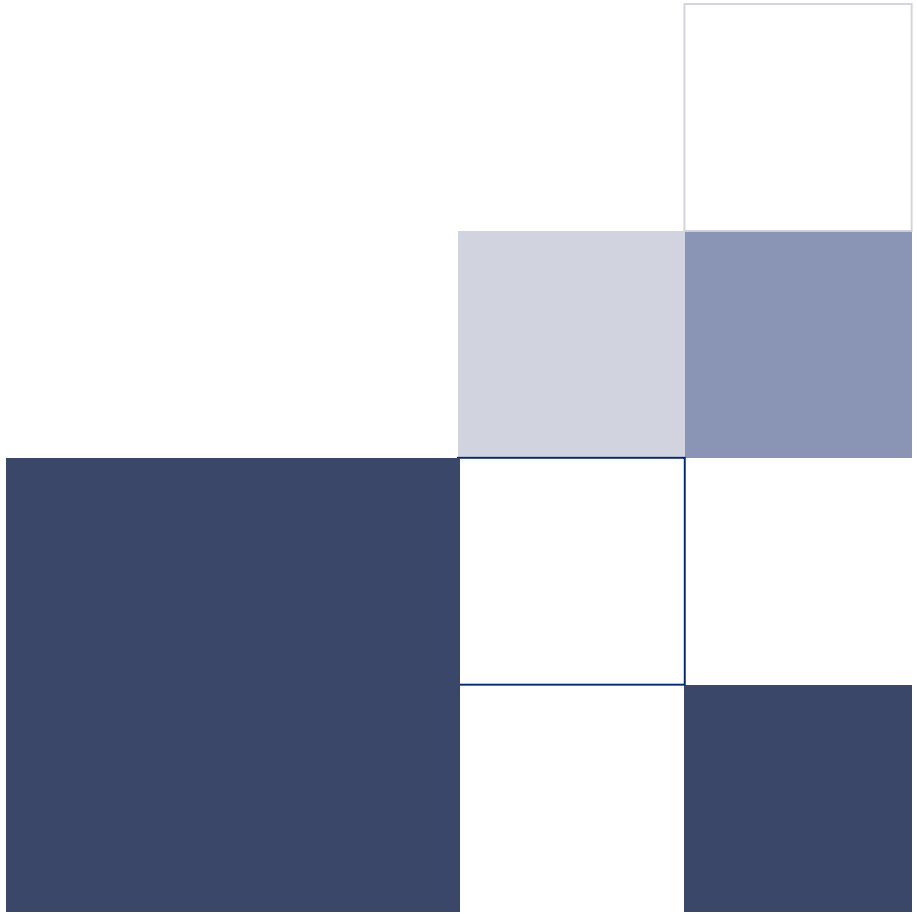
IBS
Precision Engineering



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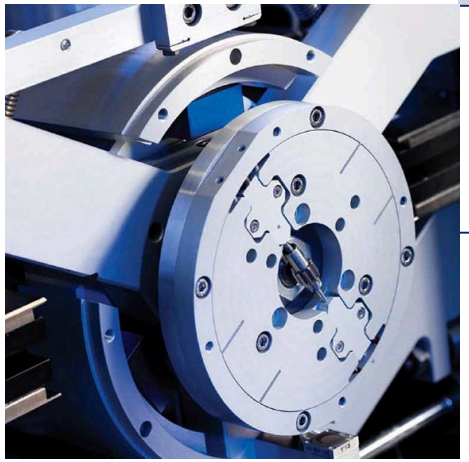
Measurement of HLEM Aspheres

High Level Expert Meeting Samples with Isara 400

Overview

- Isara 400
  - Design concept
  - Traceable uncertainty
  - Collaboration PTB
  - Soft materials at CERN
- HLEM 2018: Aspherical lens measurements
  - Measurement HLEM optics
  - Results of Sample 2, 3, 4, 5, 6, 7, 8
  - Reversal measurement
- Conclusions

IBS
Precision Engineering



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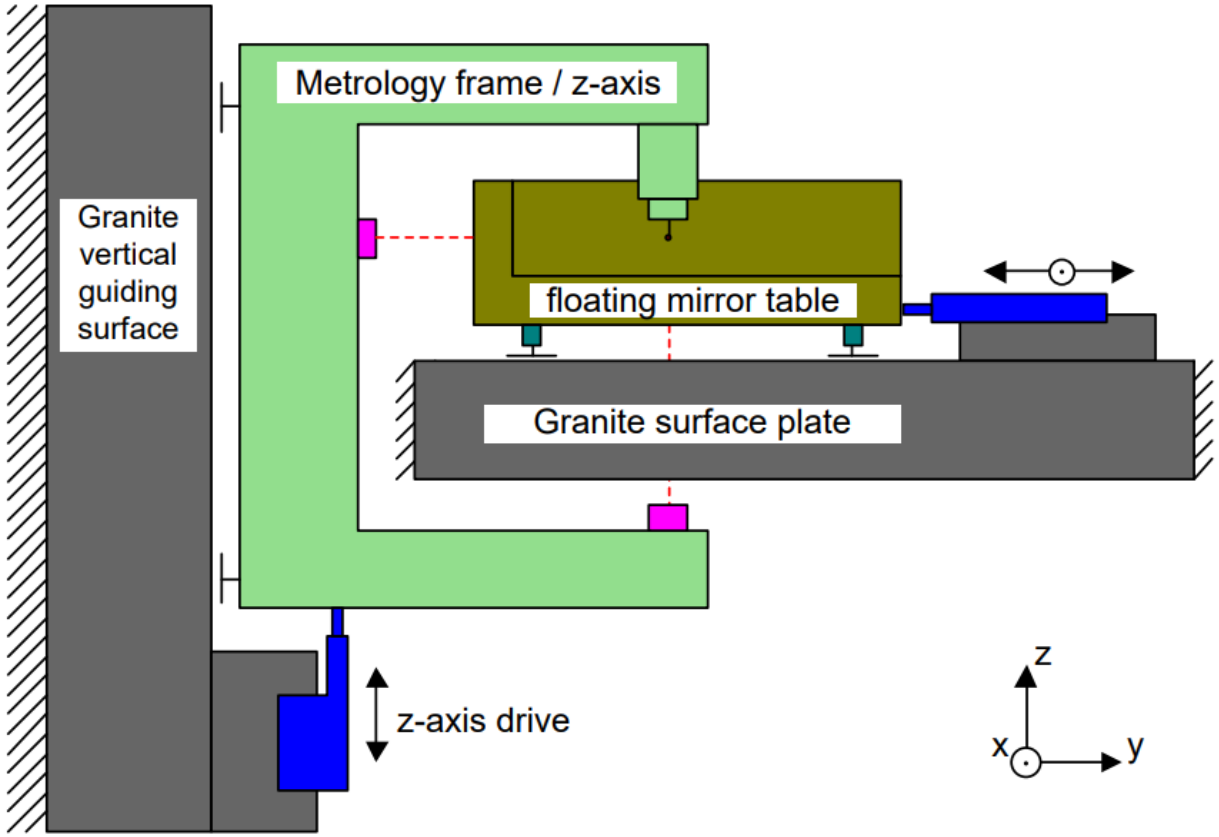
Isara 400

Design concept

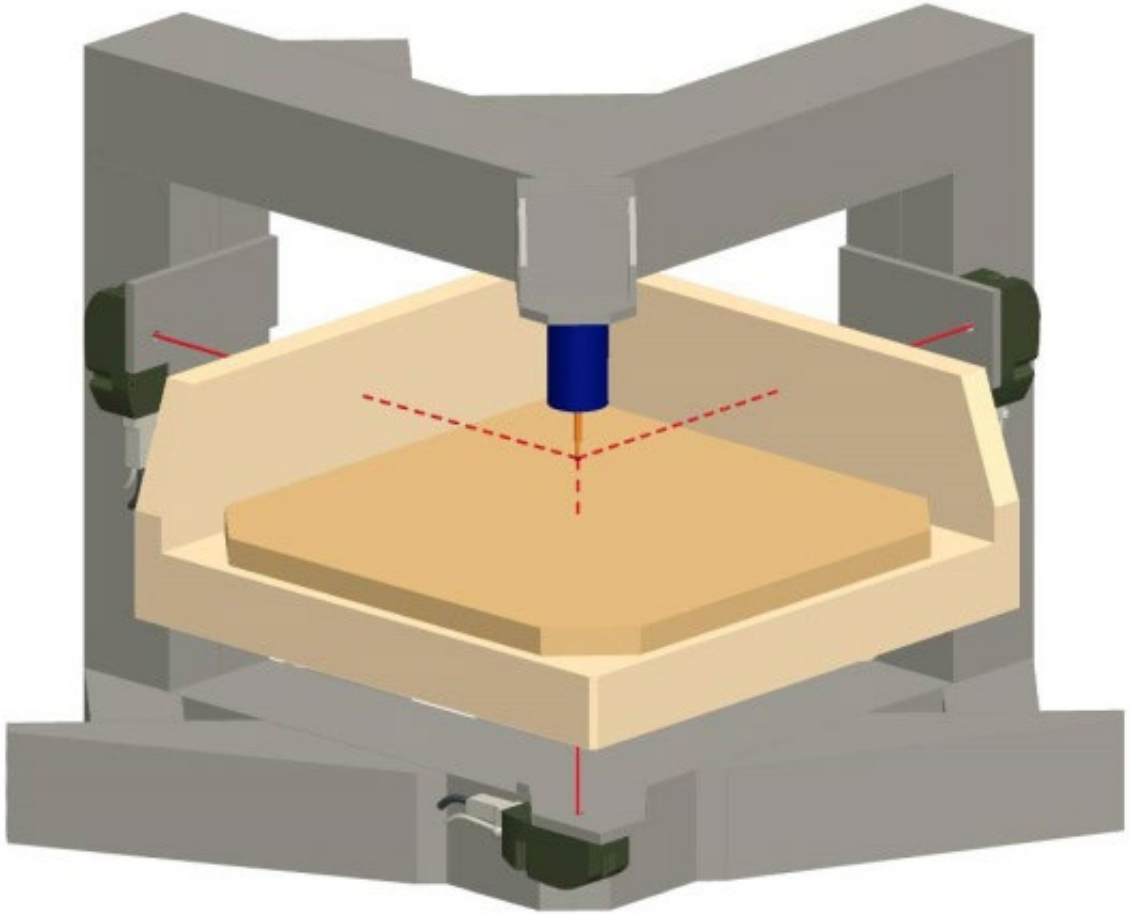
- Isara 400 offers 3D ultra precision and a large measuring volume:
  - Measuring volume 400 x 400 x 100 mm
  - Traceable measuring uncertainty: : U_{1D} = 50 nm (k=2)
  - Full 3D measurement (-90º to +90º)
  - Product mass up to 32 kg
  - Air bearings for 3D scanning
  - Exchangeable probe with kinematic mount
    - 3D probe system: Triskelion 3D ultra precision tactile probe
    - Other possible probe systems: Optical probes, capacitive probes, oscillating fiber probes etc.

Design concept

- Abbe principle in 3D:
  - Measurement systems remain in line with measurement point
- X/Y movement of mirror table, Z movement of metrology frame

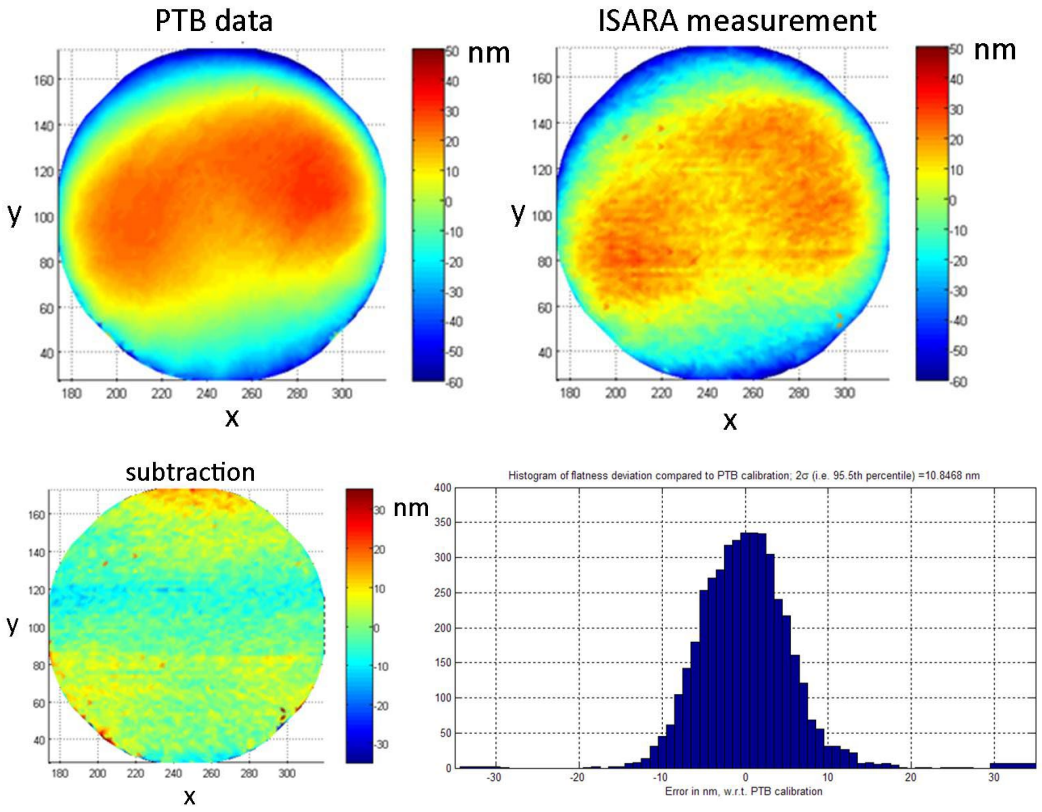


Design concept



Design concept

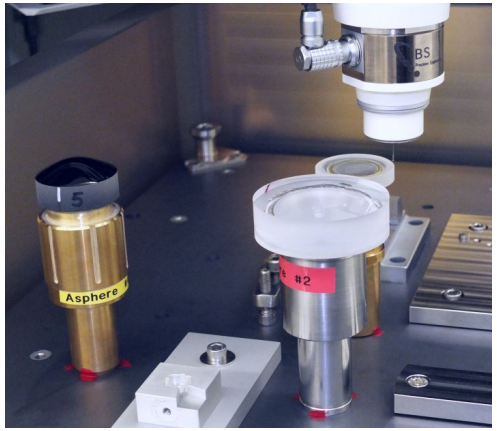
Traceable uncertainty

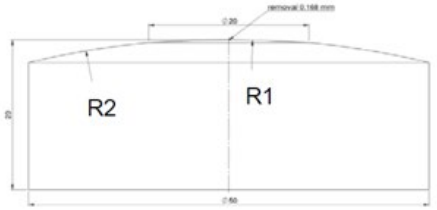


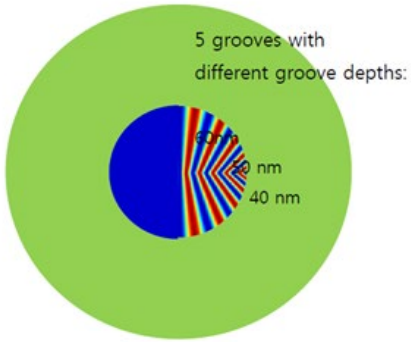
- Uncertainty proven within 11nm

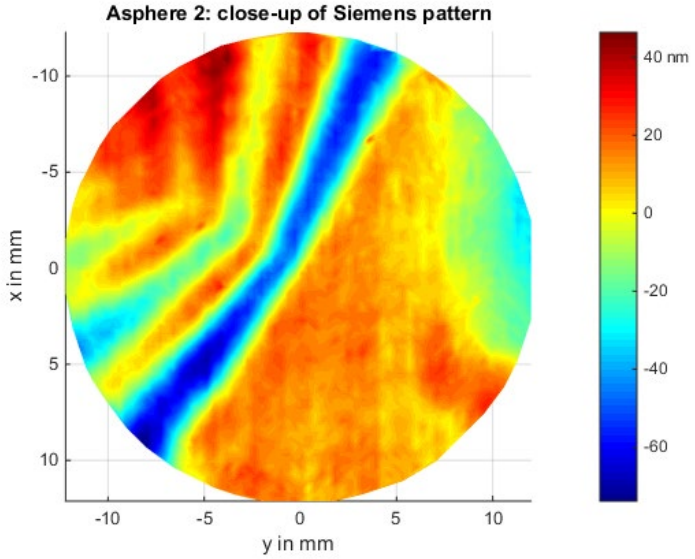
Collaboration PTB

- Several EMRP & EMPIR projects
  - JRP-i08 Microparts
  - EMRP IND10 Metrology for absolute form
  - EMPIR - 15SIB01 FreeFORM
- High Level Expert Meetings
  - Free-form optics



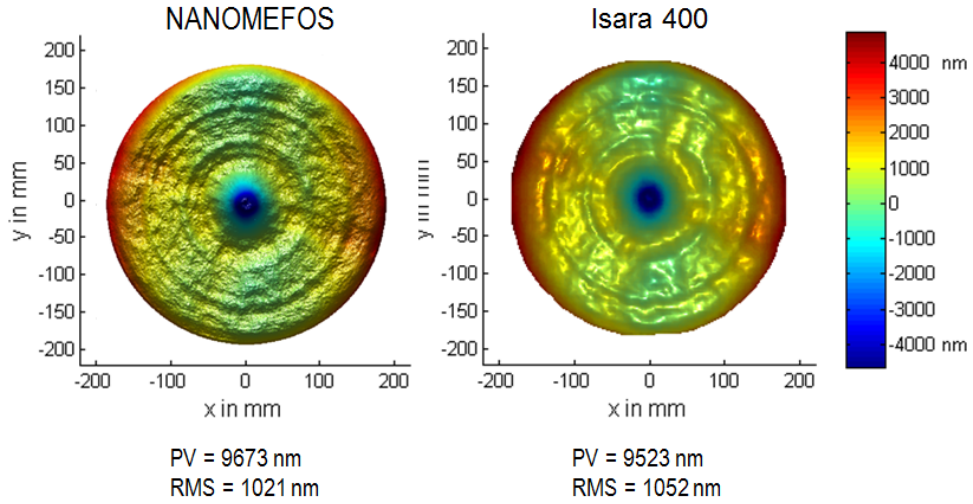


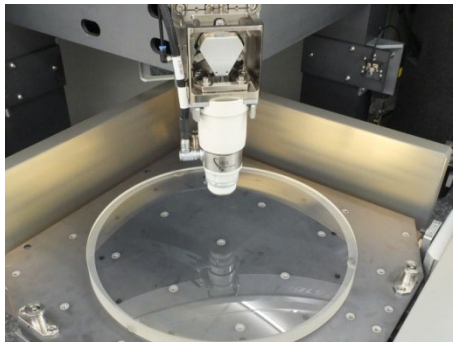


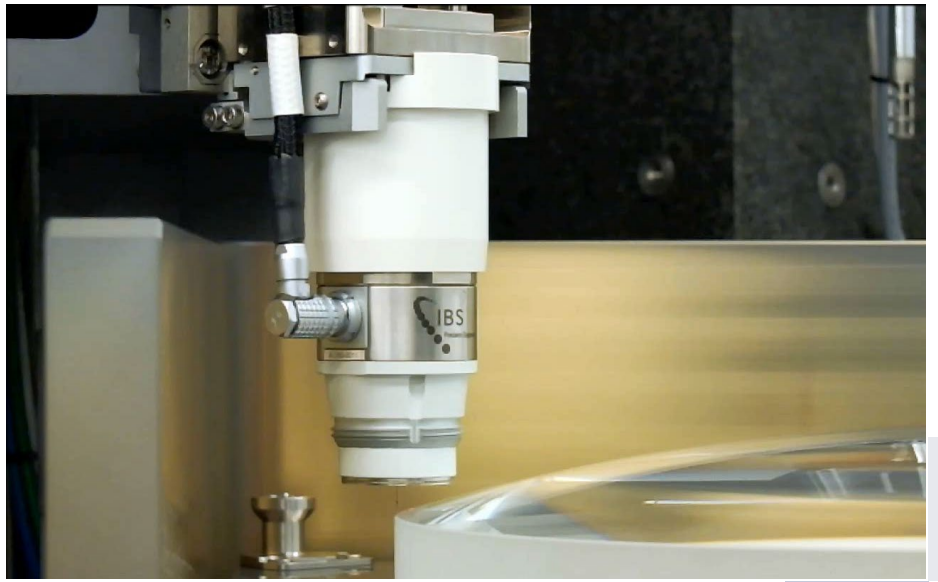


Collaboration PTB on Isara 400

- Several EMRP & EMPIR projects
  - JRP-i08 Microparts
  - EMRP IND10 Metrology for absolute form
  - EMPIR - 15SIB01 FreeFORM
- High Level Expert Meetings
  - Free-form optics

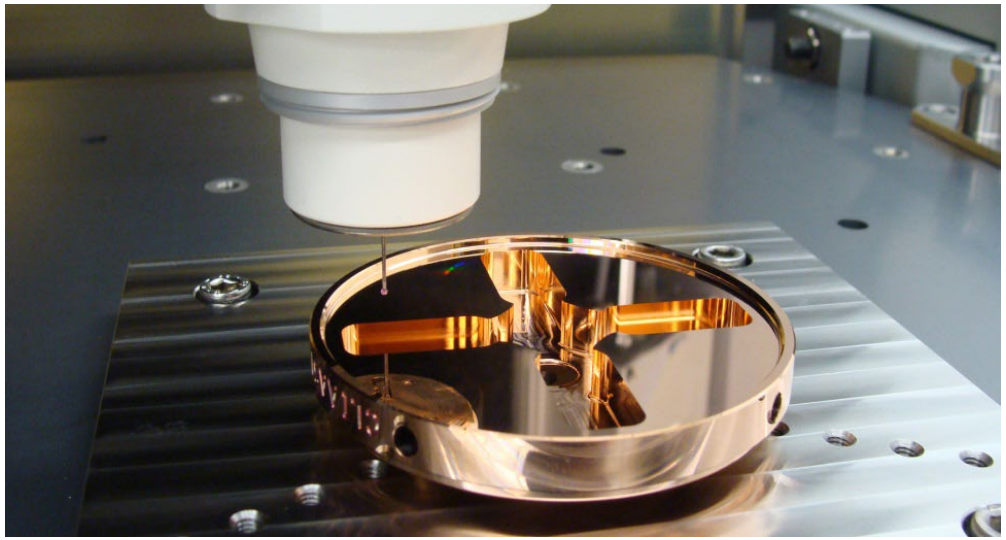


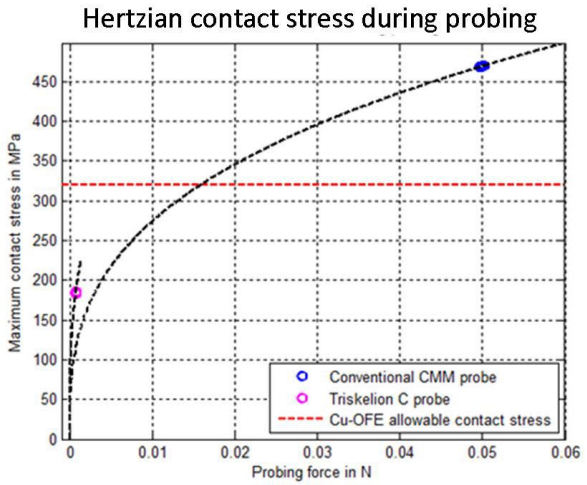


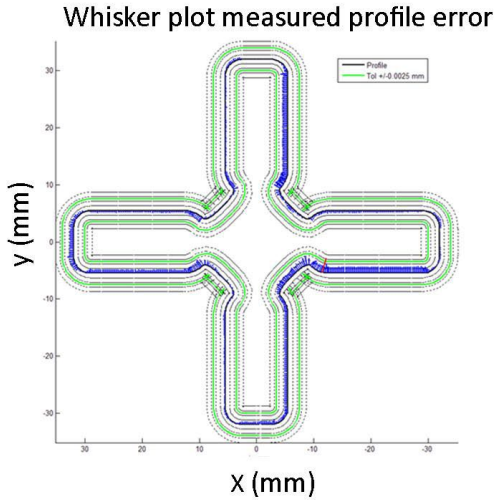


Soft materials at CERN

- Cern “CLIC” project
- Oxygen-free copper discs - unique internal profile
- Measured with respect to several geometric references







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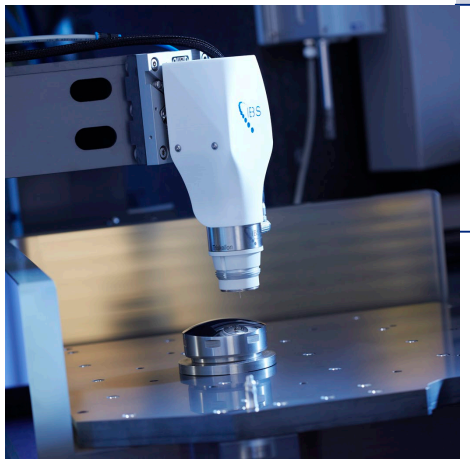

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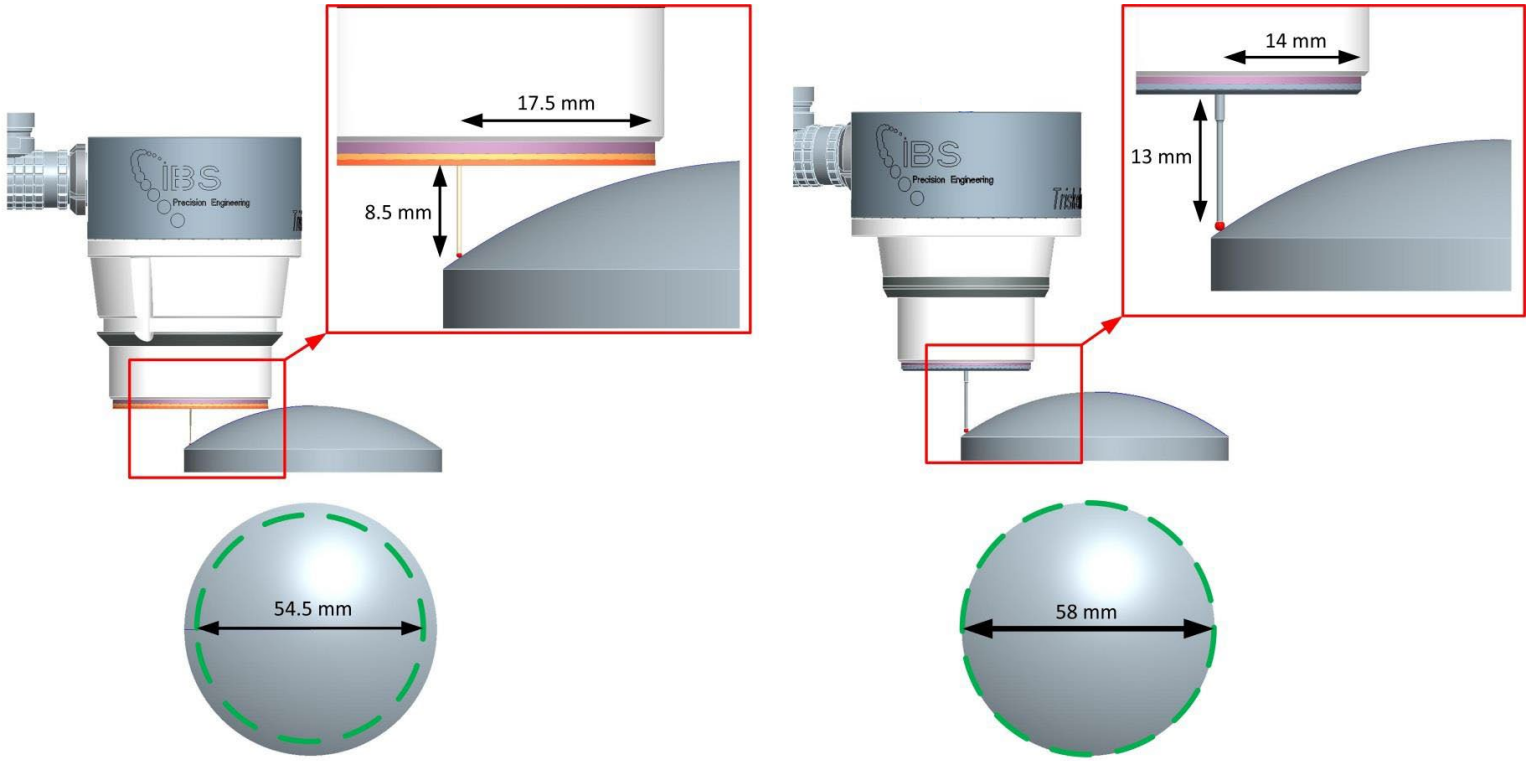
HLEM: Aspherical lens measurements

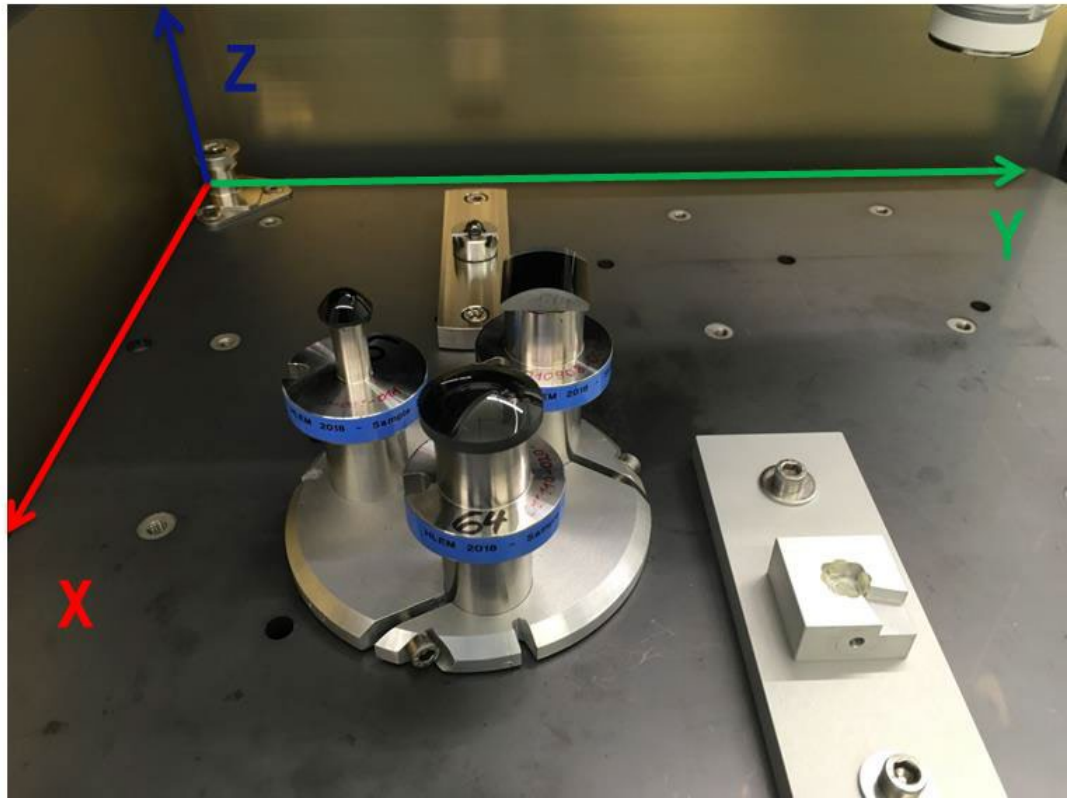
Measurement HLEM optics

- Triskelionup tactile probe
- Slopes to 90º until probe body limit

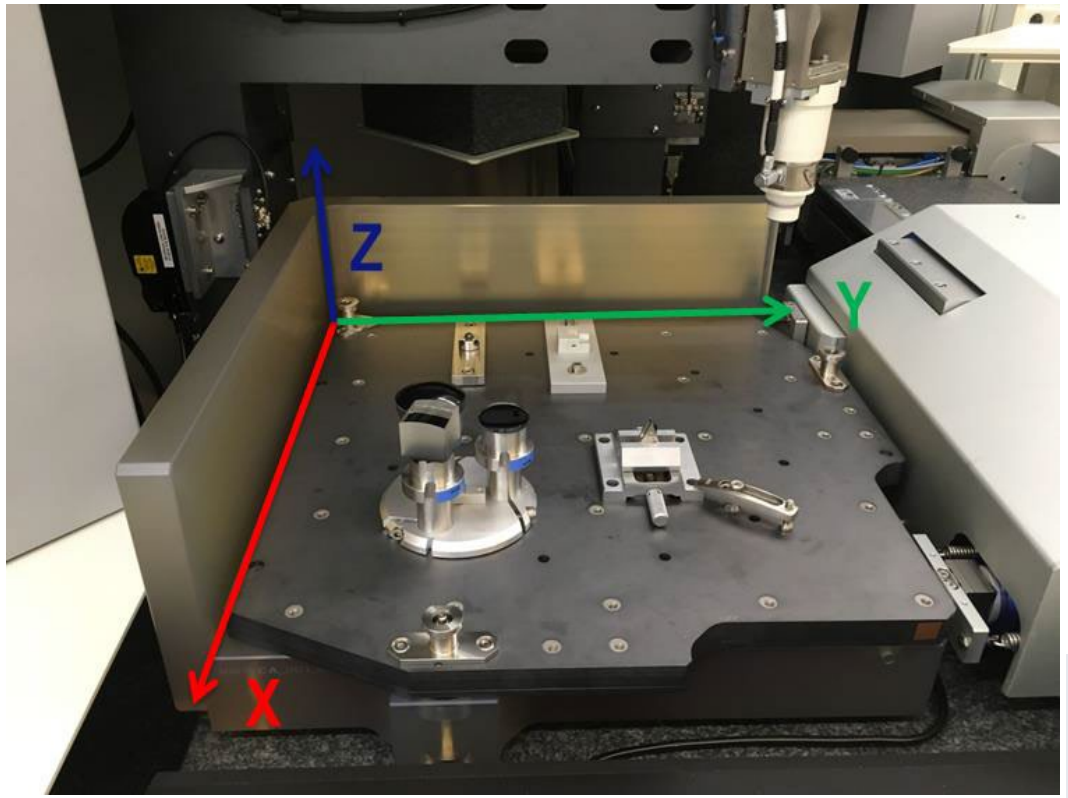


Measurement HLEM optics

Measurement setup sample 2, 3, 4

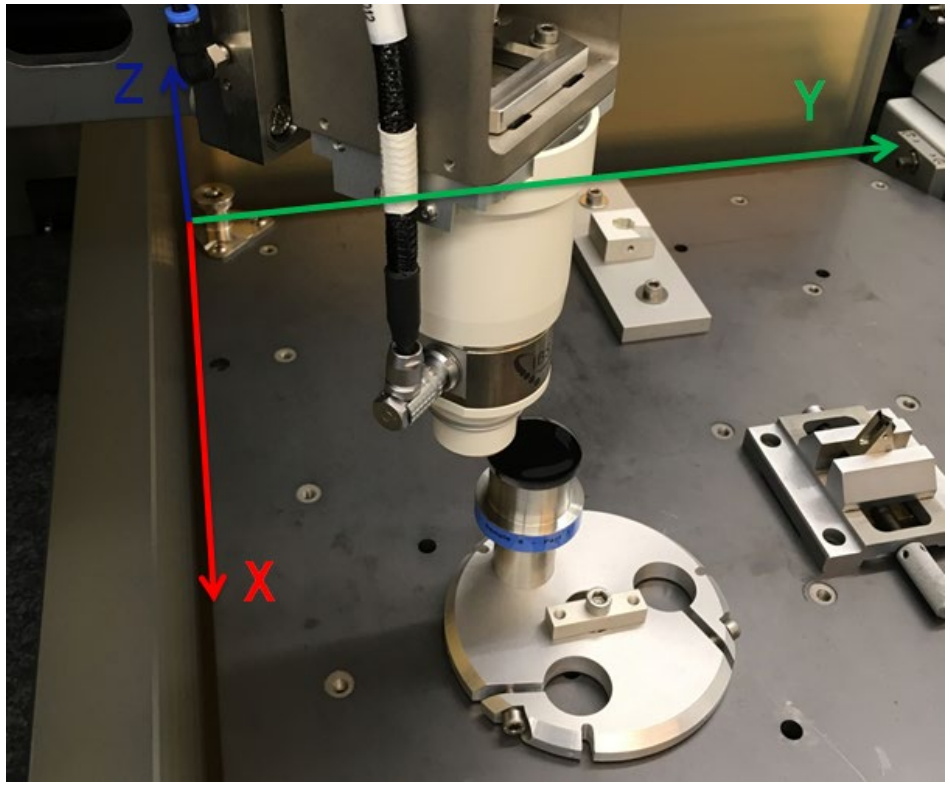


Sample 5, 6, 7

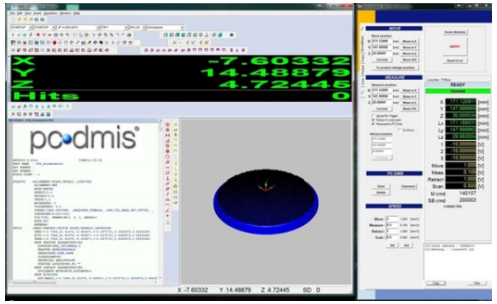


Measurement HLEM optics

Measurement setup sample 8



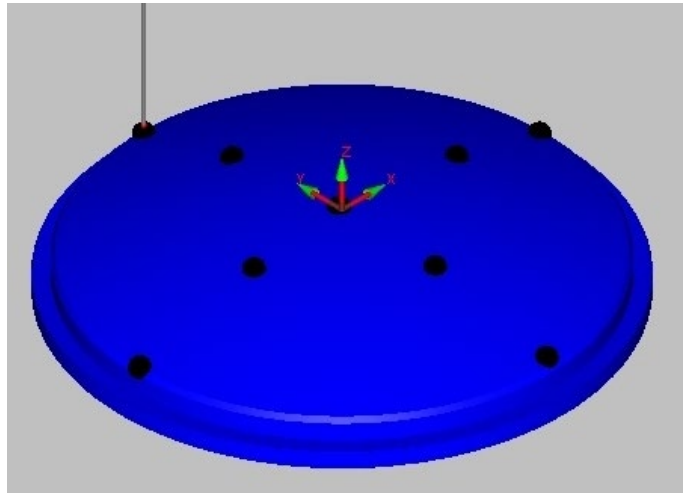
- Grid measurement
  - Fine grid of measurement points
  - Best fit alignment
  - Analyze form deviations

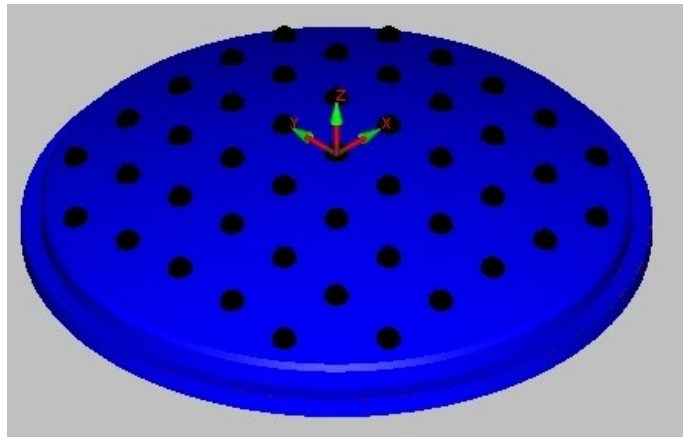


- Scan measurements
  - Not performed (due to availability)

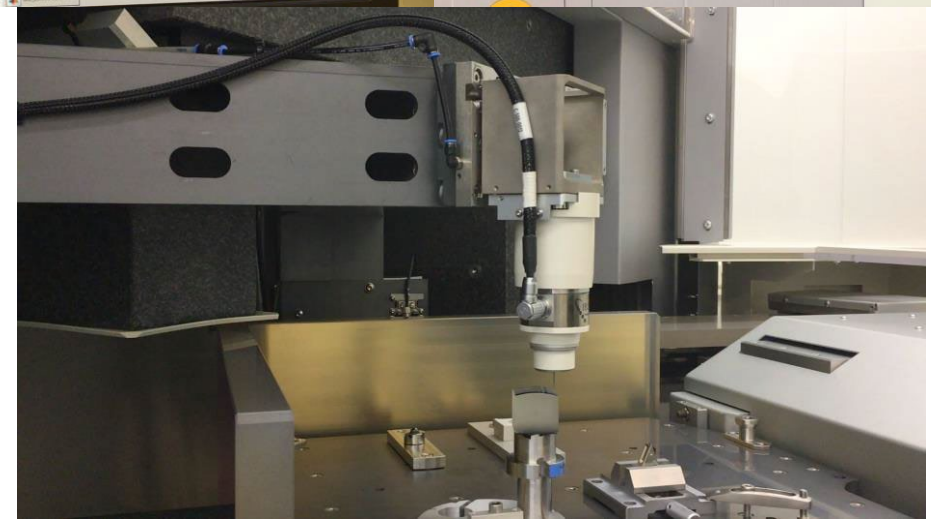
Measurement HLEM optics

- Alignment
  - Step 1: manual probing of 9 points
    - Calculate best fit alignment (x,y,z,Rx,Ry,(Rz))
    - Only manual action needed
  - Step 2: perform automated coarse grid
    - Recalculate best fit alignment
- Very quick on-machine alignment
  - Setup time: ~30 min
  - Automated alignment also for more complex and free-form optics



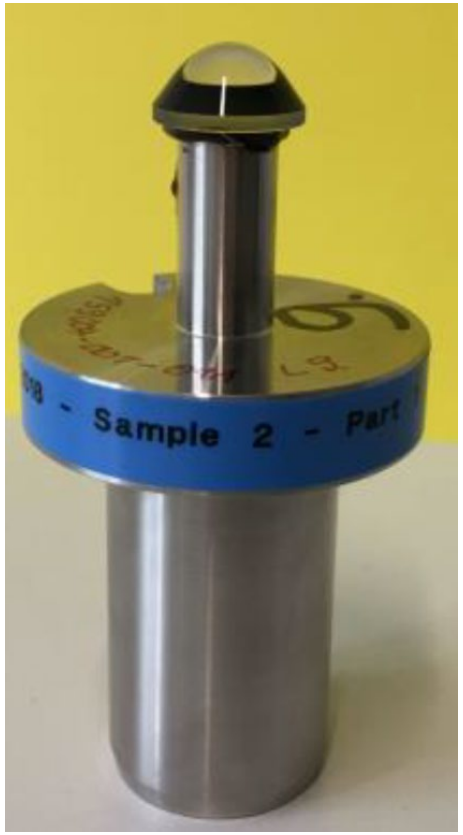


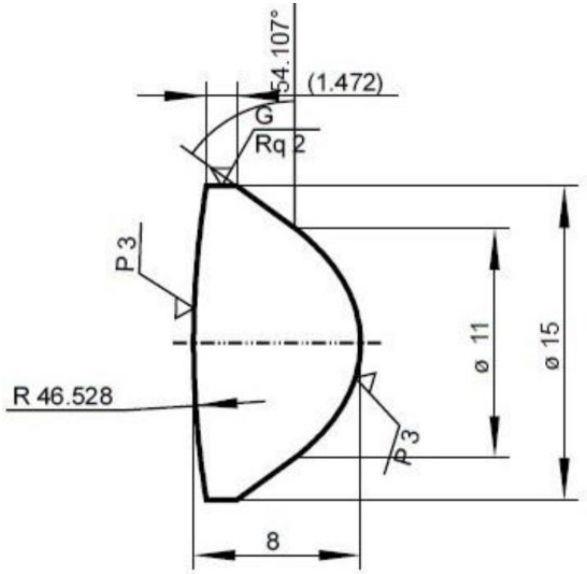
Measurement HLEM optics



Measurement Sample 2

- Small Asphere





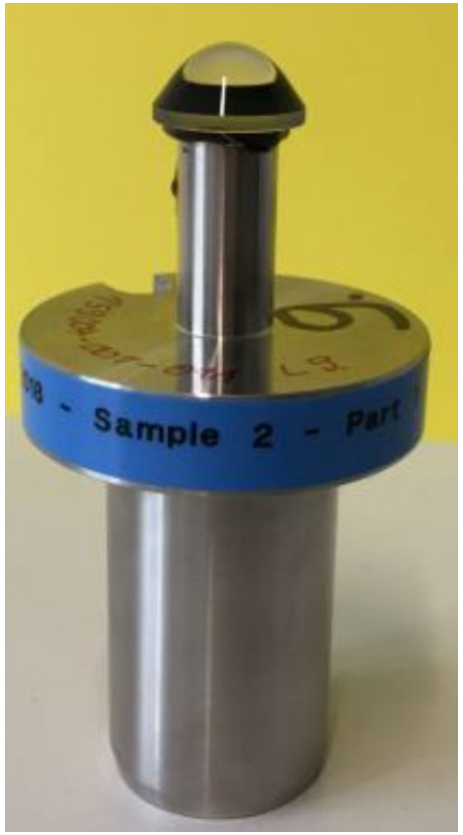
$$z(h)=\frac{h^2}{R\left(1+\sqrt{1-(1+k)\frac{h^2}{R^2}}\right)}+\sum_{i=2}^{n} A_{2i}h^{2i}$$

R	=	5.446
k	=	-0.17
A_4	=	-0.00029559792
A_6	=	-6.3943709e-006
A_8	=	-3.025556e-007
A_{10}	=	1.409072e-008
A_{12}	=	-1.2183175e-009
A_{14}	=	4.0114145e-011
A_{16}	=	-6.9463522e-013

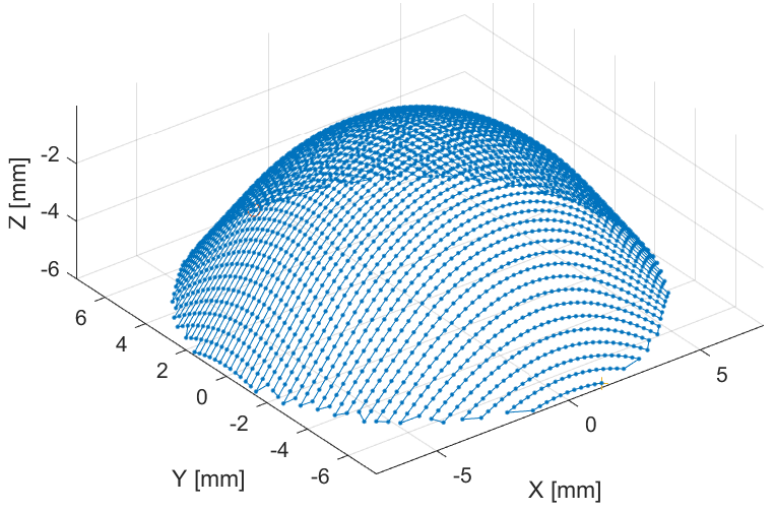
h	z(h)
0.0	-0.000000
1.0	-0.092160
2.0	-0.372932
3.0	-0.855888
4.0	-1.565864
5.0	-2.541486

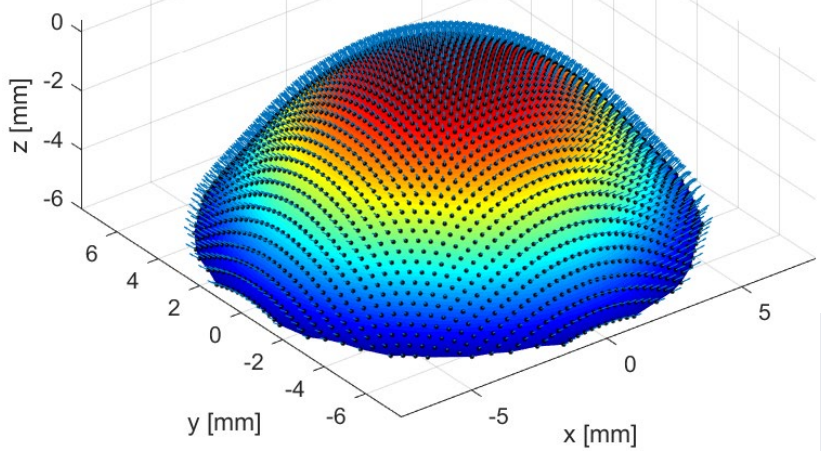
Measurement Sample 2

- Small Asphere



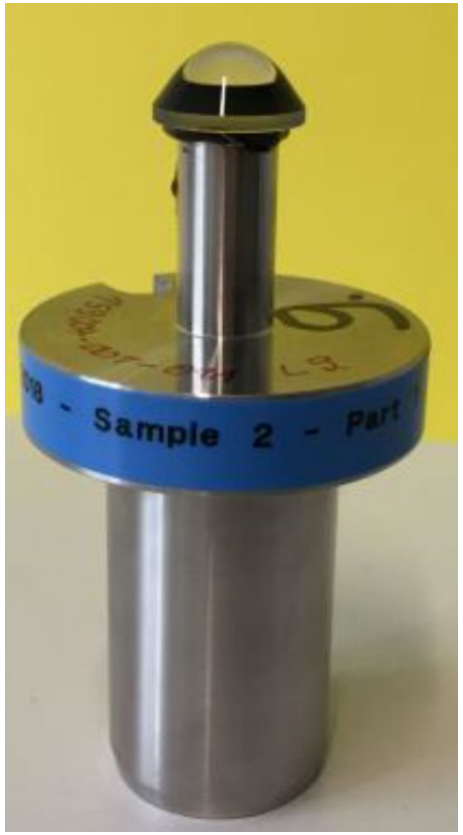
- Grid spacing: 0.26 mm
- Number of points: 2682
- Measured diameter: 14.7 mm
- Probe used: Triskelion A-250-0011 (Ø 500 µm Ruby tip)



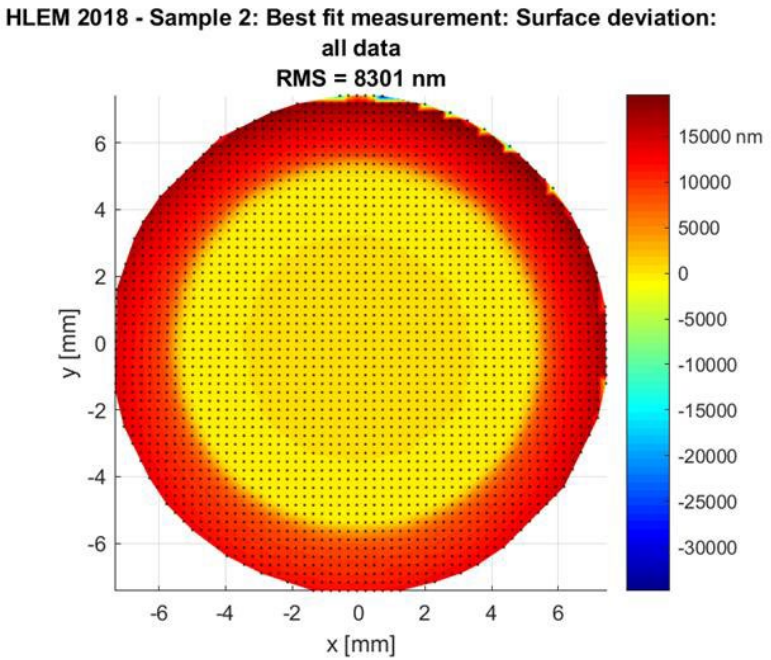


Measurement Sample 2

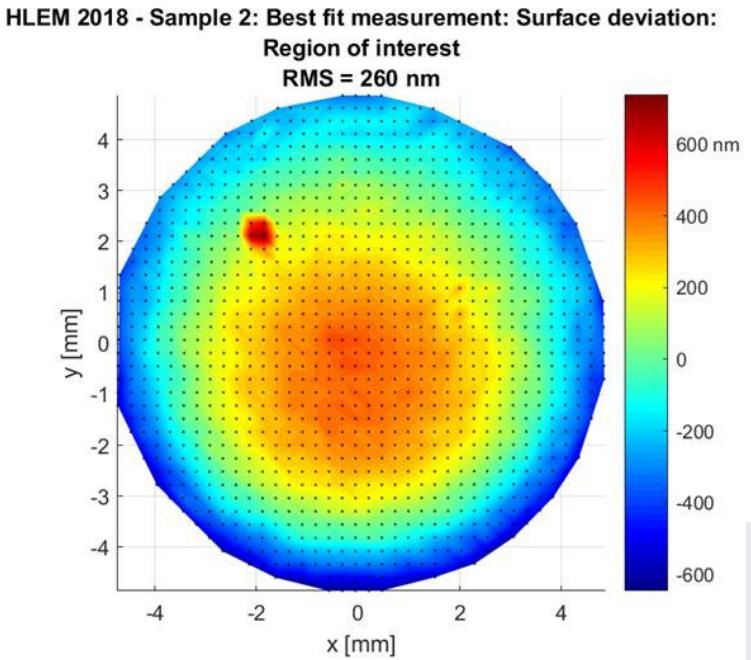
- Form deviation to theoretical design



Full aperture 14.7 mm

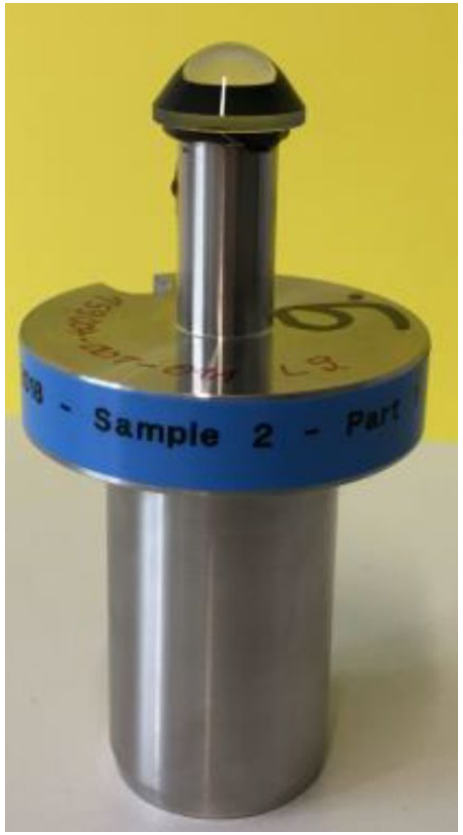


11 mm aperture



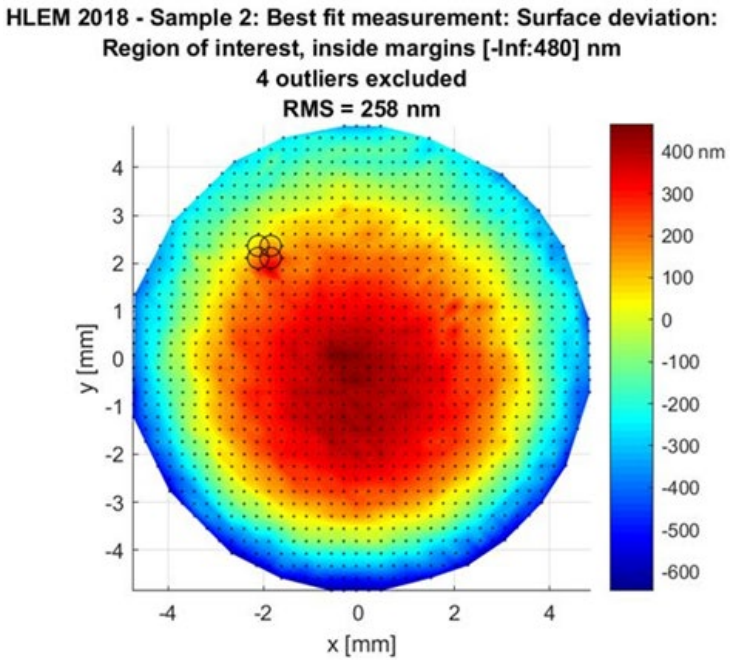
Measurement Sample 2

- Form deviation to theoretical design

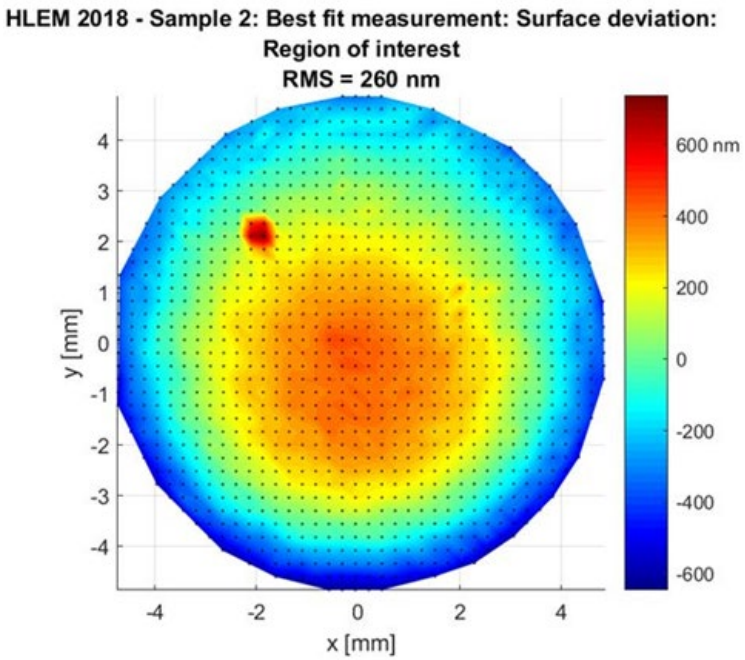


11 mm aperture

Outliers removed

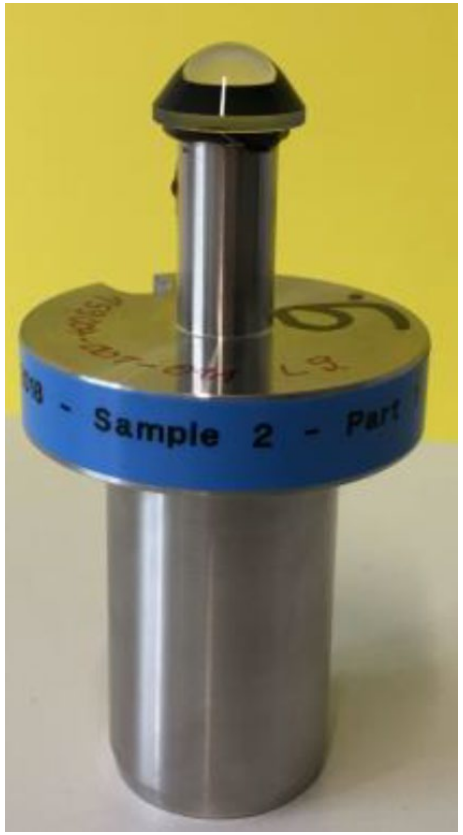


11 mm aperture



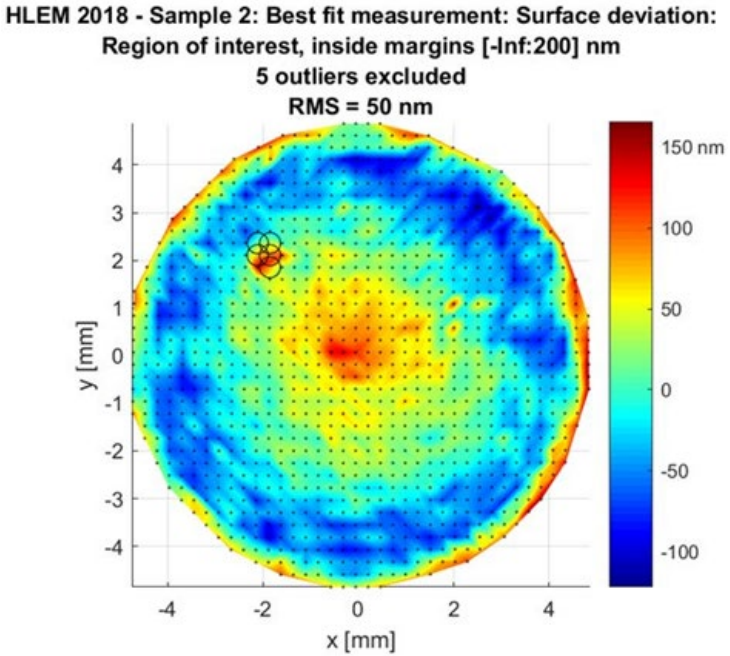
Measurement Sample 2

- Form deviation to theoretical design



Best fit radius

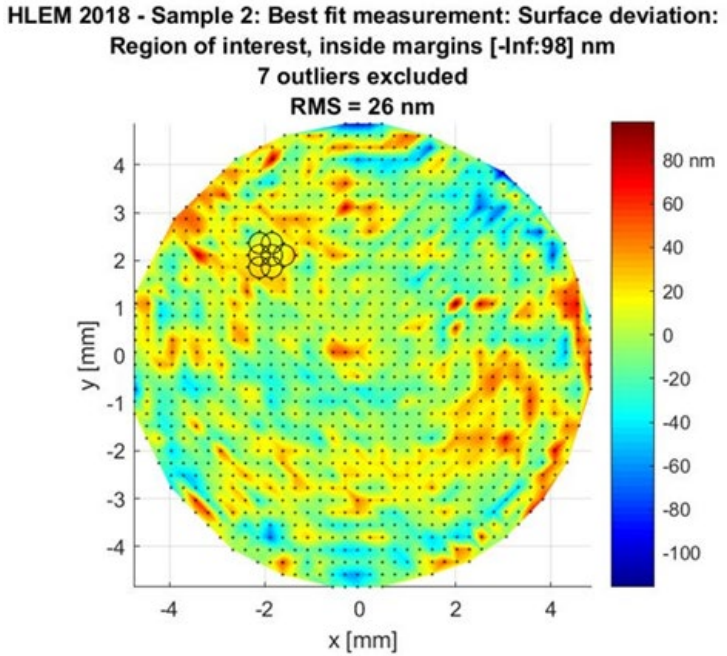
ΔR = -1.014 µm (-0.019%)



Best fit radius & k

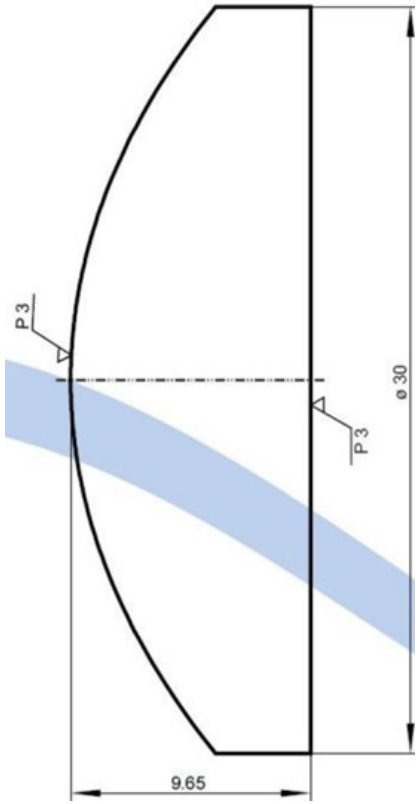
ΔR = -1.825 µm (-0.034%)

Δk = -0.000595 (-0.350%)



Measurement Sample 3

- Small Asphere



$$z(h)=\frac{h^2}{R\left(1+\sqrt{1-(1+k)\frac{h^2}{R^2}}\right)}+\sum_{i=2}^{n} A_{2i}h^{2i}$$

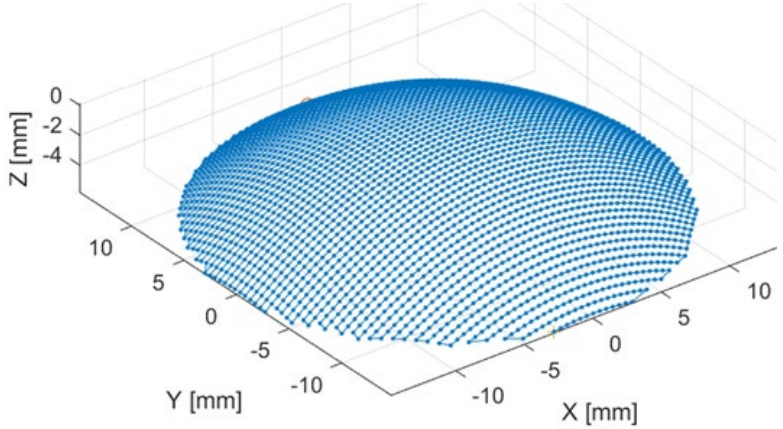
R	=	20.20 ±0.05%
k	=	-1
A_4	=	5.4144542e-006
A_6	=	-8.0413315e-010
A_8	=	-2.9871189e-012
A_{10}	=	-1.4917927e-015
A_{12}	=	1.3777317e-018
A_{14}	=	4.4258023e-021
A_{16}	=	-3.4927668e-024

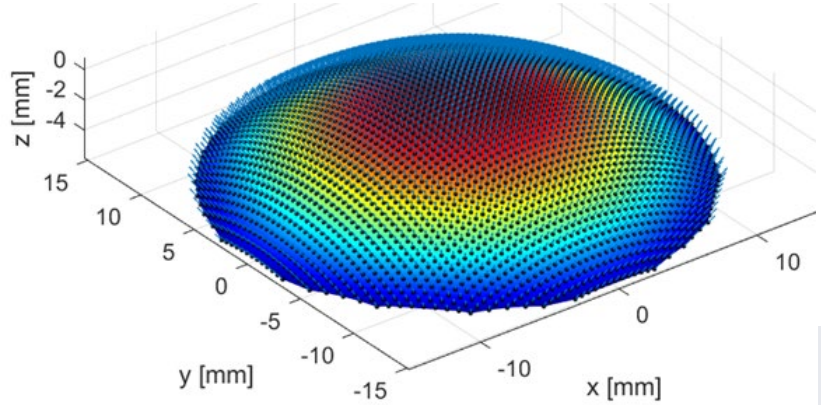
h	z(h)
0.0	-0.000000
2.0	-0.099096
4.0	-0.397422
6.0	-0.898064
8.0	-1.606074
10.0	-2.528276
12.0	-3.672870
14.0	-5.048712
15.0	-5.826023

Measurement Sample 3

- Small Asphere

- Grid spacing: 0.48 mm
- Number of points: 3125
- Measured diameter: 29.5 mm
- Probe used: Triskelion A-250-0011 (Ø 500 µm Ruby tip)

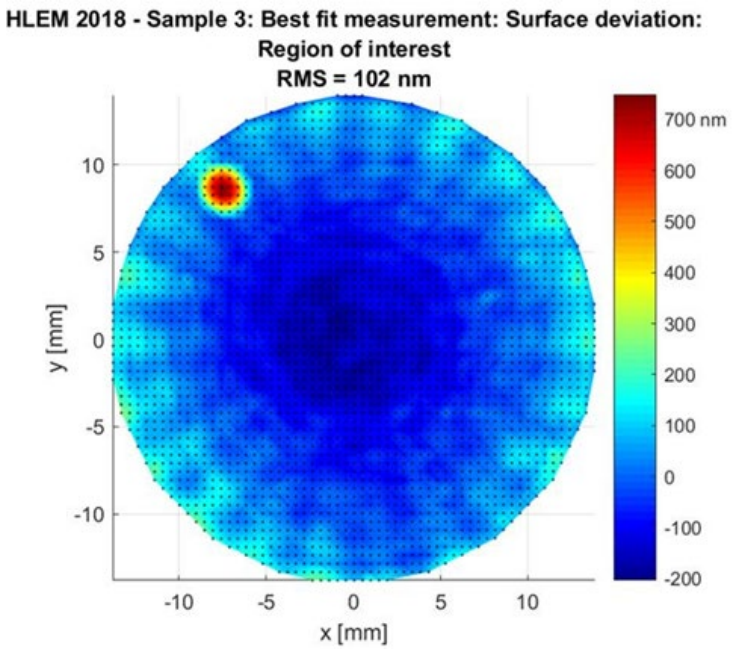




Measurement Sample 3

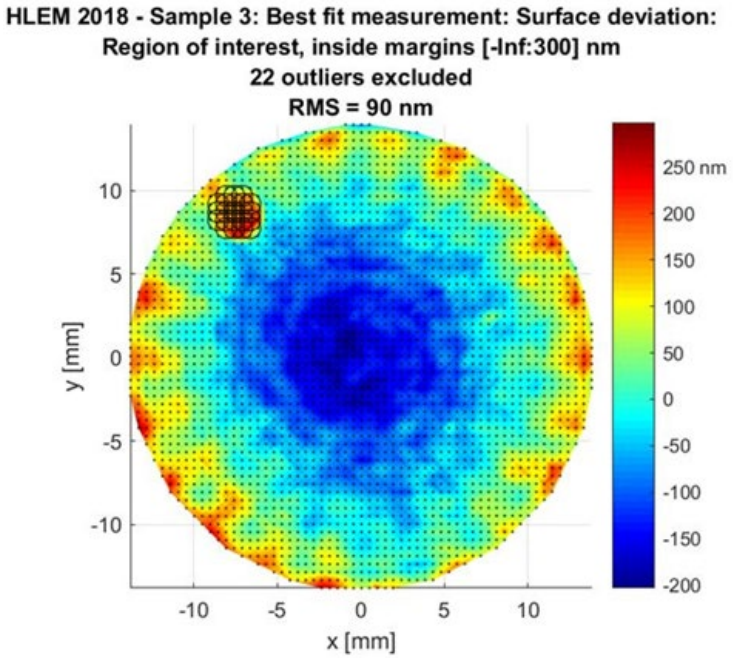
- Form deviation to theoretical design

29.5 mm aperture



29.5 mm aperture

Outliers removed

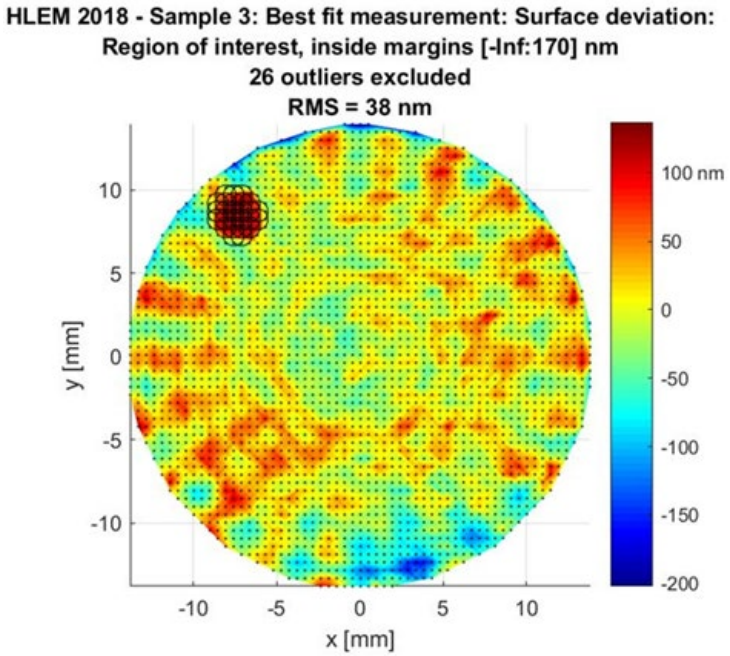


Measurement Sample 3

- Form deviation to theoretical design

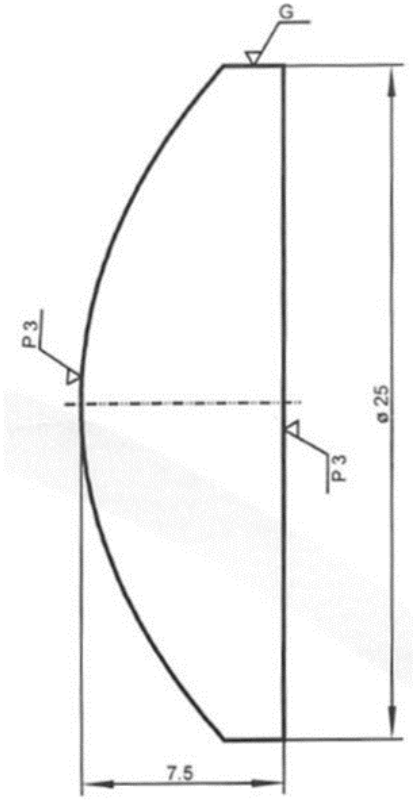
Best fit radius

ΔR = 1.232 µm (0.006%)



Measurement Sample 4

- Non circular cylinder
  - Aspherical cylinder



$$z(h)=\frac{h^2}{R\left(1+\sqrt{1-(1+k)\frac{h^2}{R^2}}\right)}+\sum_{i=2}^{n} A_{2i}h^{2i}$$

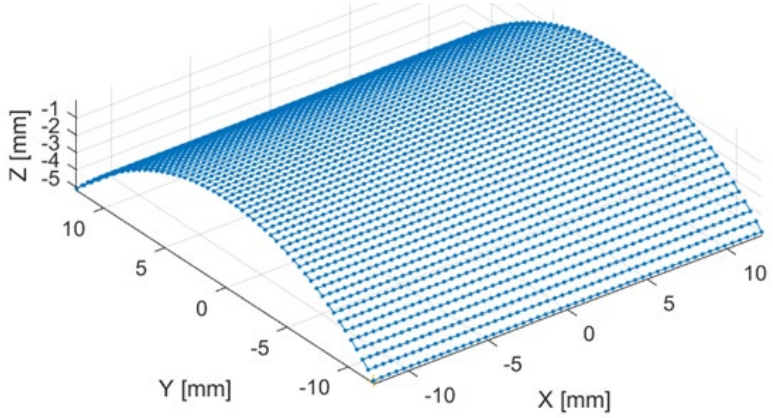
R	=	15.538 $^{+0.5\%}_{+0\%}$
k	=	-1
A_4	=	1.1926075e-005
A_6	=	-2.9323497e-009
A_8	=	-1.8718889e-011
A_{10}	=	-1.7009961e-014
A_{12}	=	3.5481542e-017
A_{14}	=	6.5241296e-020

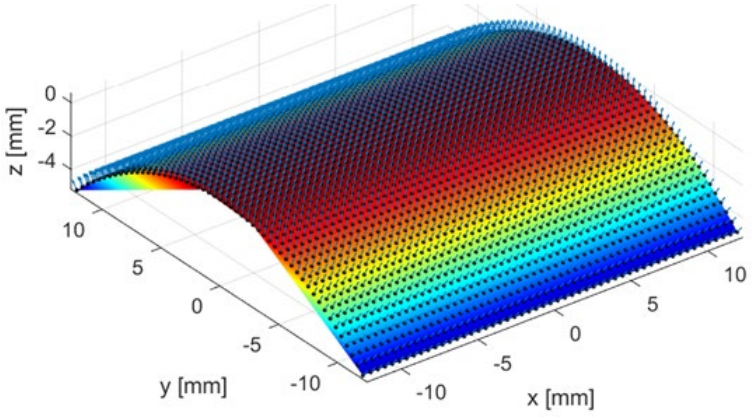
h	z(h)
0.0	-0.000000
2.0	-0.128907
4.0	-0.517907
6.0	-1.173737
8.0	-2.107218
10.0	-3.332246
12.0	-4.863642
12.5	-5.295897

Measurement Sample 4

- Small Asphere
  - Aspherical cylinder

- Grid spacing: 0.47 mm
- Number of points: 2809
- Measured diameter: 24.4 x 24.3 mm
- Probe used: Triskelion A-250-0011 (Ø 500 µm Ruby tip)

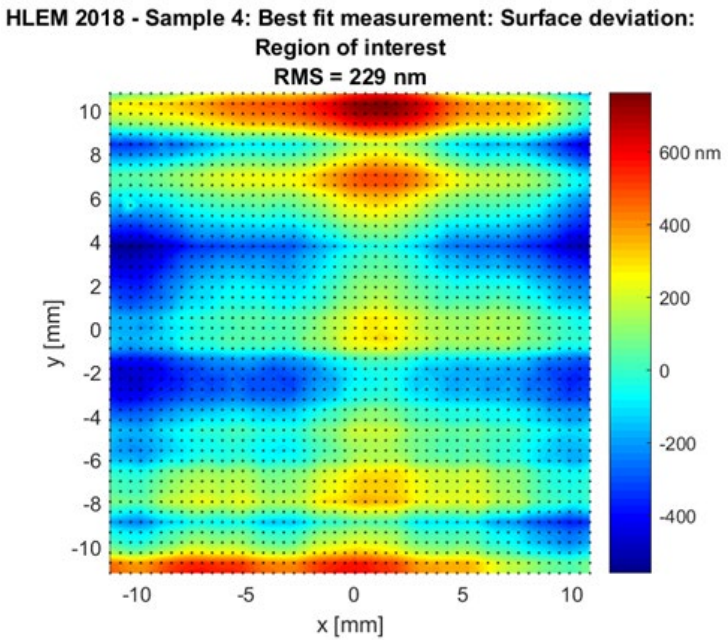




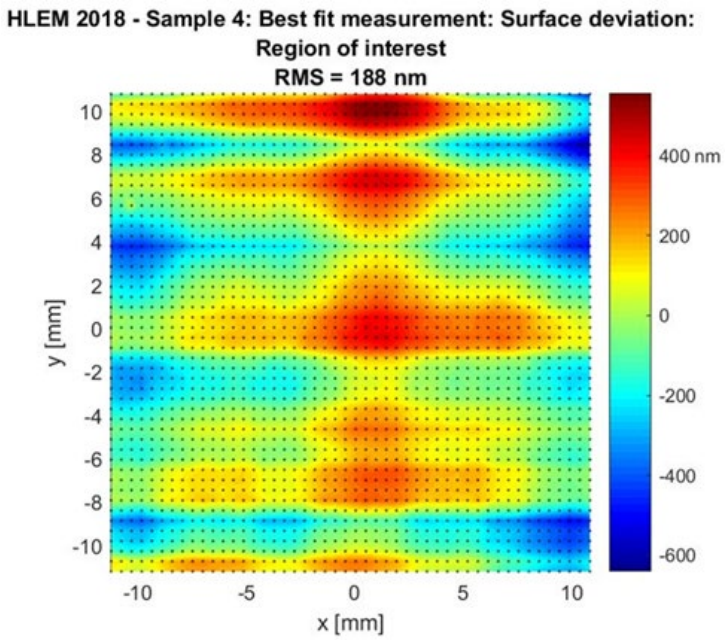
Measurement Sample 4

- Form deviation to theoretical design

Full area

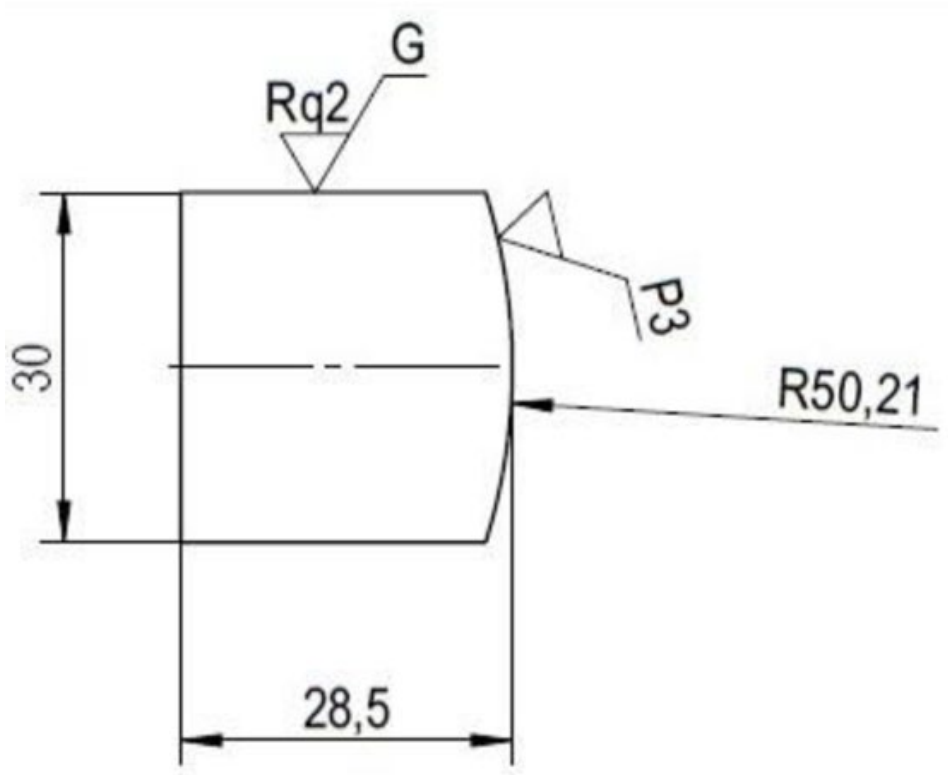


Best fit radius & k
ΔR = 1.643 µm (0.011%)



Measurement Sample 5

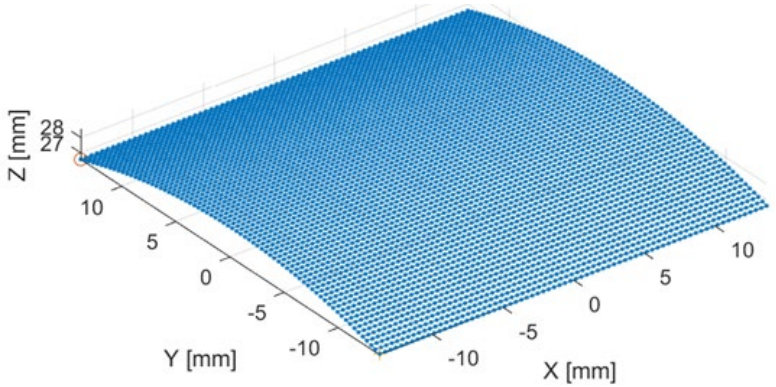
- Cylinder optic

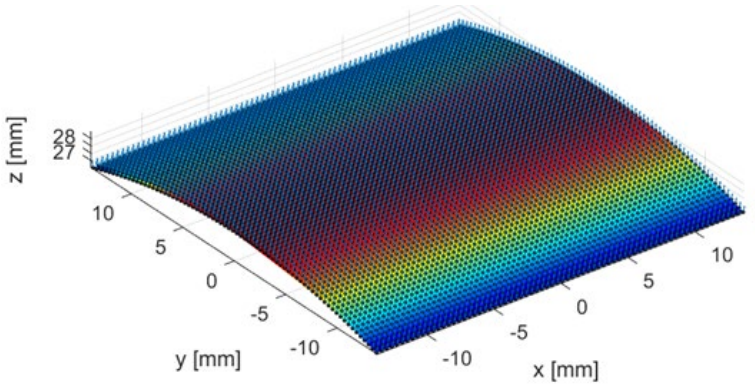


Measurement Sample 5

- Cylinder optic

- Grid spacing: 0.39 mm
- Number of points: 5184
- Measured diameter: 24=7.4 x 27.5 mm
- Probe used: Triskelion C-500-0012 (Ø 1000 µm Ruby tip)

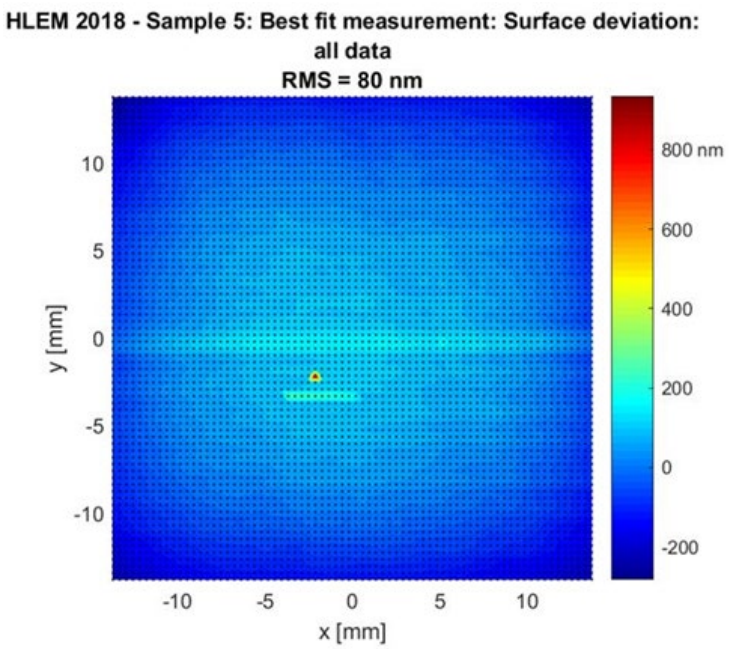




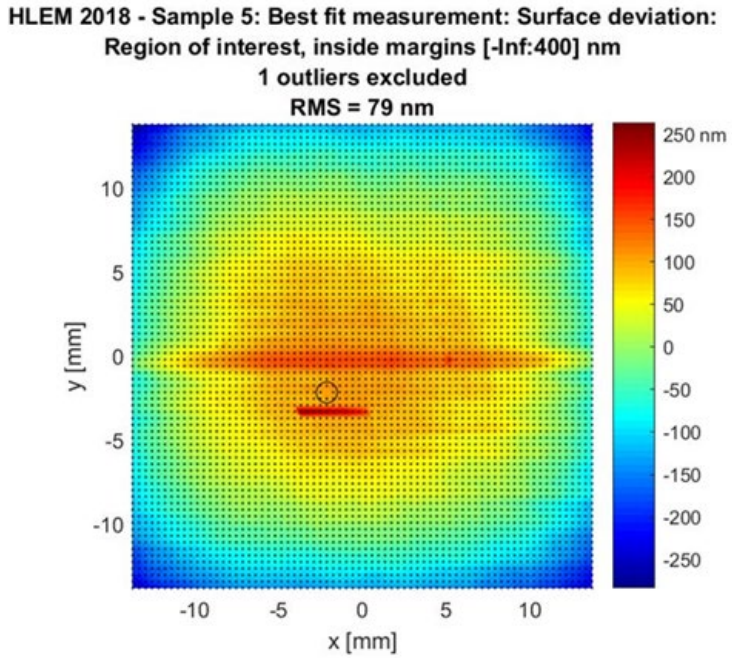
Measurement Sample 5

- Form deviation to theoretical design

Full area



After outlier removal

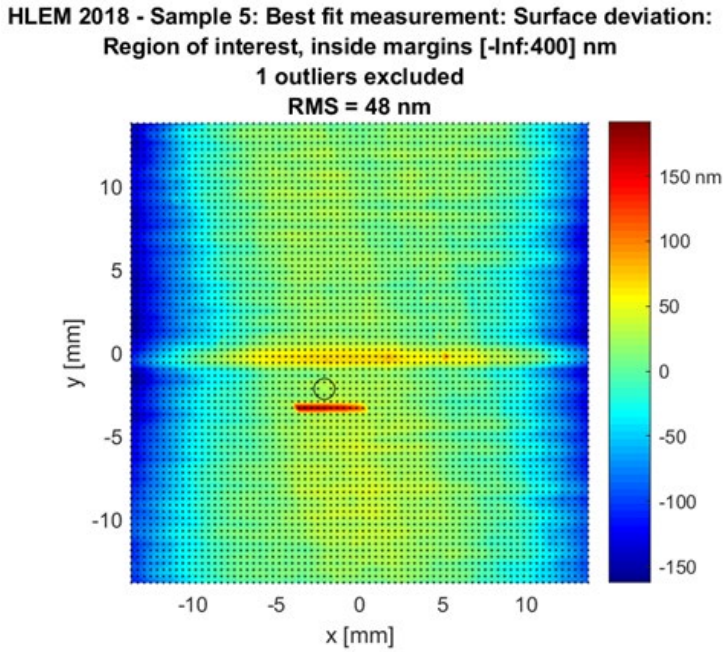


Measurement Sample 5

- Form deviation to theoretical design

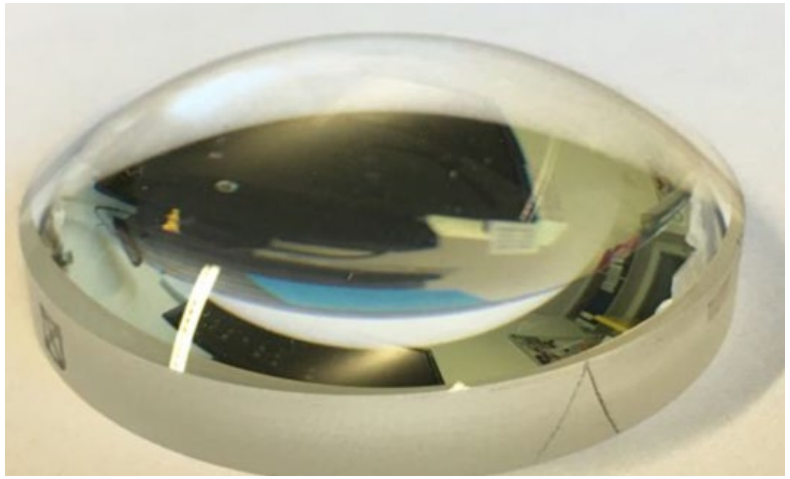
Best fit radius

ΔR = -5.462 µm (-0.011%)



Measurement Sample 6

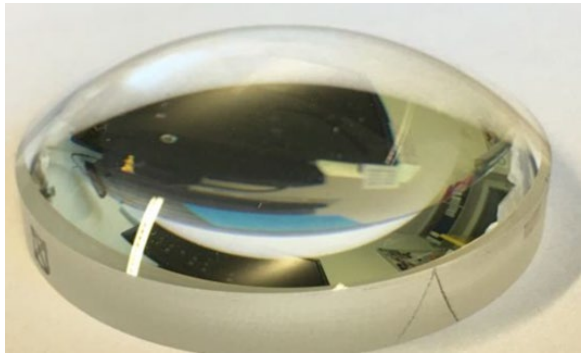
- Convex toroid
  - Rv = 40 mm; Rh = 42 mm
  - Diameter Ø 50 mm



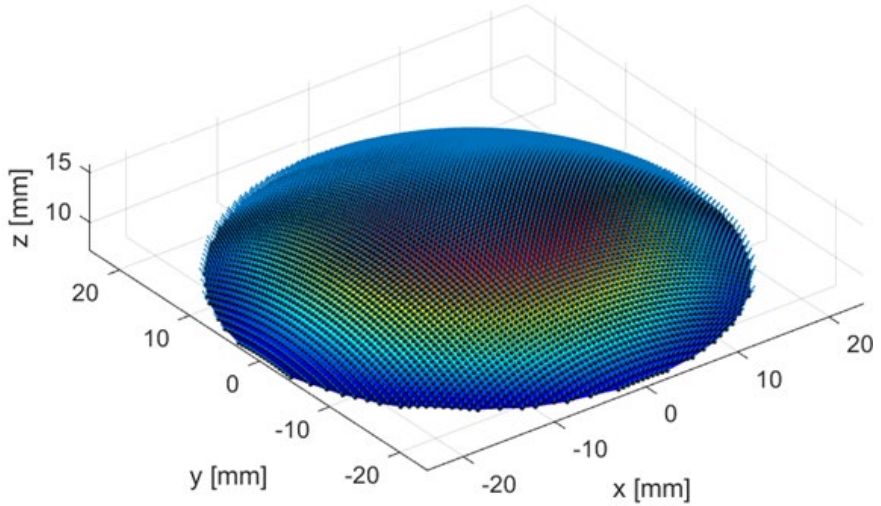
$$z(x,y) = \sqrt{\left(\sqrt{{R_h}^2 - x^2} + R_v - R_h\right)^2 - y^2} - R_v$$

Measurement Sample 6

- Convex toroid

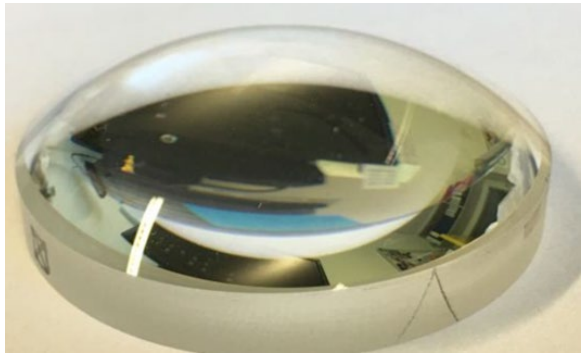


- Grid spacing: 0.53 mm
- Number of points: 6286
- Measured diameter: Ø 47 mm
- Probe used: Triskelion A-500-0012 (Ø 1000 µm Ruby tip)

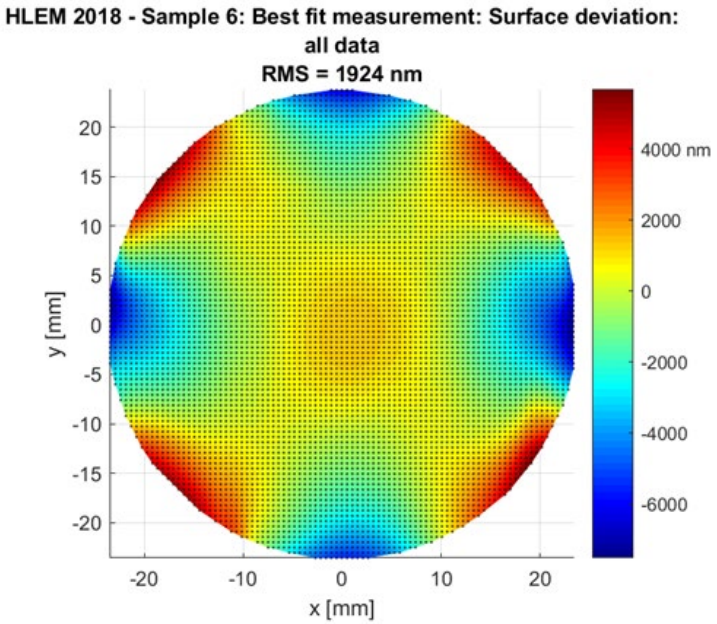


Measurement Sample 6

- Form deviation to theoretical design

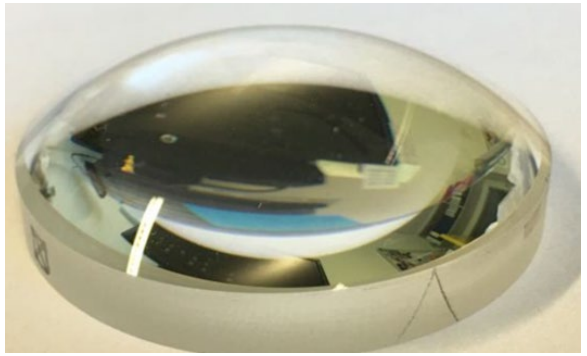


All data

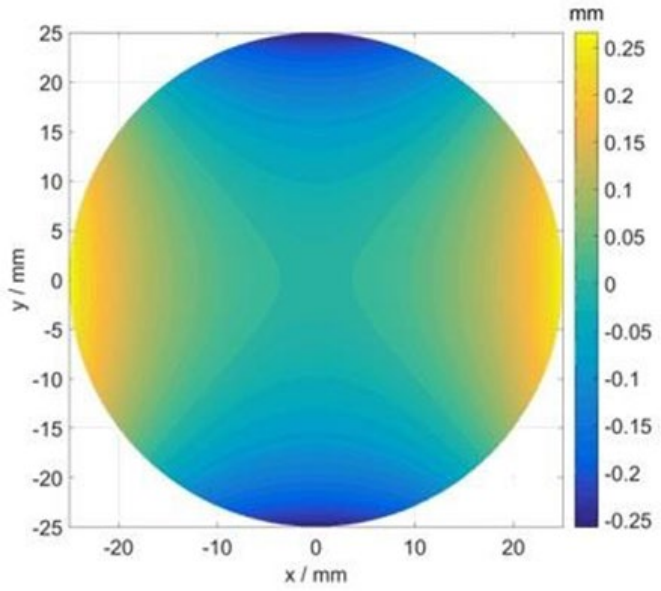


Measurement Sample 6

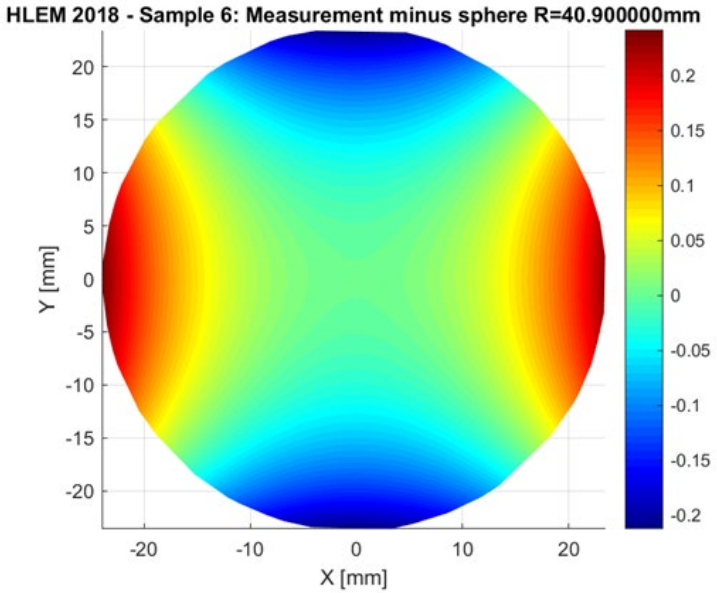
- Form deviation to theoretical design minus best-fit sphere (R=40,9 mm)



Design

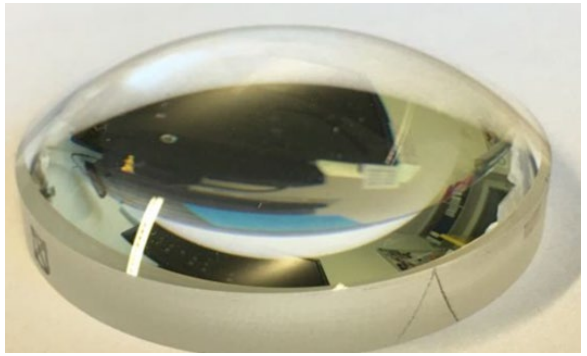


Actual measurement

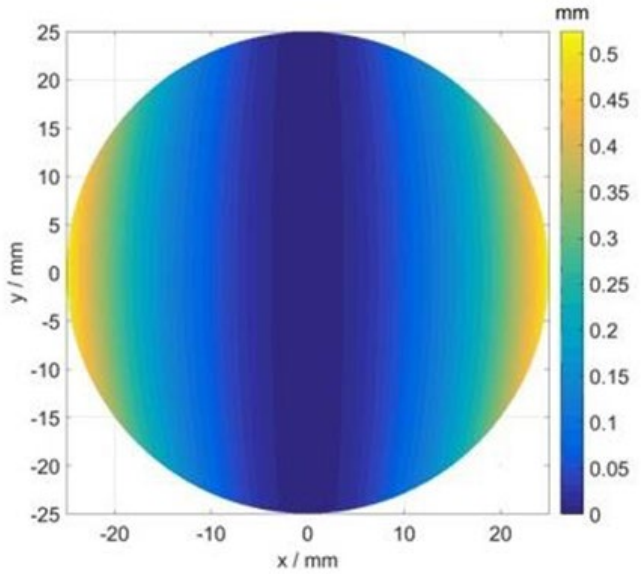


Measurement Sample 6

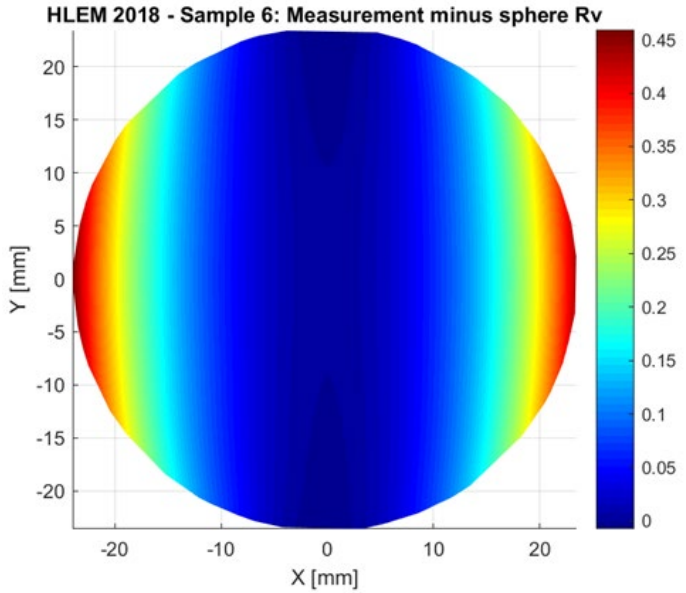
- Form deviation to theoretical design minus Rv sphere (Rv=40 mm)



Design

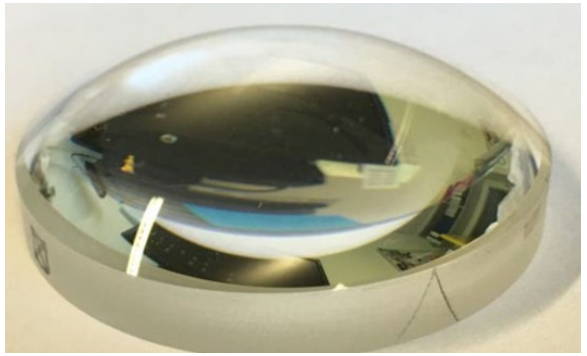


Actual measurement

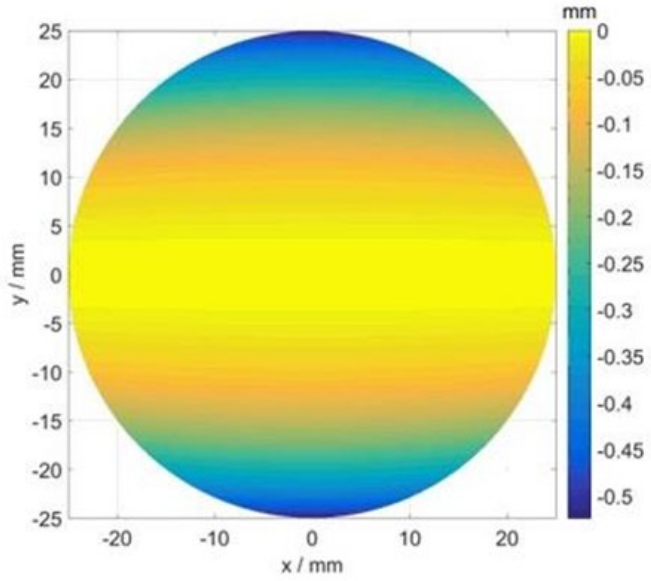


Measurement Sample 6

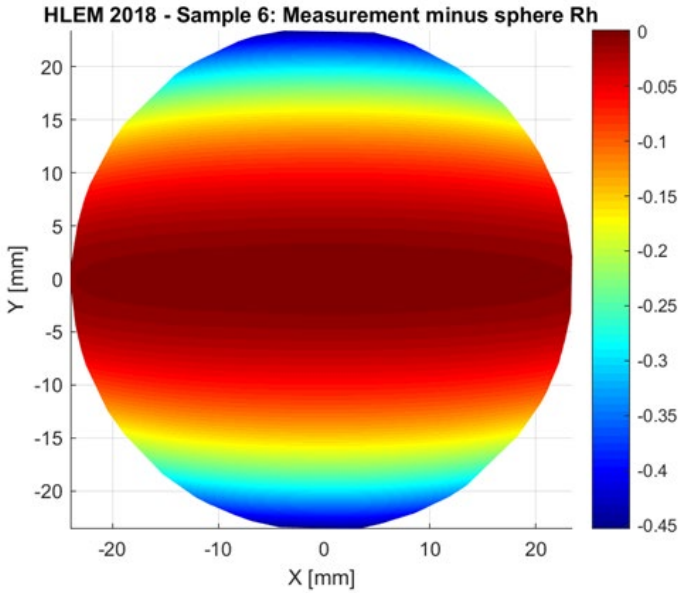
- Form deviation to theoretical design minus Rh sphere (Rh=42 mm)



Design



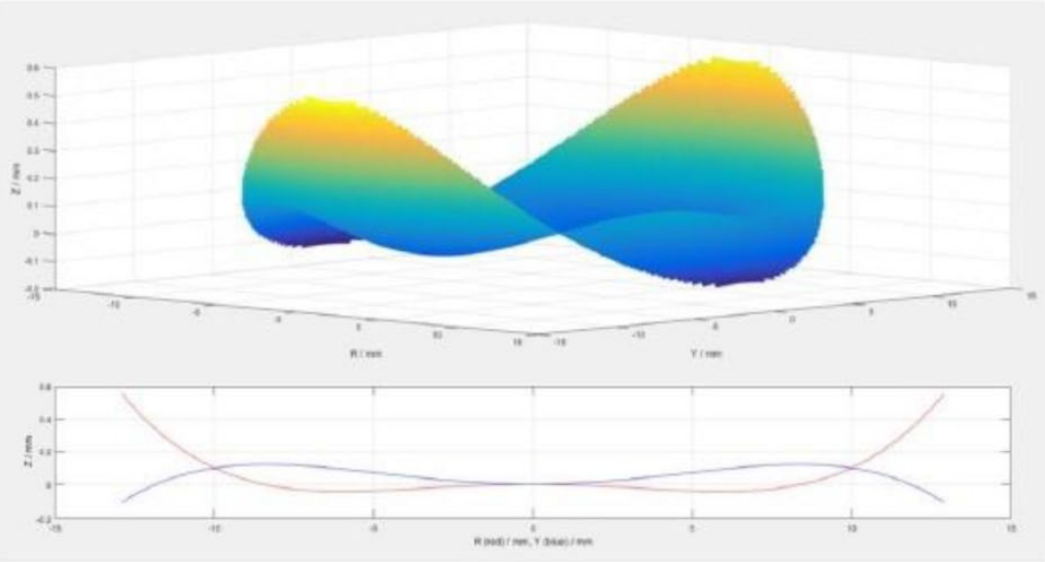
Actual measurement

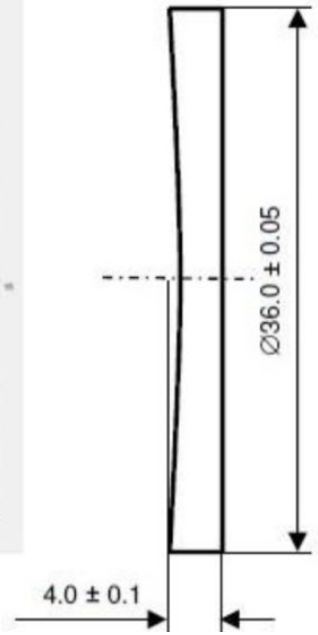


Measurement Sample 7

- 4th order polynomial freeform
  - “wild curvature”, sag ≈ 700 µm

1) $H=Ax^2+By^2+Cx^4+Dy^4$

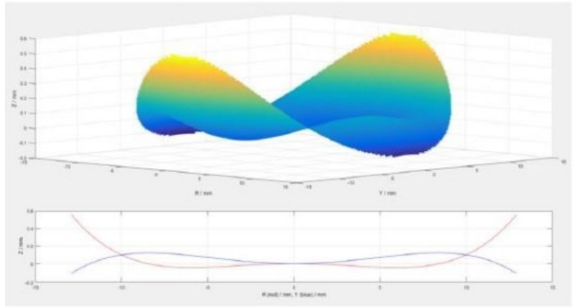




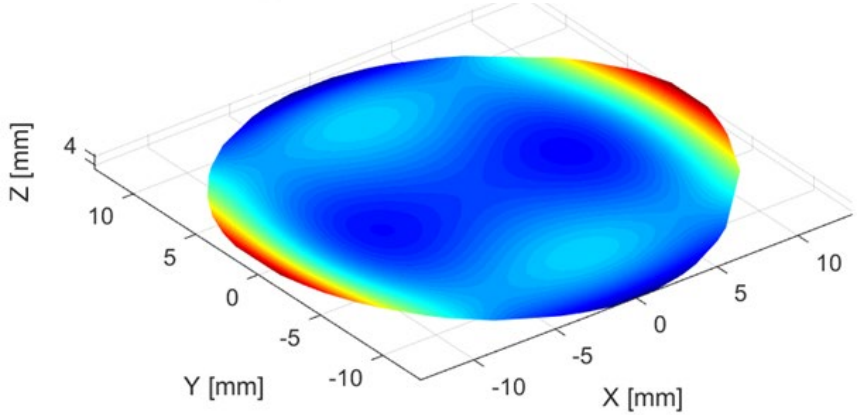
Measurement Sample 7

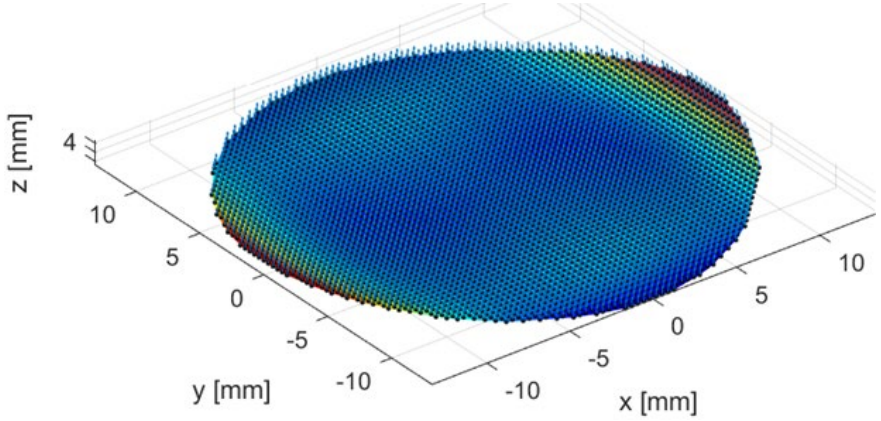
- 4th order polynomial freeform
  - “wild curvature’

1) H=Ax^2+By^2+Cx^4+Dy^4



- Grid spacing: 0.37 mm
- Number of points: 4106
- Measured diameter: Ø 26.2 mm
- Probe used: Triskelion A-500-0012 (Ø 1000 µm Ruby tip)

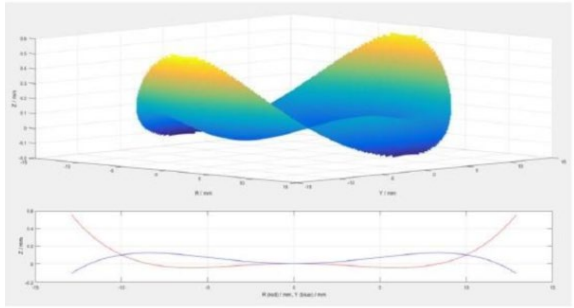




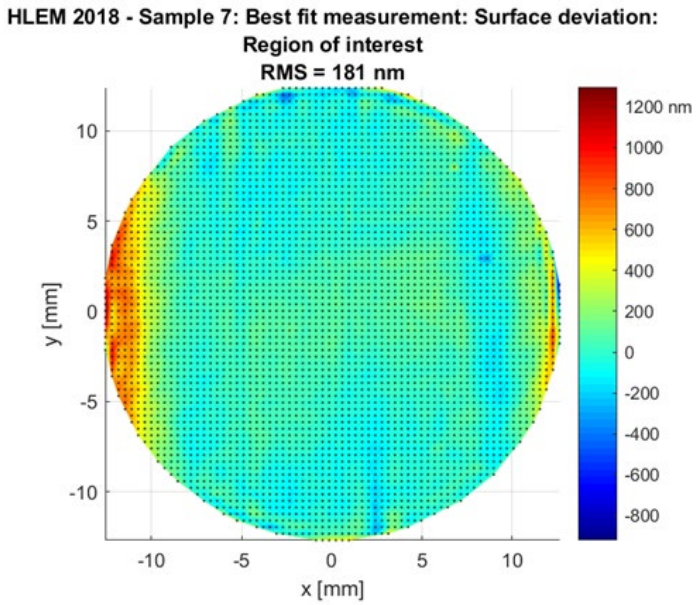
Measurement Sample 7

- Form deviation to theoretical design

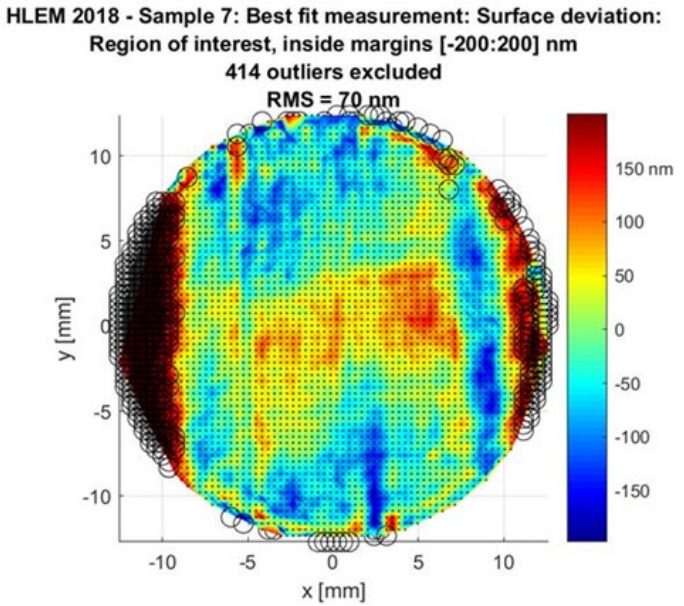
[1] $H=Ax^2+By^2+Cx^4+Dy^4$



Full aperture



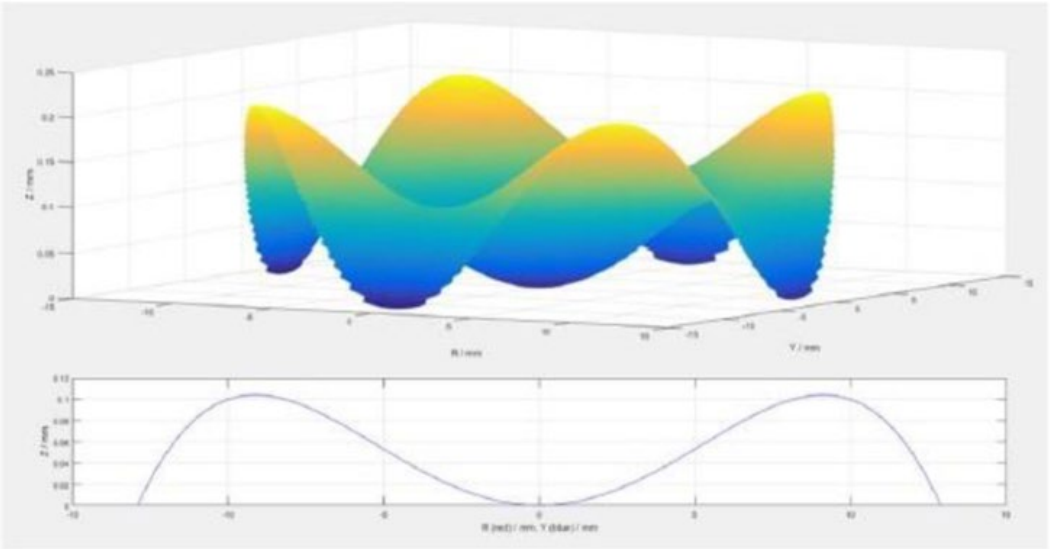
After outlier removal

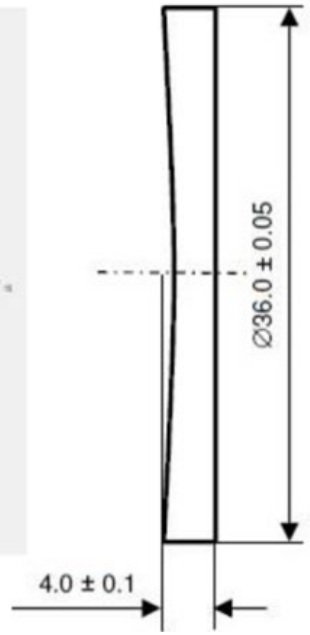


Measurement Sample 8

- 4th order polynomial freeform
  - ”mild curvature”, sag ≈ 210 µm

1) $H=Ax^2+By^2+Cx^4+Dy^4$

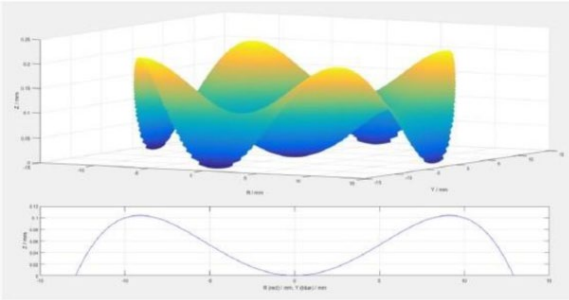




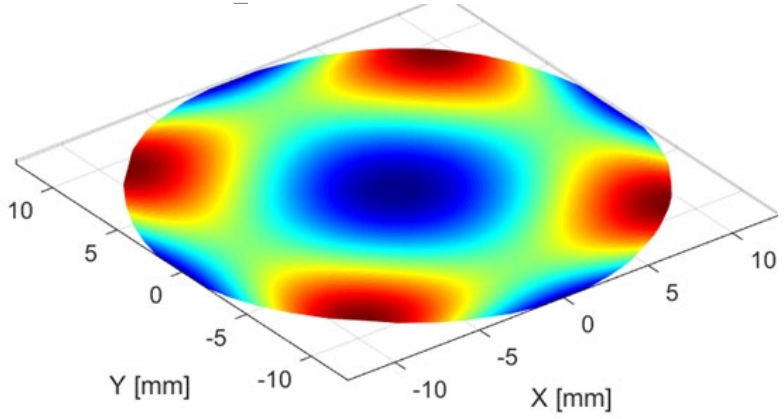
Measurement Sample 8

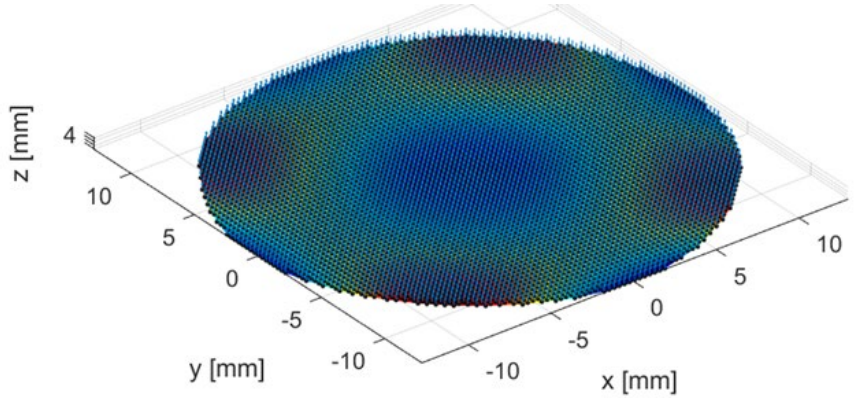
- 4th order polynomial freeform
  - “mild curvature’

[1] H=Ax^2+By^2+Cx^4+Dy^4



- Grid spacing: 0.31 mm
- Number of points: 5679
- Measured diameter: Ø 25.7 mm
- Probe used: Triskelion A-500-0012 (Ø 1000 µm Ruby tip)

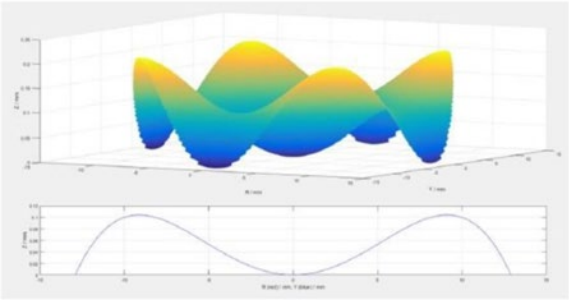




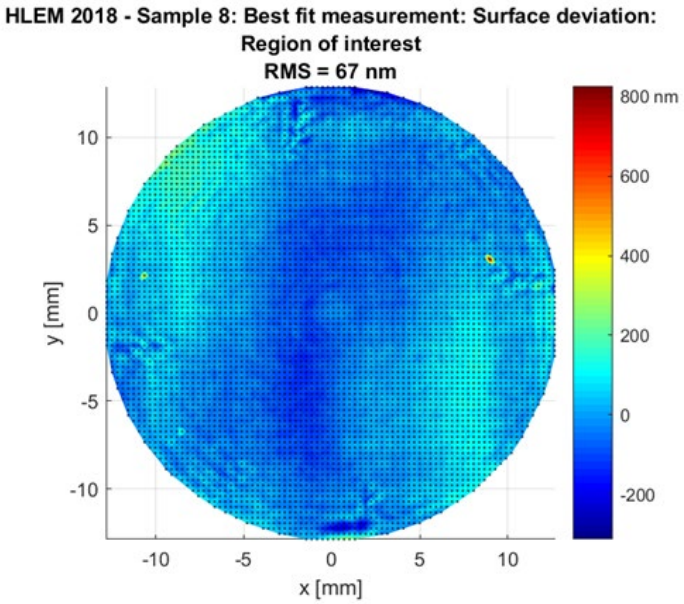
Measurement Sample 8

- Form deviation to theoretical design

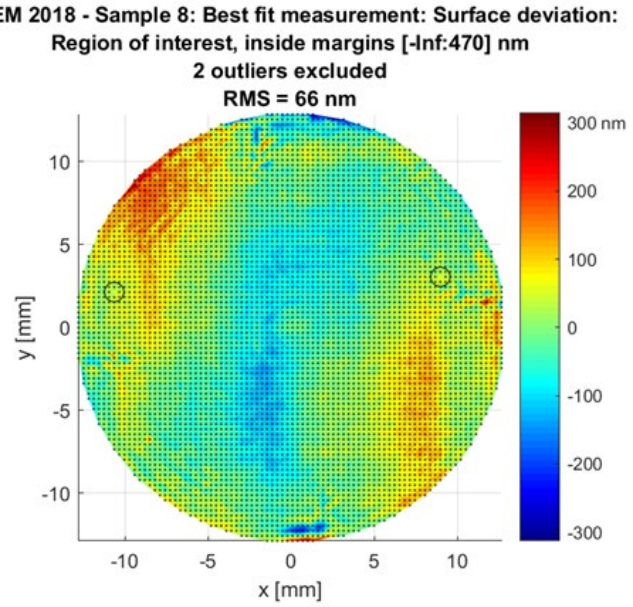
[1] H=Ax^2+By^2+Cx^4+Dy^4



Full aperture

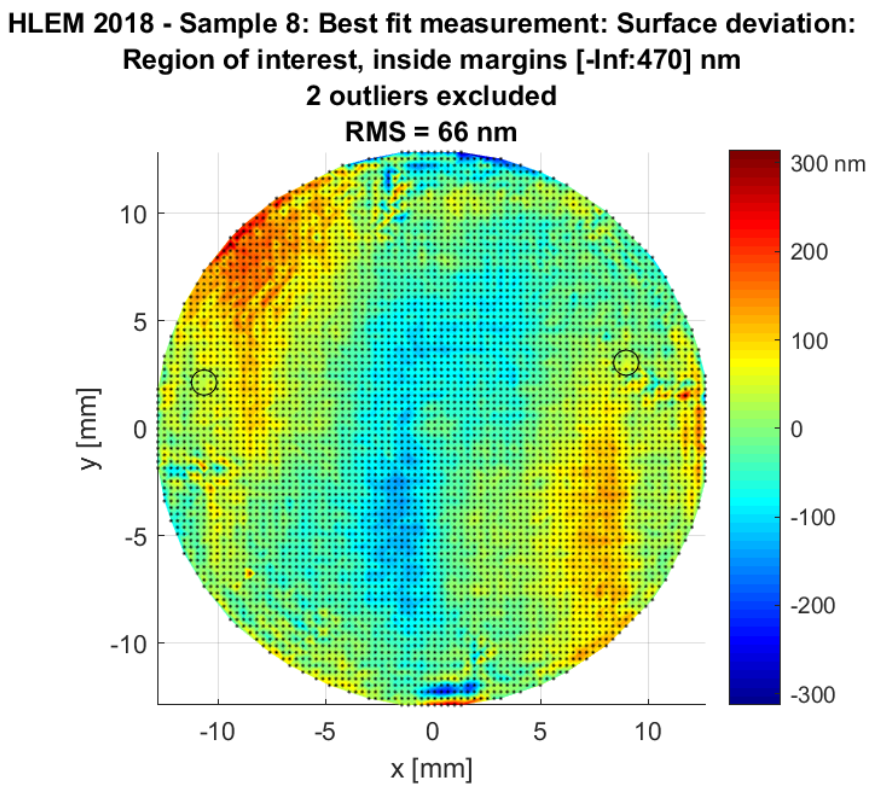


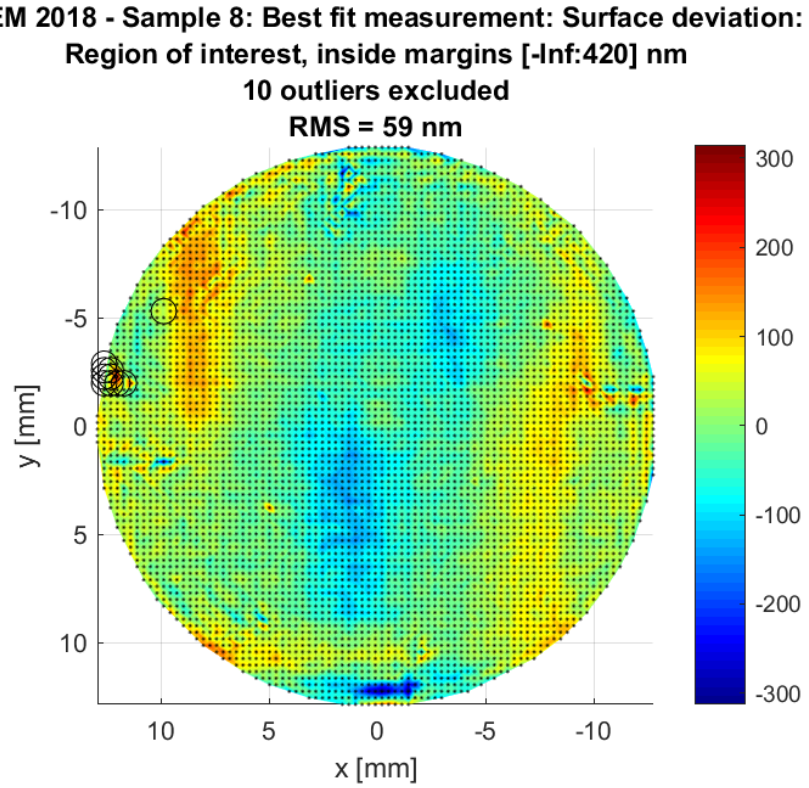
After outlier removal



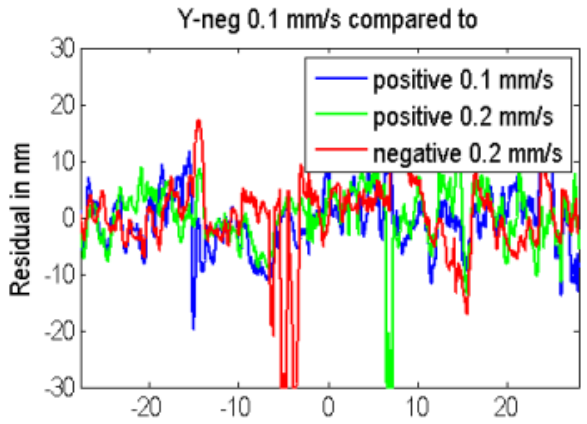
Measurement Sample 8

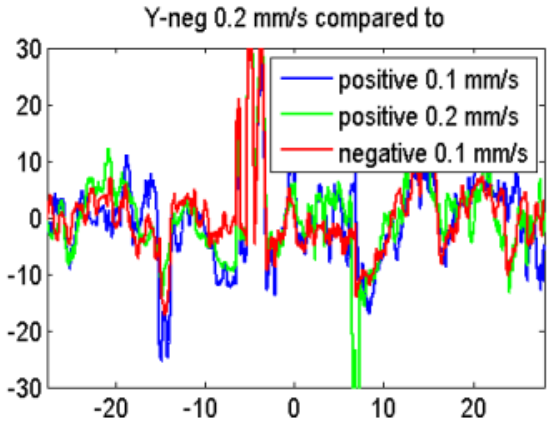
- • 180° rotated (Rz) (Contaminated measurements removed)

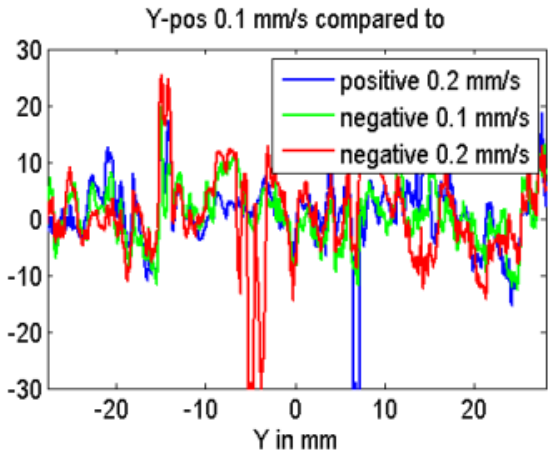




D58 Y-scan repeatablitiy







2σ in nm

	Y- 0.1 mm/s	Y- 0.2 mm/s	Y+ 0.1 mm/s	Y- 0.2 mm/s
Y- 0.1 mm/s	0	13.9853	10.3068	11.1690
Y- 0.2 mm/s	13.9853	0	16.1184	17.6691
Y+ 0.1 mm/s	10.3068	16.1184	0	13.7119
Y- 0.2 mm/s	11.1690	17.6691	13.7119	0

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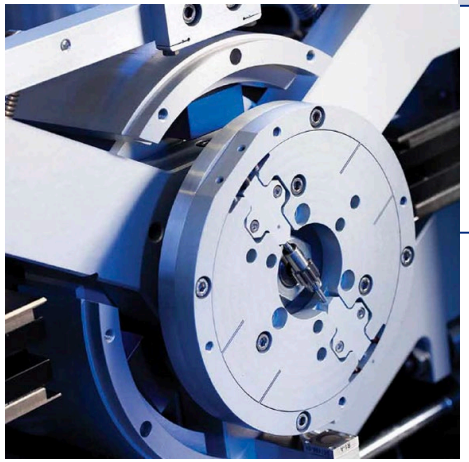
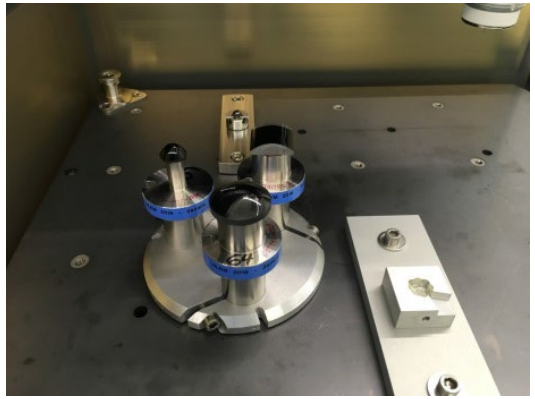
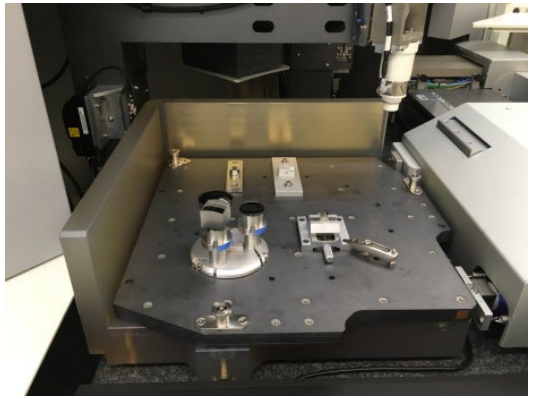
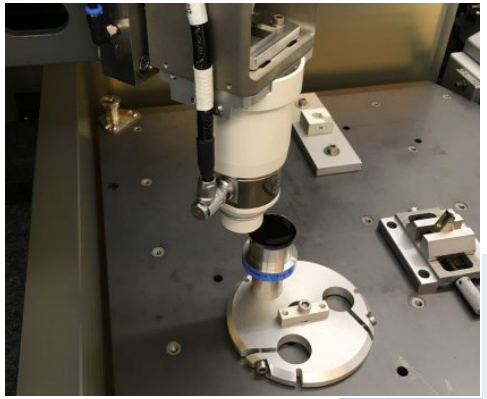


Confidential

Conclusions

Conclusions

- All 7 samples of HLEM 2018 can be measured with Isara 400
  - Single point measurements using Triskelion A and C probes
    - The Triskelion C probe could not be used for all as it did pick up some debris
- Applied alignment procedure adequate for all provided samples
  - Fully automated sequence proved very efficient
- Analysis has been performed on each sample showing actual deviation
  - Using supplied free-form coefficients or formula
  - Further extraction of R or k

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Thanks for your attention

Time to start the dialogue

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