Freeform Optics Incubator

30 OCTOBER - 1 NOVEMBER 2011

OSA Headquarters • Washington, D.C., USA

Hosted by: Pablo Benitez, *Universidad Politecnica de Madrid, Spain*
and Kevin Thompson, *Synopsys, Inc., USA*

Highlights of Presentations
Part 1 of 3
Day 1, Morning

compiled by

Kevin Thompson, PhD
Synopsys, Inc.

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8:40	**Opening Remarks: Is This History in the Making?** Kevin Thompson, *Synopsys, Inc., USA*
9:00	**Freeform Surfaces for Imaging Systems** Norbert Kerwien, *Carl Zeiss Corp., Germany*
9:25	**Current Techniques for Diamond Machining Freeform Optics** Gregg Davis, *II-VI, Inc., USA*
9:50	**Realizing an Optical System with Phi-Polynomial Freeform Surfaces** Kyle Fuerschbach, *University of Rochester, USA*
11:00	**Specifying Shape…What Could We Hope For and Can It Be Achieved** Gregory Forbes, *QED Technologies Inc., Australia*
11:25	**Smooth Radial Basis Functions Viewed as a Generalization of Multivariate Polynomials** Gregory Fasshauer, *Illinois Institute of Technology, USA*
11:50	**Moving from Phi-Polynomial to Multi-centric Radial Basis Functions** Aaron Bauer, *University of Rochester, USA*
13:15	**SMS 3D: A Freeform Optics Design Method** Juan-Carlos Miñano, *LPI, Universidad Politecnica de Madrid, Spain*
13:40	**Geometric Methods of Design of Freeform Surfaces with Prescribed Optical Properties** Vladimir Oliker, *Emory University, USA*
14:05	**A Starting Point Approach for Nonimaging Reflector Design** Cristina Canavesi, *University of Rochester, USA*
15:10	**40 years of Freeform Surfaces** Daniel Bajuk, *ZYGO EPO, USA*
15:35	**Freeform Surfaces Have Aberration Fields Too** Kevin Thompson, *Synopsys, Inc., USA*
16:00	**Two Freeform Mirror Designs with SMS 3D** Lin Wang, *Universidad Politecnica de Madrid, Spain*
17:30	**BIG BIRD** Phil Pressel, *Quartus Engineering Company, USA*
9:00	**The Art of Tailoring Freeform Surfaces for Illumination** William Cassarly, *Synopsys, Inc., USA*
9:25	**Freeform Optics at OSRAM: What We Have, What We Miss, What We Need** Julius Muschaweck, *OSRAM GmbH, Germany*
9:50	**Freeform Optics for a Linear Field of View** Fabian Duerr, *Vrije Universiteit Brussel, Belgium*
11:00	**Nonimaging Freeform Optics Applications at LPI** Pablo Benitez, *Universidad Politecnica de Madrid, Spain*
11:25	**F-RXI Photovoltaic Concentrator: A High Performance SMS-3D Freeform Köhler Design** Marina Buljan, *Universidad Politecnica de Madrid, Spain*
11:35	**Augmented Reality Displays a Playground for Freeform Surfaces** Jannick Rolland, *University of Rochester, USA*

Day 1
Morning Session

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Is this history in the making?

John Rogers, PhD
Kevin Thompson, PhD

Synopsys, Inc.

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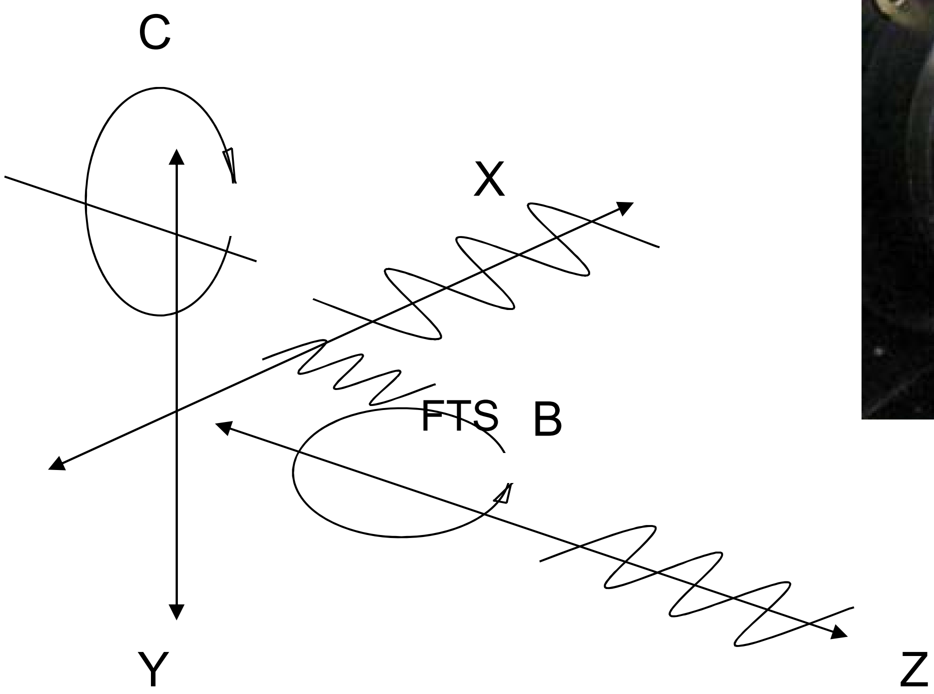
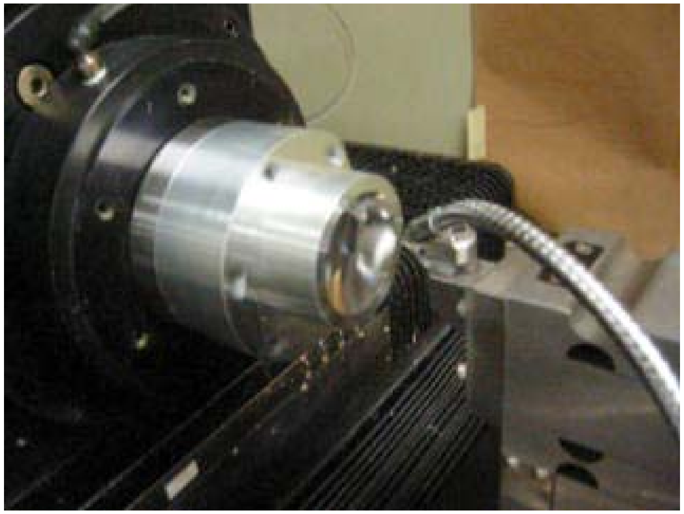
Who is here?
Imaging/Nonimaging

- **Mathematical Modeling**
- **Optical Design**
- **Optical Surface Fabrication**
- **Optical Testing**
- **Optical Systems**

This is why we're here today

Slow-Servo, C-axis diamond turning





Courtesy of Moore Nanotechnology Systems

Why are we here now?

Road Map to Surface Types / Challenges

	Spheres	Aspheres	Off-Axis Conics	φ-Polynomials	RBF-FreeForm
Surface Shape	1890	1902*	1980s	2000	Active Research
Optical Design	1905	1949*	DARPA late 90s	Active	Active Research
Fabrication	1890	2005	1980s	2007	Future Research
Test Methods	Evolution	Active	Evolution	Active	Future Research
Assembly	Evolution	Evolution	2011	Active	Future Research

Who must we satisfy?

- **The optical designer**
  - The surfaces are useless if they do not provide the necessary degrees of freedom
  - The degrees of freedom must be linearly independent (not redundant)
  - Preferably, they would be at least approximately orthogonal

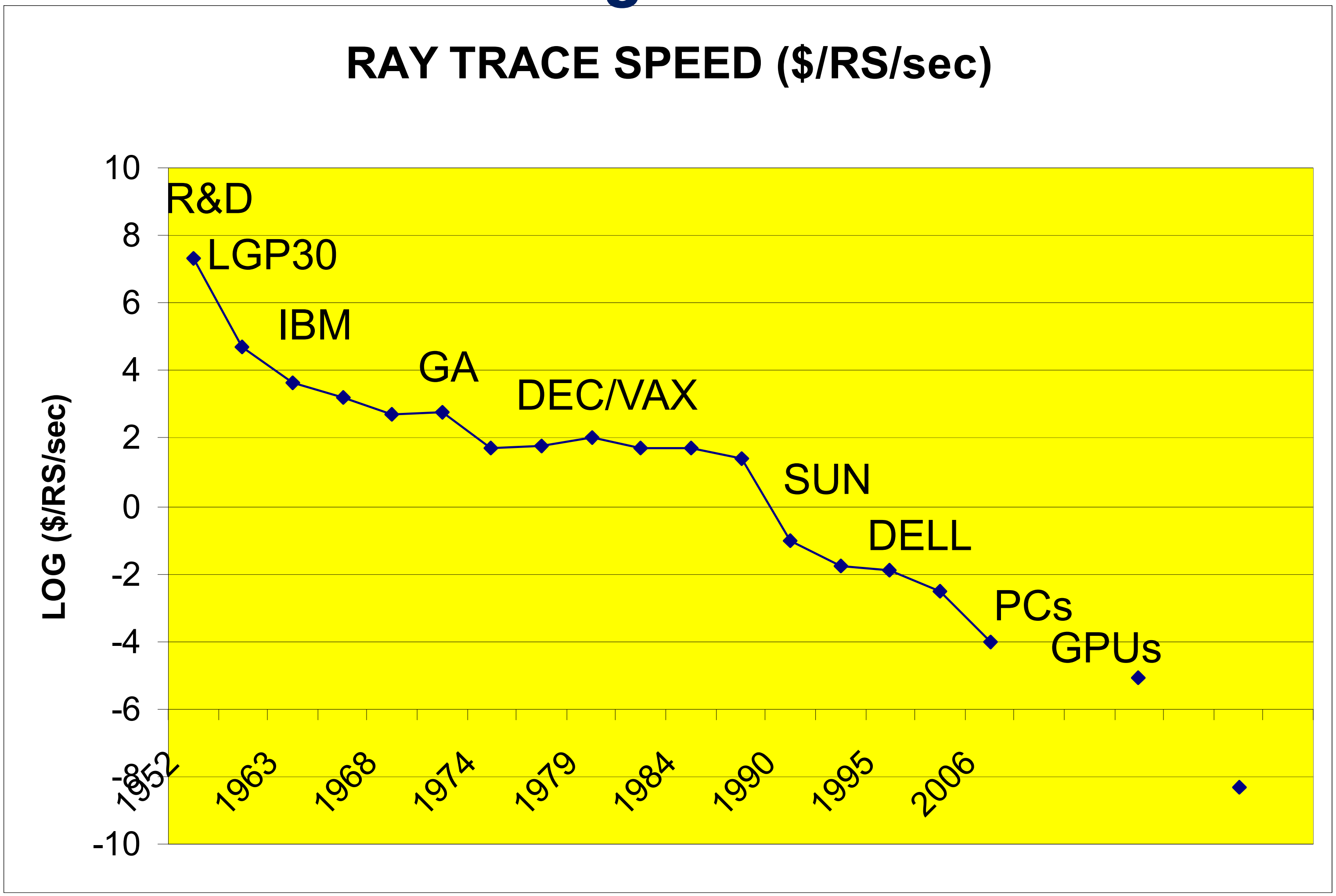
- **The fabricator**
  - The surfaces must be fabricable

- **The metrologist**
  - The surfaces must be measurable
  - The degrees of freedom must be linearly independent (not redundant)
  - Preferably, they would be at least approximately orthogonal

Surface Types that Cannot be Represented by Polynomials

- Polynomials are good at representing many types of surfaces
- …and are very bad at representing other types of surfaces:
  - Those with localized features, i.e., a groove mid-way out in the radius of a part
  - A central hole or a central peak (commonly caused by improper machine set-up)
- Polynomials (of any variety) have the property that they become either increasingly large or increasingly "wiggly" at larger radial positions
  - For a polynomial to represent anything of localized transverse scale, it must be very high order
  - If a high order polynomial is used to represent a feature at the center or at an intermediate zone, it is not possible for the polynomial to "calm down" and represent a smooth surface outside that zone.
- As a result, localized features are simply "not seen" by the polynomials
  - The polynomials effectively filter out such features

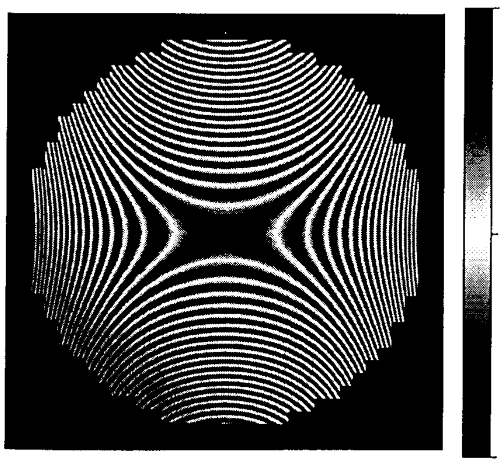
Optics is Compute Intensive
Ray surfaces per second (per $) is an interesting metric



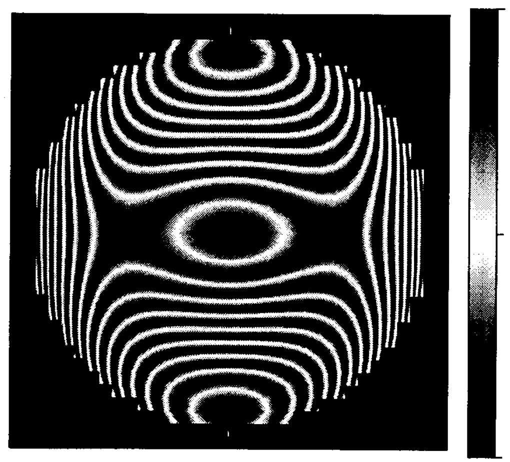
One of the most ambitious freeform mirror projects prior to 2000 resulted in the repair of the HST

The COSTAR Anamorphic Aspheres
Uncompensated, at Center of Curvature

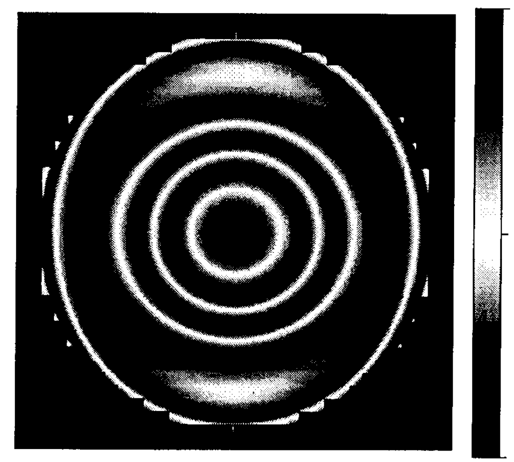
FOS



HRS



FOC



Faint Object Spectrograph

High Resolution Spectrograph

Faint Object Camera

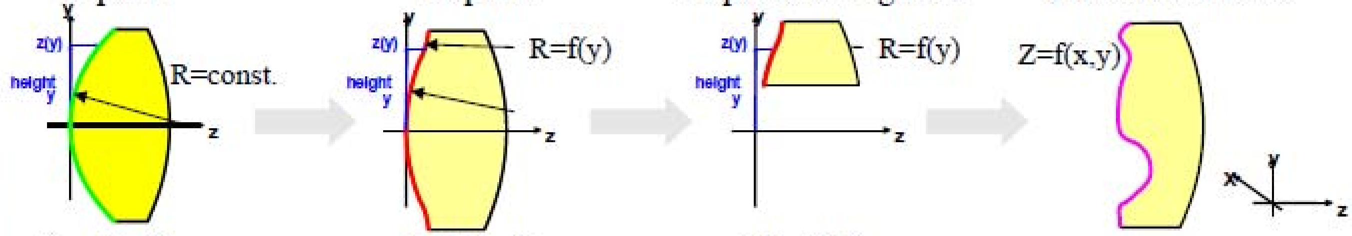
Freeform Surfaces
for Imaging Systems

Freeform surfaces –
Practical added Value
for Imaging Systems ?!

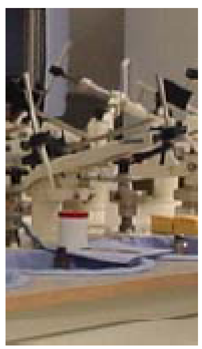
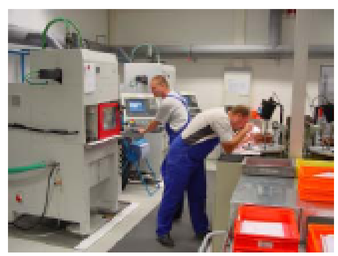
Norbert Kerwien, Wilhelm Ulrich
Carl Zeiss AG, Corporate Research & Technology

From Spheres to Freeform Optics

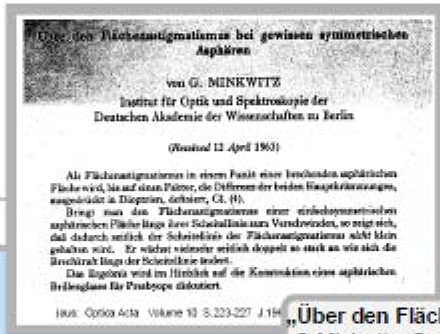
providing new Degrees of Freedom for Optical Design



	Sphere	Asphere	Aspherical Segment	Freeform Surface
Parameters	fixed Radius, rot. Symmetry	variable Radius, rot. Symmetry	variable Radius, virtual Symmetry	Loss of any Symmetry
Quality	Radius, Roughness	Radius, Deviation from Radius $\Delta z(y)$, Roughness	Radius, Deviation from Radius $\Delta z(y)$, Center, Roughness	Deviation from Surface Description, Roughness →Power Spectrum

The Progressive Lens Problem
stated and defined by Minkwitz's Theorem



Über den Flächenastigmatismus bei gewissen symmetrischen Asphären

von G. MINKWITZ

Institut für Optik und Spektroskopie der Deutschen Akademie der Wissenschaften zu Berlin

(Received 12 April 1963)

Als Flächenastigmatismus in einem Punkt einer brechenden asphärischen Fläche wird, bis auf einen Faktor, die Differenz der beiden Hauptkrümmungen, ausgedrückt in Dioptrien, definiert, Gl. (4).

Bringt man den Flächenastigmatismus einer einfachsymmetrischen asphärischen Fläche längs ihrer Scheitellinie zum Verschwinden, so zeigt sich, daß dadurch seitlich der Scheitellinie der Flächenastigmatismus nicht klein gehalten wird. Er wächst vielmehr seitlich doppelt so stark an wie sich die Brechkraft längs der Scheitellinie ändert.

Das Ergebnis wird im Hinblick auf die Konstruktion eines asphärischen Brillenglases für Presbyope diskutiert.

(aus: Optica Acta Volume 10 S.223-227 J.19

„Über den Flächenastigmatismus ….“
G.Minkwitz, Optica Acta Vol.10,(1963)

Problem

increase of curvature -> surface astigmatism

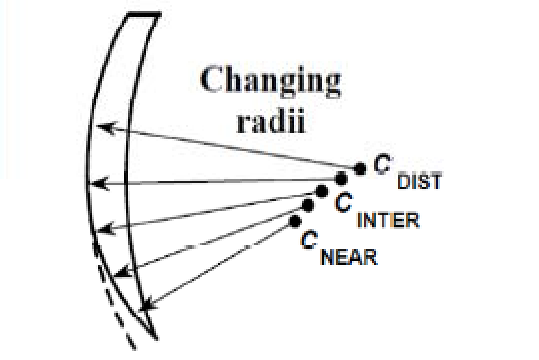
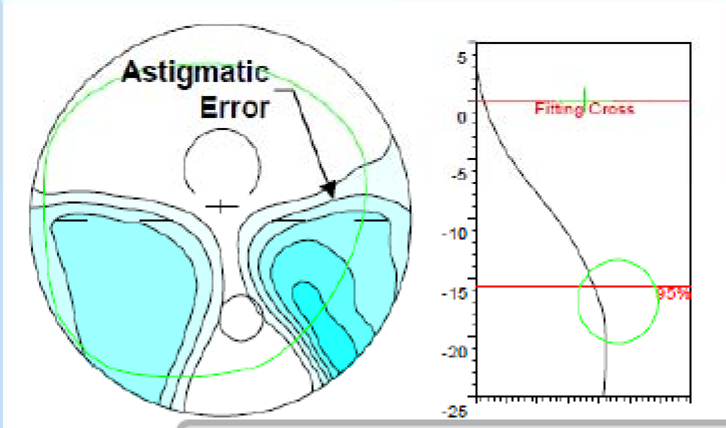


Figure 1. Cross-sectional representation of a progressive lens surface. The shorter radius of curvature in the near portion at point C_{NEAR} provides a stronger surface power than the longer radius of the distance portion at C_{DIST}.



„Fundamentals of of progressive addition lens design….“
D. Meister, Lens Talk Vol.23, (1998)

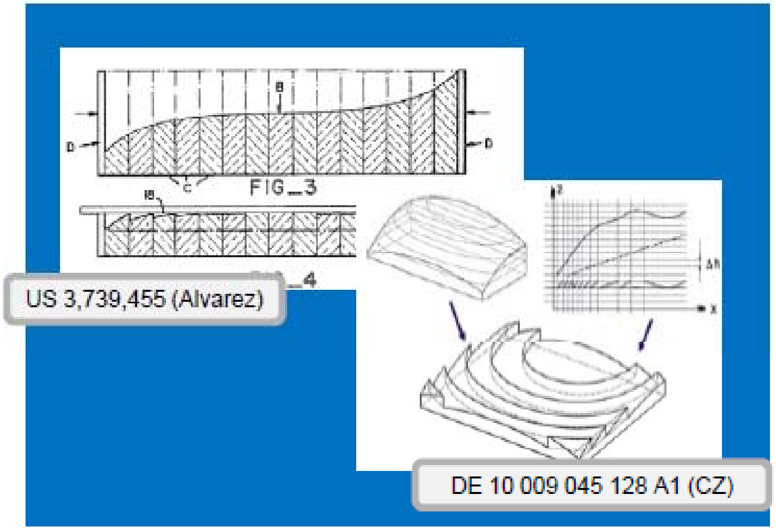
There is no progressive lens without these typical optical errors !

Freeform Fresnel Optics
to get ultra compact Design Solutions

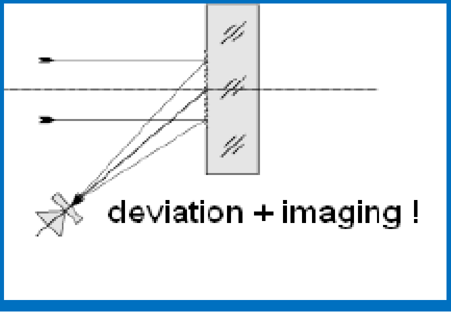
Principle firstly shown by L. Alvarez in 1973 and followed by further inventions for specific applications

Transform a general freeform surface to a „Segmented Freeform-Fresnel"

Advantages
- ultra compact
- all degrees of a freeform system

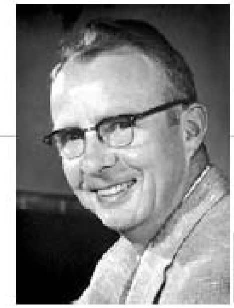


Example: Deviation and Imaging
allow to replace a tilted imaging freeform mirror by a flat non-tilted segmented fresnel-freeform-mirror



A great Invention

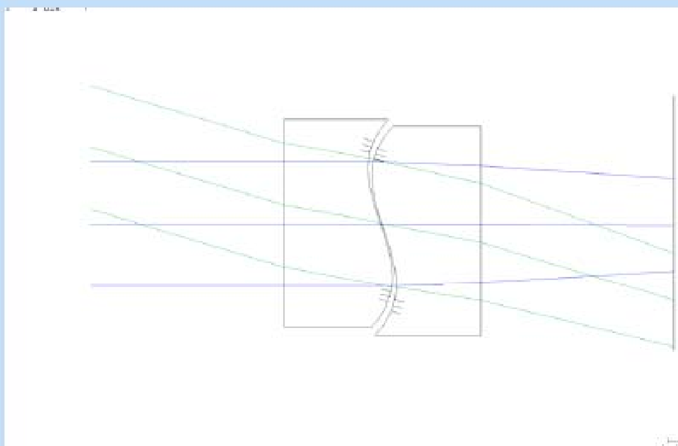
the functional Principle of Alvarez Plates

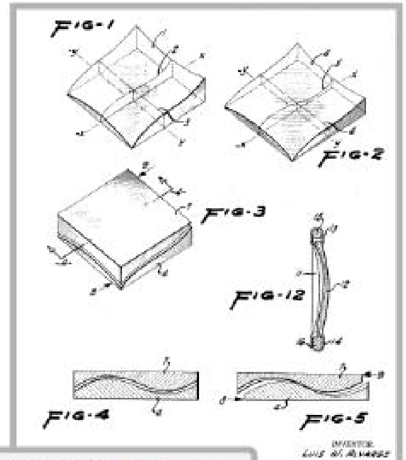


L.W. Alvarez
(1911–1988)

A pair of movable adjacent optical elements with flat outer surfaces and two inner matching aspherical surfaces

- invented by L.W. Alvarez in 1964 and
- Led the ideas of Kitajima (1926), Lewis (1941) and Birchall (1949) to practical use





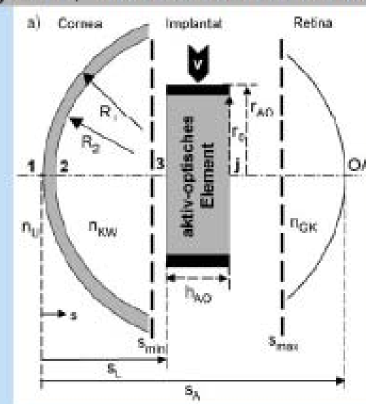
US 3,305,204 (L.W. Alvarez)

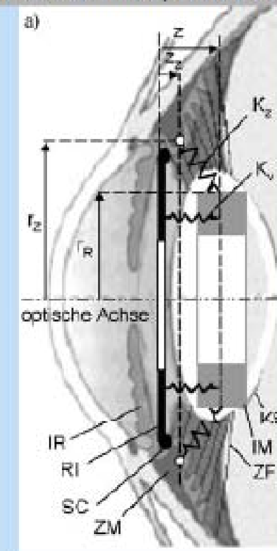
Ideas of high-interesting Applications (3)
for use as an accomodative intraocular Lens

Two-Element variofocal IOL

long-term stability ?

Neues mechatronisches System für die Wiederherstellung der Akkomdationsfähigkeit des menschlichen Auges
by Mark Bergmann, Schriftenreihe der Universität Karlsruhe, Band 17, (2007)





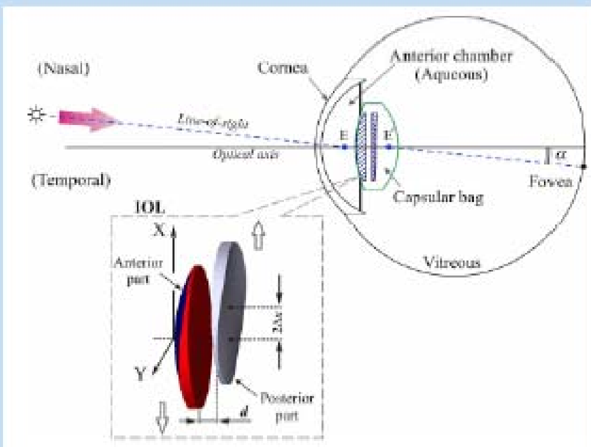
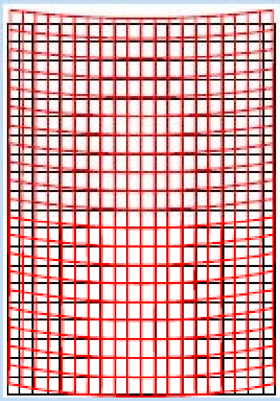


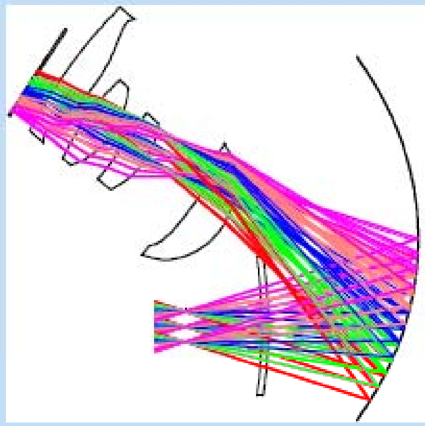
Fig. 2. Model eye with the accommodative IOL (horizontal section).

Cubic optical elements for an accommodative intraocular lens
by A. Simonov et. al., Optics Express Vol 14 No17, (2006)

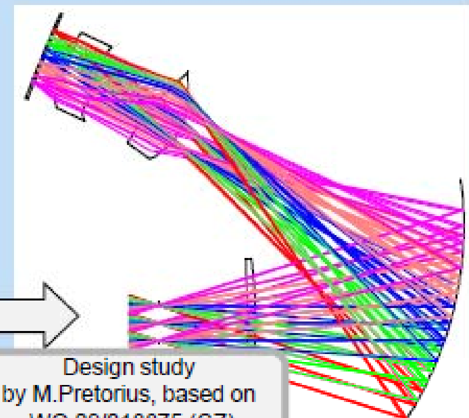
Ergonomics require tilted powered Combiner

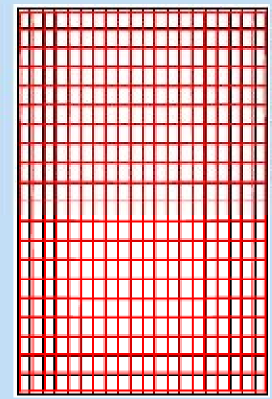
effectively compensated by using Freeforms





Design study
by M.Pretorius, based on
WO 09/018875 (CZ)



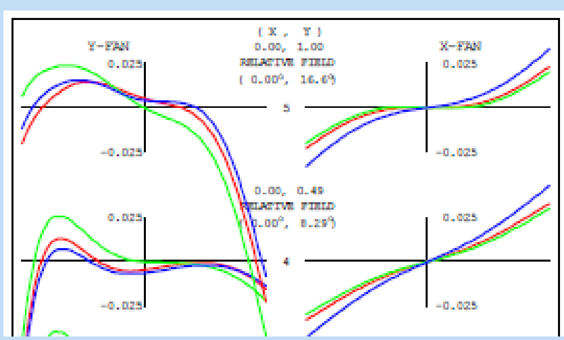


Classic design:

4 lenses (3 asph) + DOE

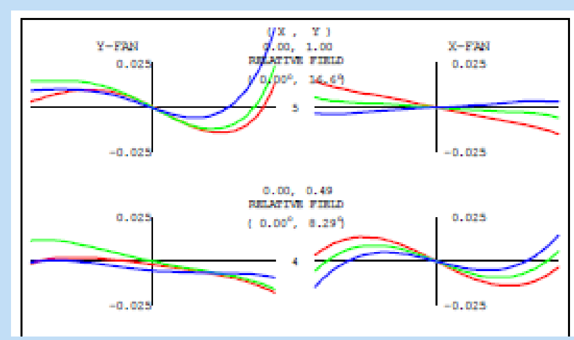
Freeform design:

2 freeform lenses + DOE



improved

- **wavefont**
- **distortion**
- **telecentricity**



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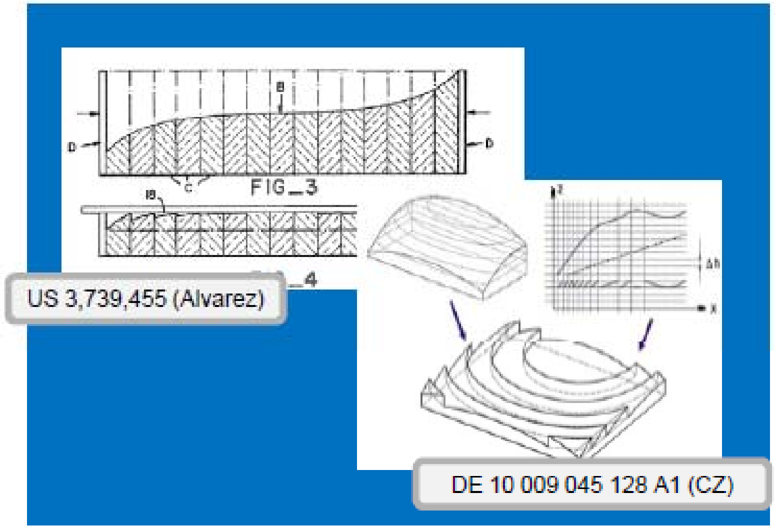

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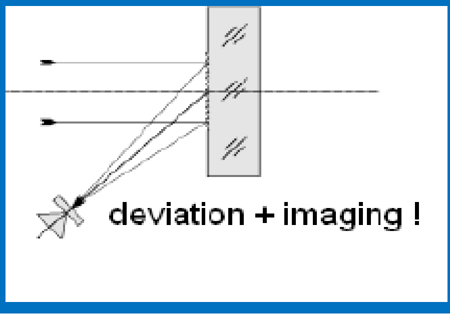
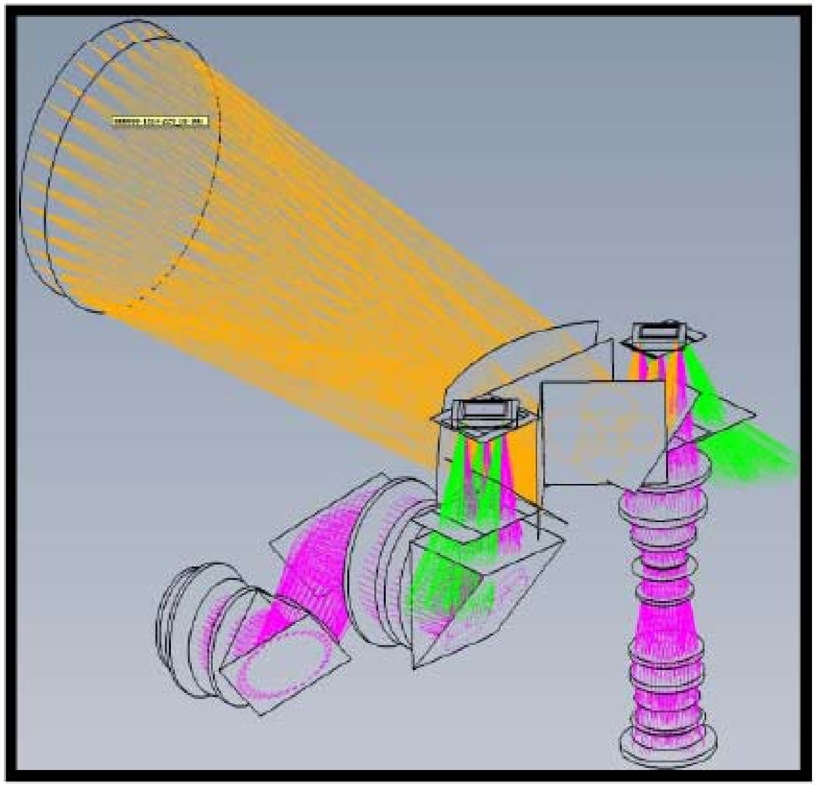
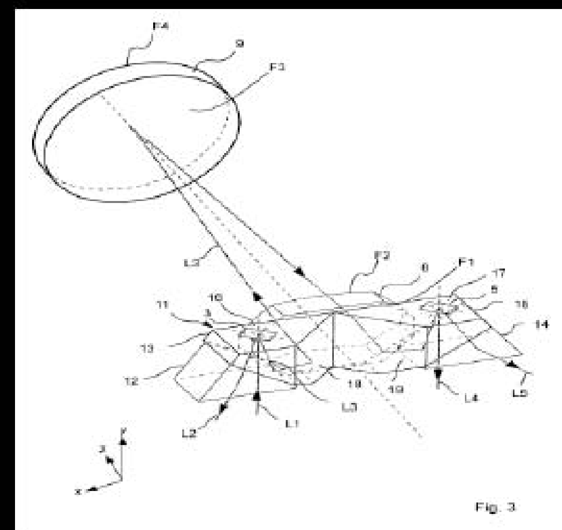


…based on a new Optical Design Concept

reducing Straylight to a Minimum
using slightly assymmetrical Optics with Freeforms





$$z = \frac{(x^2 + y^2)/R}{1 + \sqrt{1 - (1+k)\cdot\frac{(x^2+y^2)}{R^2}}} + \sum_{m,n=1}^{\infty} C_{m,n} \frac{1}{N_{Radius}^{m+n}} x^m y^n$$

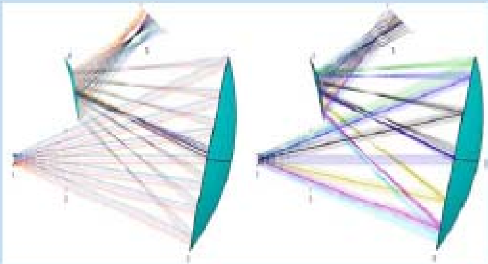
DE 10 2008 029 789 B4 (CZ)

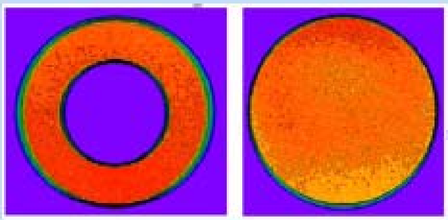
Reflex-free Design Concepts

Two Solutions Approaches

Reflective design concept

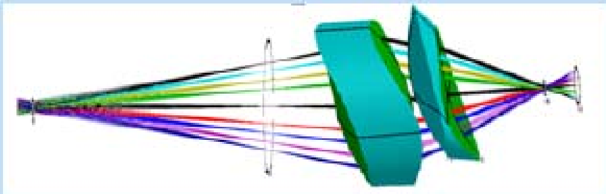
SPIE Proc. Vol 7100, (2008) &
US 2010/0014052 A1 (CZ)

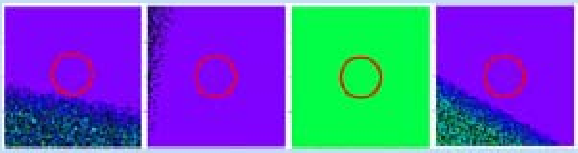




Refractive design concept with tilted lens elements

SPIE Proc. Vol 7652, (2010) &
DE 102010008629 A1 (CZ)



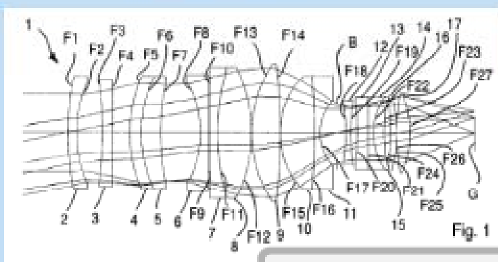


Design Study

ultra compact anamorphic Lenses
with outstanding Performance

Design study

Anamorphic freeform concept

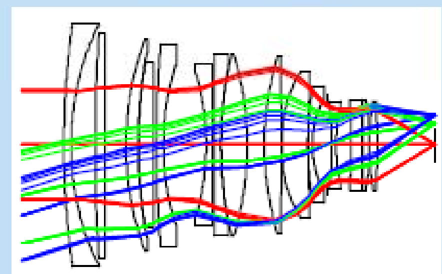


US 2009 0268305 A1 (CZ)

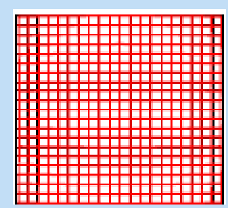
Idea

- close-to-field freeform -> distortion
- close-to-stop freeform -> on-axis ast
- freeform surfaces need less space than crossed large cylinder or toric lens elements

Freeform design study for 35mm



tracklength	195 mm
# lens elements	15
aspect ratio	2:1
F#	1.4
distortion	1%
MTF	very good



Summary: Many potential Applications

increasing Complexity provides new Degrees of Freedom

Benefical Use of Freeforms

Freeforms recommended for	Examples of potential applications
• Unobscurecd mirror systems to avoid self-vignetting	• telescopes, binoculars, ophthalmic lenses
• EDoF-components	• progressive lenses, intraocular lenses
• Tilted object or image planes and tilted components	• projector sytems, scanner systems
• Intentionally tilted or decentred components	• combiner in HMD and HUD, retina camera
• Wavefront error compensation elements	• manufacturing errors, lens heating , …
• Ultra compact folded systems	• mobile phones
• Anamorphic imaging	• Cinema camera lenses
• Unavoidable nonsymmetric components	• beamsplitter plates

➢ **Enabling for many non-symmetrical imaging systems**
➢ **Improving performance**
➢ **Reducing size and weight significantly**
➢ **Reducing costs => still a challenge**

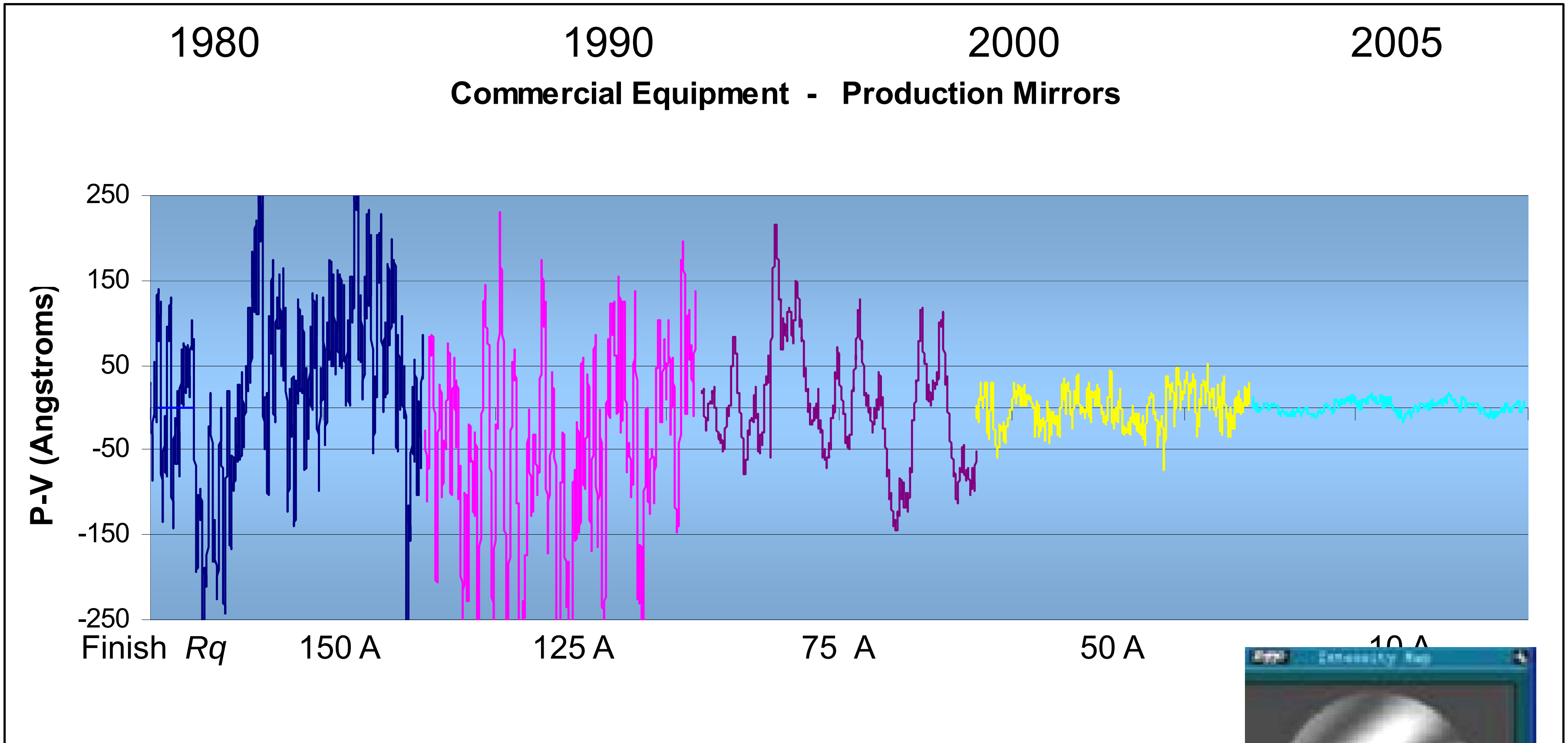
Current techniques for diamond machining freeform optics

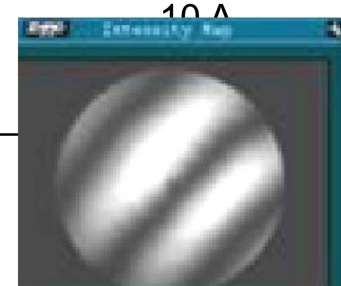
Gregg Davis
Gary Herrit
Alan Hedges

Context: laser beam shaping optics

- Traditional 2-axis machining
  - Gaussian to flat-top circle
- Slow Tool Servo (STS)
  - Gaussian to flat-top square/rect/hex
- Fast Tool Servo (FTS)
  - Low Coherence to flat-top square/rect/hex
- Micromilling
  - Lens array mold insert

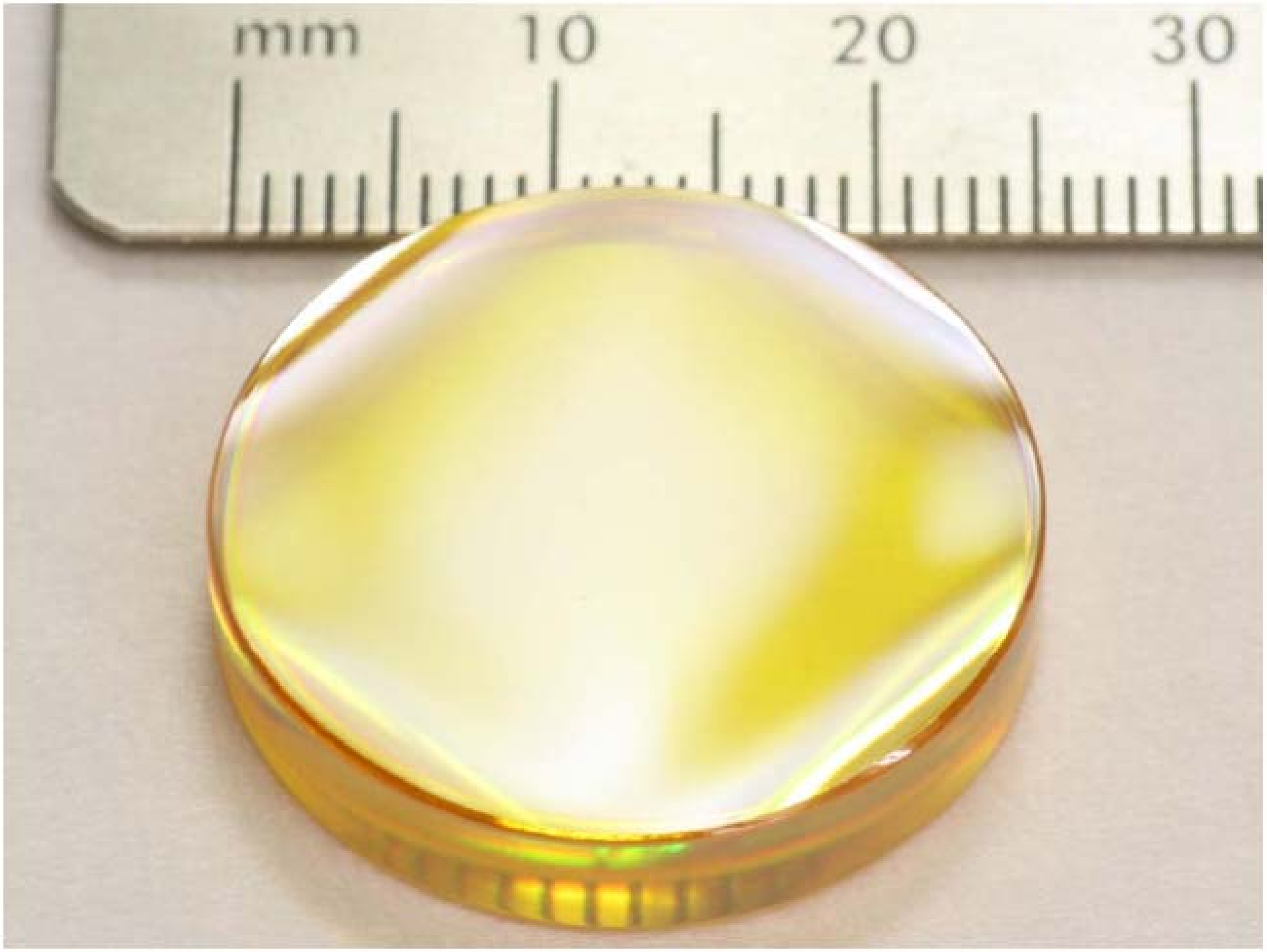
J. Schaefer has tracked the progress of diamond turning (IODC 2006)





profile data is actual measured data taken from production mirrors cut on commercial equipment

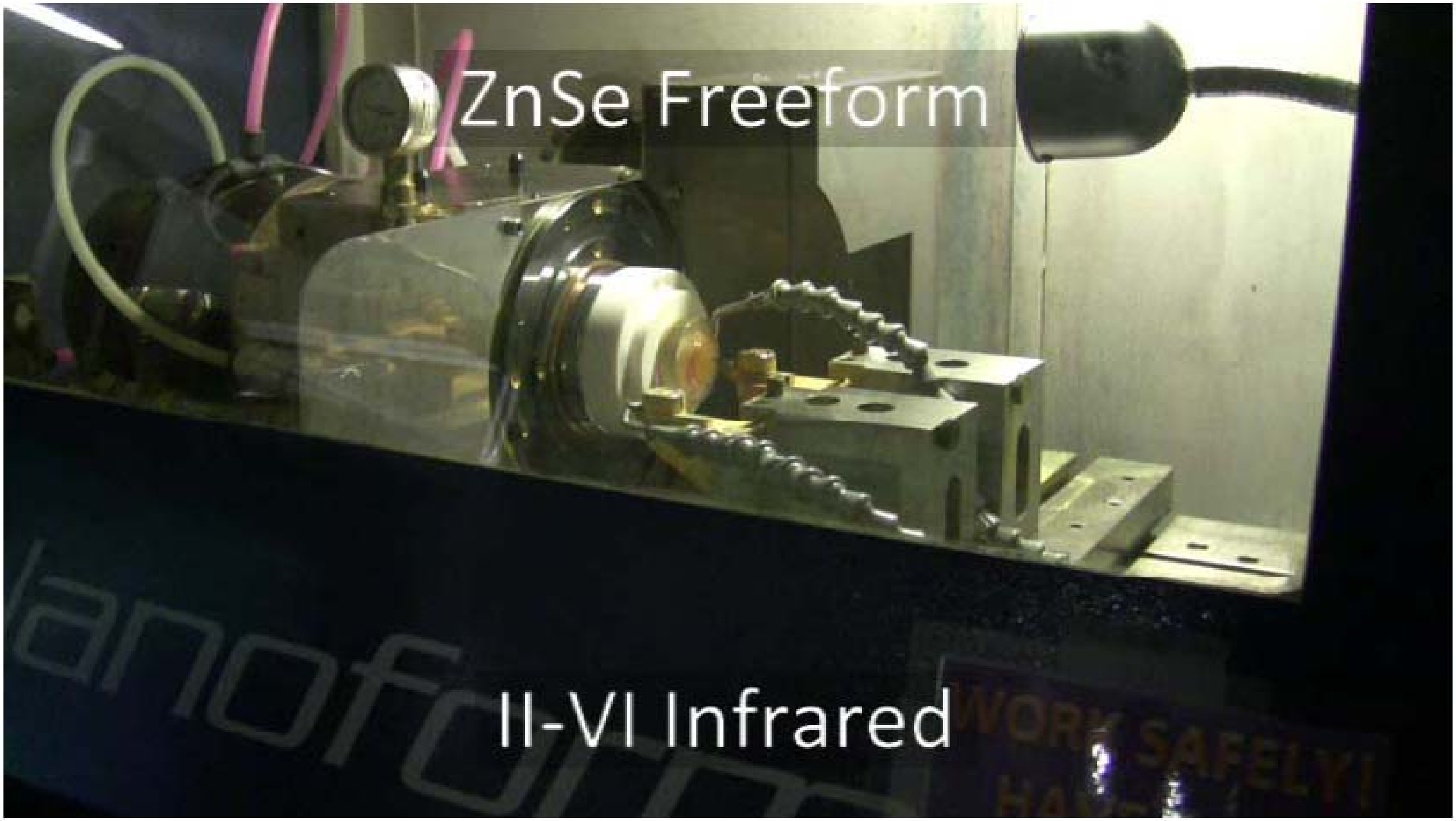
Gaussian to square flat-top



Active Application Areas
Beam-shaping optic comparisons

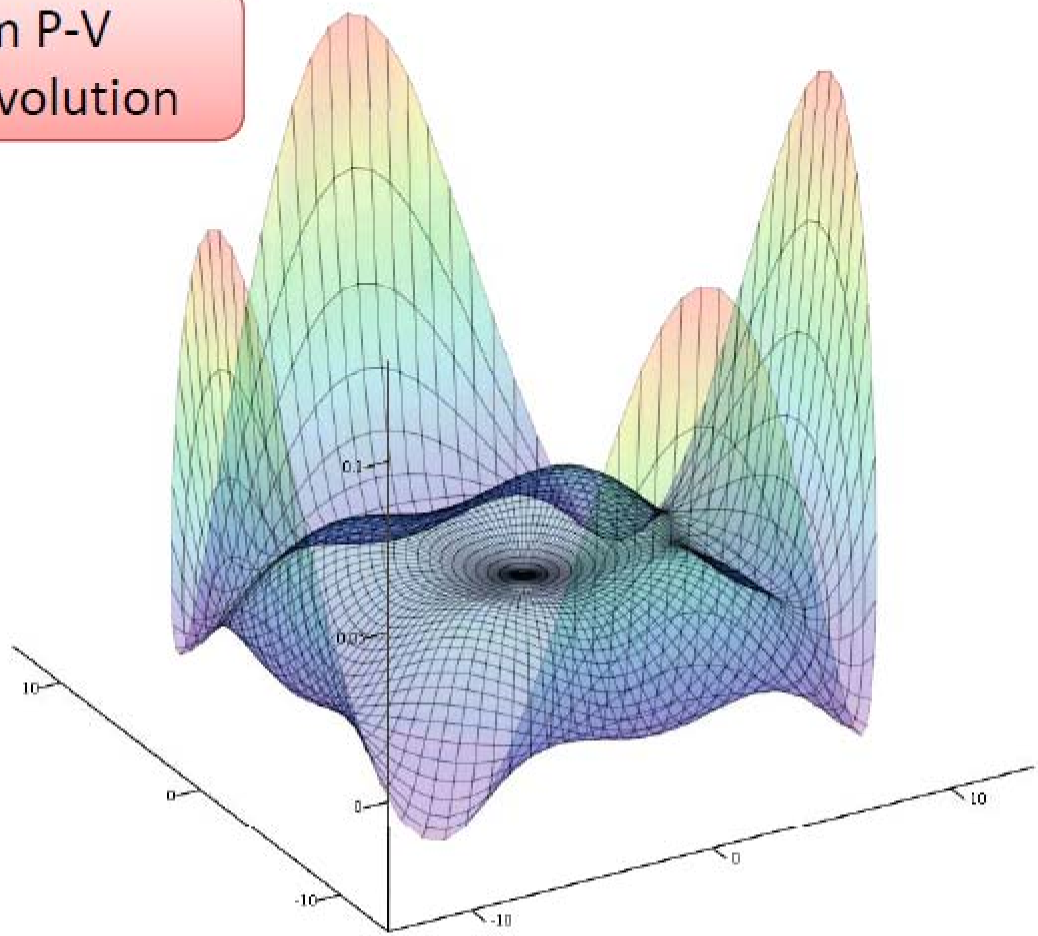
Optic Type	Free Space Beam Converter	X-Y Freeform Polynomial	Beam Integrator	Micromilled Lens Array
Focus Shape	Flat-top circle	Flat-top square/rect/hex	Flat-top square/rect/hex	Array of spots
Diamond Turning Tech	Base DT Lathe	+ C-axis encoder and STS	+ C-axis encoder and FTS	Micromilling Machine
Tech Cost	$250k - $300k	$300k - $350k	$425k - $475k	$400k - $600k
Setup Time (hr)	2	2	3	10
Machine Time/Piece (hr)	0.5	12	12	4
Programming Complexity	Low	Medium	Medium	High
Size for Comparison	1.5"	1.5"	1.5"	Very Small
Cost Range Low Quantity	$1000 - $2500	$3000 - $5000	$3000 - $5000	$3000 - $15000
Cost Range High Quantity	$500 - $1500	$2700 - $4700	$2700 - $4700	$1000 - $3000

Slow Tool Servo

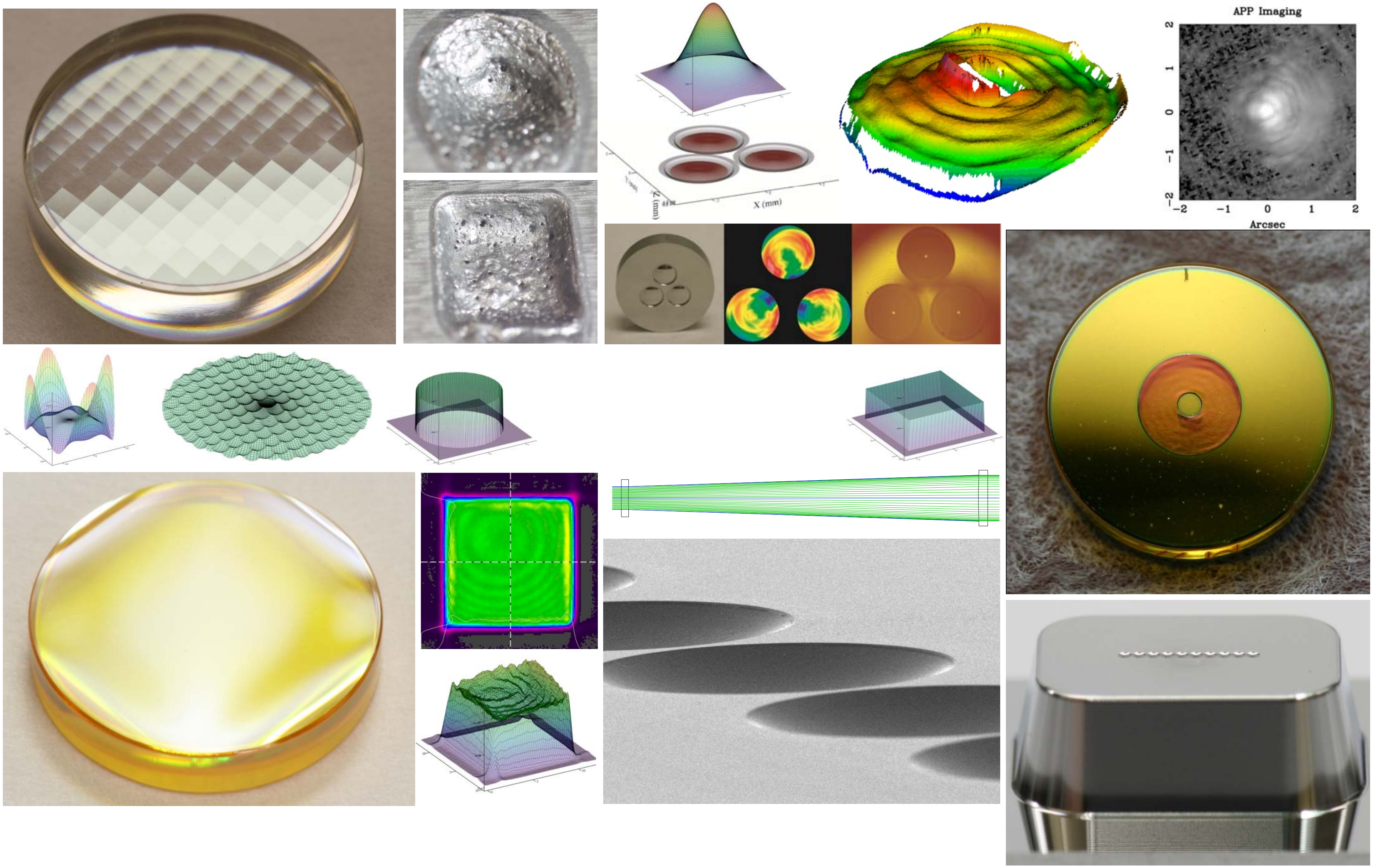


Freeform X-Y Polynomial

0.159 mm P-V
4x per revolution



Some Current Samples



Realizing an Optical System with φ-Polynomial Freeform Surfaces

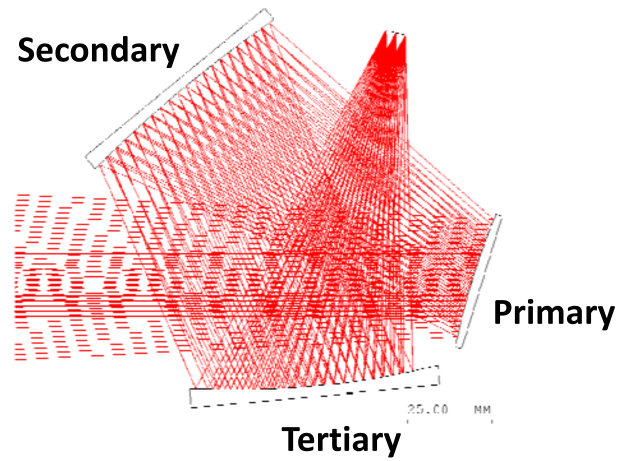
Kyle Fuerschbach
University of Rochester
Prof. Jannick Rolland
University of Rochester
Kevin Thompson, PhD
Synopsys

www.odalab-spectrum.org

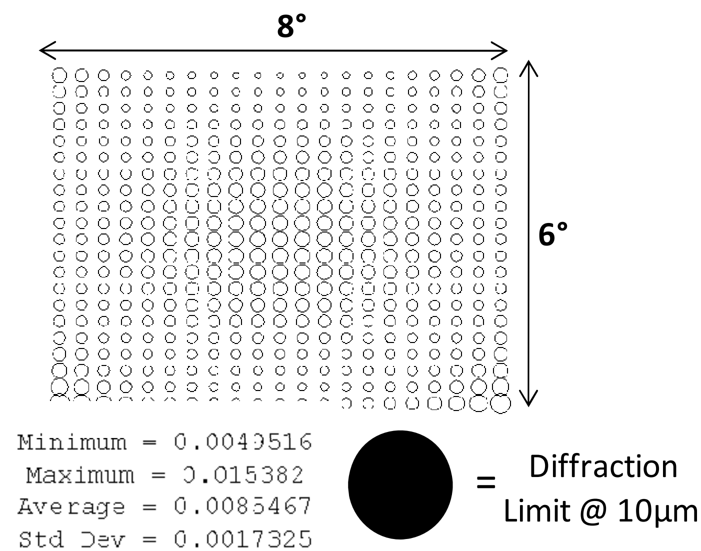
Predictable Success

A new family of optical systems enabled by φ-polynomial surfaces

- φ-polynomials are used for optimization in defined manner
  - For field constant correction
    - Use at or near stop surface
  - For field dependent aberration
    - Use for surfaces away from stop



- Possible to reach solution
  - RMS wavefront error at λ = 10 μm less than $\lambda/50$ over 10° FFOV



Fuerschbach et al., "A new family of optical systems employing φ-polynomial surfaces," Opt. Express 19 (2011)

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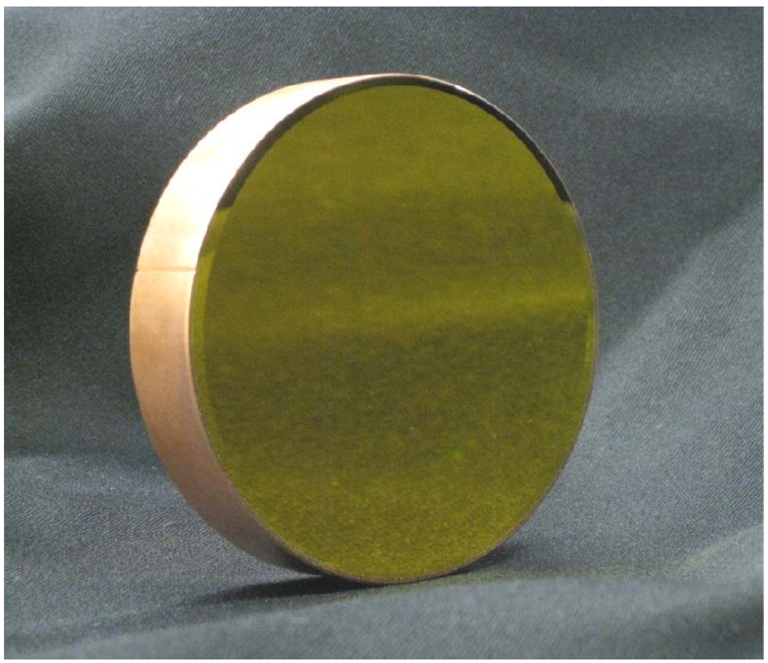
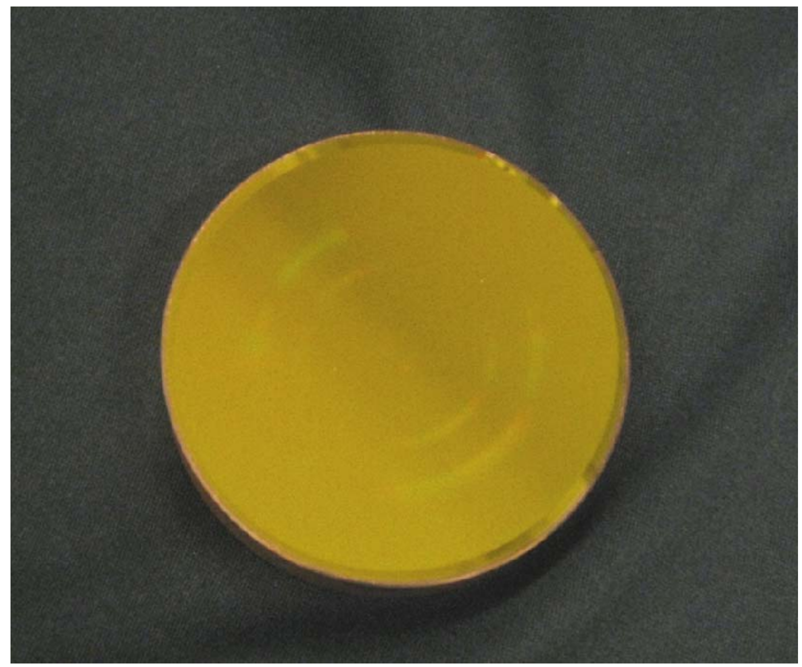
Fabrication

- Secondary mirror has been diamond turned by II-VI Infrared Inc.





II-VI INFRARED ... the world leader in CO_2 laser optics

Metrology of a Freeform Mirror

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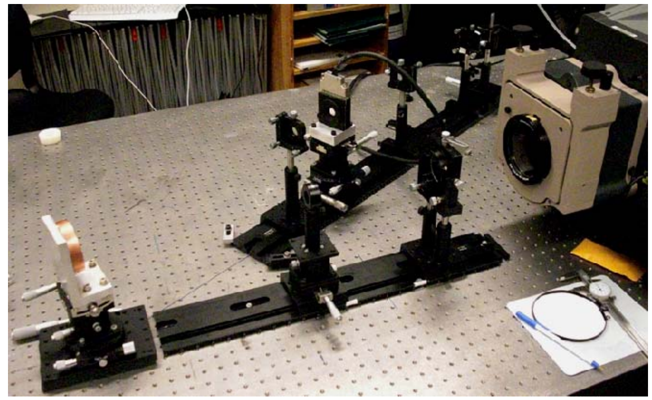
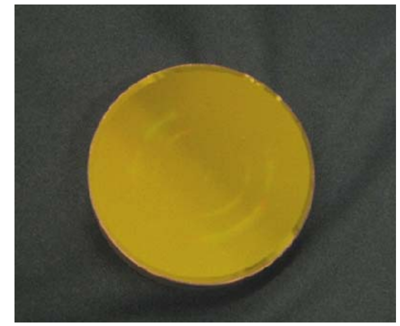
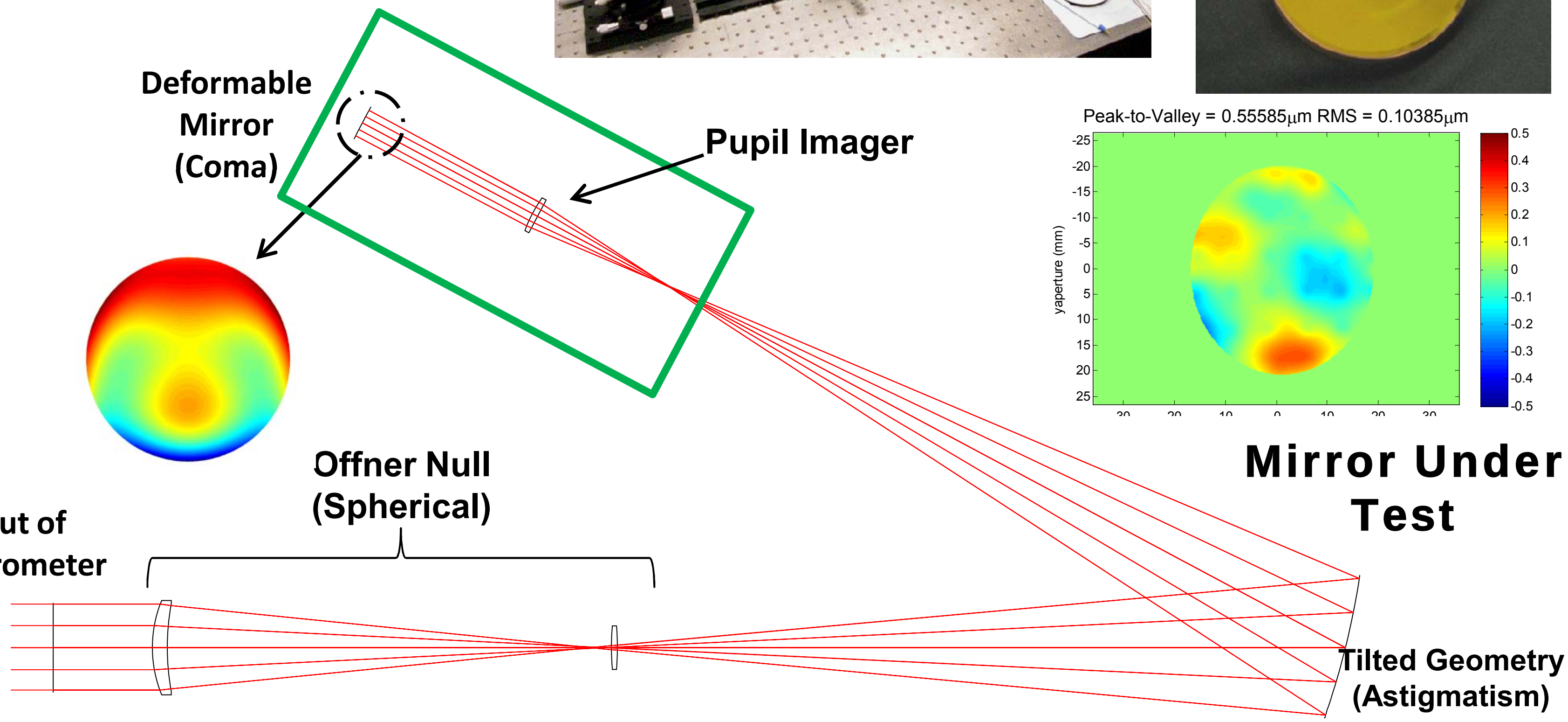
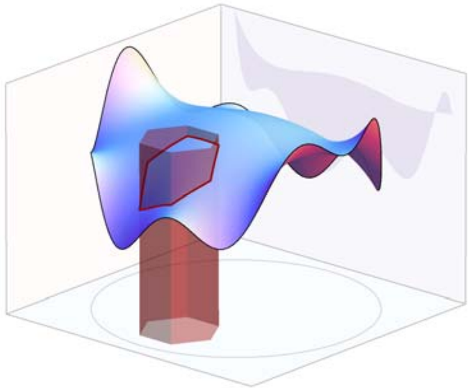








Specifying shape

…what could we hope for and can it be achieved?

Greg Forbes

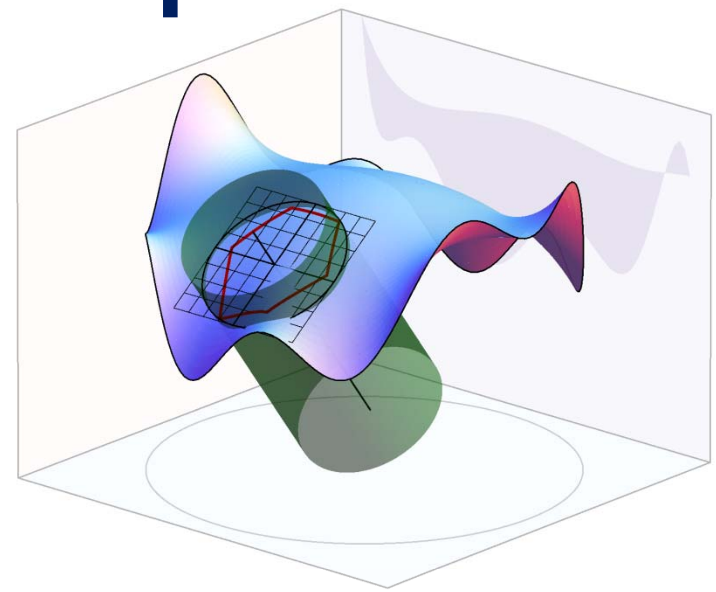
What could we hope for?

Objective: neat numbers for communication

- o Minimal # of degrees of freedom (i.e. coefficients)
- o Capability to have many when needed (future-proof)
- o Minimal # of significant digits
- o Easy to interpret (e.g. sig digs, ballpark difficulty)
- o Extension of familiar rotationally symmetric scheme
- o Robust & fast evaluation (derivs, ray tracing etc.)
- o Supports rapid estimates of manufacturability

Is “eyeball friendly” too much to ask?
How general-purpose can it be?

Three new steps…



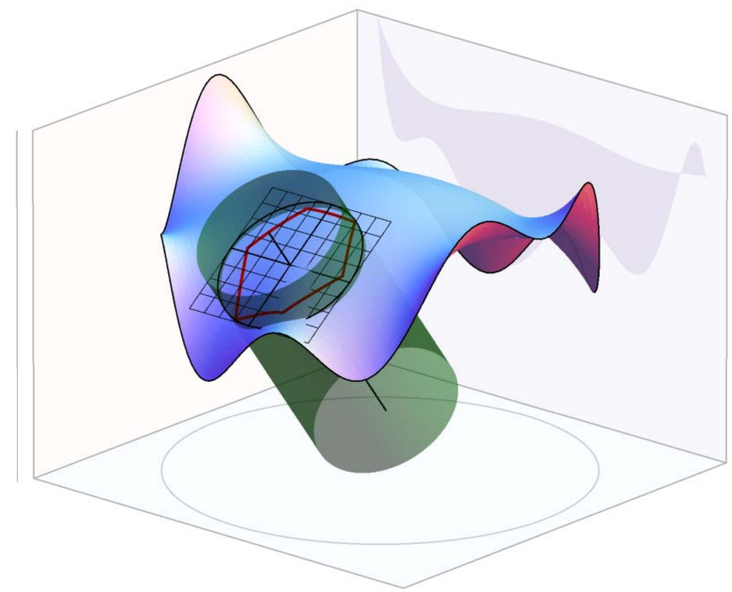
1 **Simplify orthogonalization domain by using enclosing cylinder:**

2 **Introduce non-rotationally symmetric elements a la Zernike:**

$$z(r,\theta) = \frac{c\,r^2}{1+\sqrt{1-c^2r^2}} + \frac{1}{\sqrt{1-c^2r^2}}\left\{u^2(1-u^2)\sum_{n=0}^{N} a_n^0\, Q_n^0(u^2)\right.$$

3 **Orthogonalize wrt mean square gradient to construct Q^m…**

Details are found in



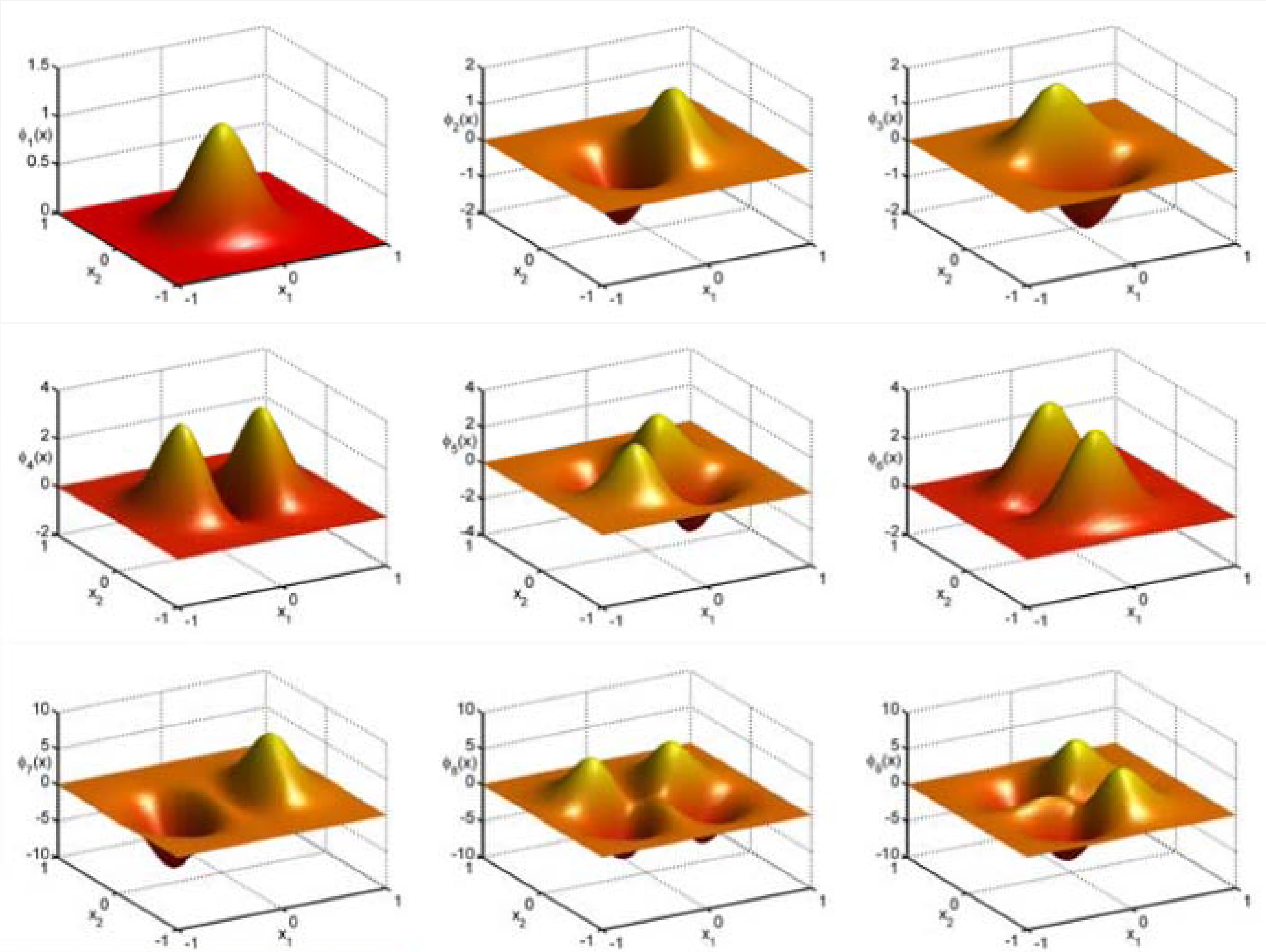
Characterizing the shape of Freeform Optics
G. Forbes
Optics Express **20**(3) 2483-2499 (2012)

Smooth Radial Basis Functions Viewed as a Generalization of Multivariate Polynomials

Greg Fasshauer

Department of Applied Mathematics
Illinois Institute of Technology
Partially supported by NSF Grant DMS–1115392

Presented at
Freeform Optics Incubator Meeting
OSA, Washington, D.C.
October 31, 2011



$\phi_1(x)$
$\phi_2(x)$
$\phi_3(x)$
$\phi_4(x)$
$\phi_5(x)$
$\phi_6(x)$
$\phi_7(x)$
$\phi_8(x)$
$\phi_9(x)$
x_1
x_2

Summary

- We provide a (general) technique for stable evaluation of RBF interpolants when ε is so small that ill-conditioning overwhelms the traditional approach to RBF interpolation ("flat-limit" regime):
  - RBF-QR for interpolation (shown here for 1D example)
  - Eigenfunction regression for approximation (used for 2D examples)
- MATLAB code available at

  `http://math.iit.edu/~mccomic/gaussqr`

Future research topics

- Try for other "real" optical surfaces
- Apply in optics design framework (optimization, etc.)
- Analytic relationship of the parameters ε, M and α
- Anisotropic and nonuniform approximation
- Fast (iterative) algorithms
- Other kernels

Moving from φ-Polynomial to Multicentric Radial Basis Functions

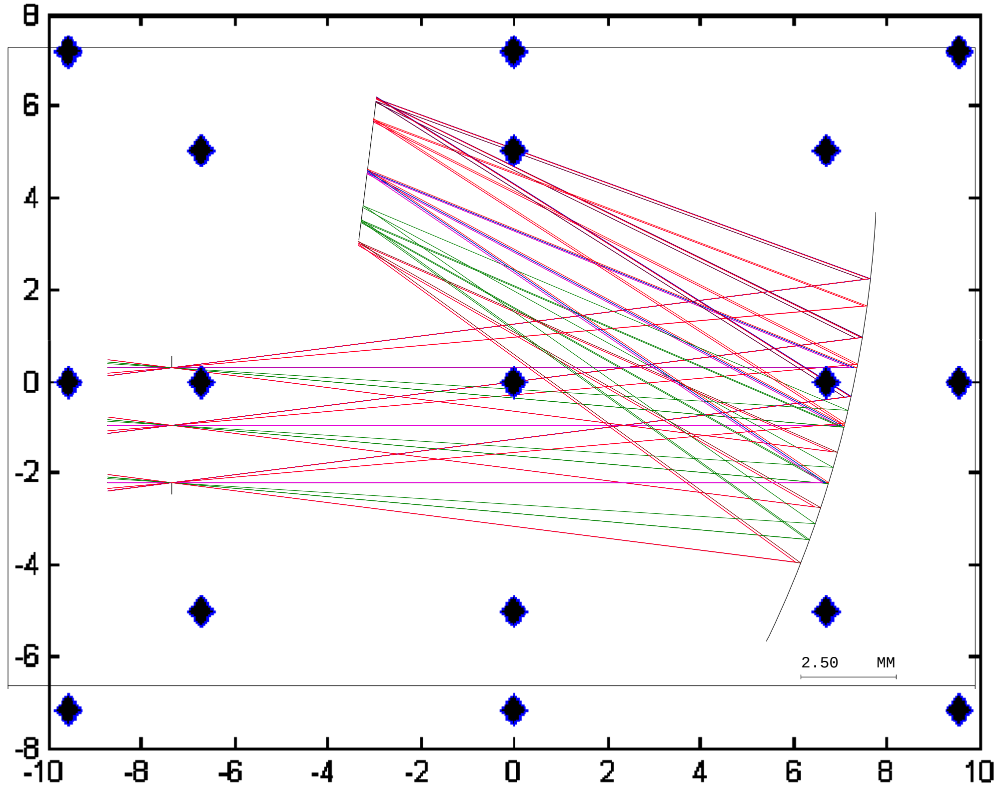
Aaron Bauer
with Ilhan Kaya and Prof. Jannick Rolland

OSA Freeform Optics Incubator Meeting
October 31, 2011

www.odalab-spectrum.org

Design Study

- Single Reflector
- 20^0 x 14^0 FOV
- 3 mm Entrance Pupil
- 14^0 Mirror Tilt
- ~300 Bases



Field Points used during Optimization

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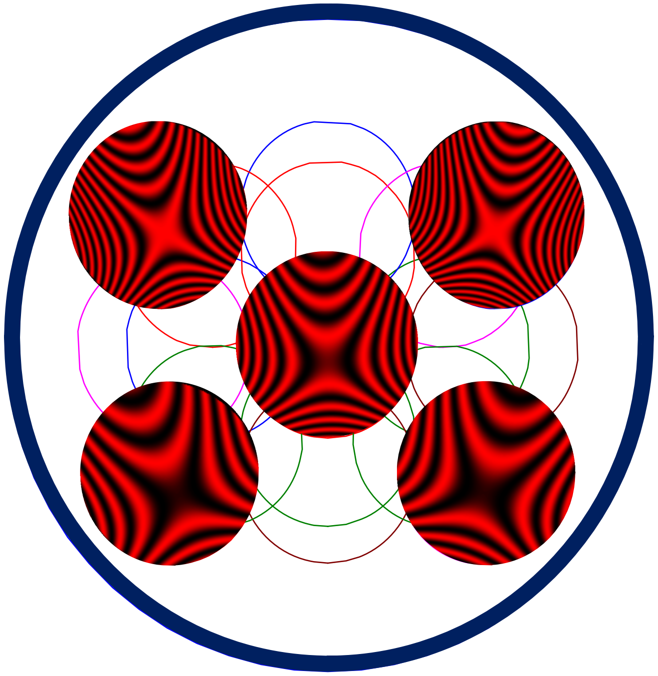
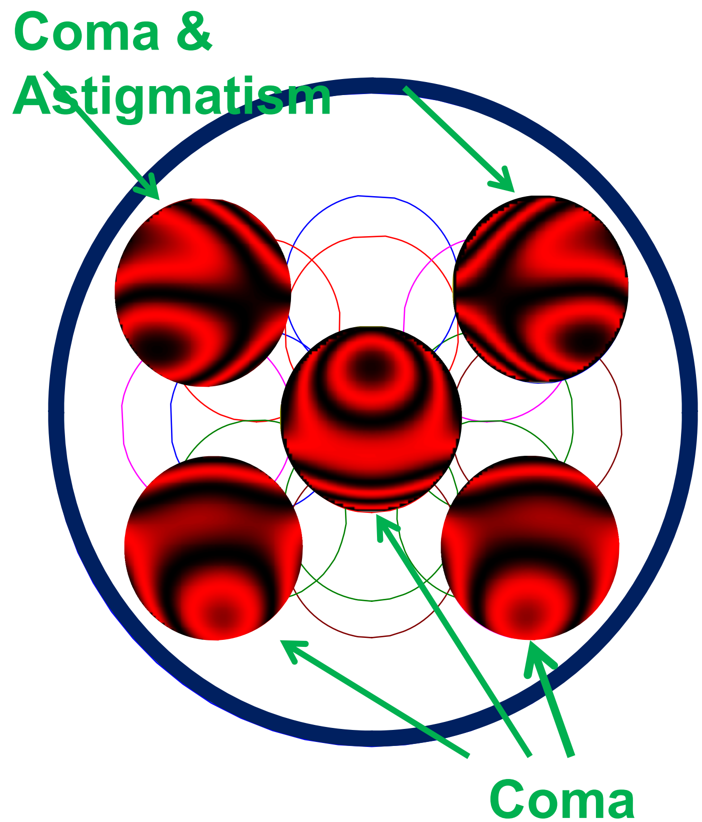
Footprint Plot: Before and After



Tilted Spherical Mirror



With RBF Added

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