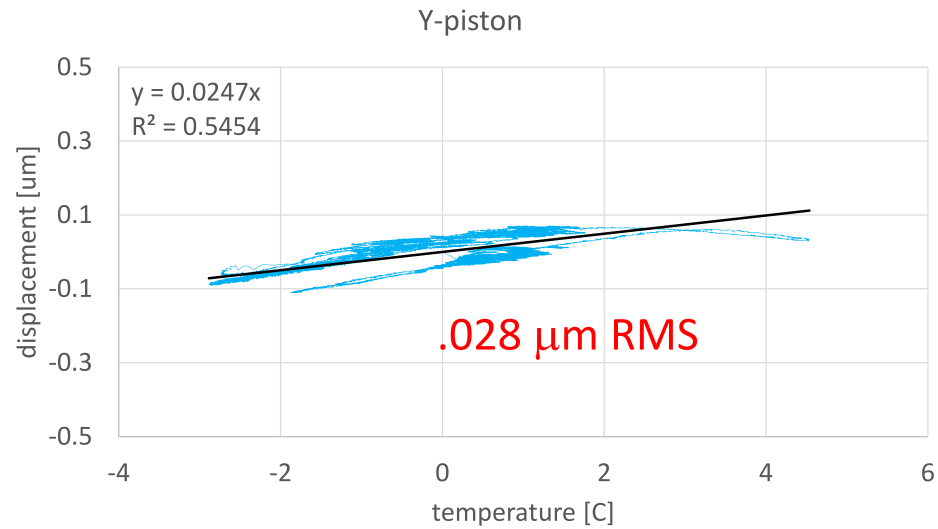
Measures 4DOF;
piston Y, lateral shift X,
dihedral X-rot and
yaw Y-rot

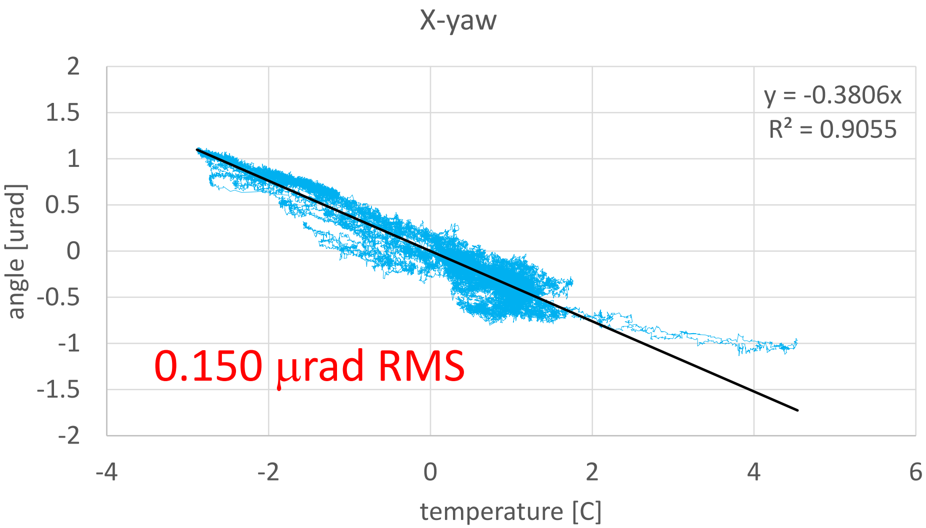
Long term stability over 6 months

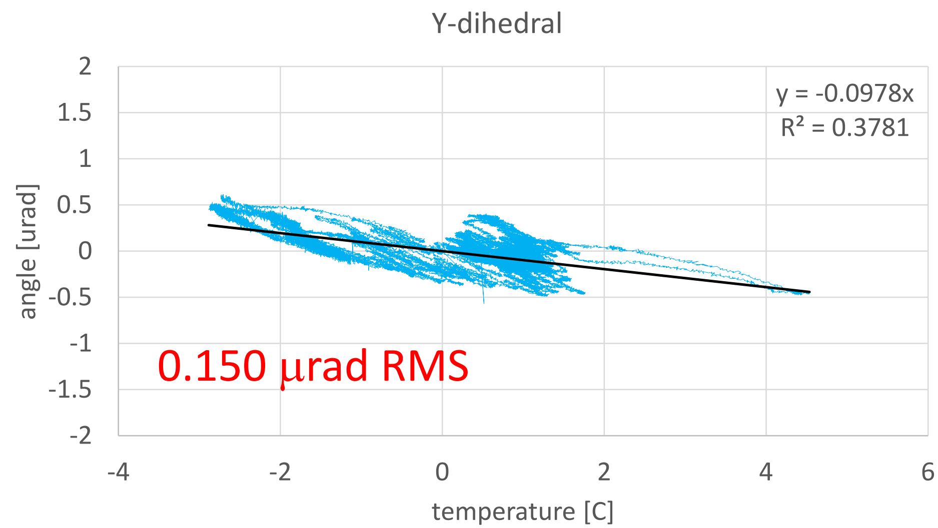


Temperature dependence







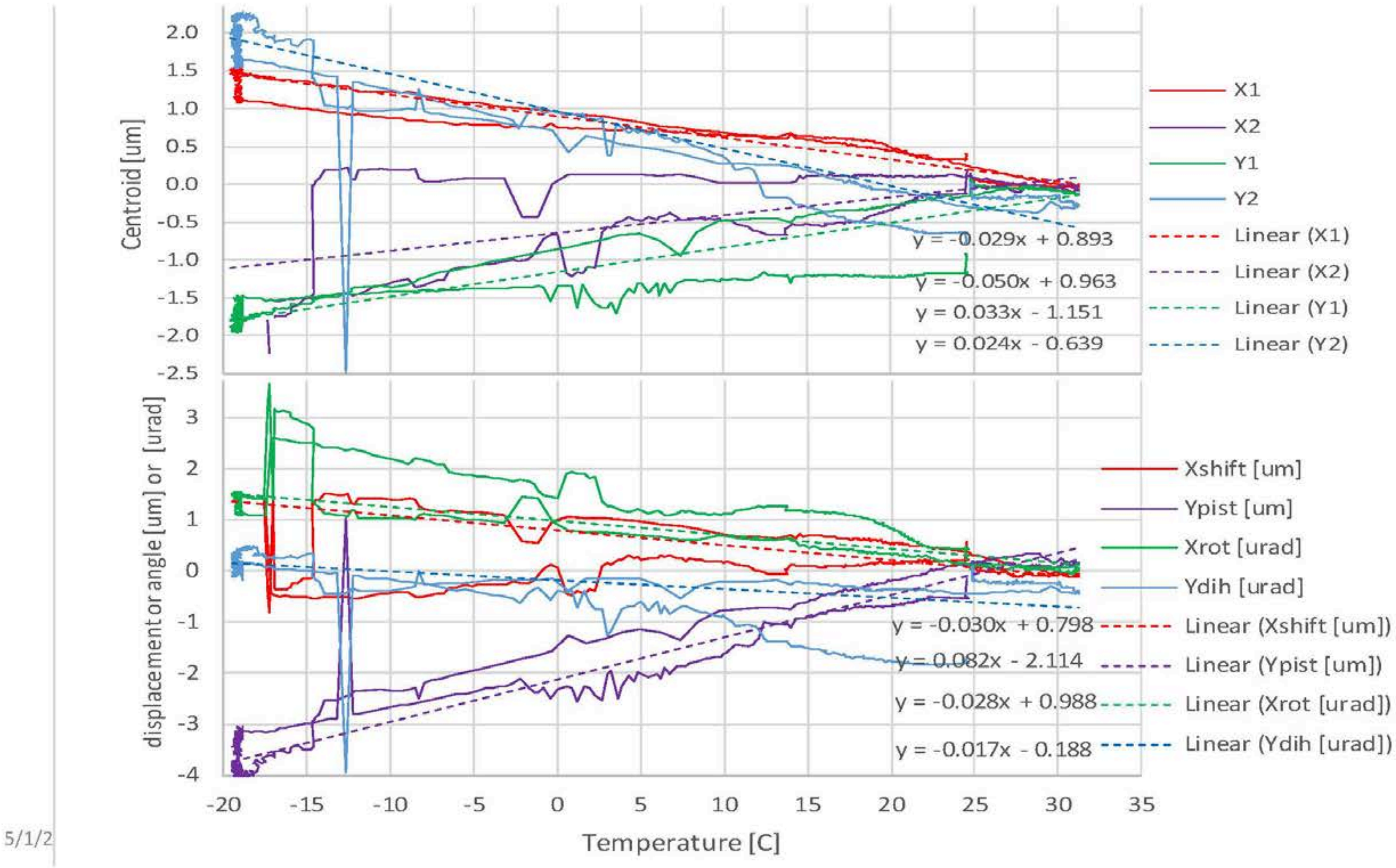


IDS temperature test

Put IDS modules mounted on Zerodur block inside Styrofoam box inside a small freezer and cycle between +20 C and -20 C.

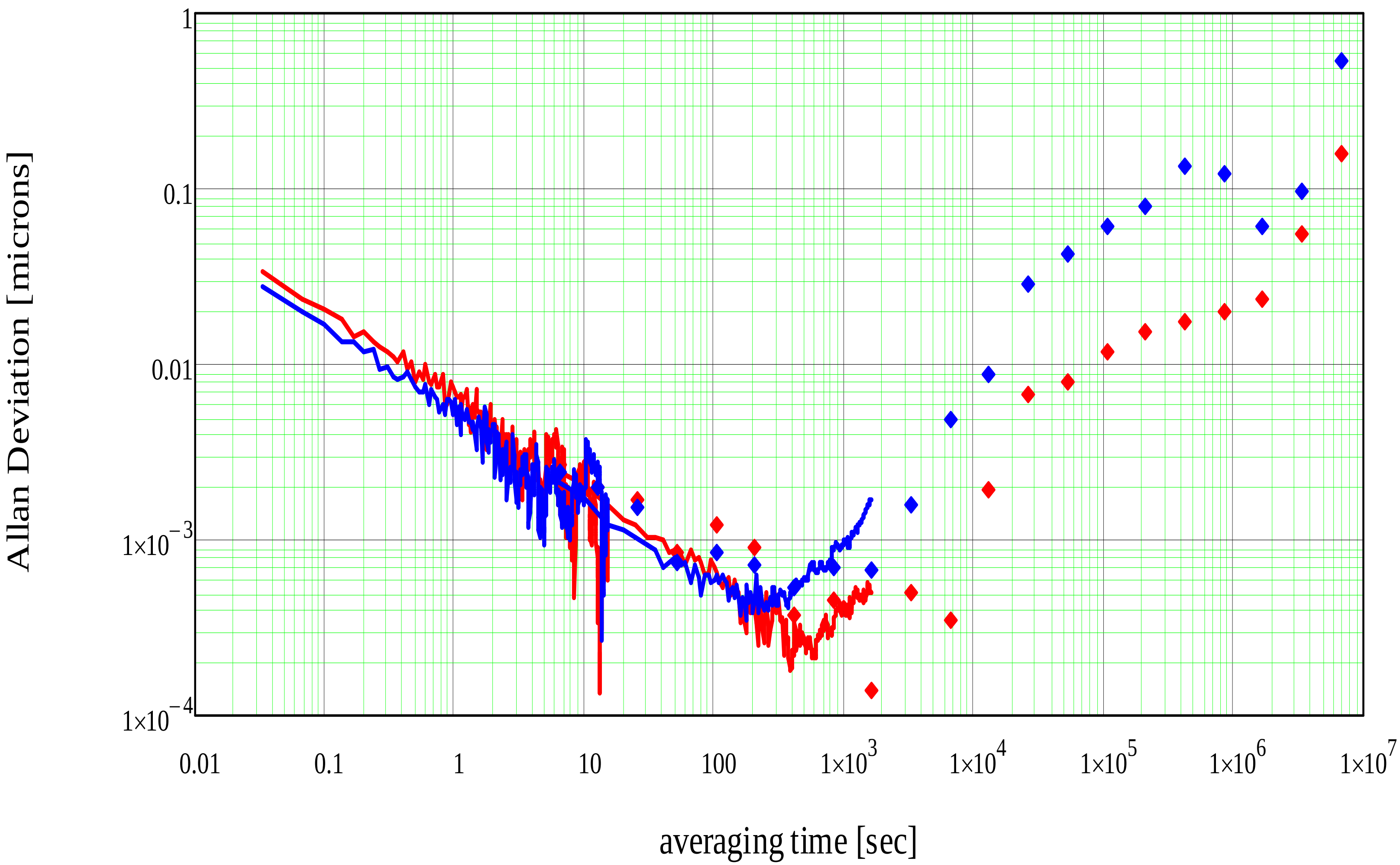
Measured <0.08 μm/C

Temperature dependence

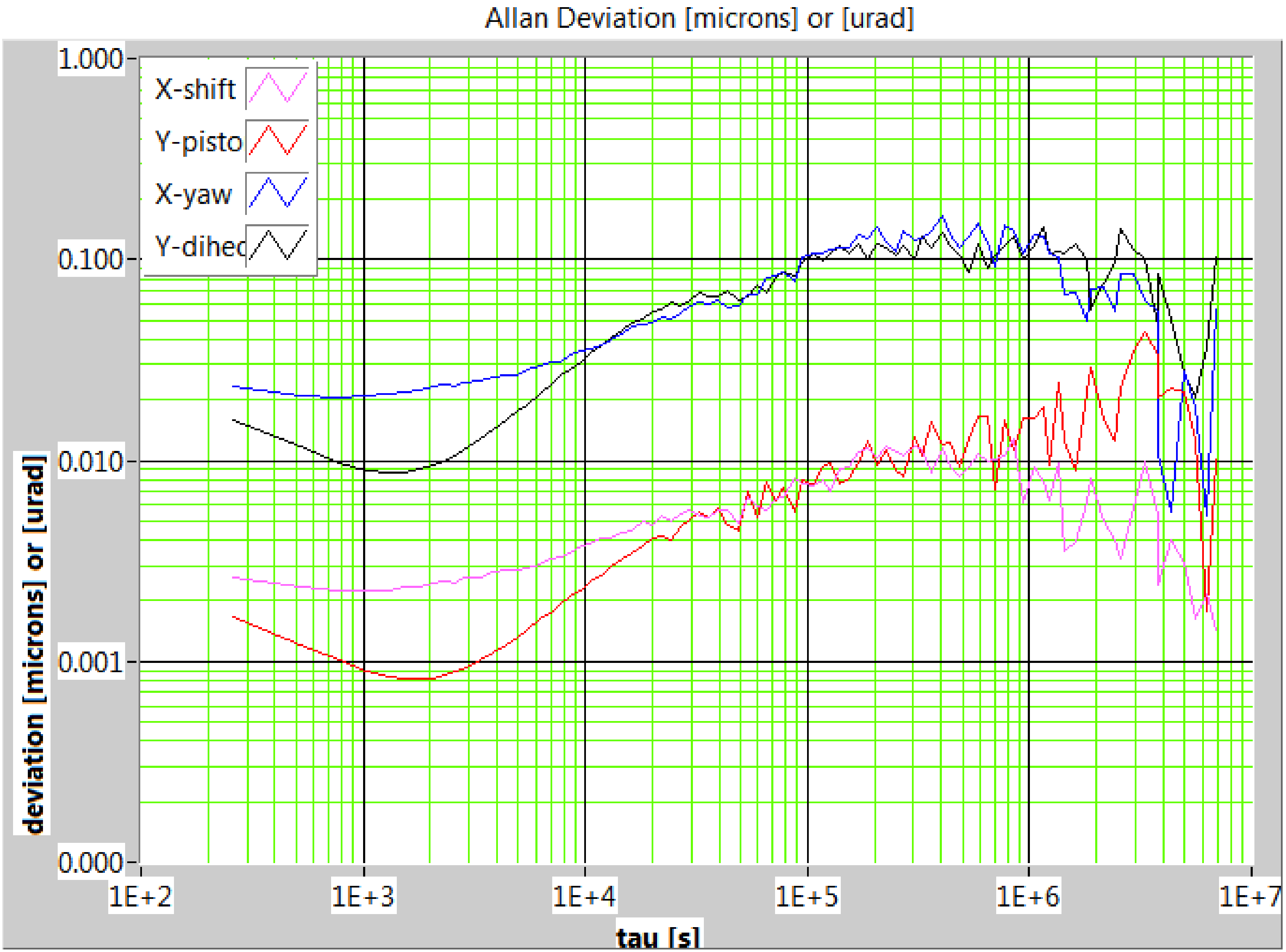


Allan Deviation of test bed IDS

- Measurements over 6 months

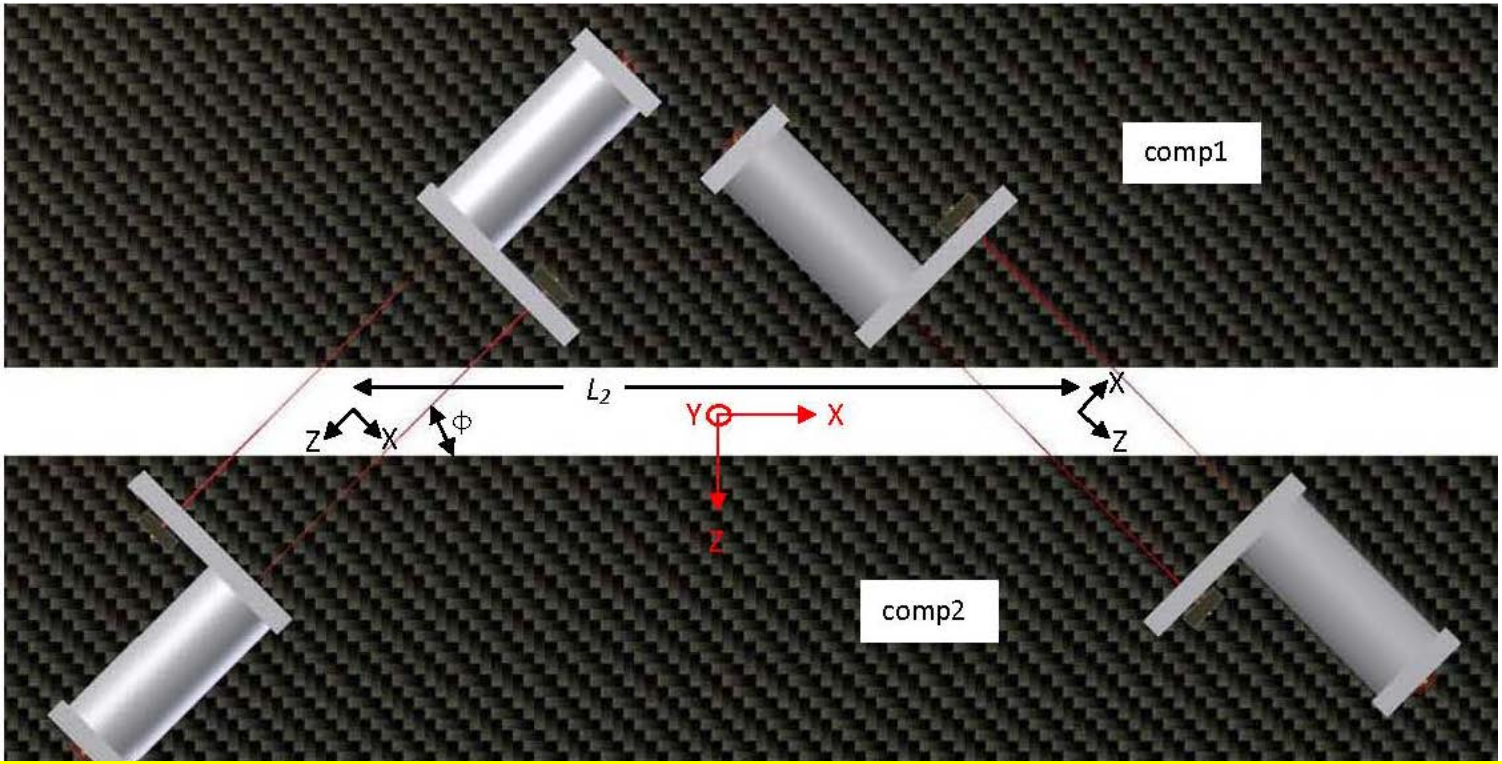


Long term stability of prototype IDS pair



Measure 6 Degrees of Freedom

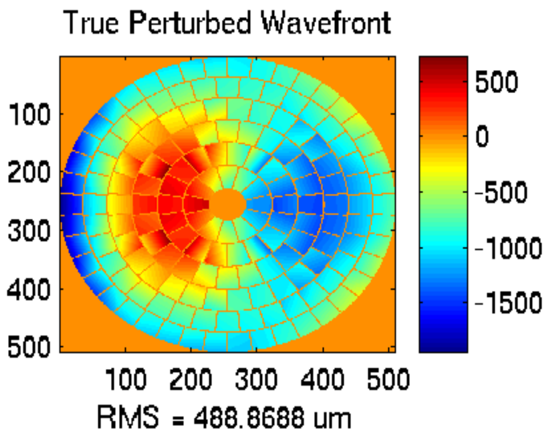
- Measuring 6DoF greatly improves the surface control performance
- Two pairs of IDS modules (4 collimators and CCDs) does this very efficiently



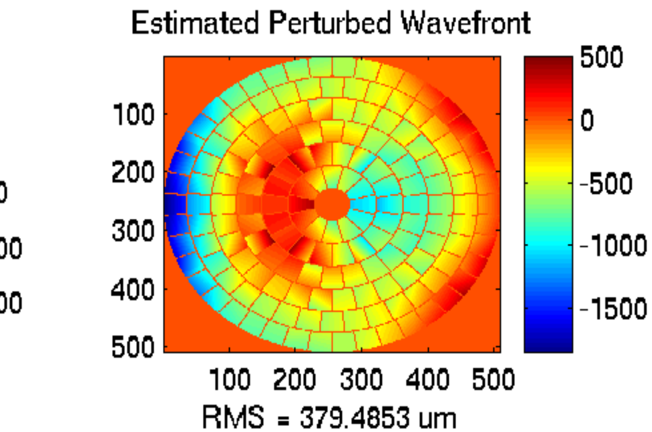
- IDSs easily meet CCAT linearity, noise and stability requirements
  - Deviations from linear <0.1 µm over ±1 mm: requirement < 1 µm
  - Noise <0.05 µm in one 0.1 sec frame, <0.1 in 1 sec: requirement < 0.1 µm in 1 sec
  - Temperature dependence <0.01 µm/C with linear temperature correction:
    - requirement < 0.01 µm/C
  - Measures 6 DOF

Surface control

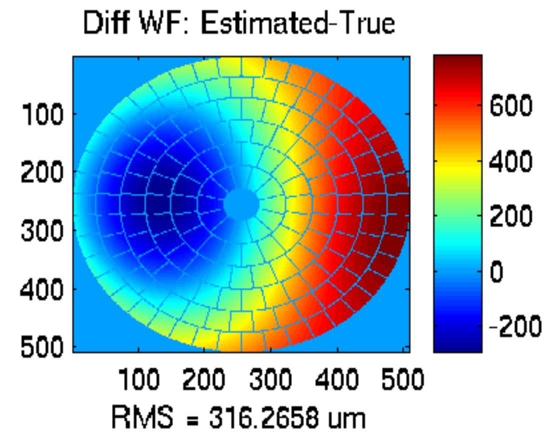
FEM gravity deformation
at horizon

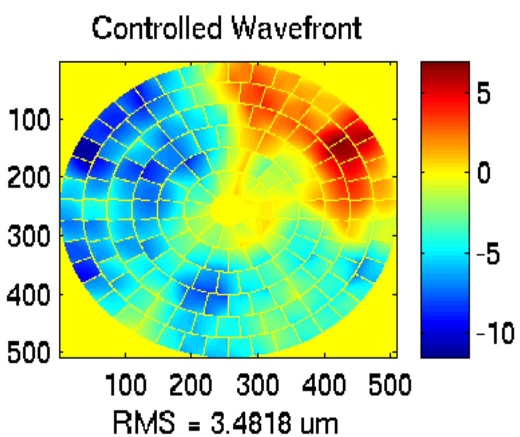


Estimated WFE state
0.5 µm RMS sensor noise

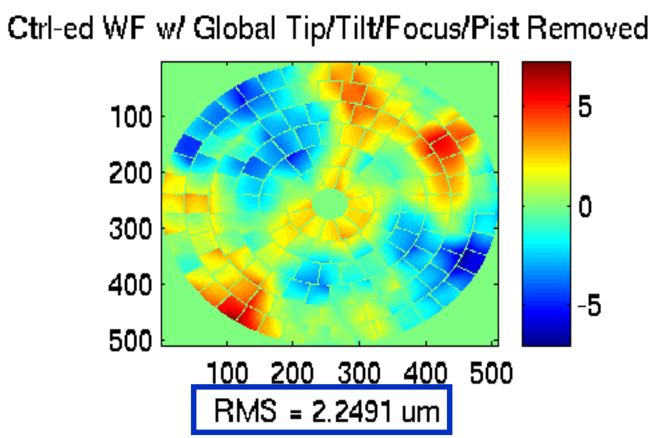


Effect of shifted
secondary position



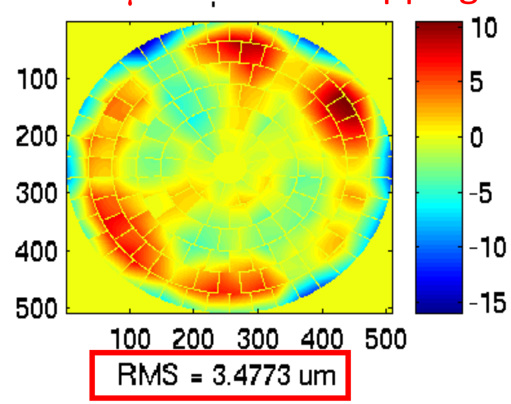


WFE with control on



Refocus and repoint

Add 1 µm uniform cupping



CCAT