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# The 3D Measurement and Analysis of Aspheric Surfaces

J.W.McBride
DMAC January 2009

# With Contributions From

| | | |
|---|---|---|
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| Dr Kevin Cross | Ph.D | TaiCaan |

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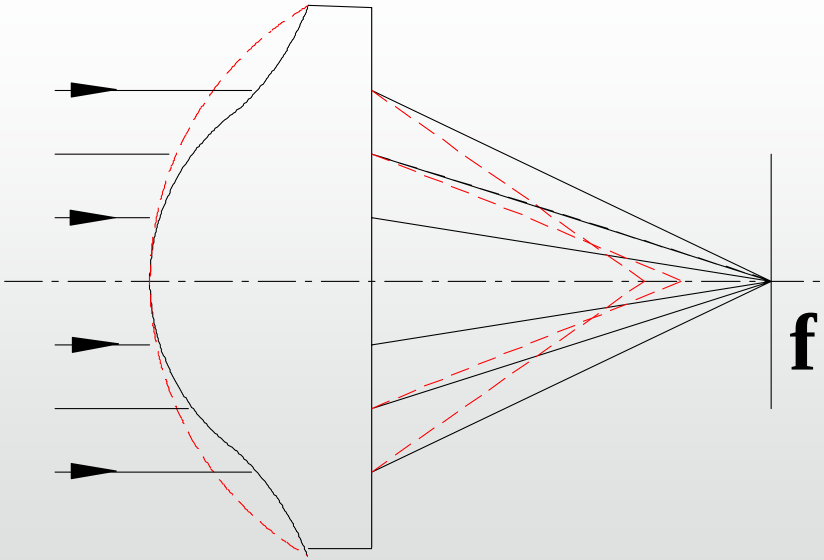
# Selected References

- Sun, W., McBride, J.W. and Hill, M. (2009) A new approach to characterising aspheric surfaces. *Precision Engineering*, 40pp. (In Press)
- Boltryk, Peter J., Hill, Martyn, McBride, John W. and Nasce, Antony (2008) A comparison of precision optical displacement sensors for the 3-D measurement of complex surface profiles. *Sensors and Actuators A: Physical*, 142, (1), 2-11.
- Sun, Wenjuan, Hill, Martyn and McBride, John. W. (2008) An investigation of the robustness of the nonlinear least-squares sphere fitting method to small segment angle surfaces. *Precision Engineering*, 32, 55-62.
- McBride, John and Maul, Christian (2004) The 3D measurement and analysis of high precision surfaces using con-focal optical methods. *IEICE Transactions on Electronics*, E87, (8), 1261-1267.
- Hill, M., Jung, M. and Mcbride, J.W. (2002) Separation of form from orientation in 3D measurements of aspheric surfaces with no datum. *International Journal of Machine Tools & Manufacture*, 42, (4), 457-66.
- Jung, M., Cross, K.J., McBride, J.W. and Hill, M. (2000) A method for the selection of algorithms for form characterisation of nominally spherical surfaces. *Precision Engineering*, 24, (2), 127-138.
- McBride, J.W. and Cross, K.J. (1996) The measurement and analysis of the three-dimensional form of curved surfaces. *International Journal of Machine Tools Manufacture*, 36, (5), 597-610.

# Talk Outline

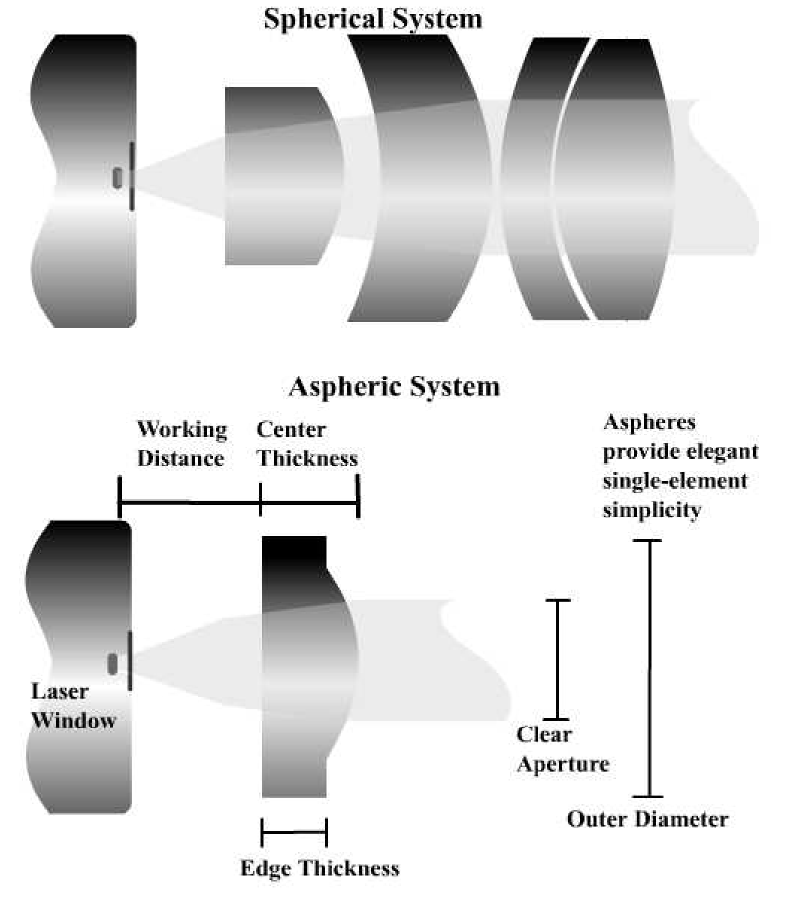
- Introduction. Why use aspheric surfaces when spherical surfaces have been used for 100’s years.
- The Measurement problem. Spherical to Aspheric surfaces.
- The Analysis problem.
- Some Conclusions.
- Future Directions.



# Application of aspheric surfaces

.... millimetre .... centimetre .... meter ....

# Aspheric Surfaces?



Reduce spherical aberration

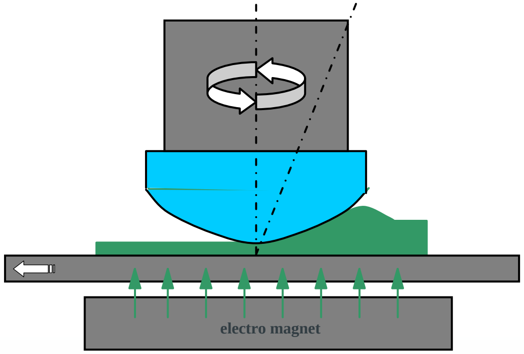
Reduced number of optical components

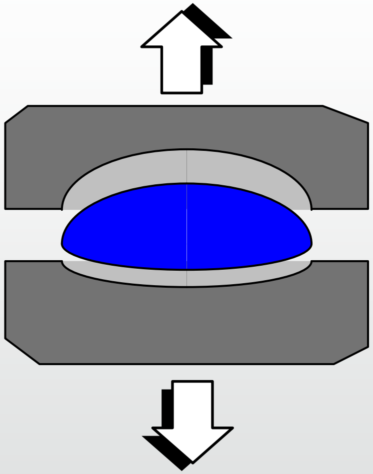
Reduced weight

Lower cost

# Manufacturing an Aspheric

- Diamond Turning
- Grinding
- Moulding
- Hybrid methods
- Thermal Replication





# Defining the Aspheric Surface

A rotationally symmetrical surface that gradually varies in surface power from the centre towards the edge in a radial fashion.

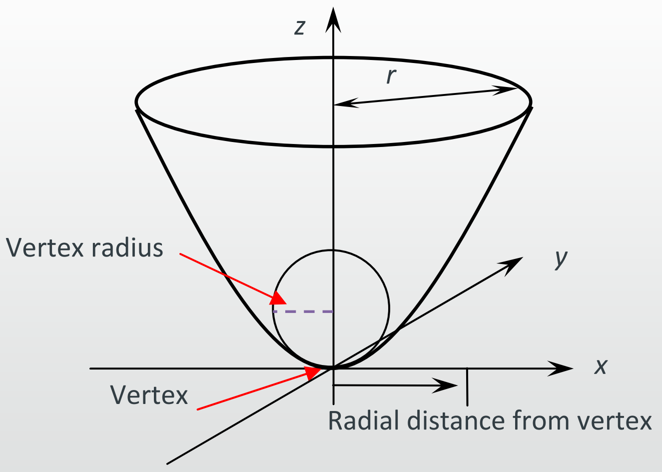
$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + A_4 r^4 + A_6 r^6 + A_8 r^8 + A_{10} r^{10} + A_{12} r^{12} \qquad (1)$$

$$r = \sqrt{x^2 + y^2}$$

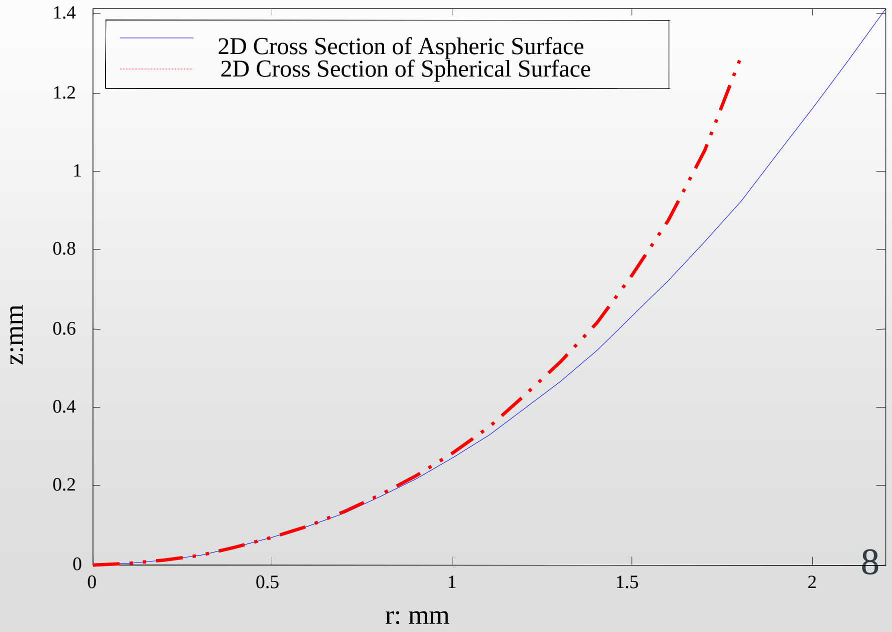
$k$ is the conic constant

$c$ is the reciprocal of vertex radius (1/R)

$A_4$ $A_6$ $A_8$ $A_{10}$ $A_{12}$ are polynomial coefficients



*Schematic of an aspheric surface*



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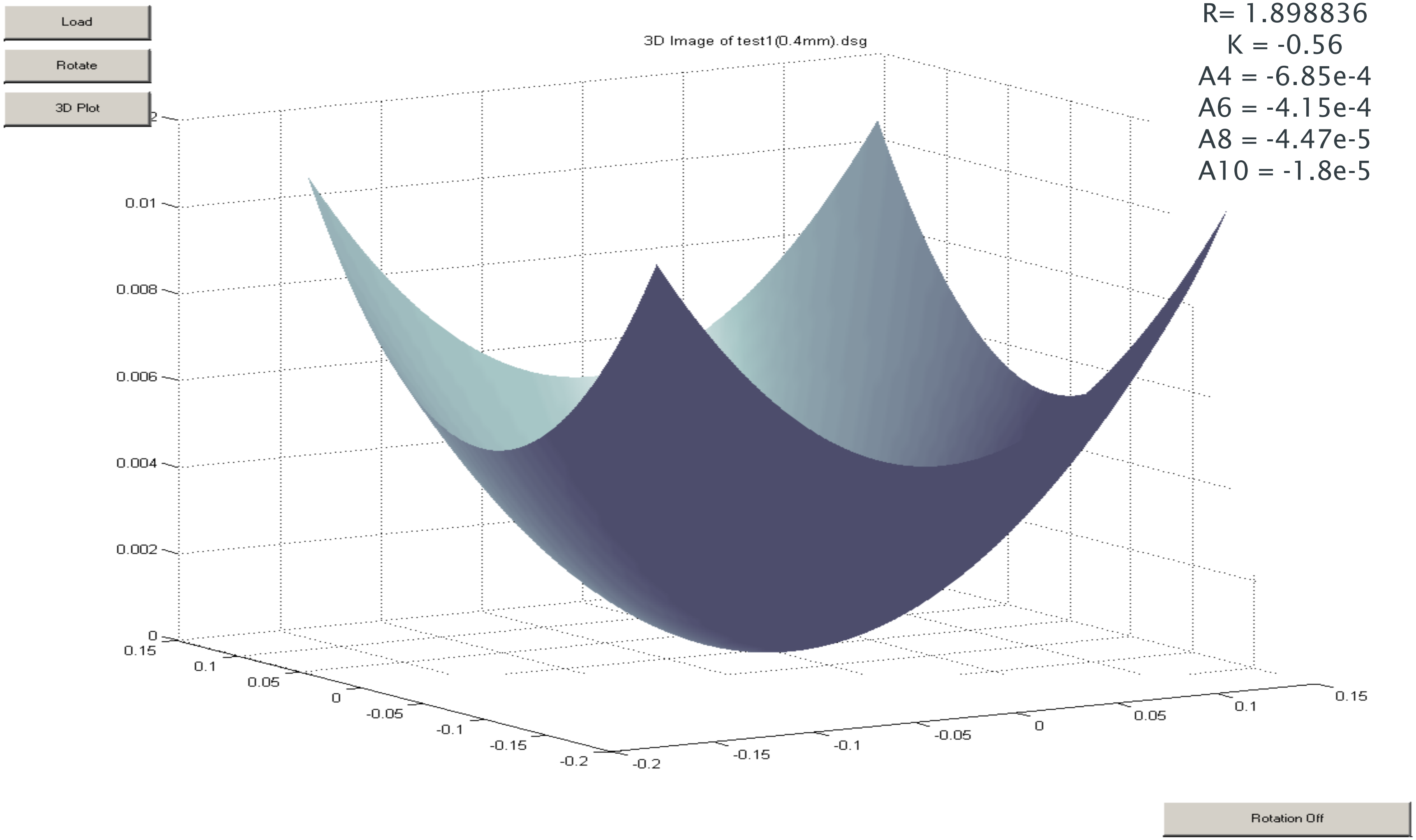
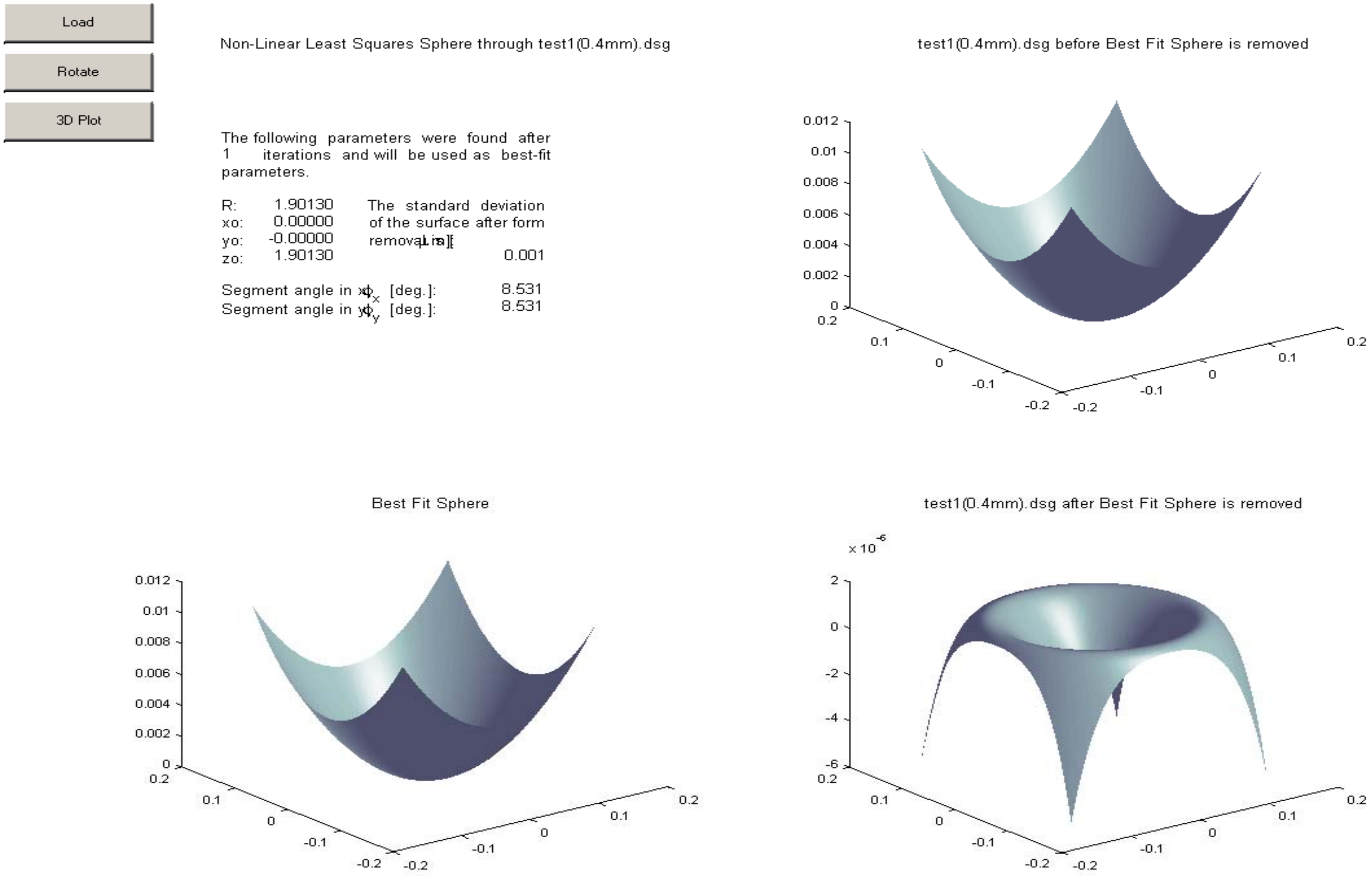
# Modelling the Surface.

# BODDIES 2000 Software



R= 1.898836
K = -0.56
A4 = -6.85e-4
A6 = -4.15e-4
A8 = -4.47e-5
A10 = -1.8e-5

# Application of Non-Linear LSSF



Non-Linear Least Squares Sphere through test1(0.4mm).dsg

The following parameters were found after 1 iterations and will be used as best-fit parameters.

R: 1.90130
xo: 0.00000
yo: -0.00000
zo: 1.90130

The standard deviation of the surface after form removal is [µm]: 0.001

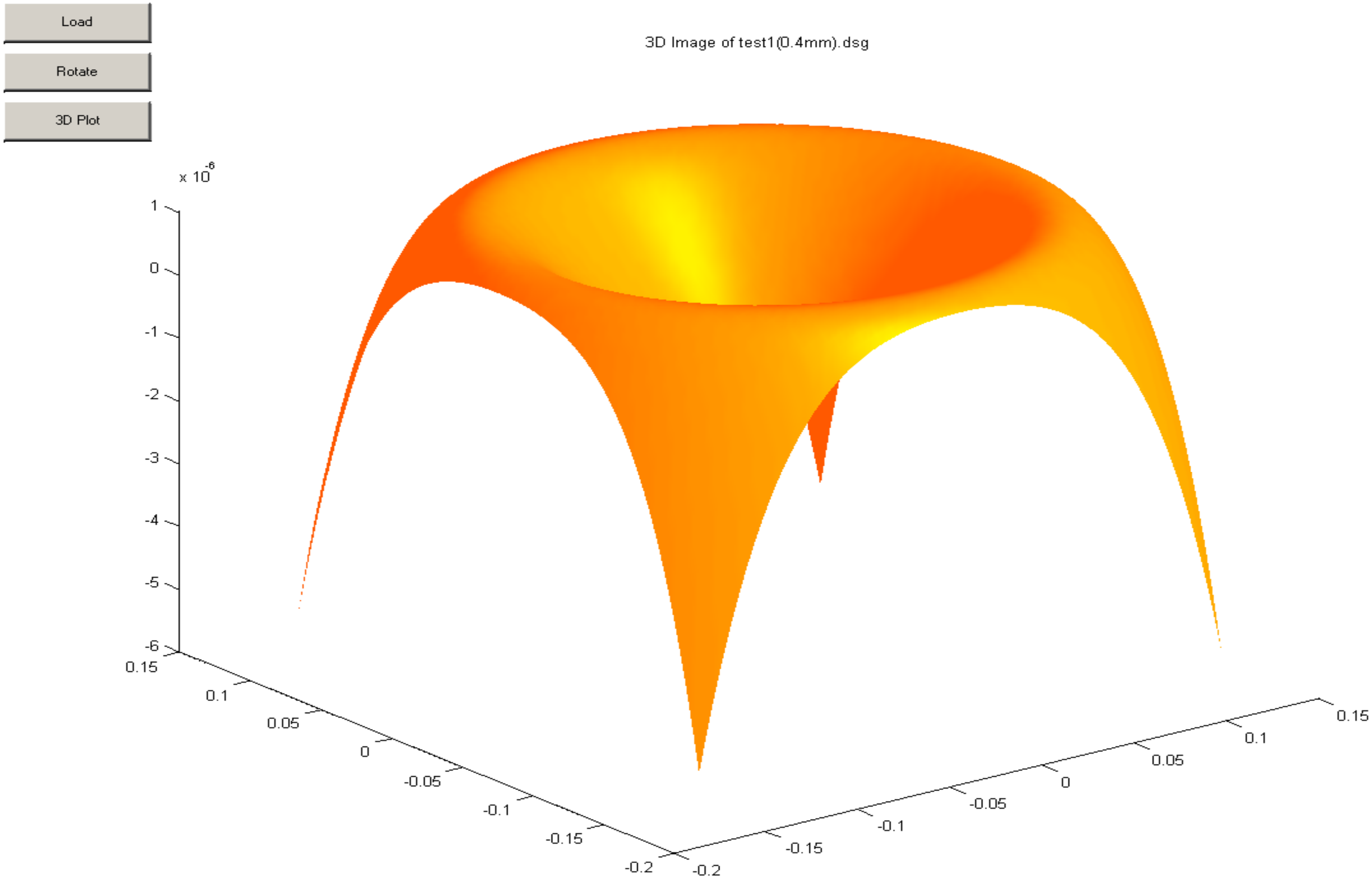
Segment angle in x $\phi_x$ [deg.]: 8.531
Segment angle in y $\phi_y$ [deg.]: 8.531

test1(0.4mm).dsg before Best Fit Sphere is removed

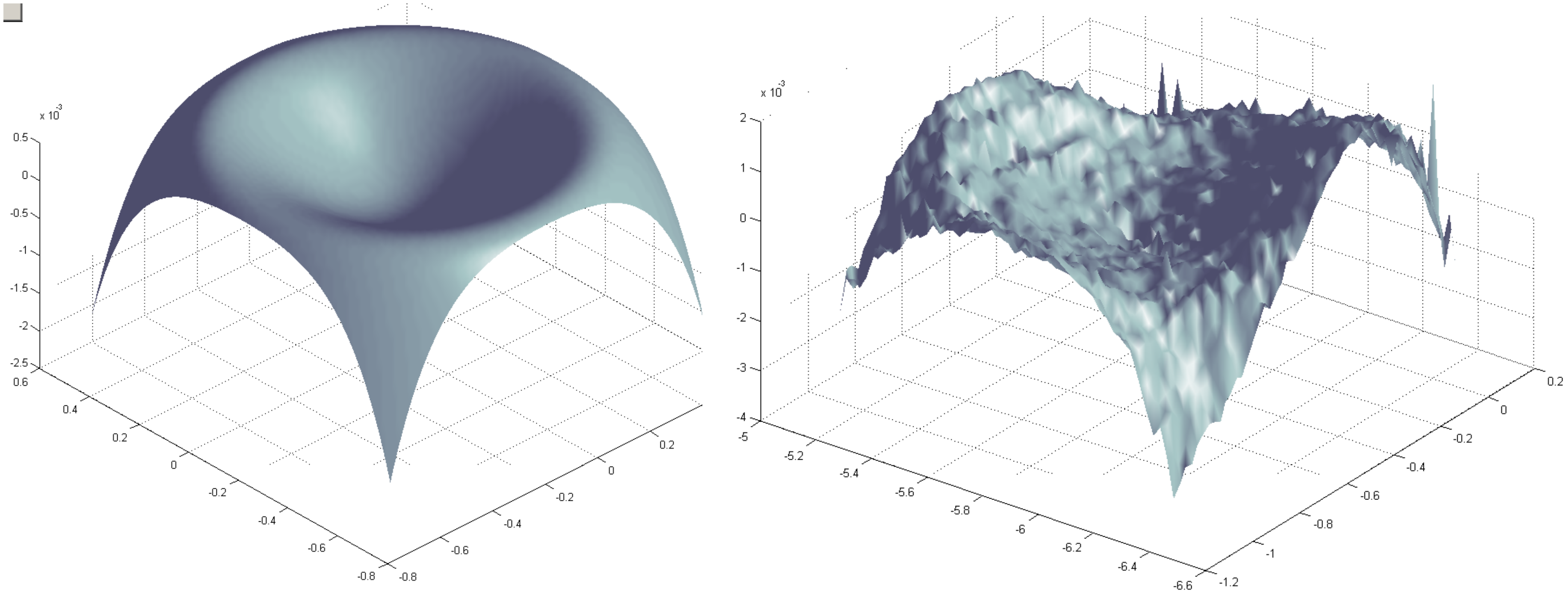
Best Fit Sphere

test1(0.4mm).dsg after Best Fit Sphere is removed

# The Residual Surface



# The Model and Real data



Design data with best fir R = 1.994mm and the inverted measured data with best fit R. 1.95625mm

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# The Measurement Problem.

# EXTREME--Large and Nano optics

Surface Manufacture

Surface Measurement

Surface Characterisation

Selection of measurement system

## Contact method

1. Stylus--Taylor Hobson
   - Allow large surface angles and areas to be measured

     New: swing arm profilometer are being developed to measure large optics (UCL, NPL & Zeeko Ltd)
   - Measurement setup relatively flexible

   Error resources:
   - Shape of stylus head
   - …

   Disadvantage
   - Scratch soft surfaces

## Non-contact method

1. Interferometer--Arizona University
   - High reliability
   - Have difficulty in measuring
   - System set up complicated

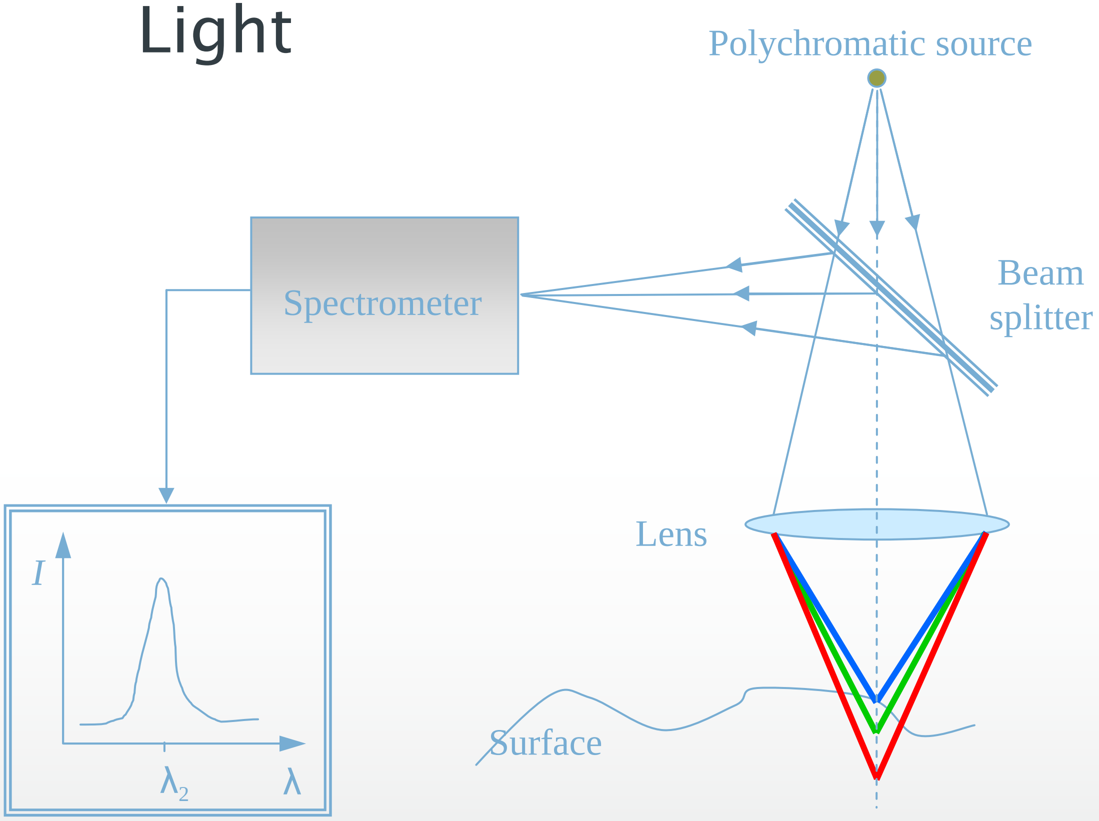
   Error resources:
   - Manufacture of CGH or null lenses
2. Optical scanning systems—Southampton University
   - Fast scanning speed
   - Flexible measurement setup

   Error resources:
   - Sensor errors
   - Table errors
   - System alignment errors

# 3D Non-Contact Measurement Methods

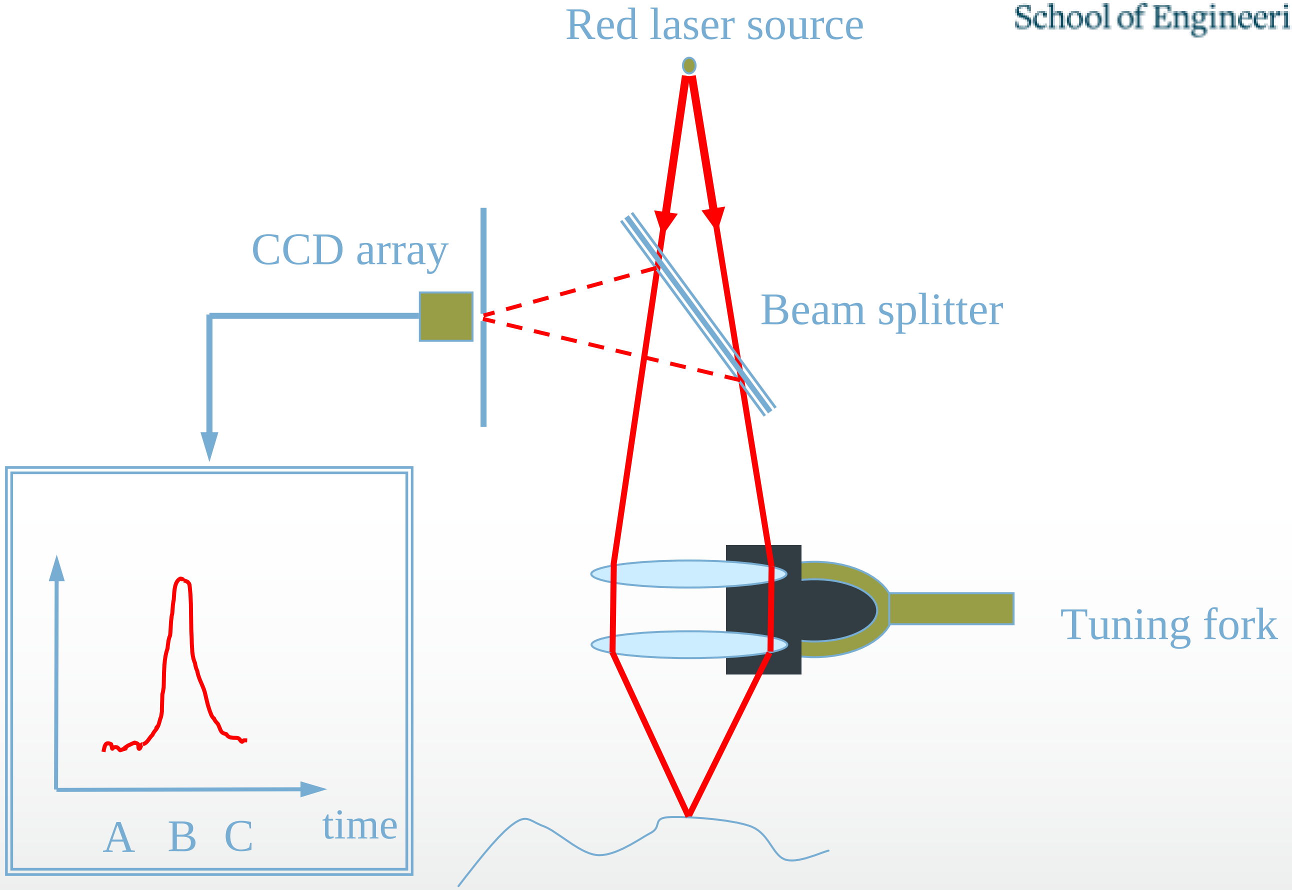
- Interferometry- relative to a reference surface, usually spherical. Issues of angular tolerance.
- Holographic references. These are expensive and relate to a specific surface. Each surface type requires a new reference.
- Con-focal Sensors. Limited by angular tolerance and quality of motion system.

# SENSOR (1) Con-Focal White Light



Schematic of the measurement principle for the WL system

# SENSOR (2) Con-Focal Laser



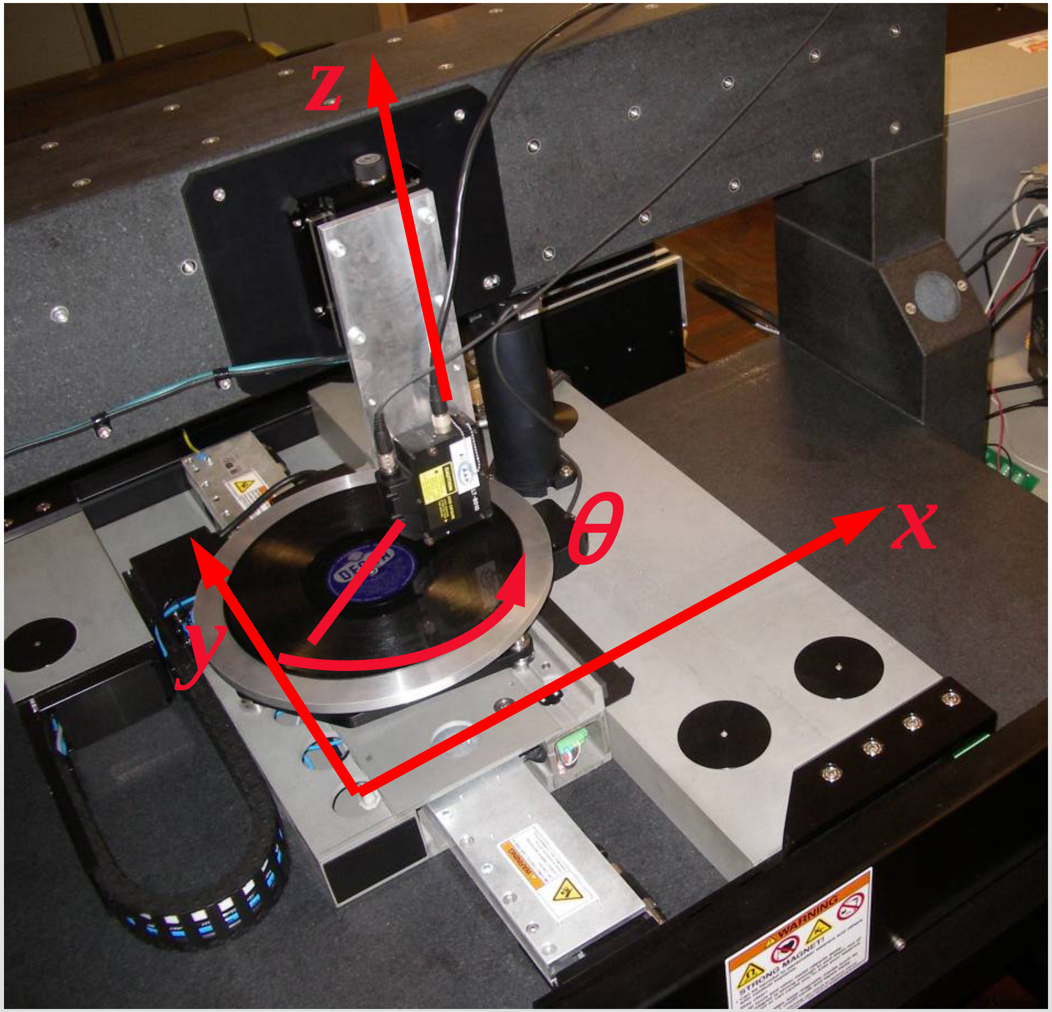
Schematic of the measurement principle for the CL

# Sensor study: sensor comparison parameters

| Sensor | Spot size (µm) | Sample frequency (kHz) | Gauge range (mm) | Axial resolution (nm) |
|---|---|---|---|---|
| TL | 30 | 2 | 10 | 1000 |
| CL | 2 | 1.4 (0.08) | 0.6 / 17° | 10 |
| WL | 7 | 1 -4 | 0.35 / 27° | 10 |

# Overview of system

- System provides planar ($x$,$y$) travel of carriage on air bearing
  - Air bearing provided by ~5µm air 'cushion'
  - Moving carriage fitted with a rotation stage
  - Sensor mounted on overhead granite gantry, whose height controlled by 10nm resolution stage
  - 4 axis of motion



# Air bearing system with 22mm calibration ball

Residual Map of Surface after Form Removal

Data 101x101 4mm x4mm

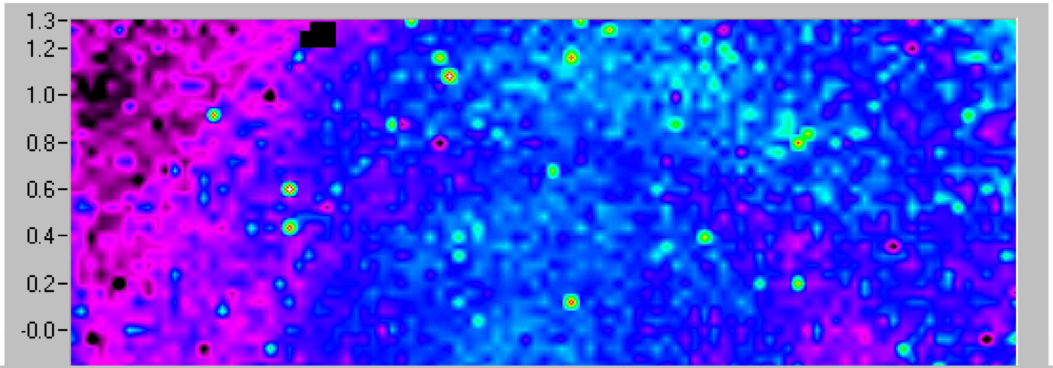
Radius Error = 46μm

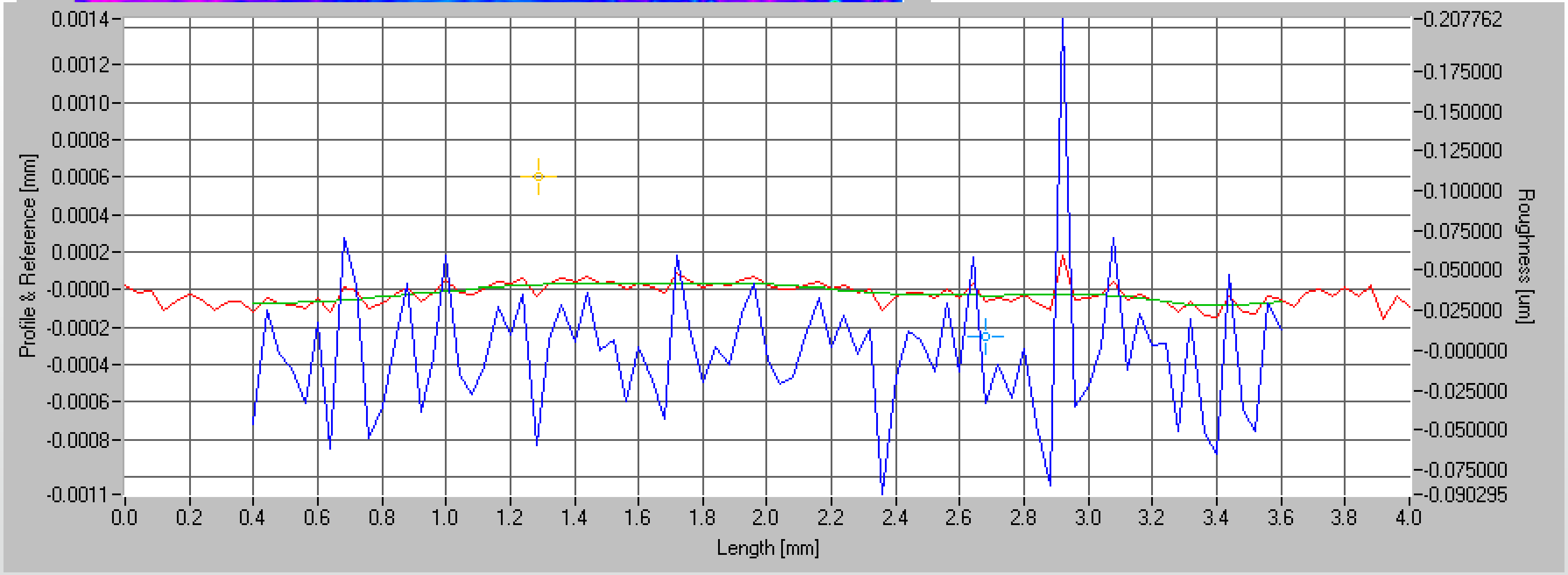
σ = 74nm

Radius Error NLLS = 44.8μm

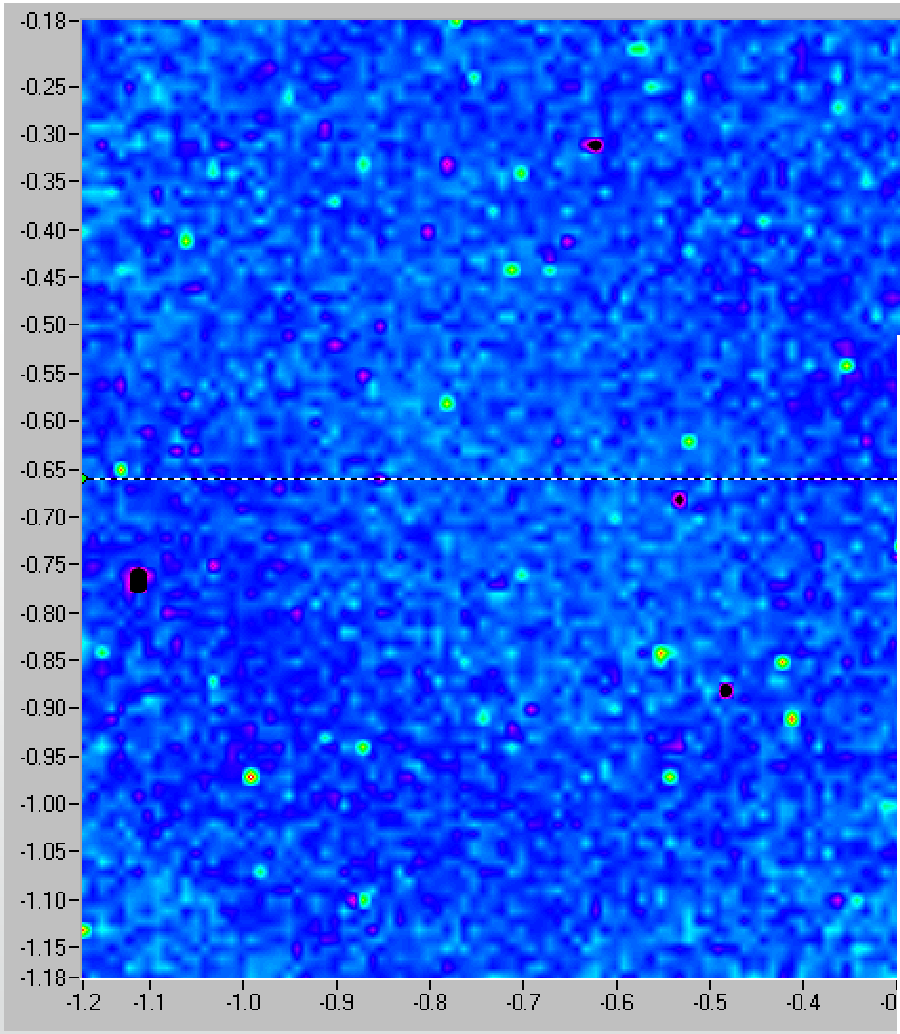
Sa = 33nm with 0.8mm filter

Ra = 29nm with 0.8mm filter





# 1mm x 1mm measurement area

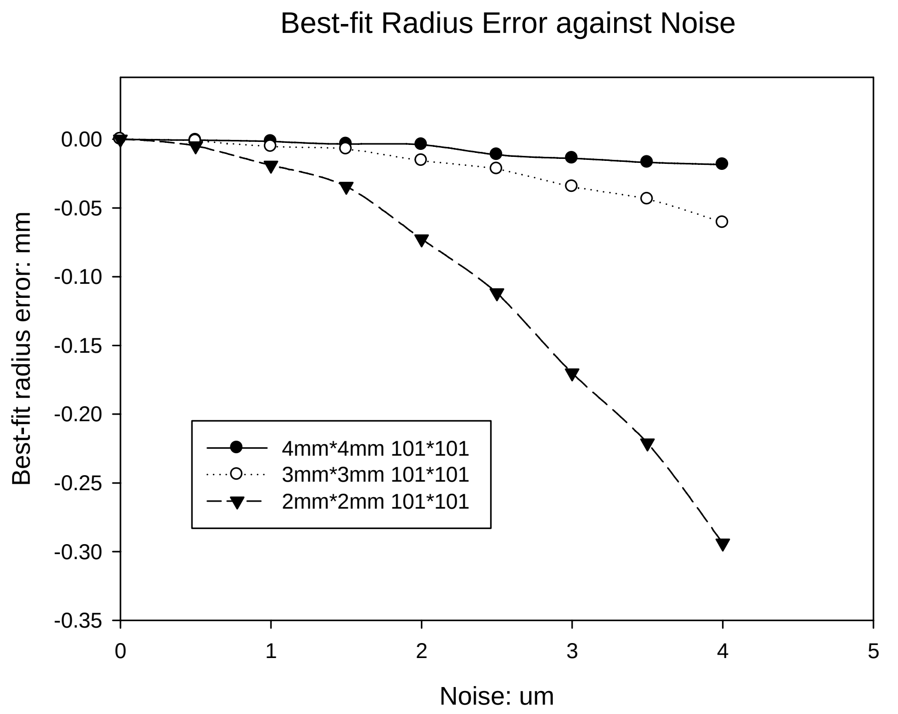


Residual Map of Surface after Form Removal

Data 101x101 1mm x1mm

Radius Error = 76.3μm

Ra = 21nm with 0.25mm filter


Best-fit Radius Error against Noise

# The Analysis Problem.

# EXTREME--Large and Nano optics

Surface Manufacture

Surface Measurement

Surface Characterisation

Pre-processing the data

Direct comparison between design and measured surfaces

- Information of design surface required
- Surface area out of measurement limits can not be compared

Simplified models

- Sphere model—can only be used when the measured surface form close to spherical surfaces
- Polynomial model
  Close to design surface form

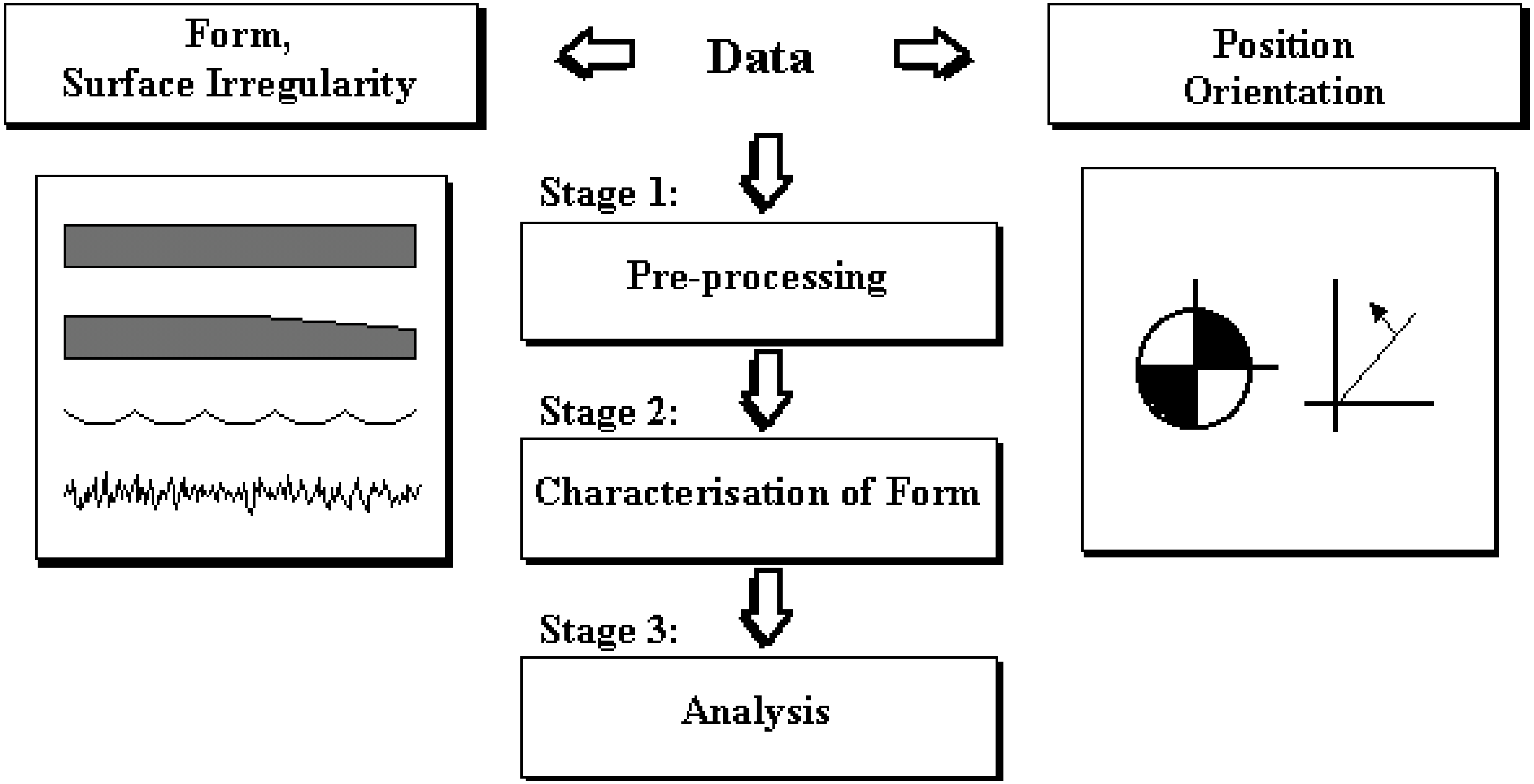
*Model has to be reconsidered once the measured surface area changed.*

Total aspheric fit—developing

- Allow surface parameters to be compared to design value
- Allow information of measured surface to be stored
- Allow measured surface to be recreated
- Allow surface information can be used in optics software such as ZEMAX

- 2D parametric solutions have been used for a number of years.
- The aim was to develop 3D parametric solutions, such that, measured surfaces can be compared to designed surfaces.
- This overcomes the subjectivity of using the residual or error map in defining the measured surface.
- The parameterised surface can be used to define changes to the manufacturing process.

# Interpretation of the Data



**Form,
Surface Irregularity**

**Data**

**Position
Orientation**

**Stage 1:** Pre-processing

**Stage 2:** Characterisation of Form

**Stage 3:** Analysis

# Pre-Processing Methods

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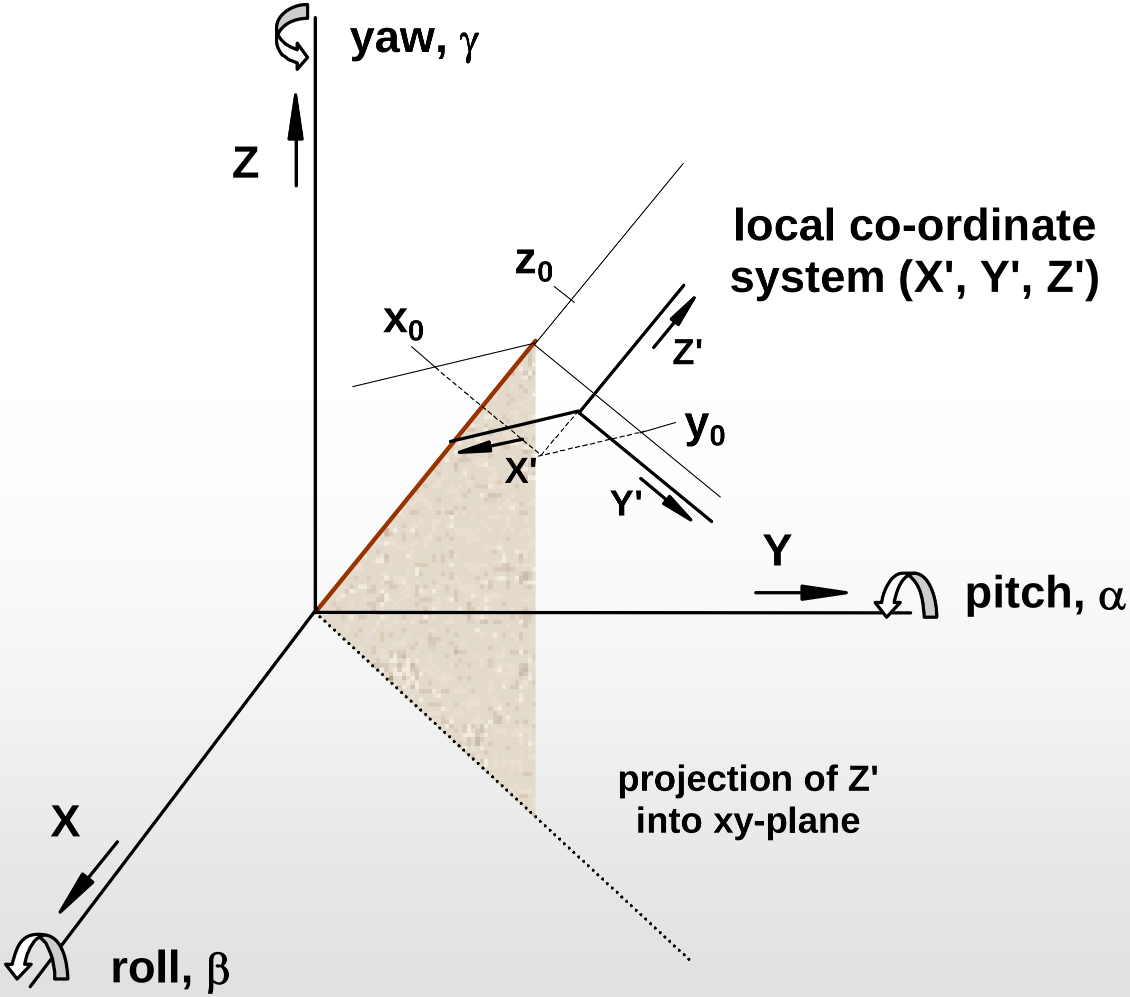
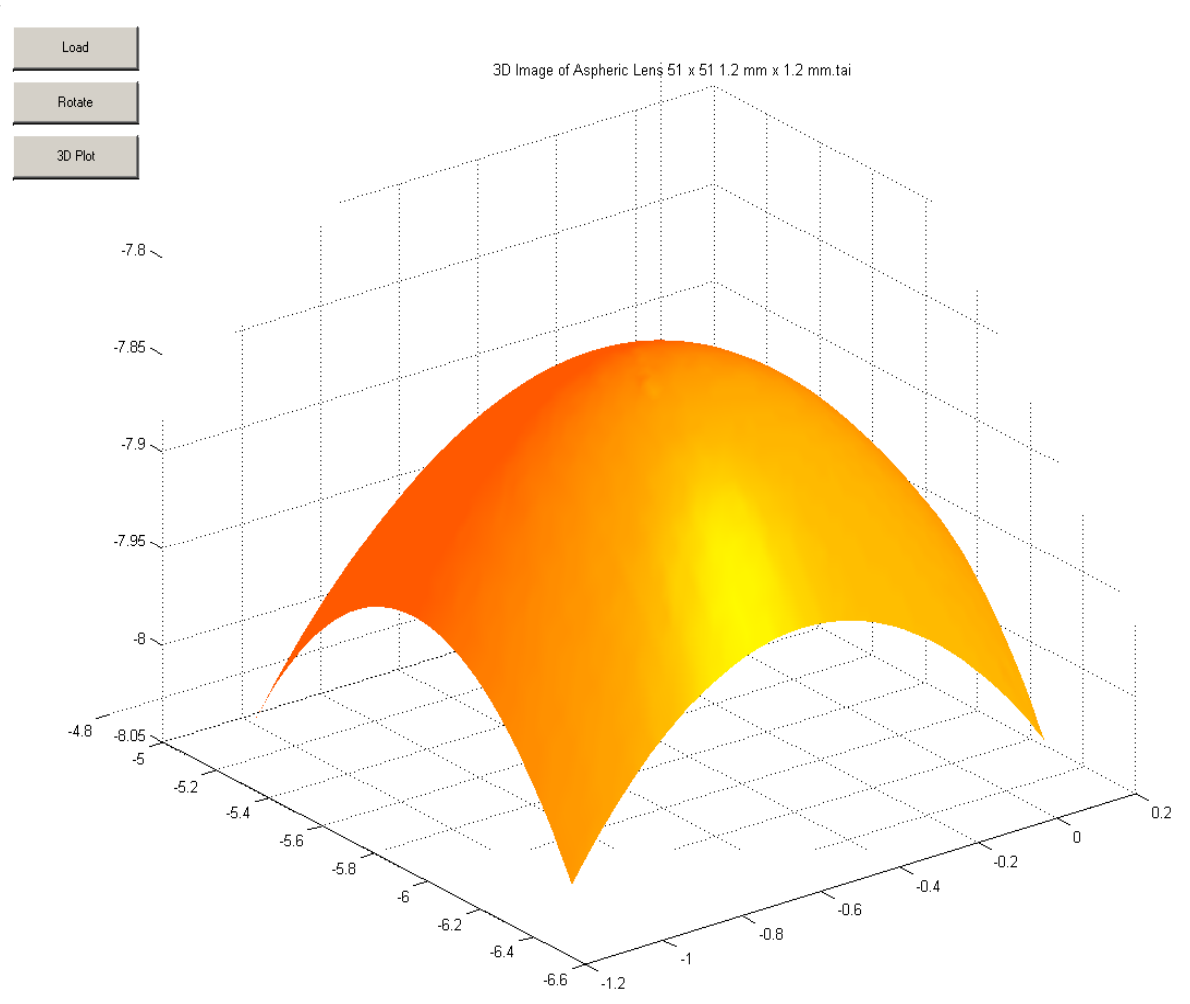


- Local axis Search*
- Contour Line Fit
- Lowest Point

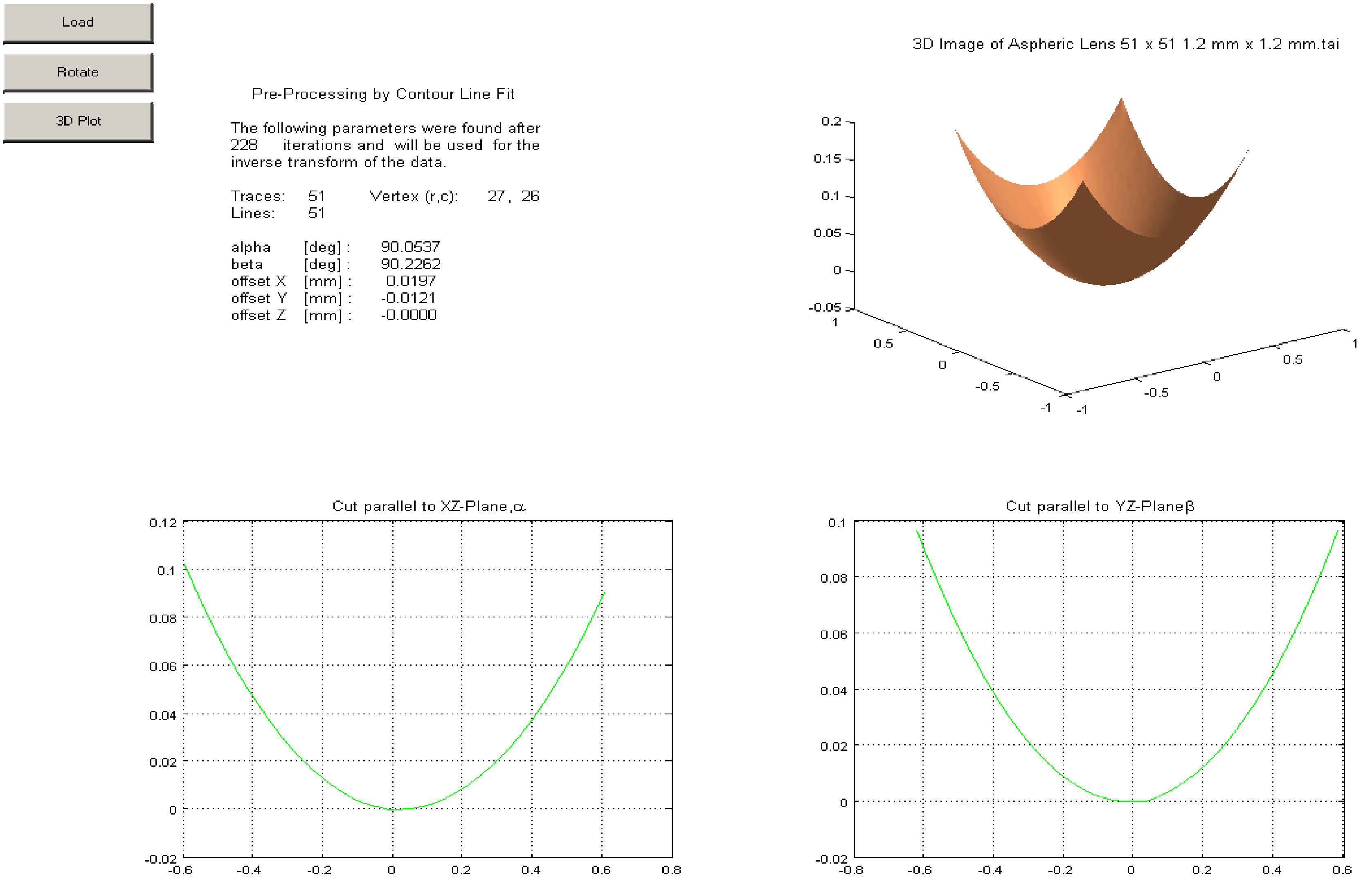
*Hill, M., Jung, M. and Mcbride, J.W. (2002) Separation of form from orientation in 3D measurements of aspheric surfaces with no datum. *International Journal of Machine Tools & Manufacture*, 42, (4), 457-66.

# BODDIES 2000



R = 1.898836
K = -0.5603343 e+000
Com =4.400000e+000
(Component Diameter)
A4 = -6.8505495 e-004
A6 = -4.1501354 e-004
A8 = -4.4705513 e-005
A10 = -1.8065968 e-005

# After Alignment of data



Pre-Processing by Contour Line Fit

The following parameters were found after 228 iterations and will be used for the inverse transform of the data.

Traces: 51 Vertex (r,c): 27 , 26
Lines: 51

| | | |
|---|---|---|
| alpha | [deg] : | 90.0537 |
| beta | [deg] : | 90.2262 |
| offset X | [mm] : | 0.0197 |
| offset Y | [mm] : | -0.0121 |
| offset Z | [mm] : | -0.0000 |

# Spherical Fitting Algorithm

- Comparison between two models in fitting spherical surfaces within small segment angle:
  - Sphere model (a conventional method)
  - Second order surface model (especially to fit near planar surfaces)

The sphere model can be used in the analysis of spherical surfaces within small segment angles

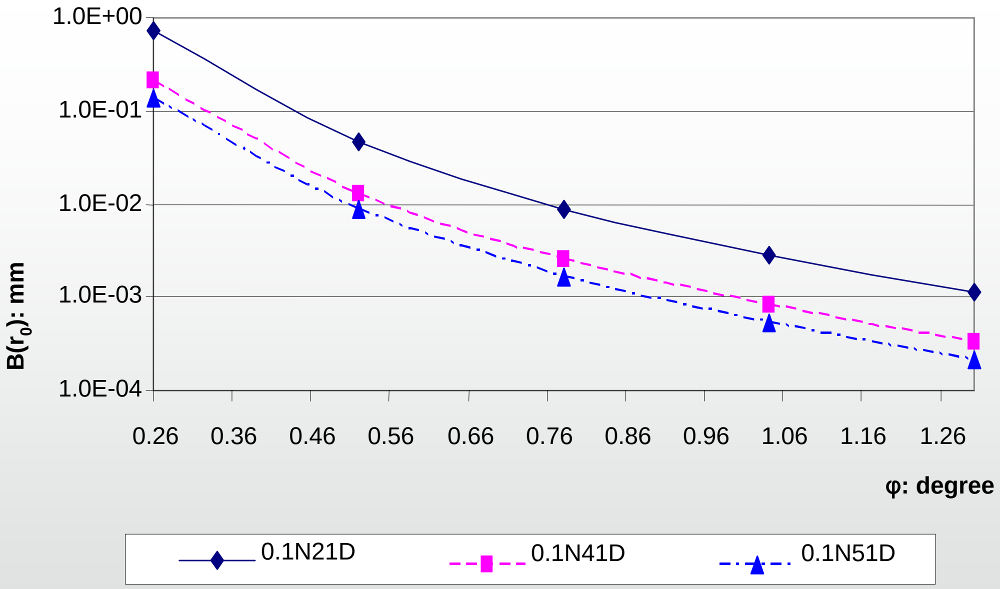
- Two aspects investigated:
  - Bias: difference between the expectation of the test results and an accepted reference value.
  - Uncertainty: a parameter that characterizes the dispersion of the values that could reasonably be attributed to the measurand (characterised by $\sigma$)

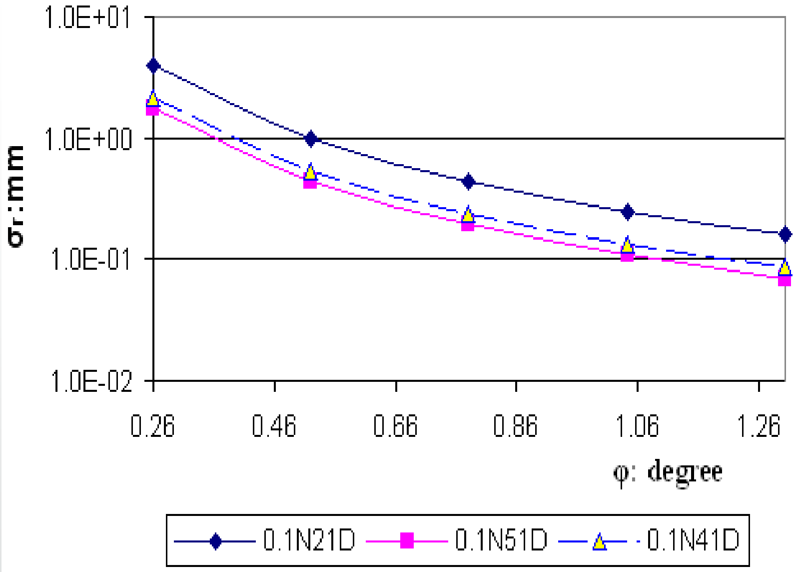
# Errors in Low Segment Angle Surfaces

Investigation of spherical surface fitting algorithms (nonlinear least-squares sphere fitting algorithm)

- Bias. A method has been developed to estimate the bias property of the nonlinear least-squares sphere fitting algorithm
- Uncertainty

Two conventional methods have been reviewed on Surfaces with 100nm noise





*Sun, Hill, McBride, (2008) An investigation of the robustness of the nonlinear least-squares sphere fitting method to small segment angle surfaces. *Precision Engineering*, 32, 55-62.

# Fitting to Aspheric Surfaces

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- Assumes a Pre-processing Stage
- Direct comparison method
  - Require surface design information
- Simplified model
  - Selection of model is critical and time consuming
  - Estimated parameters cannot be compared with design values
- Total aspheric surface fitting algorithm

  (1) Indirect method-based on the nonlinear least-squares sphere fitting algorithm

  (2) Direct method (Total Aspheric Surface Fitting Algorithm)*

  - Surface area out of maximum measurable areas can be estimated
  - Allow surface information to be stored
  - Estimated parameters can be compared with design values
  - Estimated parameters can be used for design and quality control purposes.

*Sun, W., McBride, J.W. and Hill, M. (2009) A new approach to characterising aspheric surfaces. *Precision Engineering*, 40pp. (In Press)

# Defining the Aspheric Surface

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A rotationally symmetrical surface that gradually varies in surface power from the centre towards the edge in a radial fashion.

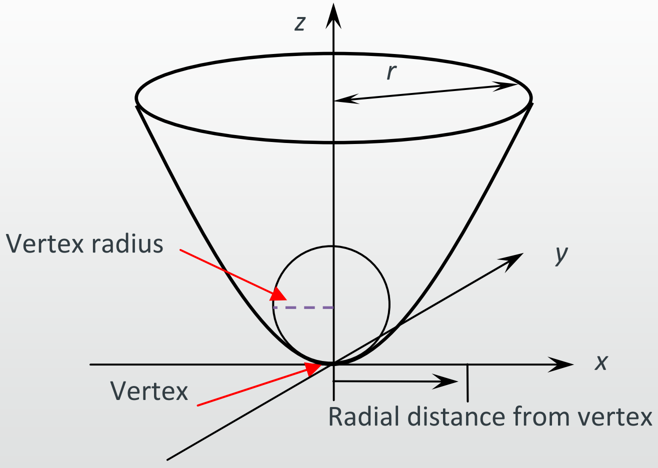
$$z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + A_4 r^4 + A_6 r^6 + A_8 r^8 + A_{10} r^{10} + A_{12} r^{12} \qquad (1)$$

$$r = \sqrt{x^2 + y^2}$$

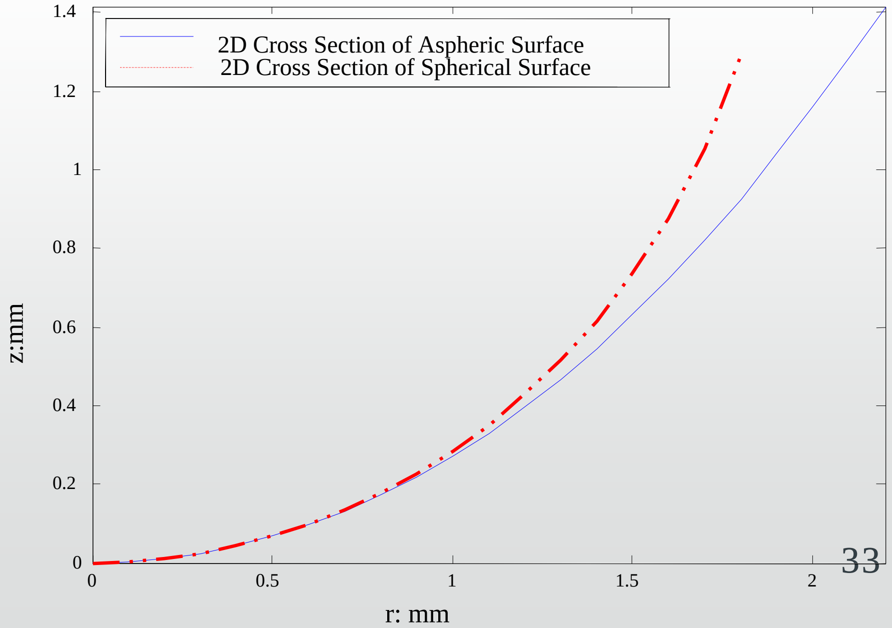
$k$ is the conic constant

$c$ is the reciprocal of vertex radius (1/R)

$A_4$ $A_6$ $A_8$ $A_{10}$ $A_{12}$ are polynomial coefficients



*Schematic of an aspheric surface*



# 1. Indirect Aspheric Fitting Algorithm

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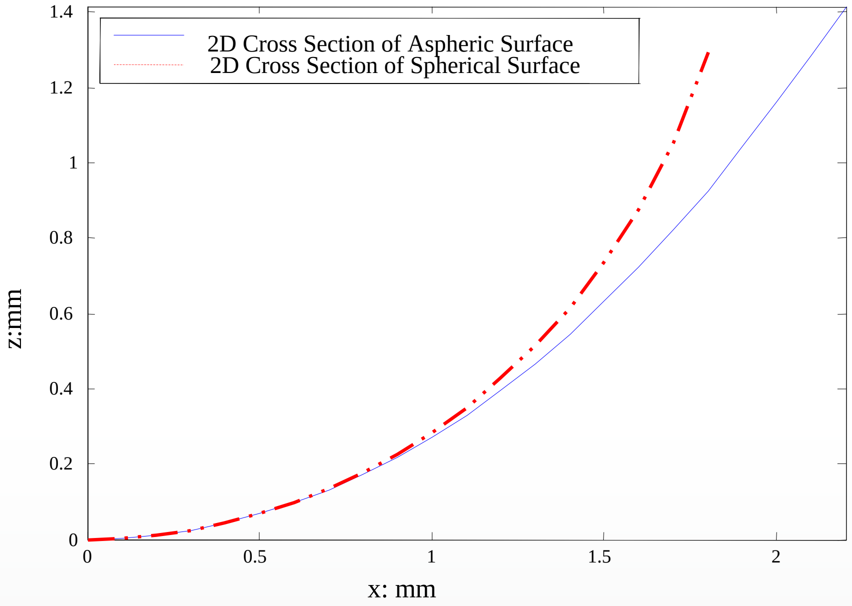

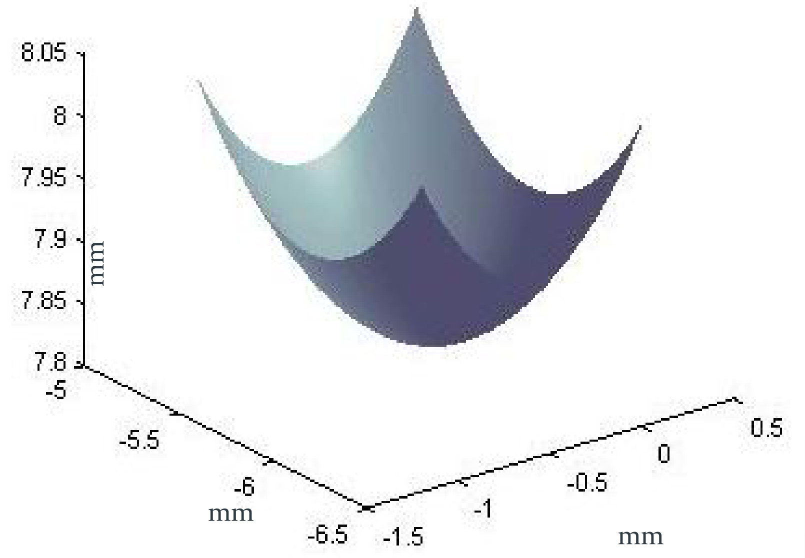

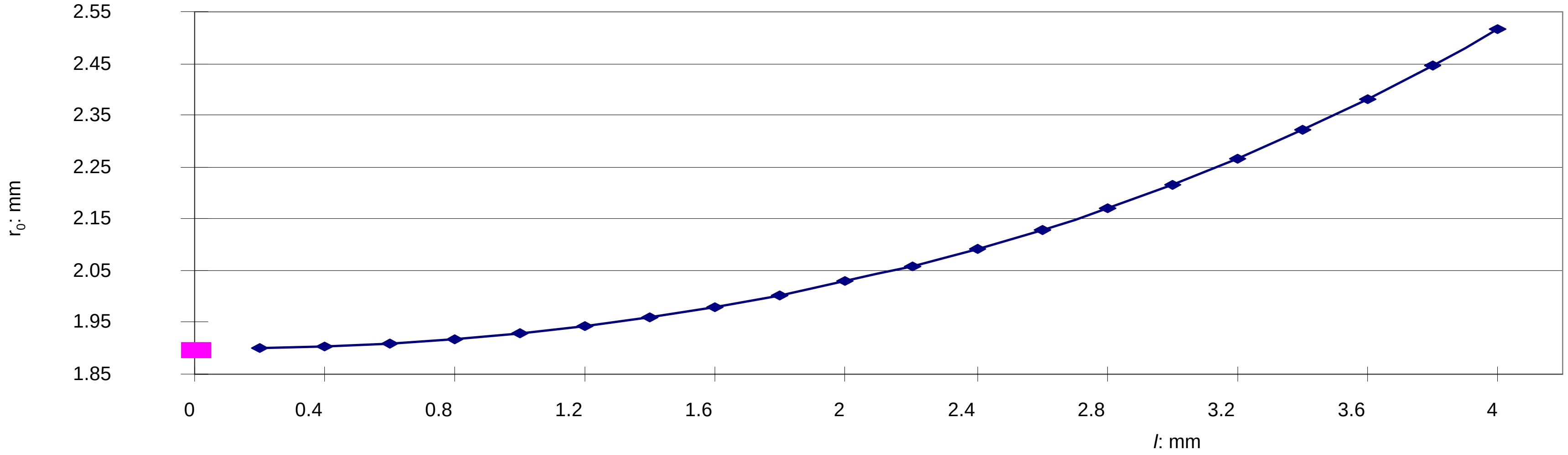

# 1. Indirect aspheric fitting method

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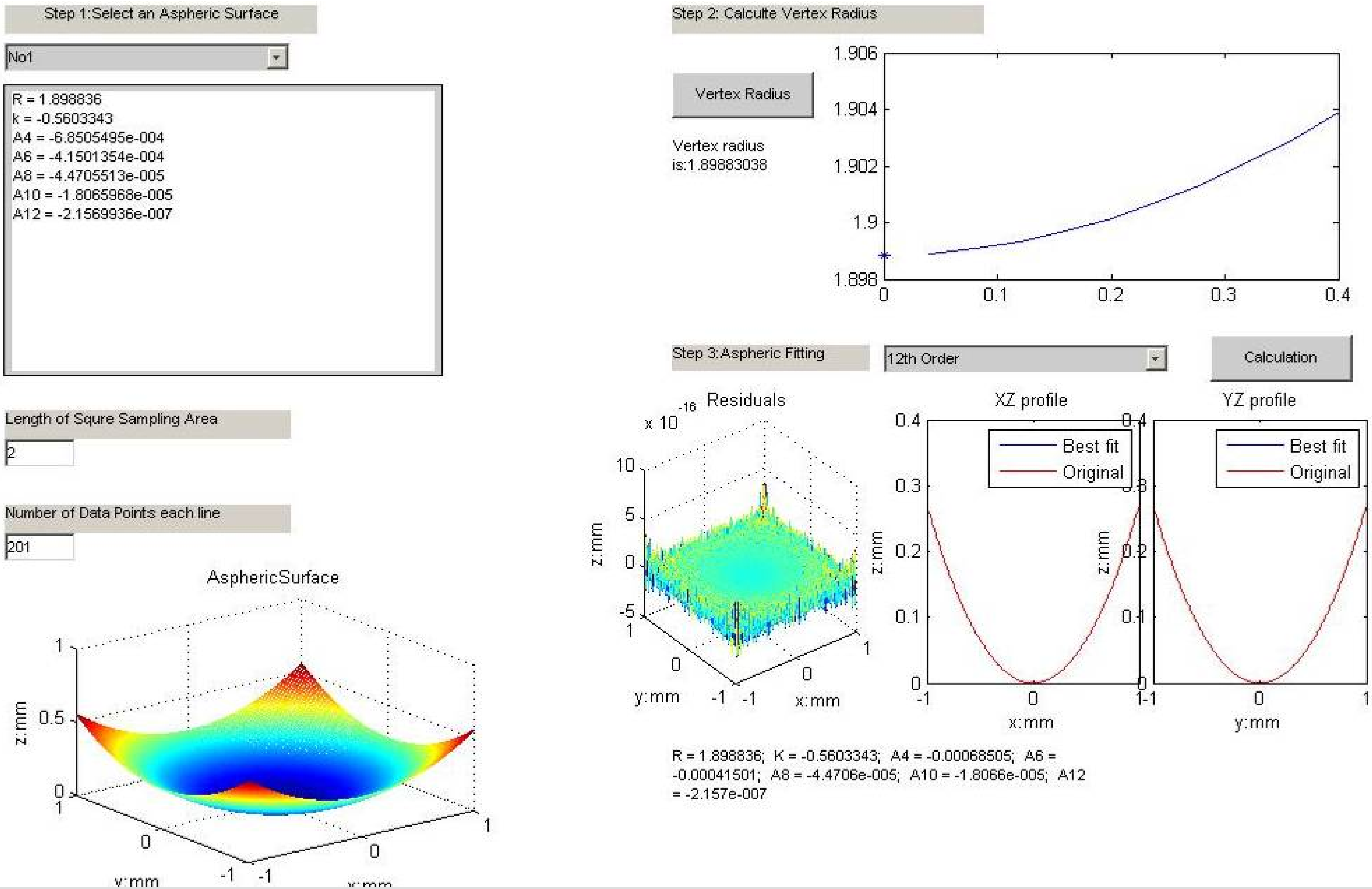


Step 1:Select an Aspheric Surface: No1

R = 1.898836
k = -0.5603343
A4 = -6.8505495e-004
A6 = -4.1501354e-004
A8 = -4.4705513e-005
A10 = -1.8065968e-005
A12 = -2.1569936e-007

Length of Squre Sampling Area: 2

Number of Data Points each line: 201

Step 2: Calculte Vertex Radius

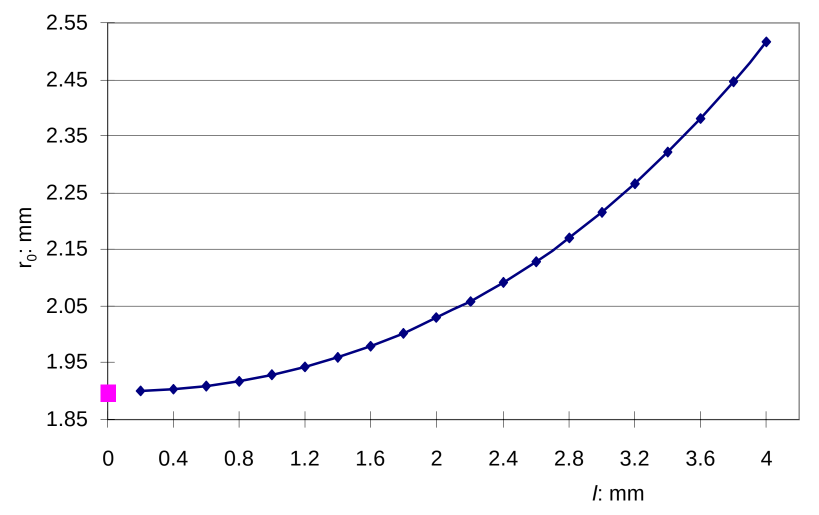
Vertex radius is:1.89883038

Step 3:Aspheric Fitting: 12th Order

R = 1.898836;  K = -0.5603343;  A4 = -0.00068505;  A6 = -0.00041501;  A8 = -4.4706e-005;  A10 = -1.8066e-005;  A12 = -2.157e-007

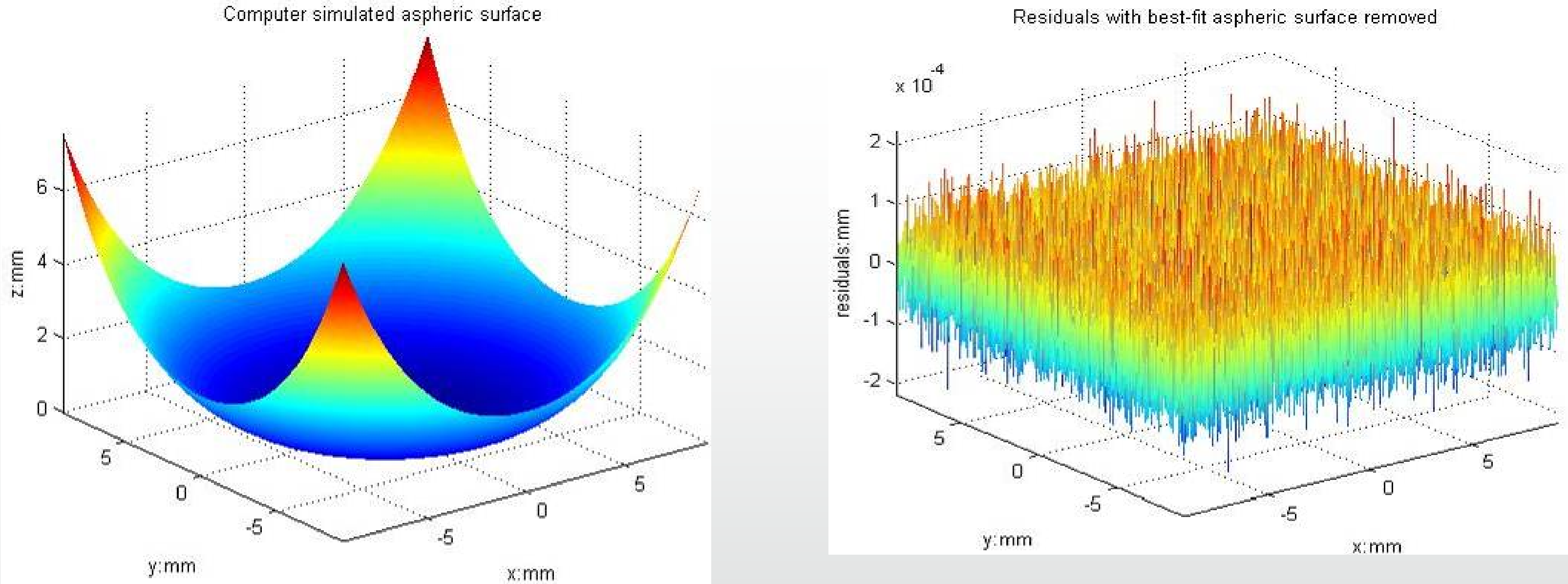
# Potential Problems in Real Surfaces

- The pre-processing method.
- The surface noise (sensor and motion system) combined with the Bias and Uncertainty associated with fitting sphere to small segment angle surface will result in uncertainty in the evaluation of the vertex radius R



# 2. Direct aspheric surface fitting method

| | $R$ | $K$ | $A_4$ | $A_6$ | *Noise(std)* |
|---|---|---|---|---|---|
| Designed | 44.577884 | -1.710312e+2 | 2.316294e-4 | 3.495852e-8 | 50 nm |
| Estimated | 44.578034 | -1.710267e+2 | 2.316284e-4 | 3.496336e-8 | 49.9991 nm |



*Fitting results of a 6th order aspheric surface superimposed with surface noise.*
*(Left): Simulated 6th order aspheric surface. (Right): Residuals with the best-fit 6th order surface removed*

# Potential Problems in Real Surfaces

- The pre-processing method.
- The surface noise (sensor and motion system) will result in uncertainty in the evaluation, however the method offers improved performance over the Indirect method.

# Future Studies

- To develop the direct aspheric fitting algorithm TAFD.
  - Investigate the algorithm performance over a wide range of surface parameters,
  - Quality of fitting: efficiency and accuracy
  - Fitting results: the bias and the uncertainty properties
- To investigate the reliability of the measurement machine.
  - To study the dominant systematic errors and the effect on measuring curved surfaces
- To optimise the pre-processing of measured data, and the link to the scanning process.
  - Sampling strategies
  - Alignment techniques
- To implement proposed fitting algorithm on measured aspheric surfaces
  - Investigate real measured surfaces
  - To develop analysis tools for fitting aspheric surfaces
  - To develop methods for linkage and feedback to manufacturing processes.