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 2 of 3
Day 1, Afternoon

compiled by
Kevin Thompson, PhD
Synopsys, Inc.

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
Afternoon Session

Illumination Optics; an Introduction
Bill Cassarly, *Synopsys, Inc., 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**
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16:00 **Two Freeform Mirror Designs with SMS 3D**
Lin Wang, *Universidad Politecnica de Madrid, Spain*

Surfaces for Illumination
Part 1 - Introduction

Freeform Incubator

Dr. Bill Cassarly
Optical Research Associates
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Illumination Optics

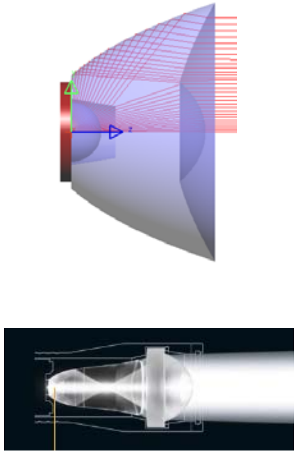
- Includes applications in virtually every industry where light must be controlled. Almost all applications now use LEDs.

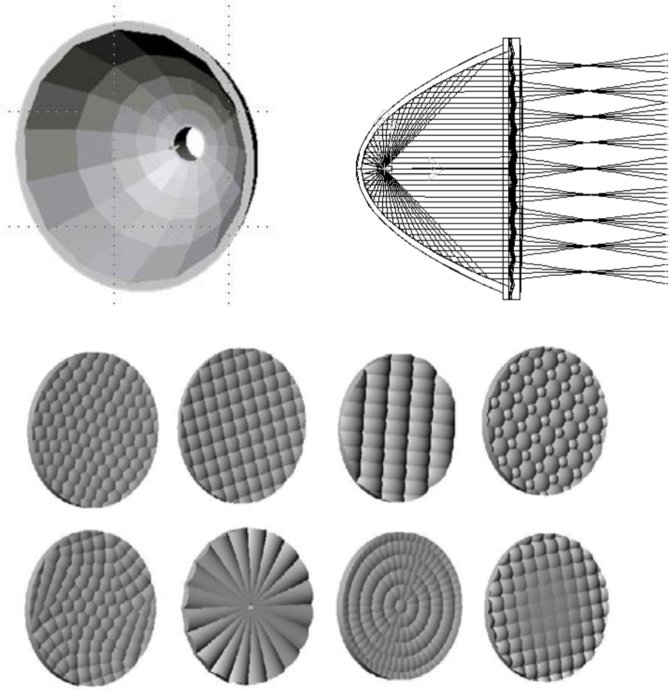
Reflector Applications

- Luminaires
- Flashlights
- Street lighting
- Medical illuminators
- Automotive headlights
- Projection displays
- Laser beam shaping

Diffusers and scatter

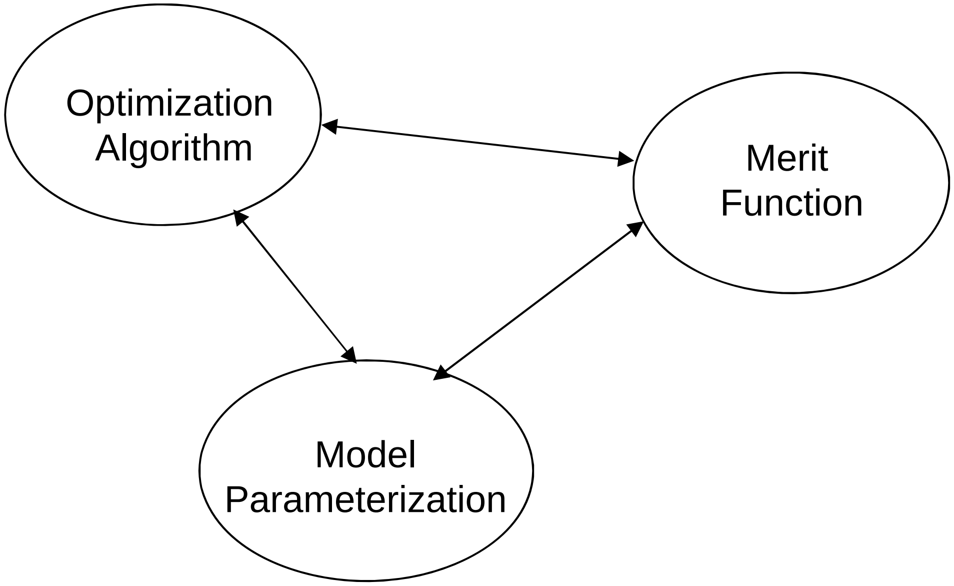
- Many illumination products combine an optic that collects light and also spread/homogenizes the beam pattern.
  - Lens arrays, faceted reflectors, diffusers





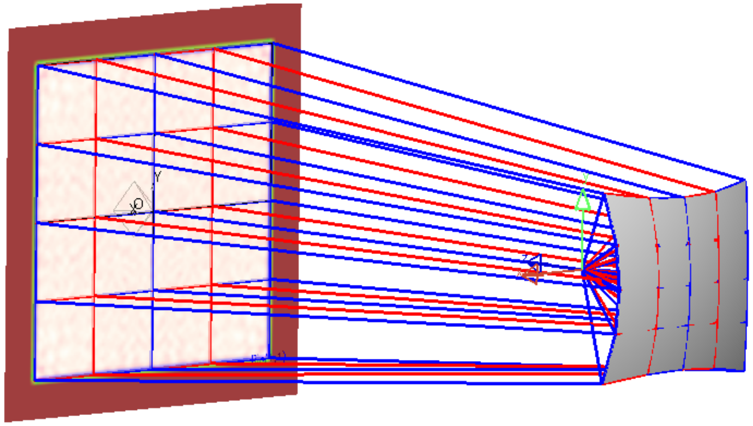
Optimization

- Optimization is the ability to automatically refine the performance of a system based upon a user specified performance criteria
- Three primary aspects of optimization
  - Efficient Optimization Algorithm
  - Smart Model Parameterization
  - Robust Merit Function



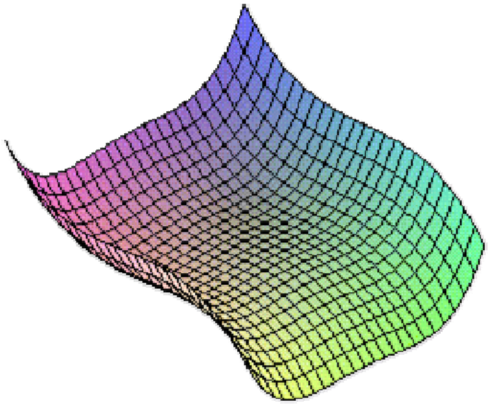
User Interface ties these elements together

Surface Parameterization

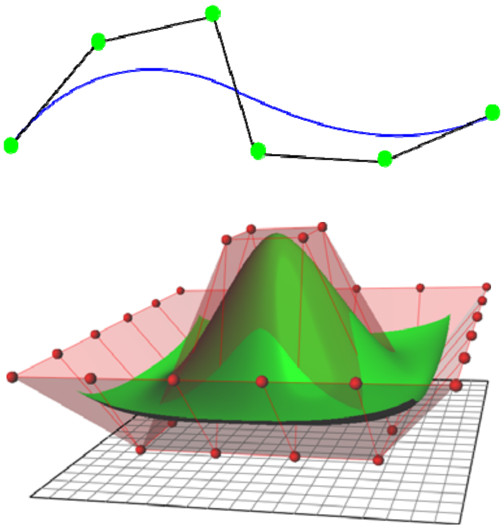


- Surfaces can be described using Equation:
  - e.g., XYPolynomial, Zernike, Asphere, etc
- Tailoring and SMS:
  - Compute prescribed surface(s) by numerical integration.
    - Often based upon a source to output mapping
    - Surface commonly represented using NURBS
- Equation that best fits NURBS sometimes used

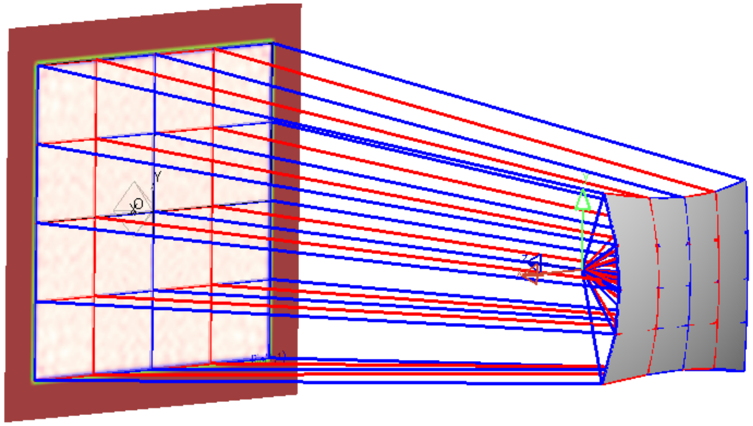
XY polynomial



NURBS curve and NURBS surface



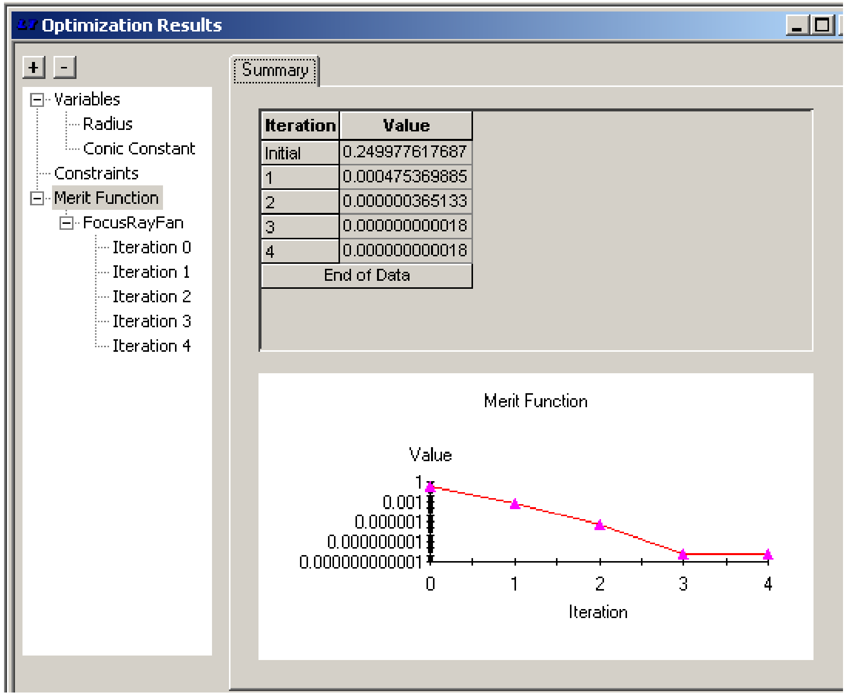
Optimization Variables



- Equation Parameters
  - – e.g., radius of curvature, XY polynomial coefficients
- Source to Output Mapping parameters
  - – e.g., Width of target, desired Illuminance

Merit Function

- For many applications, a weighted Merit Function can be used for optimization.
- Weights are used by the designer to help balance tradeoffs.
- Merit functions are often based on ray aiming.
- In illumination, binned Monte Carlo simulation results are often used.



Iteration	Value
Initial	0.249977617687
1	0.000475369885
2	0.000000365133
3	0.000000000018
4	0.000000000018
End of Data	

Basic Equation For Merit Function

$$MF = \sum W_g \sum W_i^2 (V_i - T_i)^2$$

W_g = Weight of g^{th} MF Group

W_i = Weight of i^{th} MF item in Group g

V_i = Current Value of i^{th} MF item

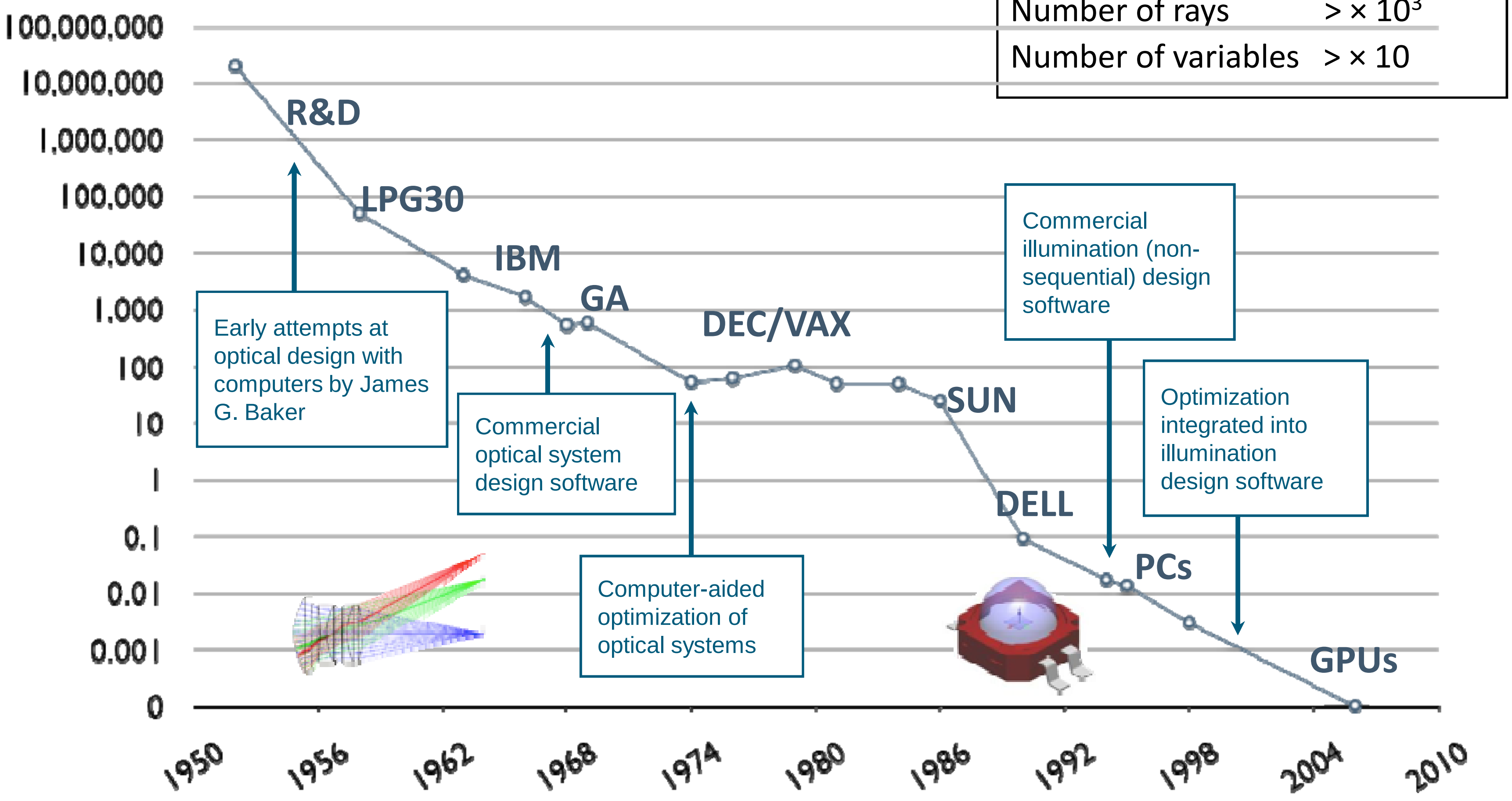
T_i = Target of i^{th} MF item

Computer Speed makes Monte Carlo Optimization feasible

Illumination vs. imaging systems

Calculations / ray	> × 10
Number of rays	> × 10^3
Number of variables	> × 10

Ray trace speed ($/RS/s)



Early attempts at optical design with computers by James G. Baker

Commercial optical system design software

Computer-aided optimization of optical systems

Commercial illumination (non-sequential) design software

Optimization integrated into illumination design software

Adapted from K. Thompson, “Optical Design, Information and Insights,” Invited, Presented to the Committee on Optical Science and Engineering, National Academy of Sciences (1996)

SMS 3D: A Freeform Optics Design Method

J.C.Miñano[1,2], Pablo Benítez[1,2]

[1]Universidad Politécnica de Madrid, Spain
[2]LPI, USA

Freeform Optics Incubator Meeting
Washington, October 31, 2011

Design methods in nonimaging optics

1. String method (1960's)
2. Flow line method (1970's)
3. Taylored Edge-ray method (1980's)

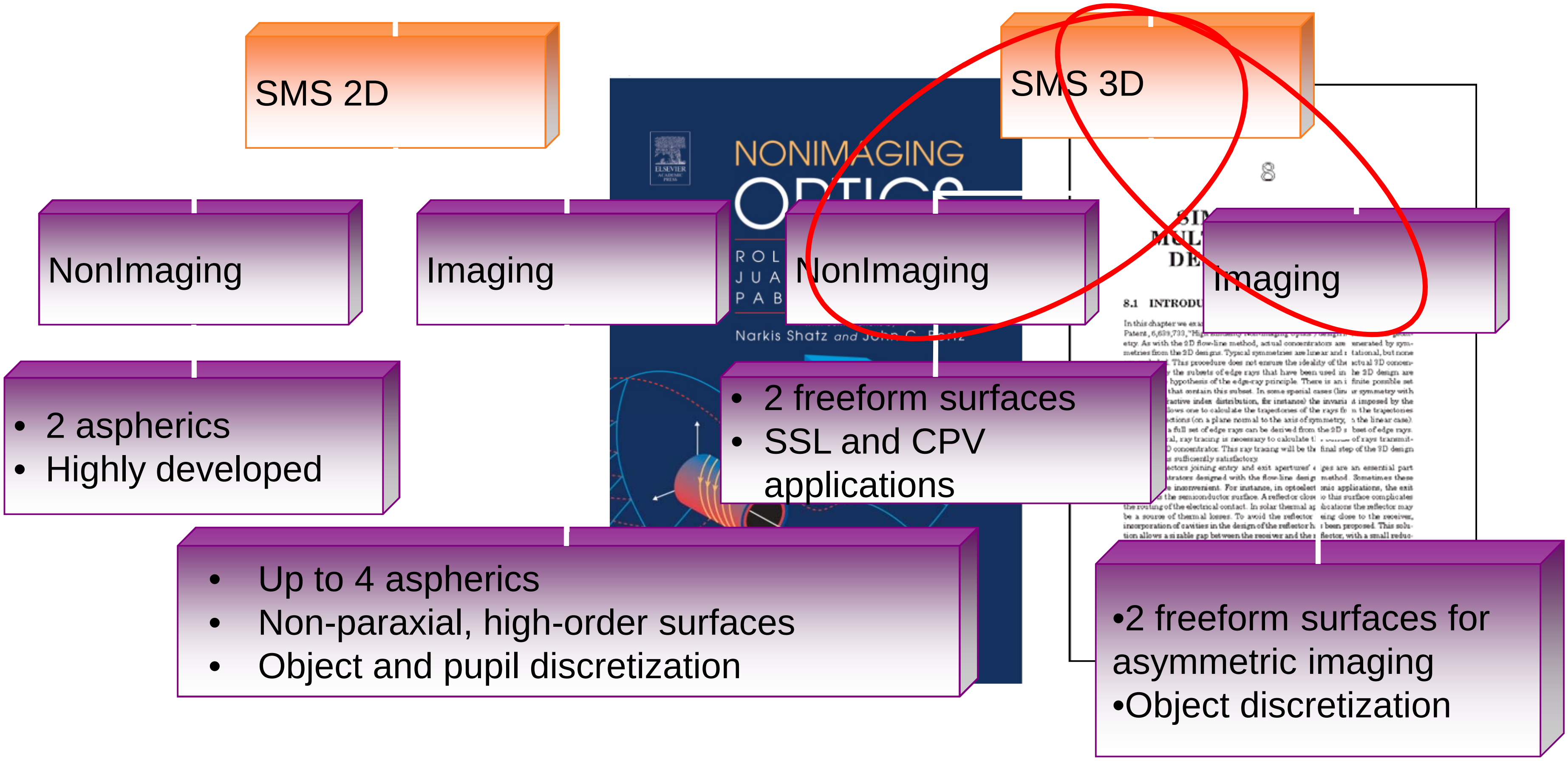
Only 2D

4. Poisson bracket method (1980's)
5. Lorentz geometry method (1990's)
6. Point-source Differential Equation methods (1960's)
7. Numerical optimization methods (1990's)
8. Simultaneous Multiple Surface (SMS) method (1990's)

2D and 3D

2D = rotational or linear symmetry
3D = freeform

SMS design method



SMS 2D

NonImaging

- 2 aspherics
- Highly developed

Imaging

- Up to 4 aspherics
- Non-paraxial, high-order surfaces
- Object and pupil discretization

SMS 3D

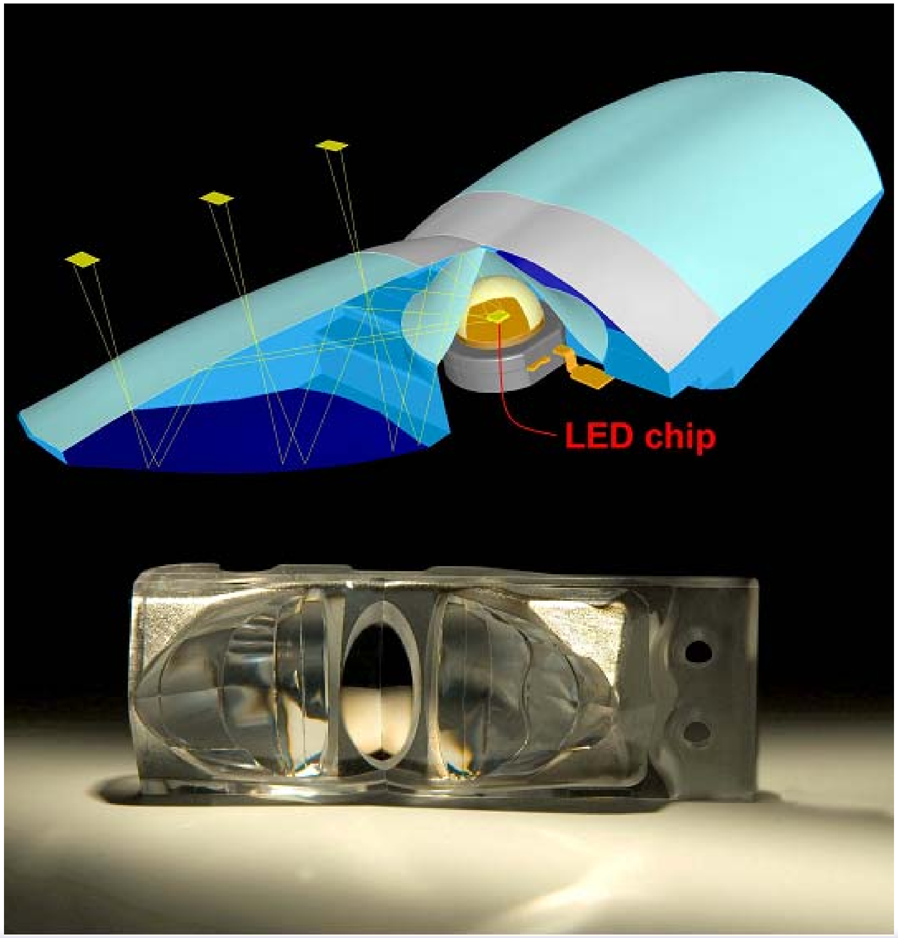
NonImaging

- 2 freeform surfaces
- SSL and CPV applications

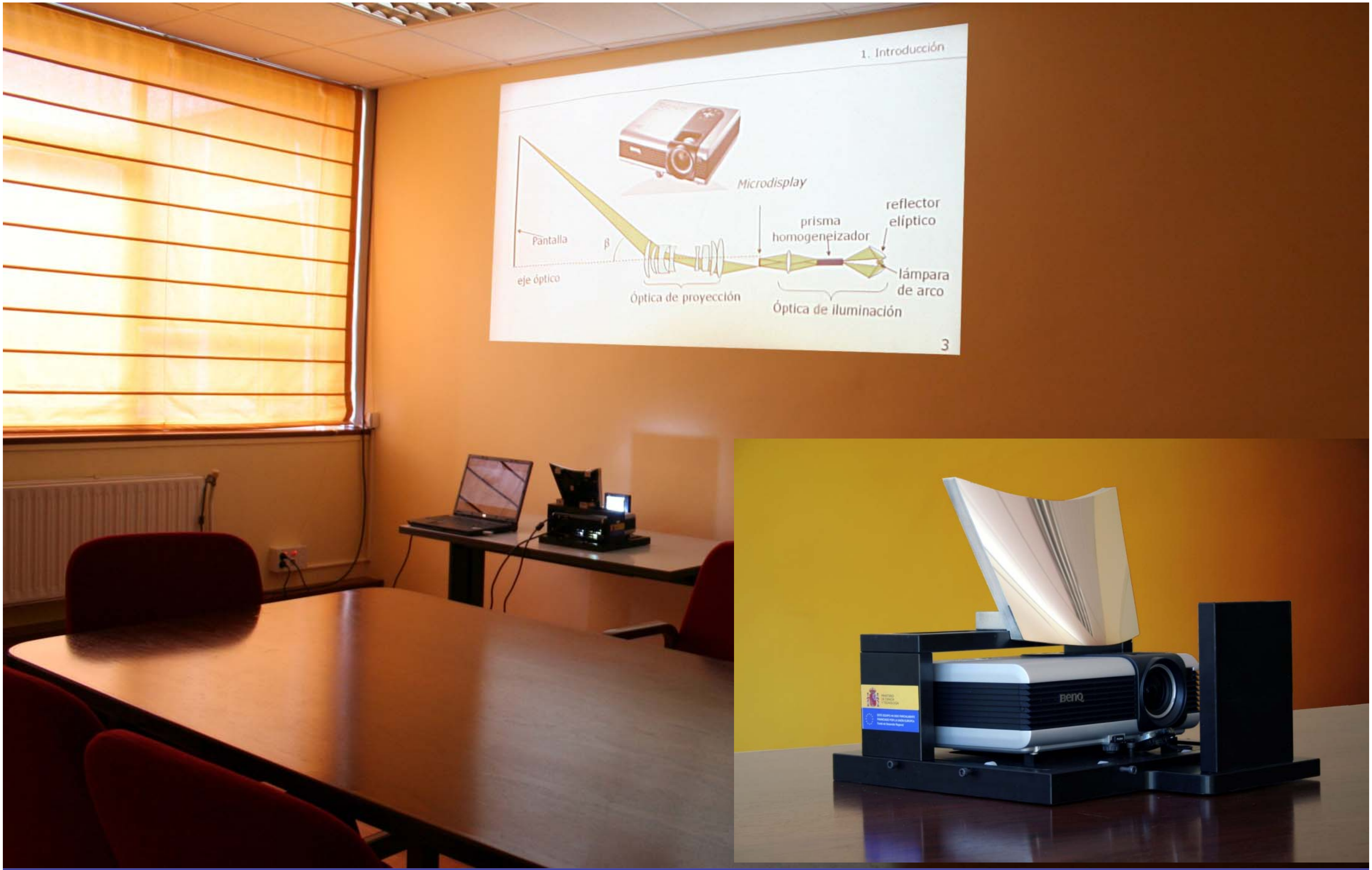
Imaging

- 2 freeform surfaces for asymmetric imaging
- Object discretization

RXI collimator



Free form RXI


1. Introducción
Microdisplay
reflector
elíptico
prisma
homogeneizador
Pantalla
β
eje óptico
lámpara
de arco
Óptica de proyección
Óptica de iluminación
3
BenQ

Conclusions

- SMS 3D is a free-form optical design method. As yet up to 2 surfaces/device have been designed. Following the same scheme as in SMS 2D, four or more free-form surfaces may be handled with this method
- As a nonimaging design tool:
  - it allows control of the size and rotation of the pinhole images of the source, which is critical for extended sources.
  - Efficiency – tolerance improvement.
  - Reflector combinations avoiding blockage
  - Compact designs
- As an imaging design tool:
  - Field contours can be better adapted to rectangles: Less optical surfaces
  - reflector combinations avoiding blockage
  - Compact designs

Geometric methods for design of freeform surfaces

Vladimir Oliker
Emory University, Atlanta
oliker@mathcs.emory.edu

Freeform Optics Incubator Meeting
Washington, DC
30 October – 1 November, 2011

Two basic approaches to design of freeform optics (See J. C. Miñano, P. Benítez, A. Santamaría, Opt. Review, 2009):

- **Numerical Optimization** of some Merit function(s). Numerous procedures exist; The design is usually a local optimum of the merit function
- **Direct methods;** require a correspondence (map) between prescribed input and output fronts
  - (a) Spherical wave fronts were considered already by R. Descartes;
  - (b) The SMS method, J. C. Miñano, P. Benítez et al.;
  - (c) Geometric methods ($\equiv$The Monge-Ampère equations), V.I. Oliker et al.

Philosophy of applying geometric methods to design of freeform mirrors/lenses:

1. Recognize special surfaces (i.e. quadric(s), Cartesian ovals,...) suitable for the problem (These usually solve the problem if one of the given intensities replaced by a sum of Dirac masses)

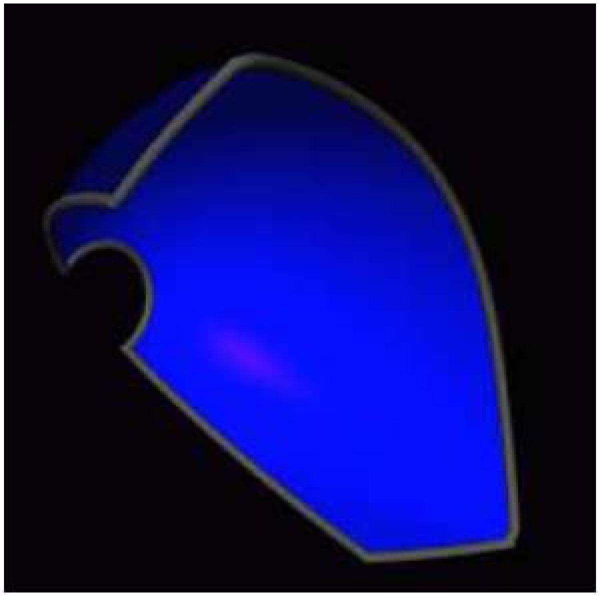
2. Describe the freeform mirrors/lenses as expressions for lower and upper envelopes of such special surfaces (This also defines convex/non-convex solutions, the admissible functions and often a very useful Fermat-like functional!)

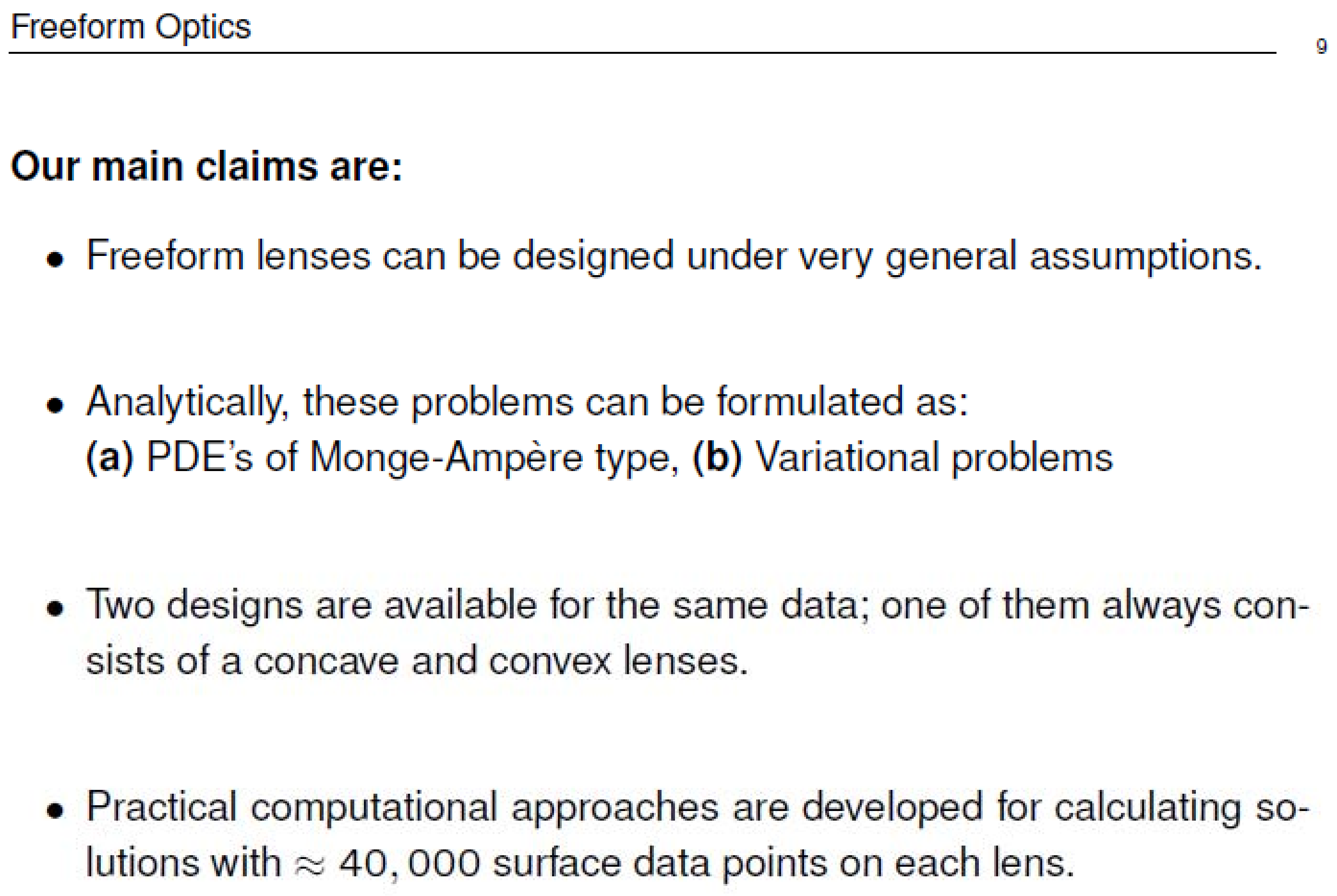
Philosophy of applying geometry to design of freeform mirror/lenses (cont-d):

3. (a) An iterative method based on a monotone variation of parameters defining special surfaces has been developed by V. Oliker et al.; This method is very general and intuitive and the procedure is guaranteed to converge to the true solution (a priori chosen by the user; may become slow when the number of special surfaces is large

3. (b) A new method was developed by V. Oliker et al. in recent years. It is based on specific rules for formulating a problem-dependent physically motivated Fermat-like functional to be optimized; the numerical scheme is guaranteed to converge to the true solution (a priori chosen by the user); it allows determination of tens of thousands of data points on each mirror/lens.

Test design 1. A freeform mirror. The mirror below transforms an intensity from a point source into a prescribed far-field distribution; the mirror was designed by V. Oliker; data for the design was supplied by J. C. Miñano, P. Benítez;





Our main claims are:

- Freeform lenses can be designed under very general assumptions.
- Analytically, these problems can be formulated as:
  (a) PDE's of Monge-Ampère type, **(b)** Variational problems
- Two designs are available for the same data; one of them always consists of a concave and convex lenses.
- Practical computational approaches are developed for calculating solutions with $\approx 40,000$ surface data points on each lens.

A starting point approach for non-imaging reflector design

Cristina Canavesi,[1] William J. Cassarly, PhD,[2]
and Prof. Jannick P. Rolland[1]

[1] *The Institute of Optics, University of Rochester*

[2] *Synopsys*

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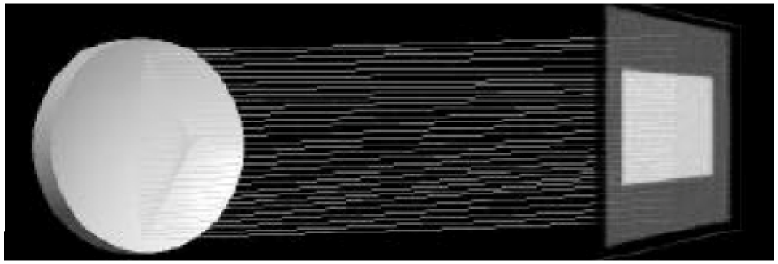
Some Reflector Design Methods

Numerical integration

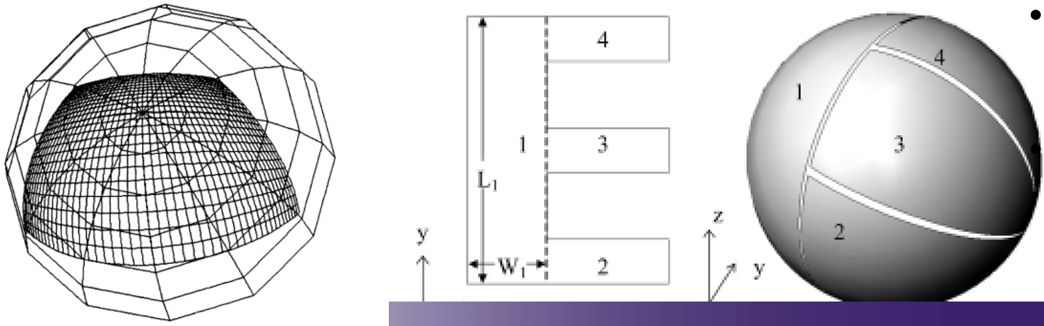
- Set up system of equations and solve numerically



- **H. Ries & J. Muschaweck, Tailored freeform optical surfaces, J. Opt. Soc. Am. A 19(3), 590-595, (2003)**
- **H. Ries, J. Muschaweck, & A. Timinger, "New methods of reflector design", OPN , 46-49 (2001)**

Variable separation mapping

- Subdivide problem in equi-flux regions and assign mapping. For unfaceted reflectors, can result in issues at the boundary.

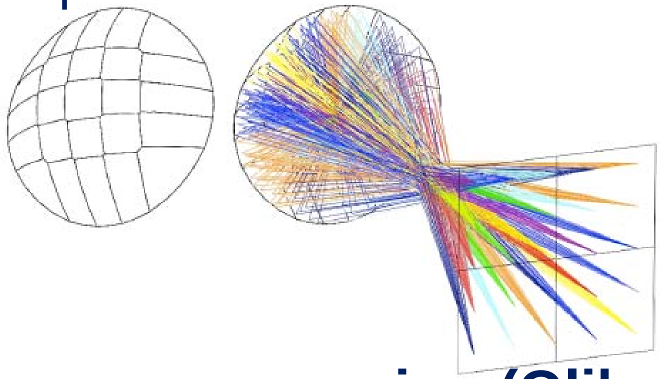


- **W. A. Parkyn, "Illumination lenses designed by extrinsic differential geometry",SPIE 3482, 389-396 (1998).**
- **L. Wang, K. Qian and Y. Luo, "Discontinuous free-form lens design for prescribed irradiance", Appl. Opt. 46(18) 3716-3723 (2007).**

Some Reflector Design Methods

Oliker supporting ellipsoids algorithm

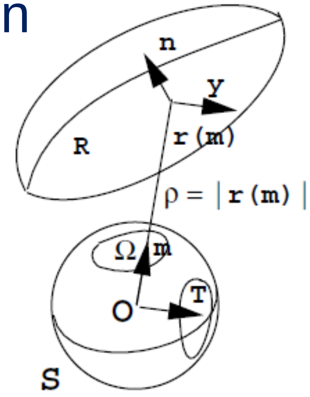
- Initially flux is all collected by one ellipsoid, then the ellipsoids are scaled iteratively to all receive rays



- V. I. Oliker, "Mathematical aspects of design of beam shaping surfaces in geometrical optics," Trends in Nonlinear Analysis, pp. 191–222 (2002)
- F. R. Fournier, W. J. Cassarly and J. P. Rolland, “Designing freeform reflectors for extended sources”, Proc. SPIE 7423, 742302 (2009)
- D. Michaelis, P. Schreiber, and A. Bräuer, “Cartesian oval representation of freeform optics in illumination systems,” Opt. Lett. 36, 918-920 (2011)

Linear programming (Oliker/Wang)

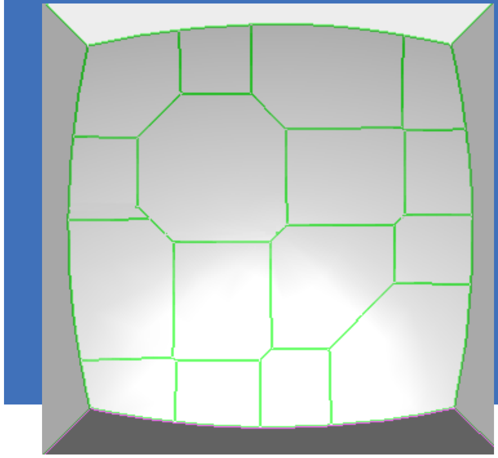
- Variational formulation



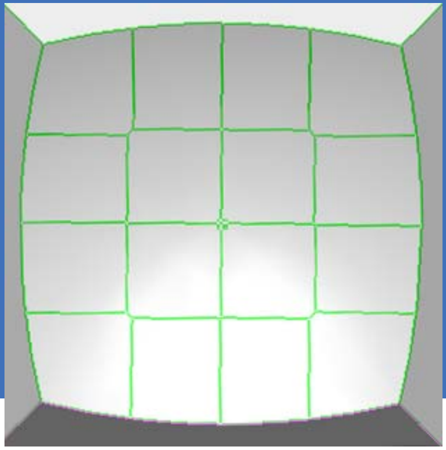
- T. Glimm and V. Oliker, “Optical design of single reflector systems and the Monge-Kantorovich mass transfer problem”, J. of Mathematical Sciences, 117(3), 4096-4108 (2003)
- Xu-Jia Wang, “On the design of a reflector antenna II,” Calc. Var. 20, 329–341 (2004)
- V. Oliker, “Geometric and variational methods in optical design of reflecting surfaces with prescribed irradiance properties”, Proc. SPIE 5942, 594207 (2005)

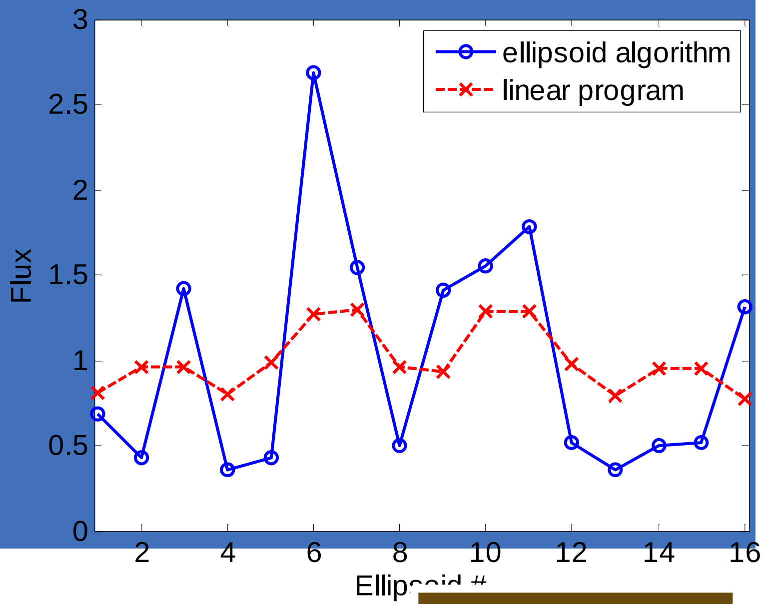
3D Example and Comparison with Supporting Ellipsoids Starting Point

Starting point from ellipsoid algorithm



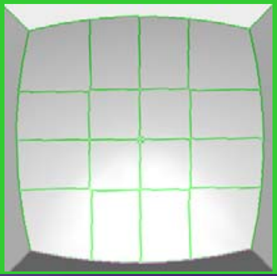
Starting point from linear program

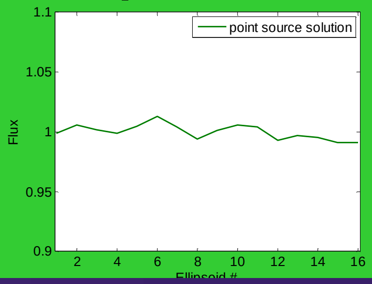


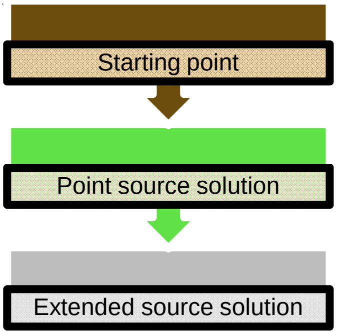


Source ± 45º
Target ± 6º

Optimized solution for point source







Starting point

Point source solution

Extended source solution

Conclusion

- The linear program finds a solution in which the rays represent intersections between paraboloids
- Running the linear programming method with a small or big number of rays per reflector yields the same focal parameters
- With a low number of rays per reflector, the linear programming starting point is better than the ellipsoids starting point (lower rms, lower peak-to-valley)

ODALab

Strengthen | Expand | Grow

40+ Years
of
Freeform Surfaces

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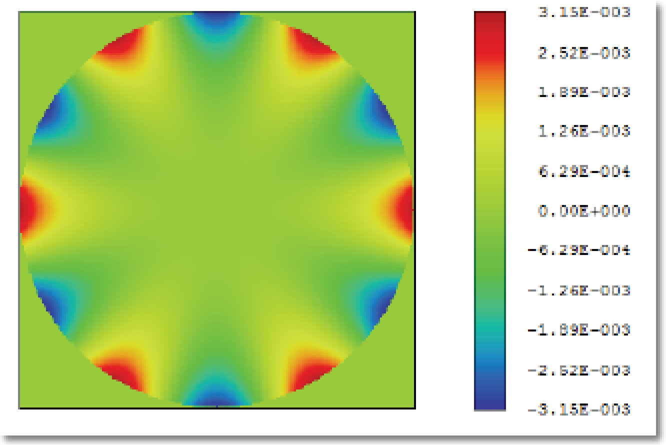
Bob Kestner
(bkestner@zygo.com)

ZYGO
Extreme Precision Optics
Richmond, CA

November 1, 2011

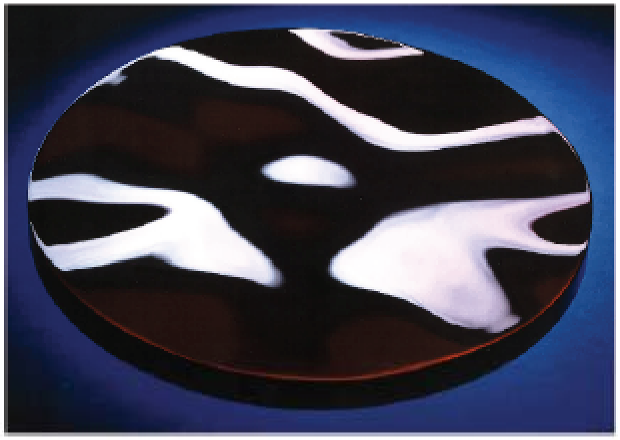
Freeform Surface Definition

- "Freeform Optical surfaces are defined as any non-rotationally symmetric surface or a symmetric surface that is rotated about any axis that is not its axis of symmetry."
    - **Design tools for freeform optics – Authors: K. Garrard; T.Bruegge; J. Hoffman; T. Dow; A. Sohn**
- Surface examples
    - Bi-cubic spline
    - Bi-variant polynomial
    - Aspheric cylinder
    - Toroid
    - Phase correctors
    - Zernike surfaces
    - Off-axis asphere
        - fabricated via freeform methods

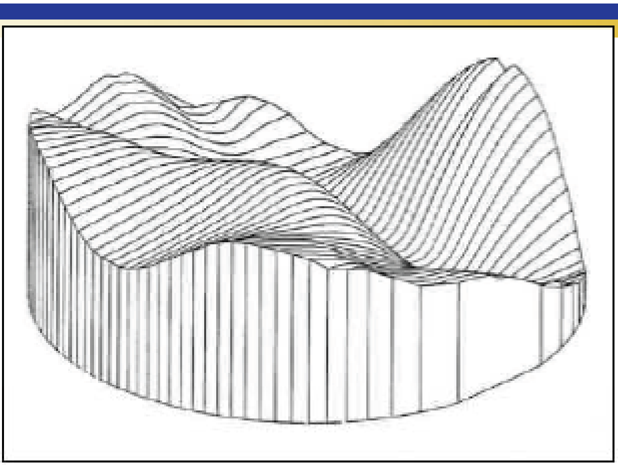


6-fold symmetry phase corrector
Courtesy of B. Catanzaro

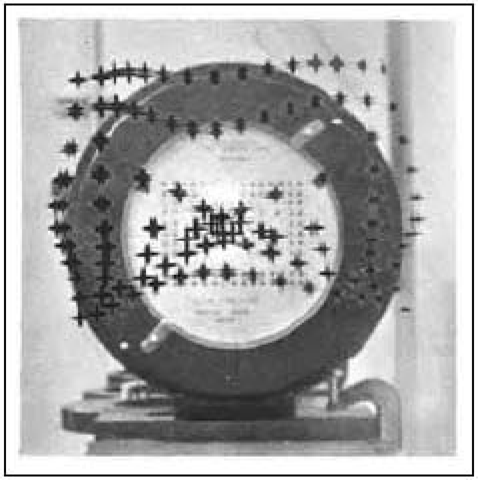
TV Phosphor Exposure Lenses



Typical TV lens profile – aspheric departure about 4mm



- TV lenses freeform aspheres were used to lithographically place phosphors on a color CRT tube face in the position where the electron beam (R,G,B) would land during use.
- Lenses were generally produced in small lots (6 to 12) for each color tube design
- TV lenses were manufactured at rates up to 40/week between 1967 and 2003

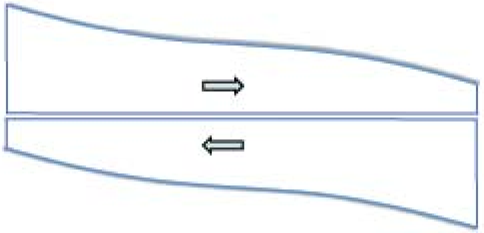


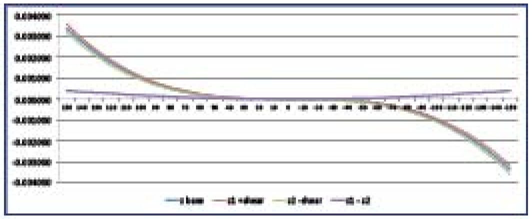
Hartmann test used to verify surface profile

Alvarez Lens Mold

- Manufactured for an automated vision analyzer
  - Cubic form of Alvarez lens produces variable power by translating two lenses rotated by 180°

Translation of rotated lens pair produces variable power

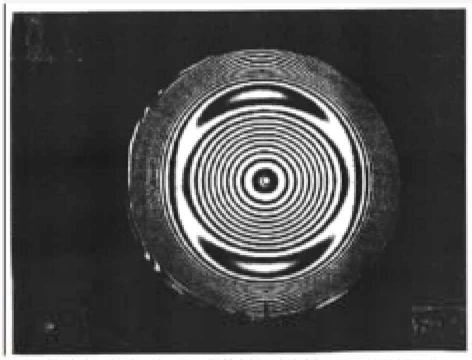




Hubble Space Telescope Optics

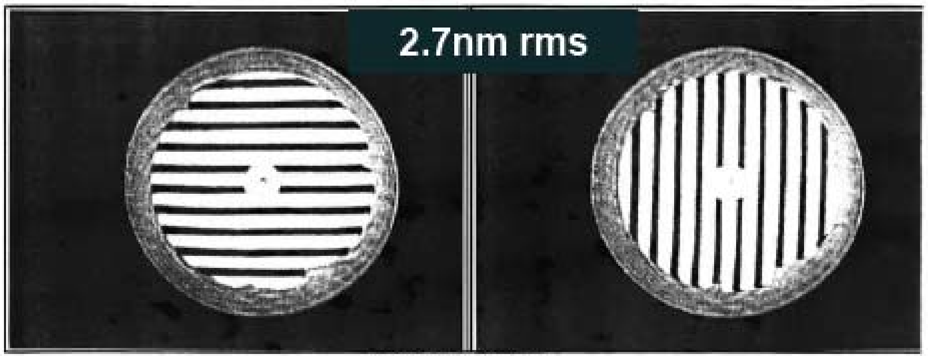
COSTAR
NICMOS
GHRS
COS
WFPC 2
STIS
ACS

Space Telescope Imaging Spectrograph (STIS) Corrector



Spherical test interferogram showing anamorphic shape

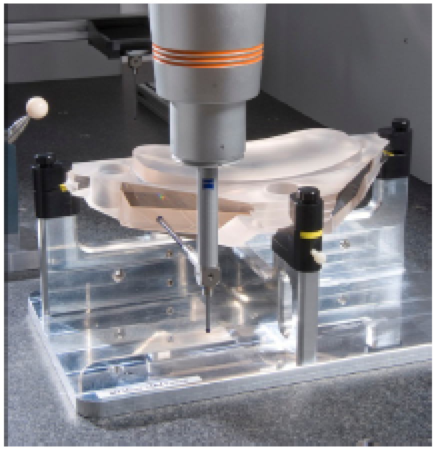
TEST RESULTS OF TEST #3 FINAL CGH TEST POST-GEOMETRY



INTERFEROGRAMS
Full surface aperture shown at best focus

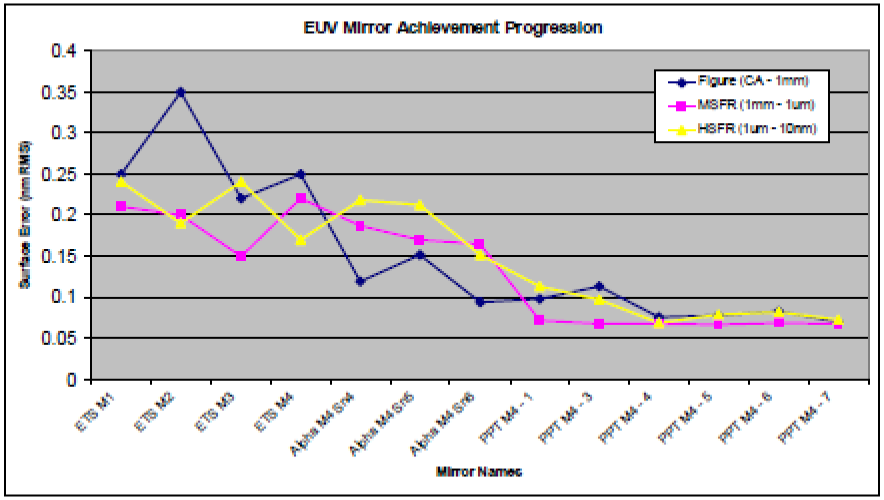
Deep Field ACS image

EUV Mirrors

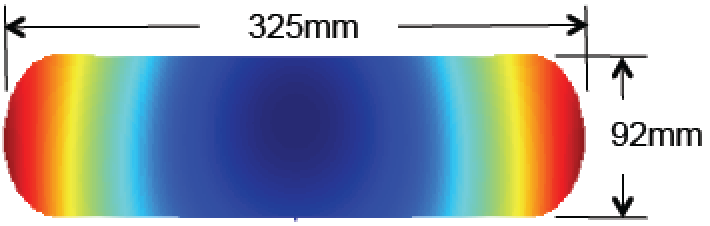


- **Zygo EPO has been supplying EUV optics to the semiconductor community since 1992**
- **Continued process improvement has resulted in 0.1nm rms results over a broad spatial spectrum from full aperture to 10nm**

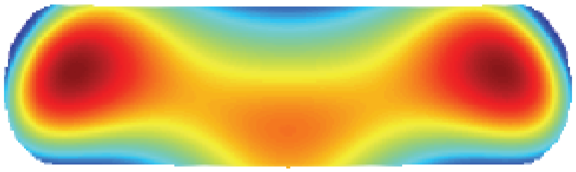
	Figure	MSFR*	HSFR*
Specification	<0.10nm rms	0.14nm rms	0.15nm rms
Results range	0.087–0.051	0.121–0.089	0.079–0.055



Lithographic Freeform Fold Mirror

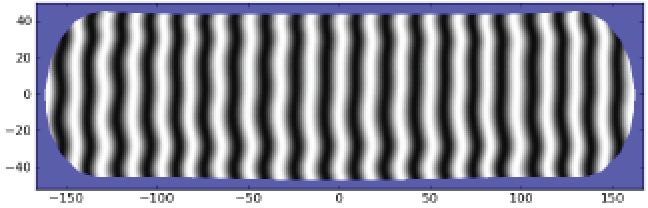


Total sagitta
37.8µm PV



Freeform component
3.6µm PV

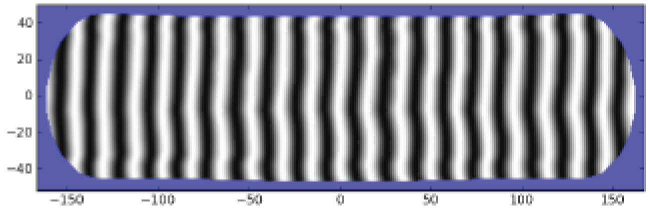
Optical & CMM metrology comparison



Optical test

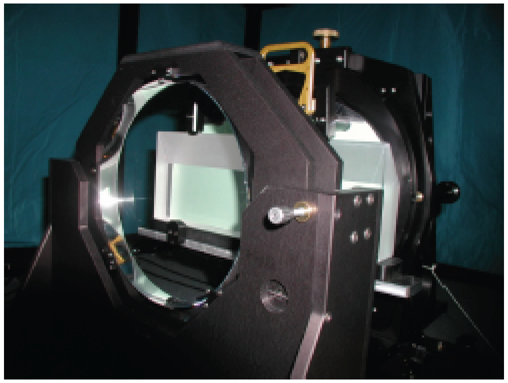
Test at completion 11.8nm RMS 82nm PV

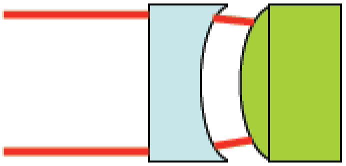
CMM measure alone well characterizes the freeform surface



CMM test
artificial fringes

0.25λ (158nm) PV requirement





3 position stitching test
using a software null

Summary

- Freeform surfaces have been manufactured for over 40 years using computer controlled fabrication methods
  - Today's processes can achieve nanometer precision

- Flexible and precise figure metrology methods are key
  - CGH interferometry
  - Stitching interferometry
  - Coordinate measuring machines
  - Metrology covering a broad spatial frequency range is required for the most demanding application
  - PSD evaluation

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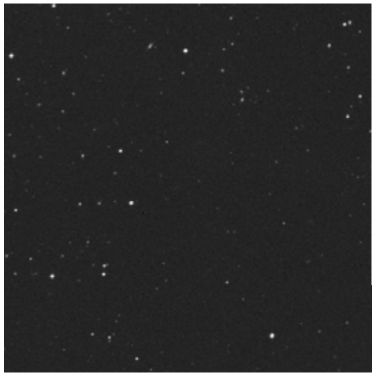
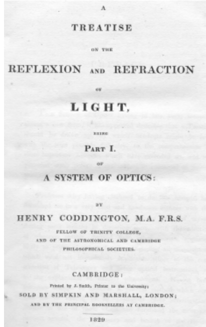
Predictable Success

Freeform Surfaces have Field Dependence Too





A
TREATISE
ON THE
REFLEXION AND REFRACTION
OF
LIGHT,
BEING
PART I.
OF
A SYSTEM OF OPTICS:
BY
HENRY CODDINGTON, M.A. F.R.S.
FELLOW OF TRINITY COLLEGE,
AND OF THE ASTRONOMICAL AND CAMBRIDGE
PHILOSOPHICAL SOCIETIES.

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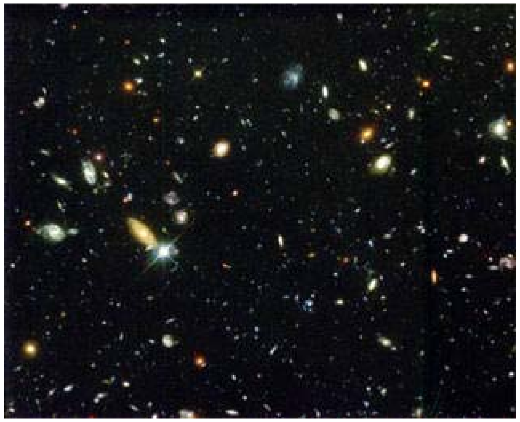
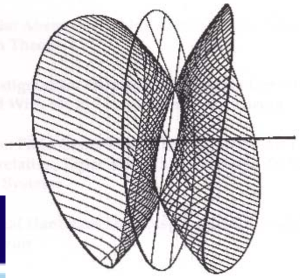
Kevin P. Thompson, PhD

Group Director, R&D/Optics, Synopsys, Inc.
Visiting Scientist, Institute of Optics, UofR





October, 2011

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*

Two flavors of Freeform surfaces

- Freeform Surfaces for Optical Design
  - **Comatic and/or Phi-Polynomial (Zernikes)**

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  - **Multi-centric Radial Basis Functions**

Freeform Optics Incubator

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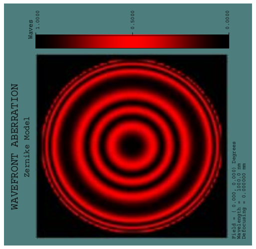
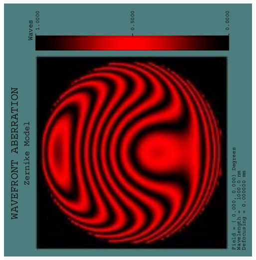
These are THE Aberrations (there are not any others)

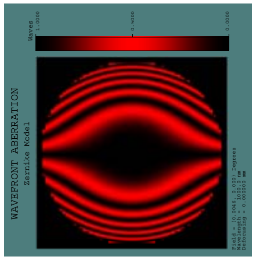
Z9

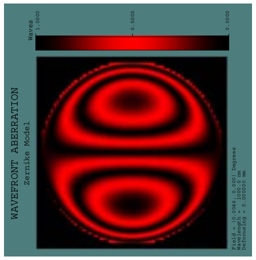




Spherical

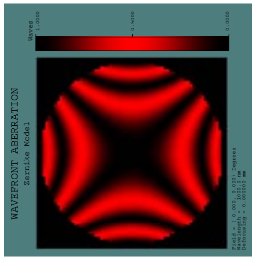
Z7/8

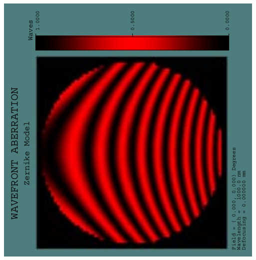




Coma

Z5/6

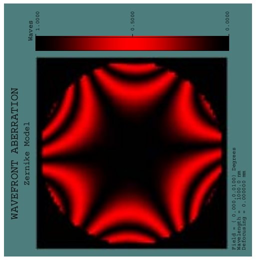




Astigmatism

Z10/11

FRINGE



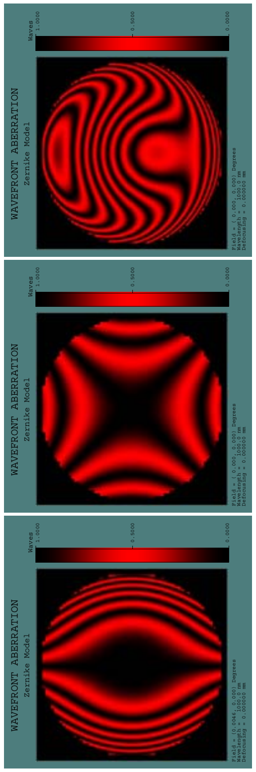
Elliptical Coma (Trefoil)

This is Important

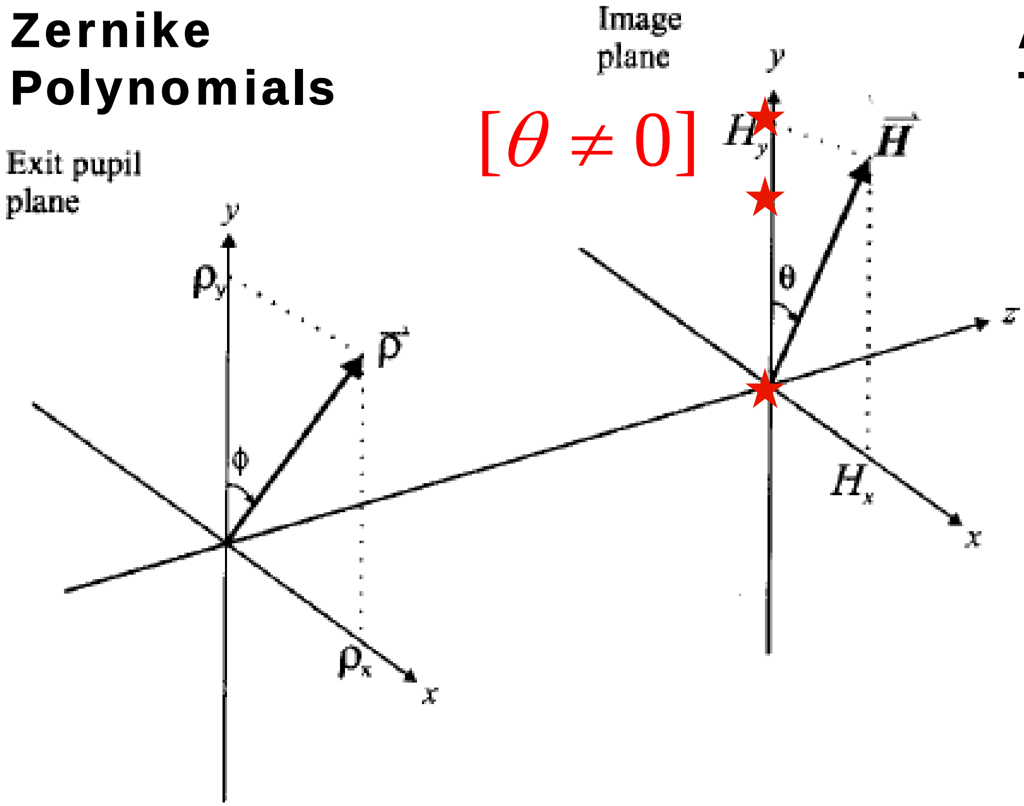
(generalizing for no symmetry)

A fundamental assumption has been that the "Y-axis" is aligned to the field point of interest – this has been a long standing impediment

Aperture

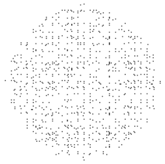


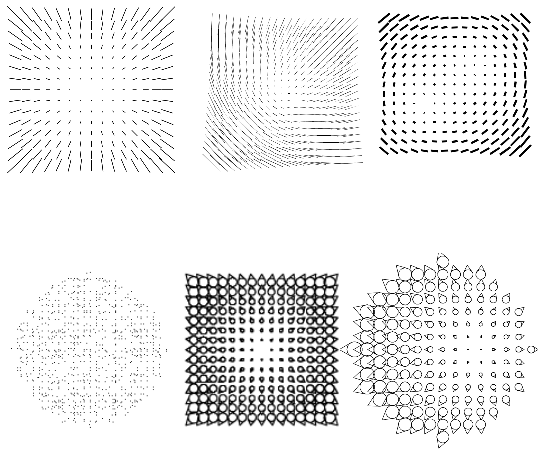
Zernike Polynomials



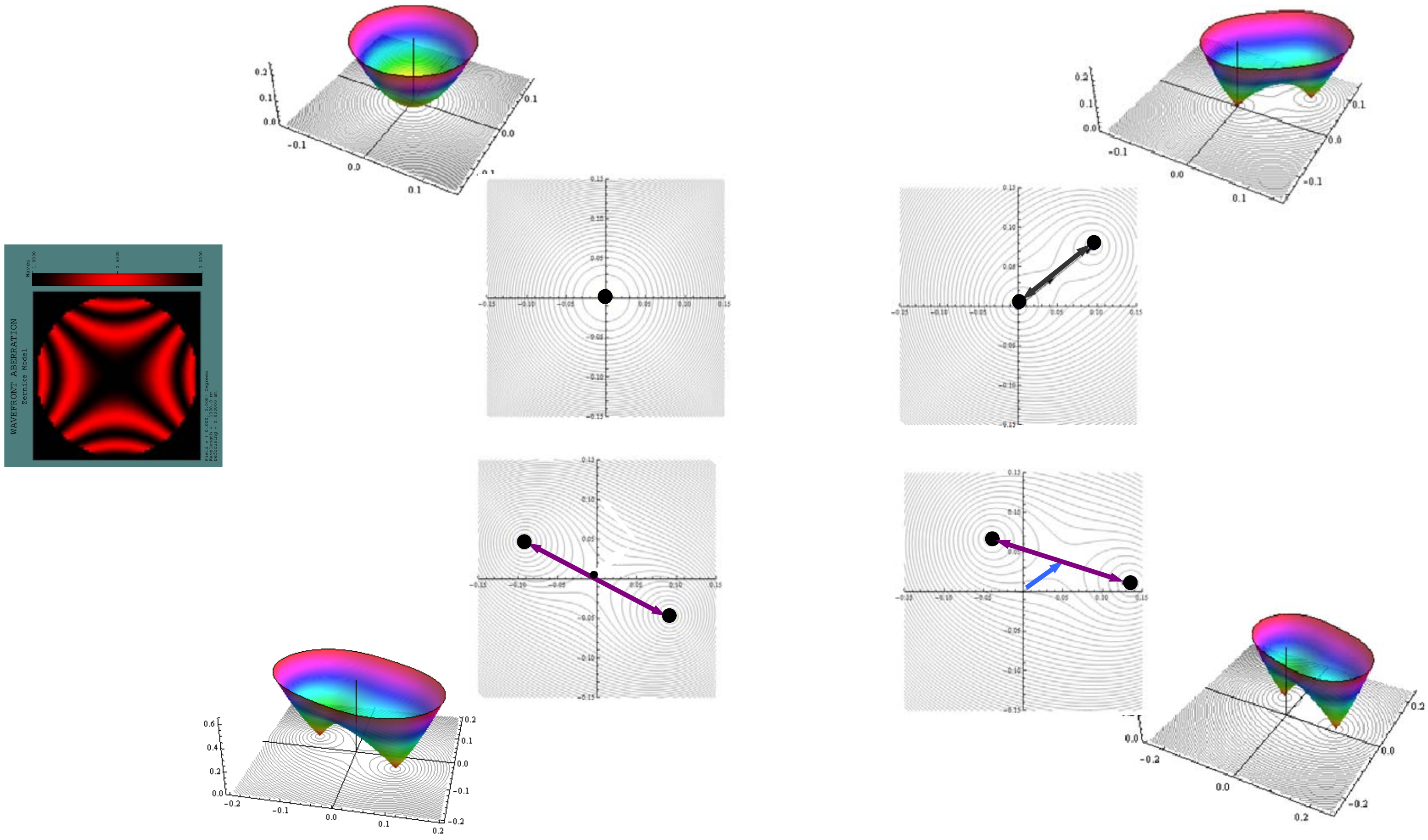
Field

Nodal Aberration Theory



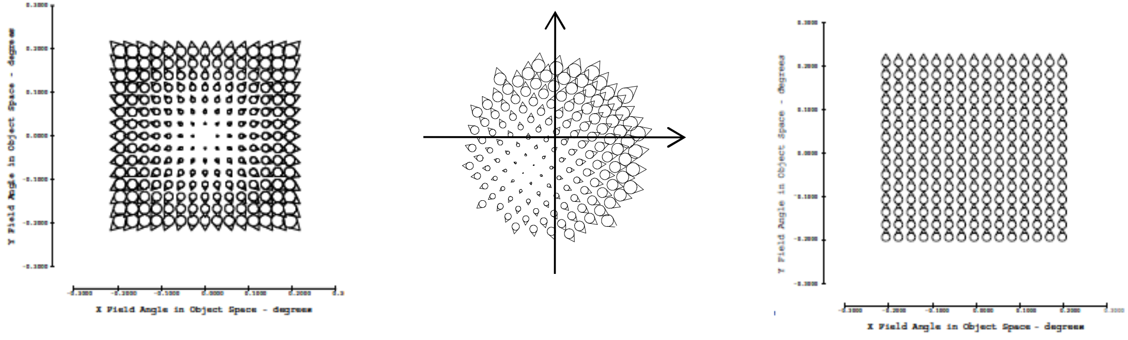


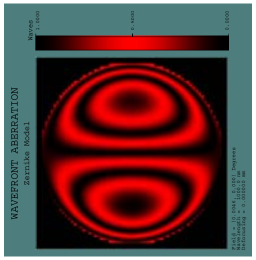
Freeform surfaces reveal the true nature of astigmatism



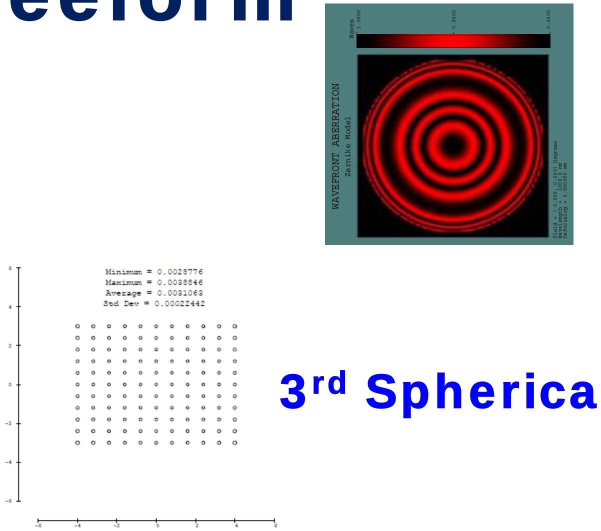
Schmid, T., J.P. Rolland, A. Rakish, and K.P. Thompson, "Separation of the effects of astigmatic figure error and misalignments using NAT", Optics Express 18(16), 17433-17447 (2010)

3rd Order Aberrations with Freeform

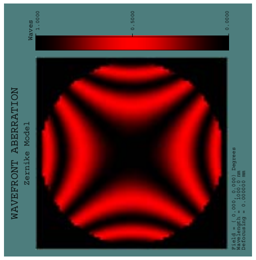


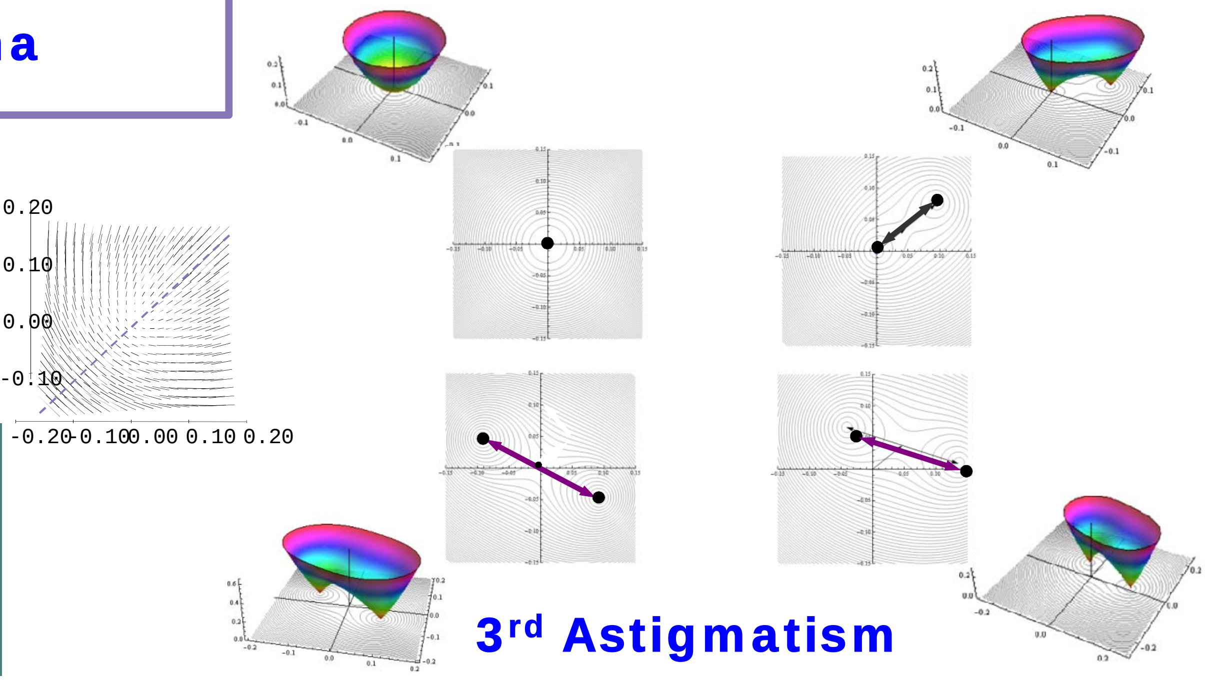


3rd Coma



3rd Spherical





3rd Astigmatism

Conclusions: Impact of “Freeform Surfaces” on Optical Design

- The addition of comatic surfaces to the suite is a dramatic advance for optical design
- The new design space is virtually unexplored and for unobscured mirror systems and intrinsically nonsymmetric designs (e.g. Head Worn Displays) the new opportunities are substantial
- Testing is the dominant impediment at this time

Two Freeform Mirror Designs with SMS 3D

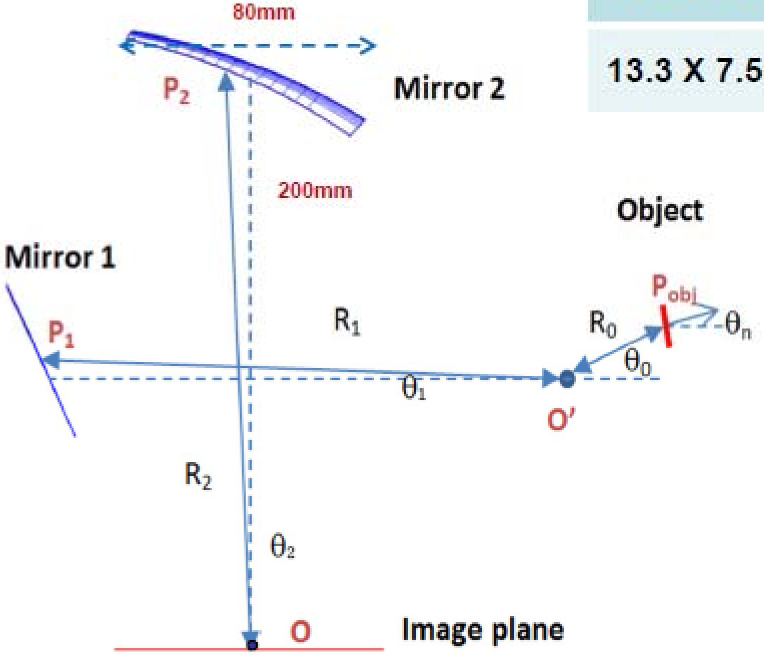
Wang Lin, Pablo Benítez, J.C.Miñano, Guillermo Biot

Universidad Politecnica de Madrid

OSA Freeform Optics Incubator Meeting
Washington, 31 October 2011

Design description

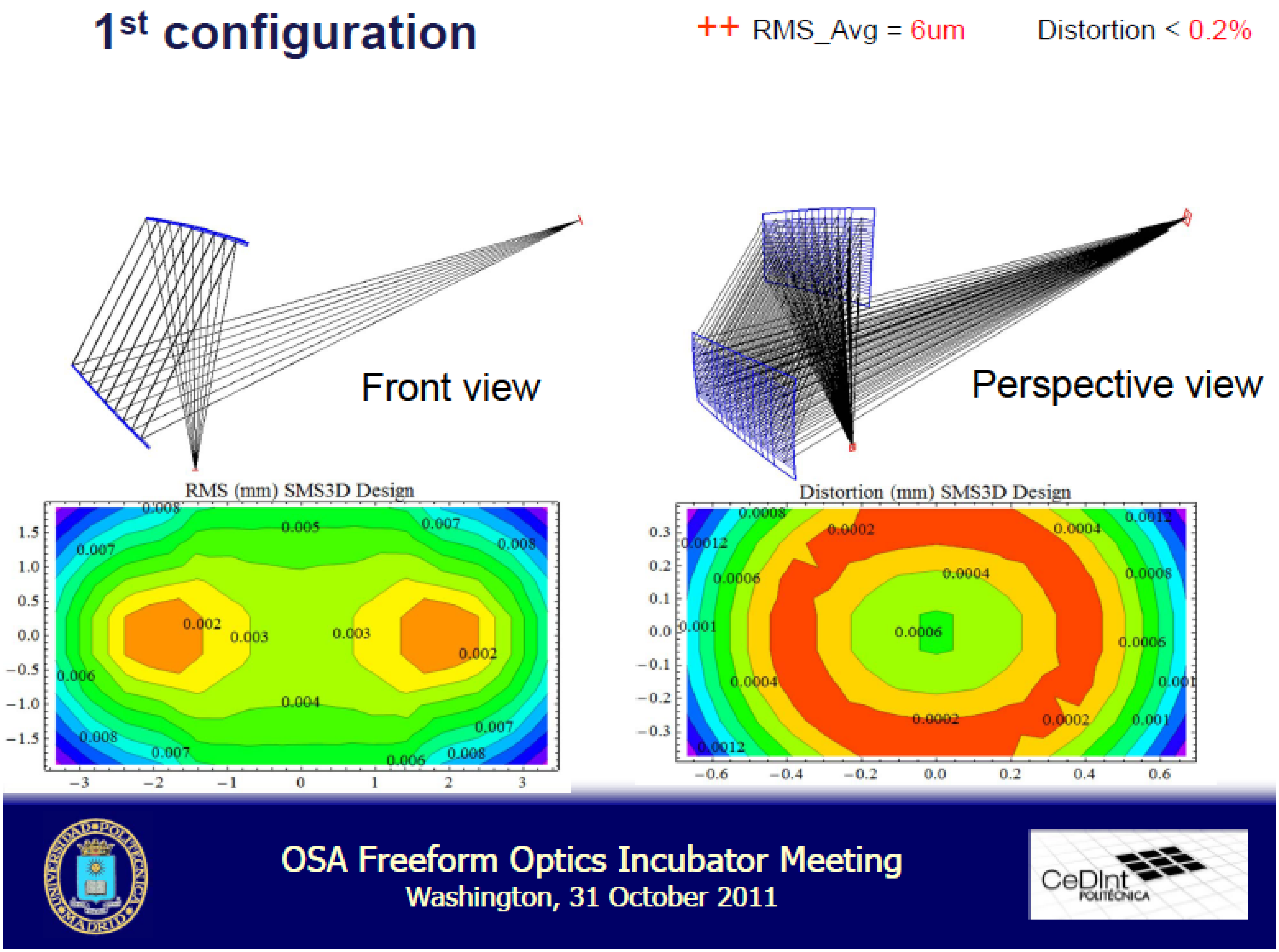
Object(16:9)	Image(16:9)	F#	Magnification
13.3 X 7.5mm	6.65 X 3.725mm	2.5	0.5



Design parameters

P_{obj} (R_0 θ_0 θ_n)	Free
P_1 (R_1 θ_1)	Free
P_2 (R_2 θ_2)	Fixed

One of two examples presented for configuration 1



1st configuration

++ RMS_Avg = 6um Distortion < 0.2%

Front view

Perspective view

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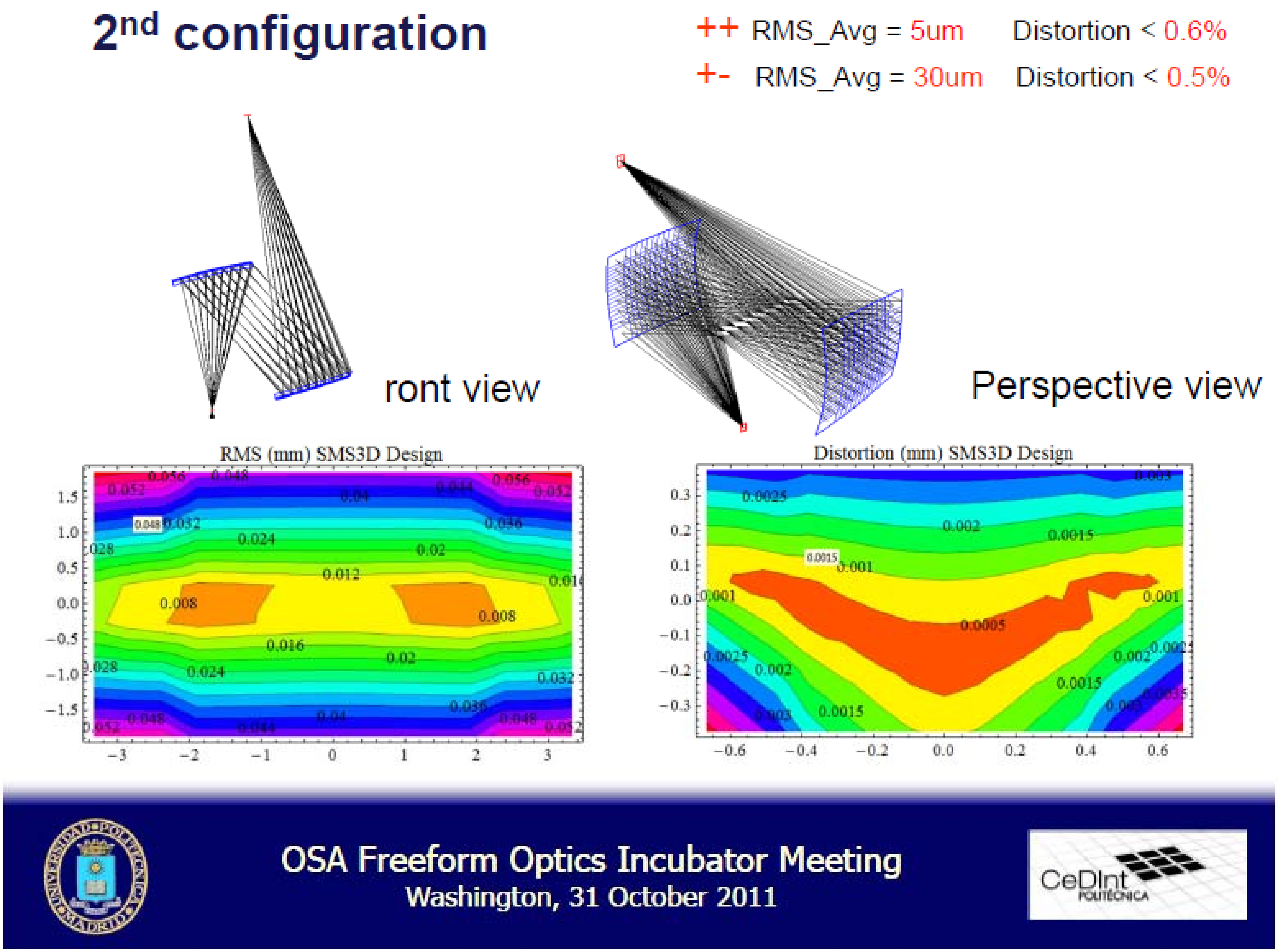
One of four examples presented for configuration 2



2nd configuration

++ RMS_Avg = 5um Distortion < 0.6%

+- RMS_Avg = 30um Distortion < 0.5%

ront view

Perspective view

RMS (mm) SMS3D Design

Distortion (mm) SMS3D Design

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Summary

- Optimization with SMS 3D method
- Exploration of 4 families of 2 configurations