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HAJIM
SCHOOL OF ENGINEERING & APPLIED SCIENCES
UNIVERSITY of ROCHESTER

Optiques FreeForm
feront elles parties de notre futur?

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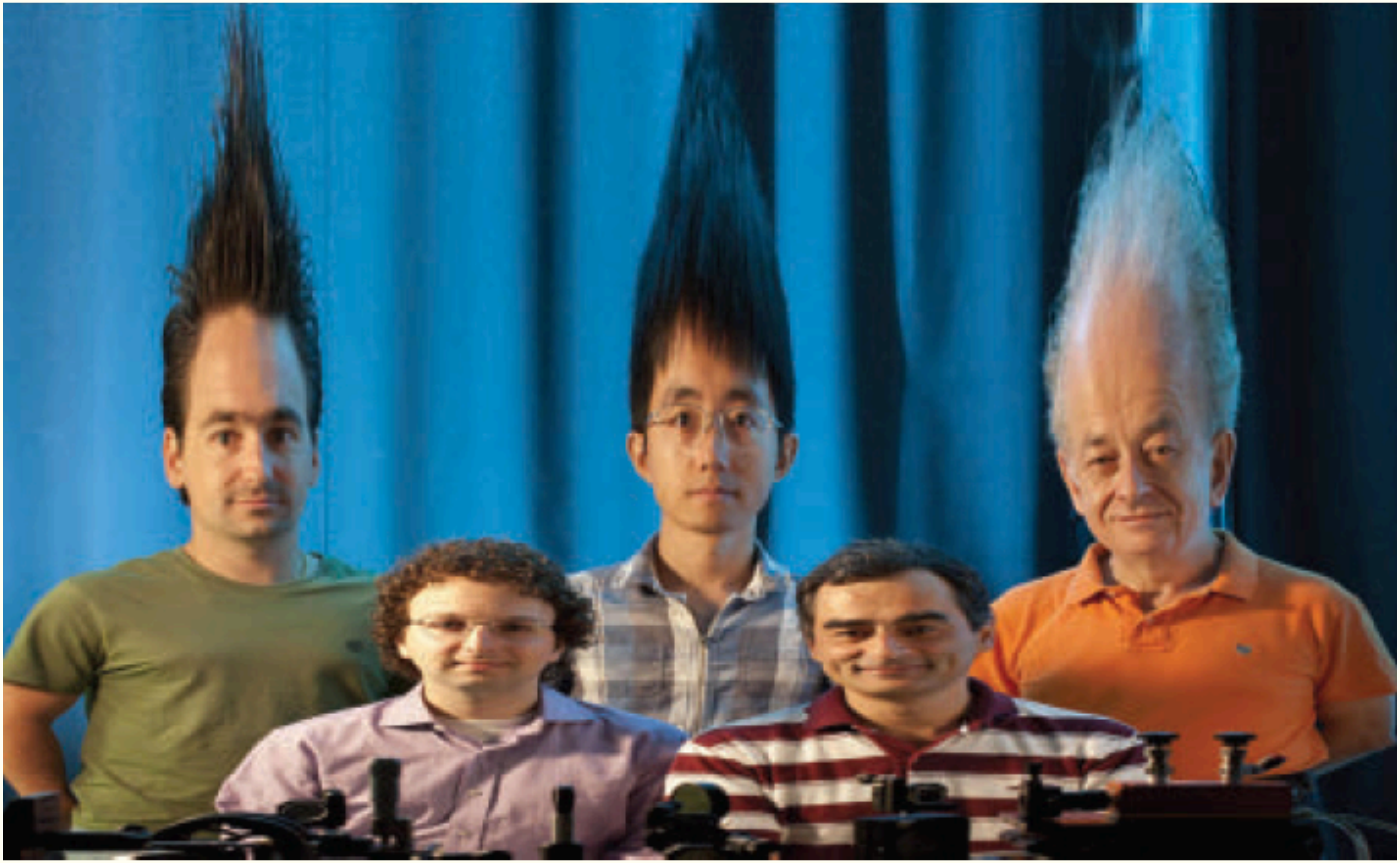
Freeform Optics Will Stretch Your Imagination



Matrix of interrelated research & industries that are involved in bringing state-of-the-art imaging systems to market

Emerging Technologies Enable New Shapes

	Spheres	Aspheres	XY-Poly	Off-Axis Conics	φ-Poly	RBF-FreeForm
Surface Shape	1890	1902*	1953	1980s	2000	Active
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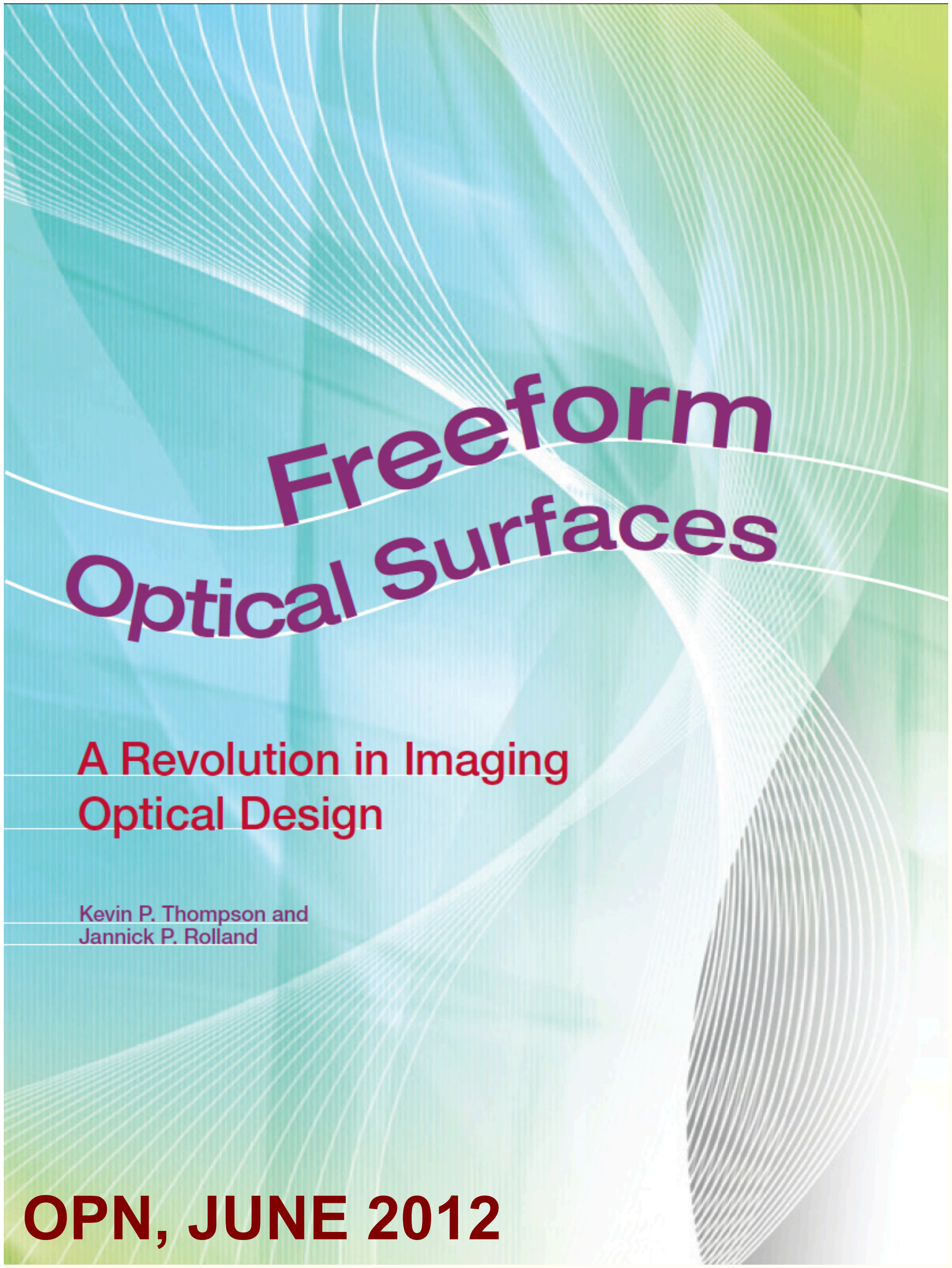
Discrete Industries

Large companies may contain all of the capabilities (e.g. SAGEM, THALES, SELEX, ZEISS).

In the commercial market, advanced research is evolving in companies that often specialize in only one cell – creating a challenge and an opportunity to better link these domains

2011 OSA Incubator Meeting on Freeform Optics



YOU CAN READ MORE ABOUT THE HISTORY OF FREEFORM OPTICS

Was written following

2011 OSA Incubator Meeting on Freeform Optics

At the OSA Headquarter in Washington DC
October 31- Nov 1st 2011

http://www.optics.arizona.edu/Colloquium/default.htm

First Signs of Freeform Optical Surfaces "XY"

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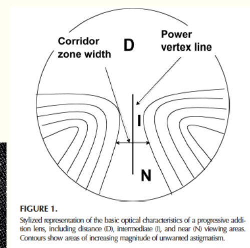
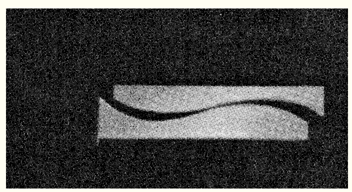
- **Progressive Lenses Design**

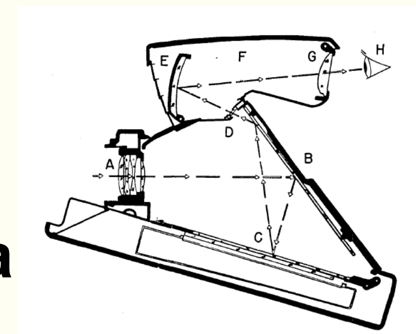


Maitenaz, 1953, French Patent 658,760
Area became active in the 90s with diamond turning of advanced molds

- **Alvarez Lens 70s**



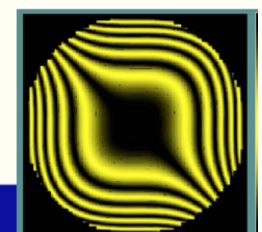
- **Polaroid SX70 Single Lens Reflex Camera**



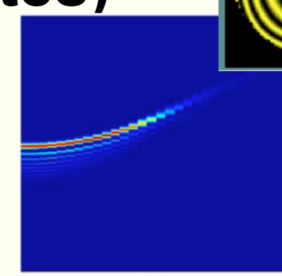
J. G. Baker, U.S. Patent 3,678,831 (1972).
W. T. Plummer, U.S. Patent 3,836,931 (1974).

in 1972 brought to the consumer market in the millions (ends 2005)

- **Computational imaging (Cubic Phase Plates)**
  Dowski & Cathey 95; Chi & George 01



- **Airy Beams Vo, ../Rolland, JOSA A 2011**



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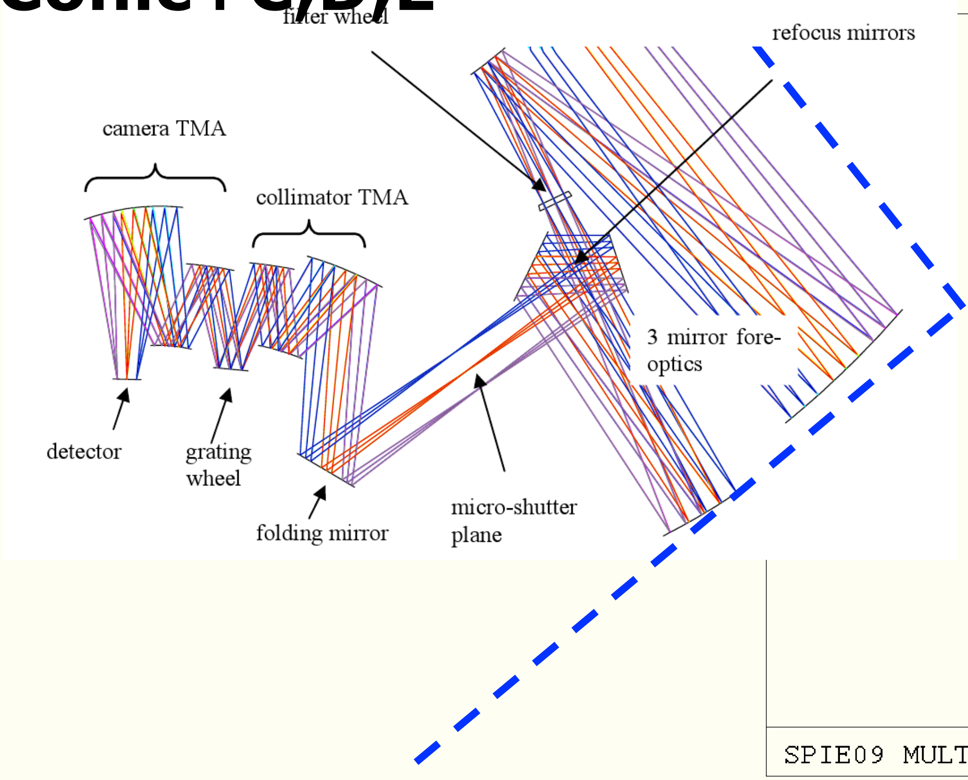
1980s - The advent of the Reagan's administration Star Wars program led to the first substantial work in **off-axis conic** optics (offset aperture) led by three mirror anastigmatic (TMA) designs by Lacy Cook/Hughes to reduce the straylight component in down-looking satellite optics. This initiated the race in the industry to develop everything needed to deliver these types of designs.

1990s – A first publication appears on the first TMA assembled by Figoski at Hughes Santa Barbara

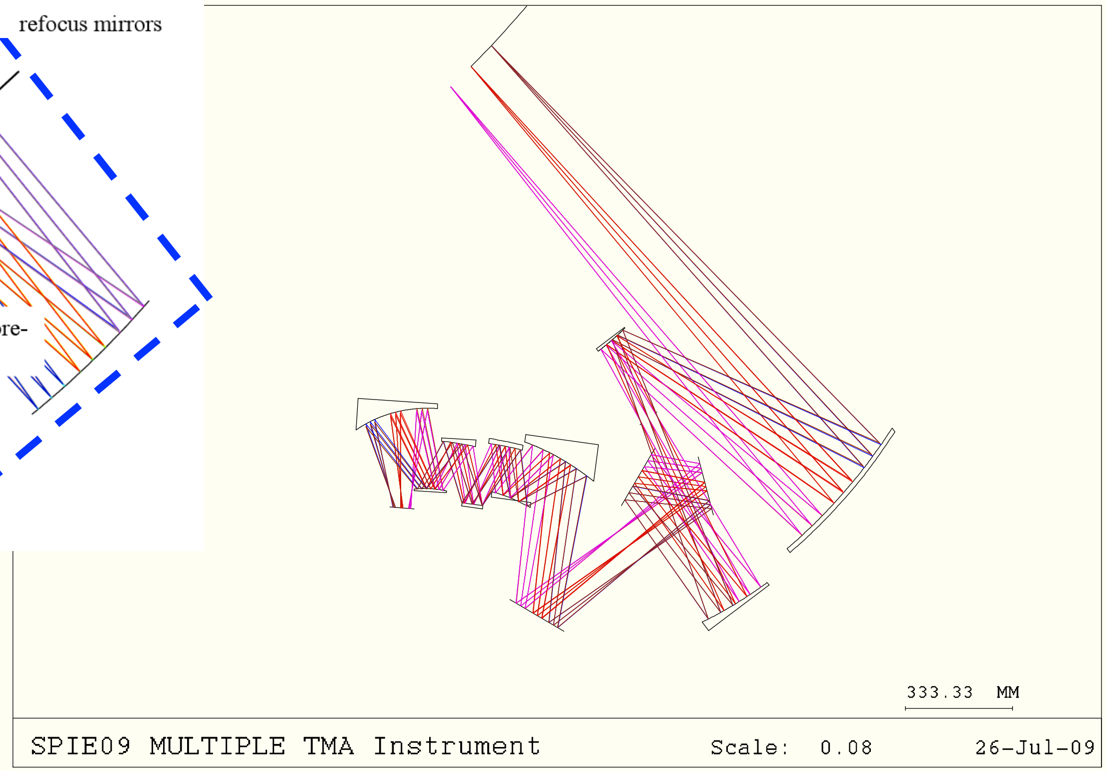
2010 SAGEM delivered multiple TMAs for the JWST (NIRSPEC)

In the last 20 years the assembly of TMAs has matured as presented recently by Roland Geyl* (Sagem) for the NIRSPEC

NIRSPEC Conic+C,D,E



An All-Conic NIRSPEC-like Example



Rolland et al. , "Using Nodal Aberration Theory to Understand the Aberration Fields of Multiple Unobscured TMA Telescopes", Proc. of the SPIE 7423 (2009).

*Roland Geyl, "JWST and NIRSPEC Optics polishing and integration", SPIE (2011)

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- Sphere
- Asphere
- Anamorphic Asphere
- x-y Polynomials - <u>early freeform surfaces used in systems</u>
- Off-axis conics

Let’s jump to the present …

To our surprise ….

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UNITED STATES PATENT OFFICE.

ERNST ABBE, OF JENA, GERMANY, ASSIGNOR TO THE FIRM OF CARL ZEISS, OF JENA, GERMANY.

LENS SYSTEM.

SPECIFICATION forming part of Letters Patent No. 697,959, dated April 22, 1902.

Application filed November 23, 1899. Serial No. 738,053. (No model.)

To all whom it may concern:

Be it known that I, ERNST ABBE, doctor of philosophy, a subject of the Grand Duke of Saxe-Weimar-Eisenach, residing at Jena, in the Grand Duchy of Saxe-Weimar-Eisenach, German Empire, have invented a new and useful Lens System, of which the following is a specification.

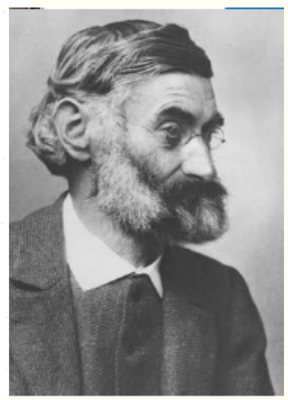
The invention relates to optical lens systems; and it consists in a means for more perfectly correcting such systems in cases where a strict union of rays is required not only in the axis, or, practically spoken, for a comparatively small field, but also beside the axis—that is to say, for image-points at a comparatively great distance from the axis—the latter correction of oblique rays comprising flattening of the image and removing of astigmatism, of distortion, and of coma produced by oblique pencils. To attain the said improved correction, spheroidal surfaces, either refracting or reflecting, are substituted for or combined with the ordinary spherical

tersect each other in or near the vertex of the spheroidal surface, (the lens-opening itself representing the pupil of entrance and the mounting of the lens the aperture-diaphragm,) so that all rays, central as well as oblique ones, pass through the same parts of the spheroidal surface, and in consequence thereof an oblique pencil issuing from an eccentric point of the object-surface cannot be otherwise modified by the said surface than the central pencil. On the contrary, by the present invention optical systems are improved in which—as, for instance, in eyepieces and in photographic objectives—the pupil of entrance or emergence (the place of the aperture-diaphragm) is situated at a less or greater distance from at least one of the lens-surfaces, so that the pencils issuing from lateral object-points traverse these surfaces at other parts than the pencil of the axial object-point.

The object of the invention is to derive advantage as to correction of oblique pencils

Patent No. 697,959, dated April 22, 1902.

99, Serial No. 738,053. (No model.)



Ernst Abbe (1840-1905)

If the values of the arc l do not exceed a certain limit, the deviation s may be represented with any desired approximation by the following function:

$$s = \tfrac{1}{4}\,k\,l^4 + \tfrac{1}{6}\,m\,l^6 + \tfrac{1}{8}\,n\,l^8 + \ldots,$$

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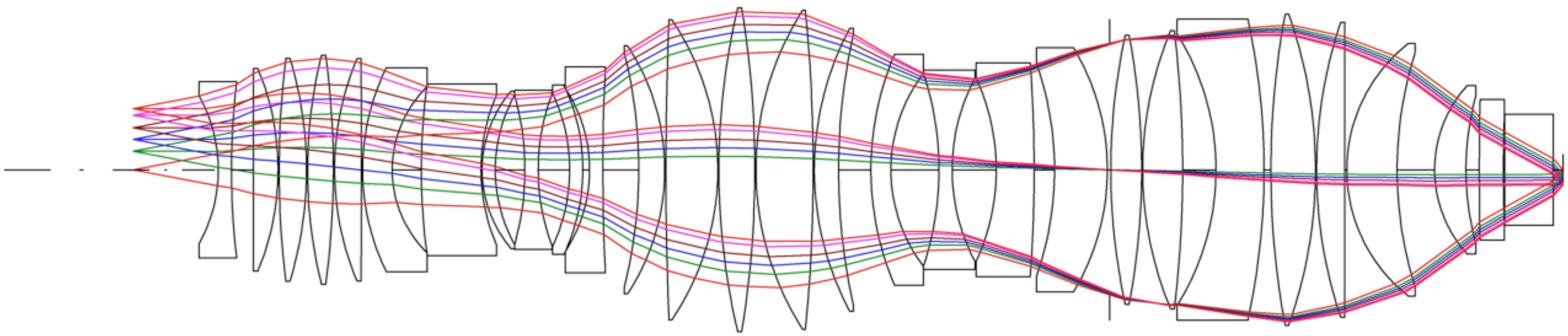
* Recently (2006) it has been demonstrated that power series aspheres are mathematically unstable and Dr. Forbes/QED has proposed a new surface formulation that avoids these instabilities



Bin Ma (**Opt. Exp. 19(22) 2011**) has shown that Q-type aspheric surfaces that are optimized with slope constraints are not only more testable, <u>an original motivation</u>, but, they can also lead to solutions that are less sensitive to assembly induced misalignments for lithographic quality lenses.

The Q-type (Q_{BFS}) aspheric description of the departure of a surface from spherical

- Based on a form of Jacobi polynomials (i.e. orthogonal set) thus avoids the numerical problems encountered with a power series description
- Importantly, the Q-type (Q_{BFS}) allow computing the RMS slope of a surface during optimization as the sum of the Q-type aspheric' coefficients squared.

$$z(\rho) = c_{\mathrm{bfs}}\,\rho^2 \Big/ \left(1+\sqrt{1-c_{\mathrm{bfs}}^2\rho^2}\right) + D_{\mathrm{bfs}}(\rho/\rho_{\max}),$$

$$D_{\mathrm{bfs}}(u) \coloneqq \frac{u^2(1-u^2)}{\sqrt{1-c_{\mathrm{bfs}}^2\rho_{\max}^2\,u^2}} \sum_{m=0}^{M} a_m\, Q_m^{\mathrm{bfs}}(u^2).$$

G. W. Forbes, "Shape specification for axially symmetric optical surfaces," Opt. Express **15**, 5218-5226 (2007).

G. W. Forbes, "Robust, efficient computational methods for axially symmetric optical aspheres," Opt. Express **18**, 19700-19712 (2010).

TILT
BTX,
BTY)

DEC
DSX,
DSY

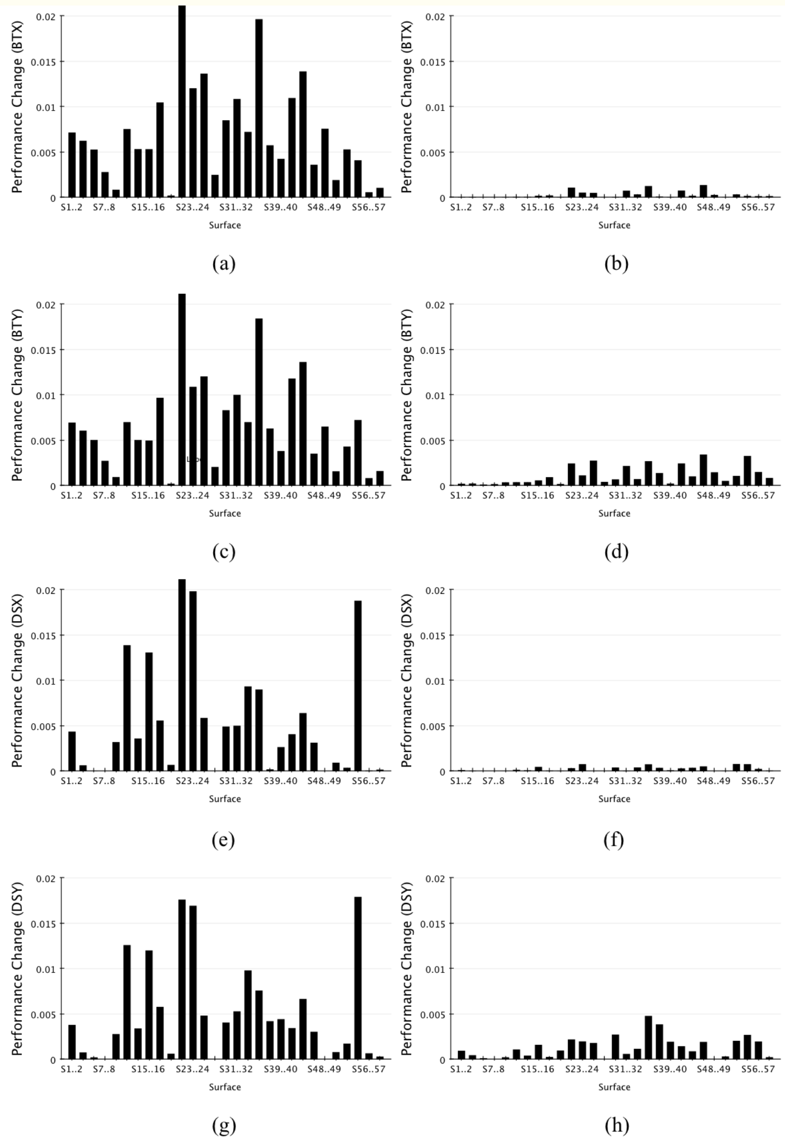
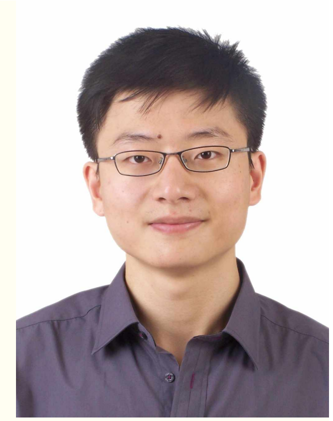
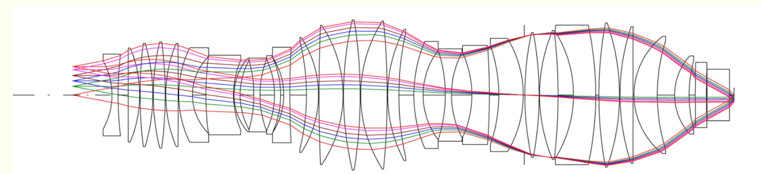


Fig. 2. Changes of RMS wavefront for each tolerance terms. (a-b) Barrel Beta Tilt (BTX 0.01 mrad). (c-d) Barrel Alpha Tilt (BTY 0. 01 mrad). (e-f) Element X-decenter (DSX 2 µm). (g-h) Element Y-decenter (DSY 2 µm). Two columns show the worst field for Q-type without slope constraints and Q-type with slope constraints, respectively.



For a representative NA 0.75 lens



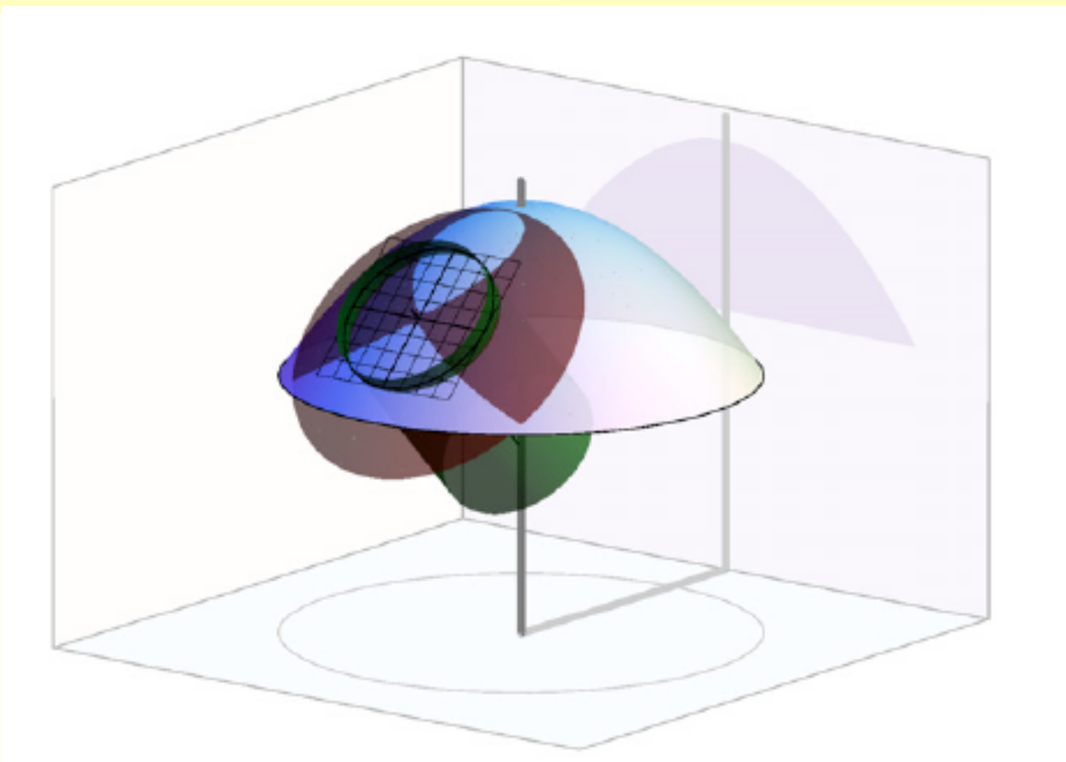
The sensitivity to tilt and decenter is reduced by more than 3X

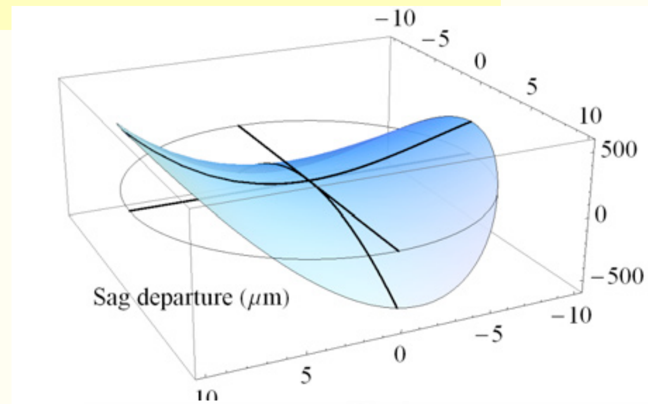
Bin Ma et al
Optics Express 19(22) (2011)

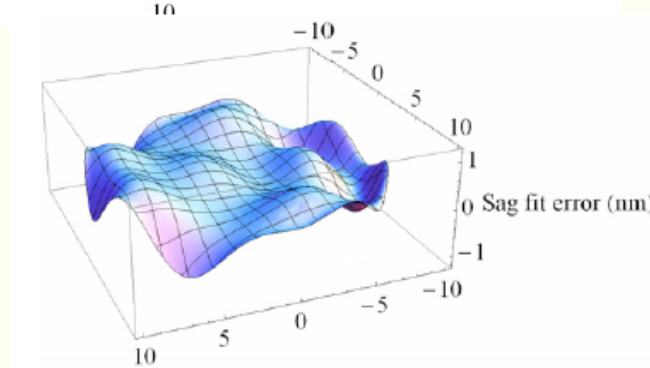
Forbes Extension to 2D

Forbes, Opt. Exp. 20(3) (2012)

$$f(\rho,\theta) = \frac{c\,\rho^2}{1+\sqrt{1-c^2\rho^2}} + \frac{1}{\sqrt{1-c^2\rho^2}}\left\{u^2(1-u^2)\sum_{n=0}^{N} a_n^0\, Q_n^0(u^2) + \sum_{m=1}^{M} u^m \sum_{n=0}^{N}\left[a_n^m \cos(m\,\theta) + b_n^m \sin(m\,\theta)\right] Q_n^m(u^2)\right\}$$







Zhao and Burge Opt. Exp. 15(26) (2007)

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Note: Aspheric surfaces only consider the *ρ* dependence

A **φ-polynomial surface** takes the form: $z = F(\rho, \varphi)$

the **sag, *z***, is represented by a function that depends on
the **radial component, *ρ***, and
the **azimuthal component, φ**

e.g. Zernike Polynomial surface

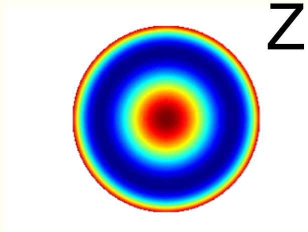
$$z = \frac{c\rho^2}{1+\sqrt{1-(1+k)c^2 p^2}} + \sum_{j=1}^{16} C_j Z_j$$

2007, slow servo is introduced to diamond turning to allow these surfaces to be fabricated, triggering activities in other industries

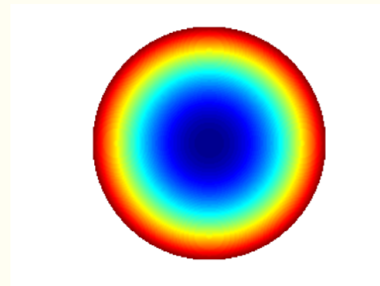
The evolution to φ-polynomials I

Spherical Base

Centered conic/asphere

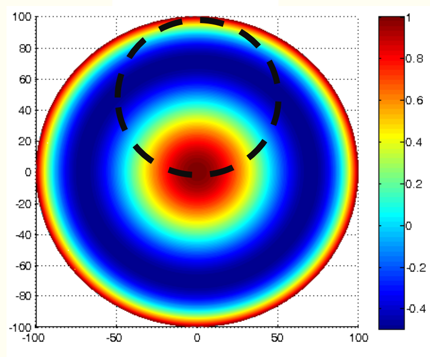


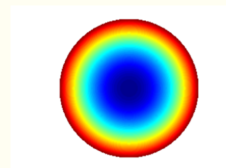
Z9



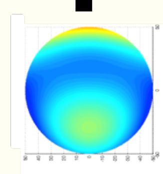
Spherical Base

Off-Center conic/asphere

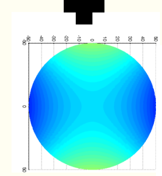




Z9 contribution



Z7/Z8 contribution



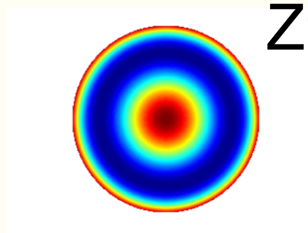
Z5/Z6 contribution

There is a fixed relationship between the terms

The evolution to φ-polynomials II

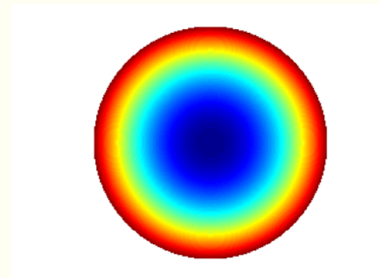
Traditional radial polynomial

+



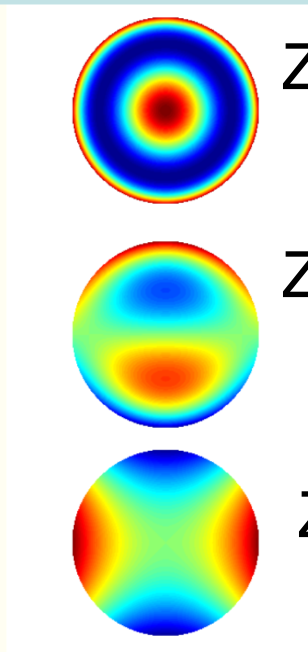
Z9

=



Base sphere/conic

+



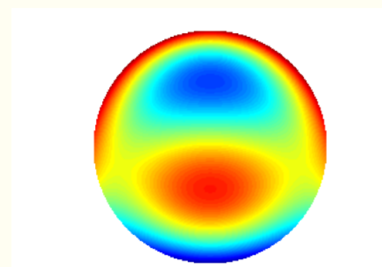
Z9

Z7/8

Z5/6

=

φ polynomial



There is a variable relationship between the terms

Aberration Fields of φ-Polynomial Surfaces

- 2012 – Kyle Fuerschbach has discovered and is establishing the direct link between φ-Polynomial Surfaces (e.g Zernike) and Nodal Aberration Theory (**To appear in Opt. Express and JOSA A**)

- This work is part of a path that has led to the optical design of the first fully rotationally nonsymmetric that is diffraction-limited at 1 micron

Fuerschbach, Thompson, Rolland "A new family of optical systems employing φ-polynomial surfaces," Opt. Express 19(22) (2011)