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 3 of 3
Day 2, Morning

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 2
Morning Session

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**
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11:35 **Augmented Reality Displays a Playground for Freeform Surfaces**
Jannick Rolland, *University of Rochester, USA*

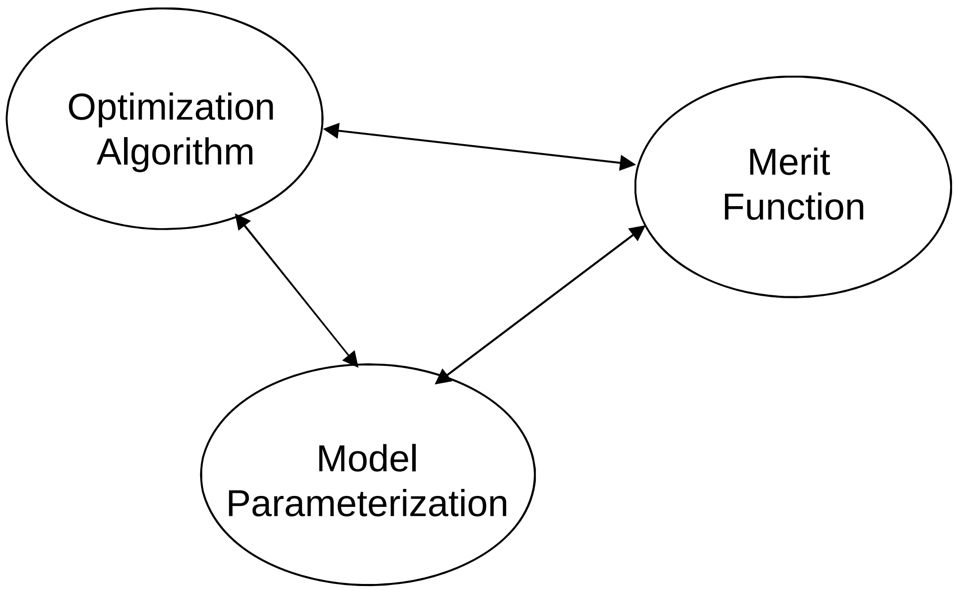
The Art of Tailoring Freeform Surfaces for Illumination
Part 2 – The State of the Art

Freeform Incubator
Nov. 1, 2011

Dr. Bill Cassarly
Optical Research Associates
williamc@synopsys.com
www.opticalres.com

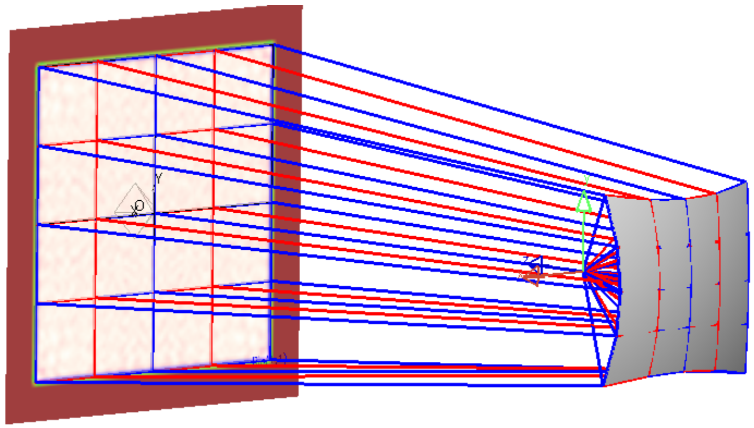
Optimization

- 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



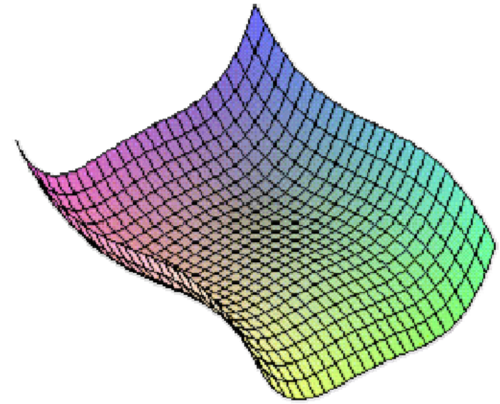
User Interface ties these elements together

Surface Parameterization

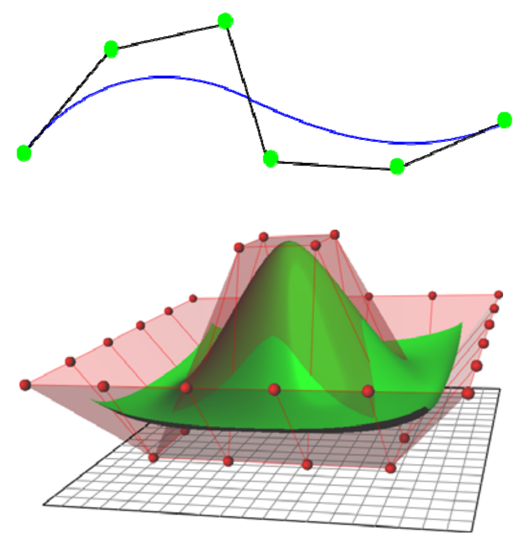


- Surfaces can be described using Equation:
  - e.g., XYPolynomial, Zernike, Asphere, etc
- Tailoring and SMS:
  - Compute prescribed surface(s) by numerical integration.
    - Often based upon a source to output mapping
    - Surface commonly represented using NURBS
- Equation that best fits NURBS sometimes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

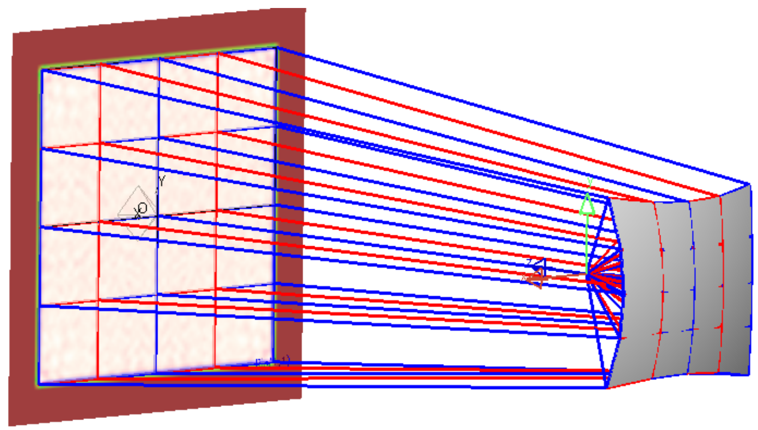
XY polynomial



NURBS curve and NURBS surface



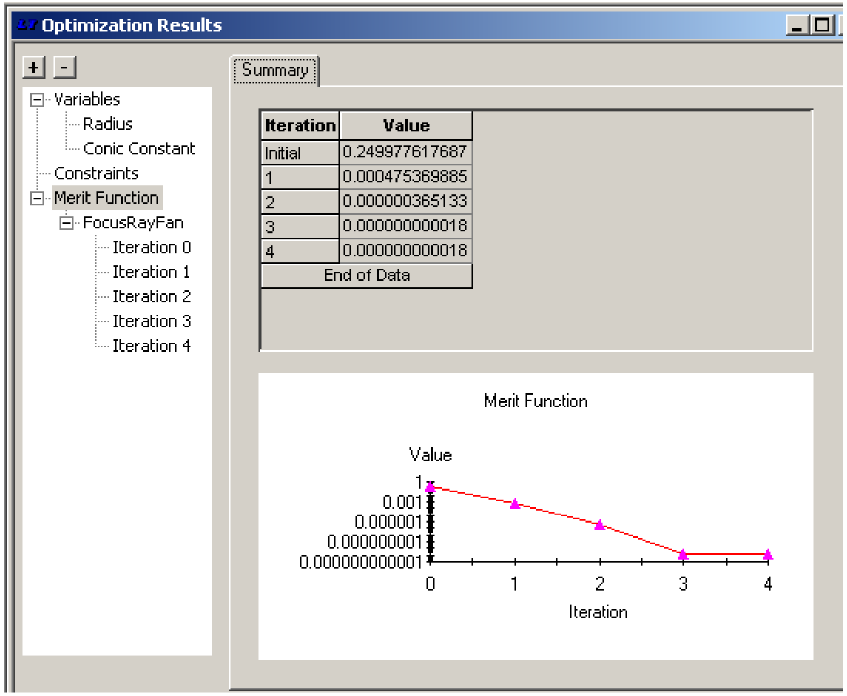
Optimization Variables



- 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.



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

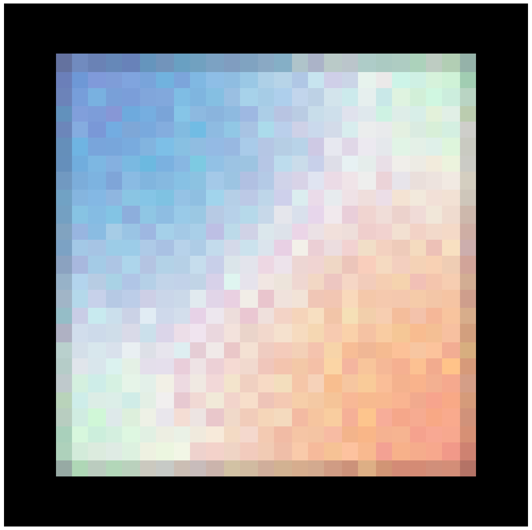
W_i = Weight of i^{th} MF item in Group g

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

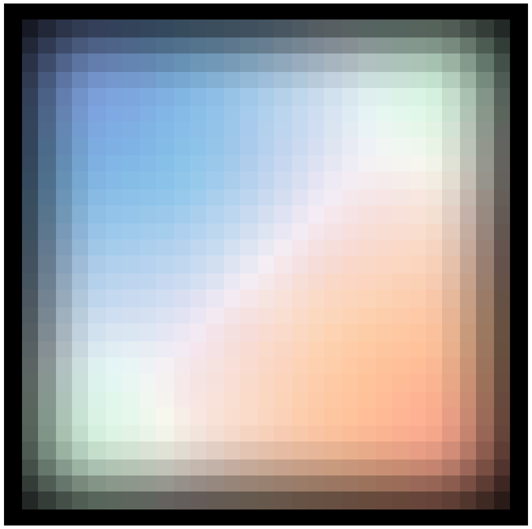
T_i = Target of i^{th} MF item

Color Smoothing, Mixing Rod example

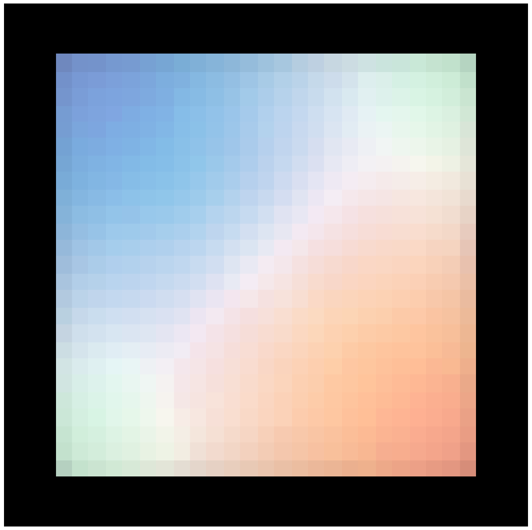
- Illumination simulation often need accurate color estimates
- Special smoothing algorithms can be used to preserve edges
  - Smoothing not performed over edge boundaries
  - ~1000 Rays per bin



Without Smoothing



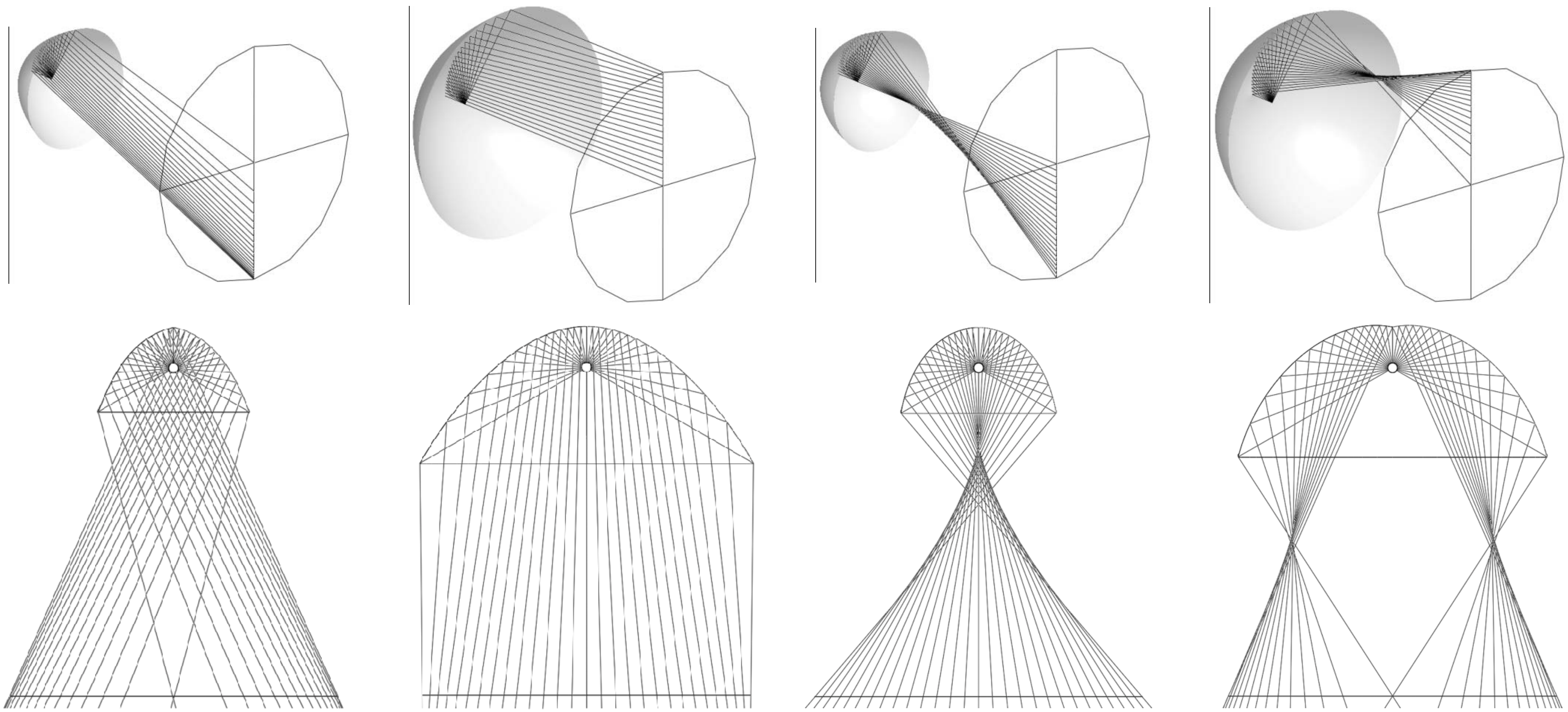
With Smoothing
Int. Width: 5 bins
Without Edge Preservation



With Smoothing
Int. Width: 5 bins
With Edge Preservation

Multiple designs can produce the same output

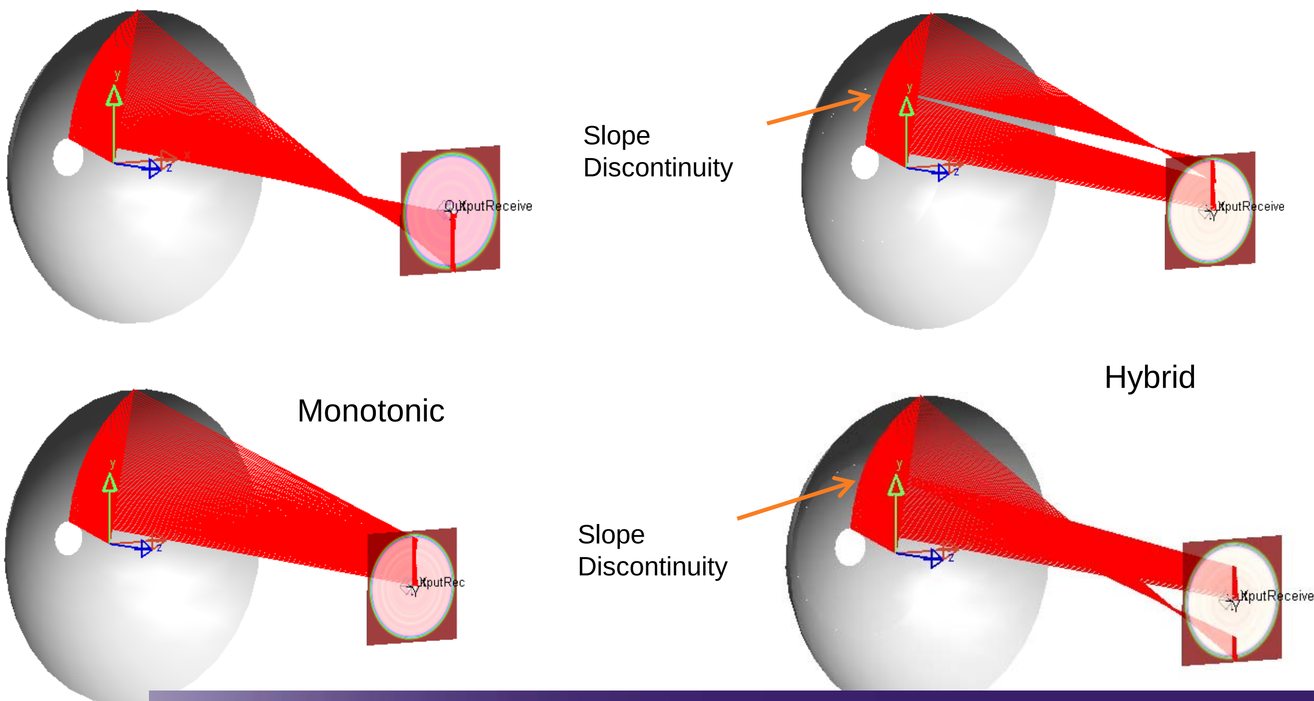
Crossing diverging	Non-crossing diverging	Crossing converging	Non-crossing converging



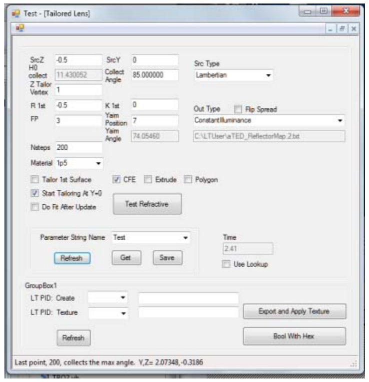
Strong lamp interference No caustics	Some lamp interference No caustics	Some lamp interference Caustic	No lamp interference Caustics

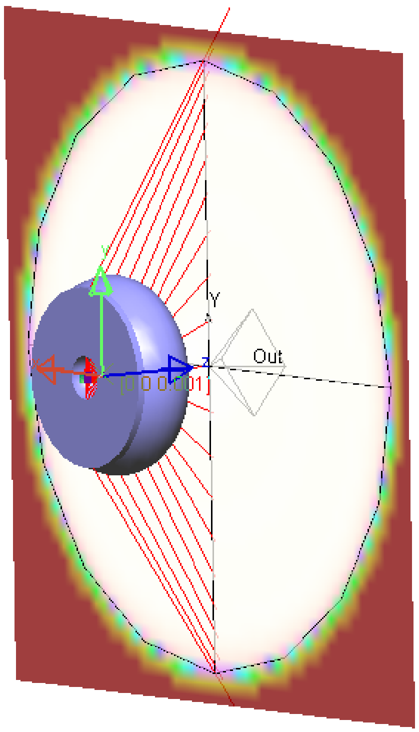
Starting Point is critical

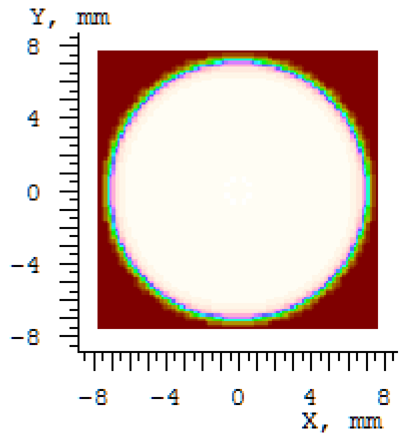
- There are multiple solutions to illumination “beam pattern” design problems.
  - Monotonic solutions are stable
  - Hybrid solutions require slope discontinuities that can require a complex surface parameterization
- Most optimization setups “allow” hybrid solutions to occur, but rarely have the right variables to find an “ideal” hybrid solution.

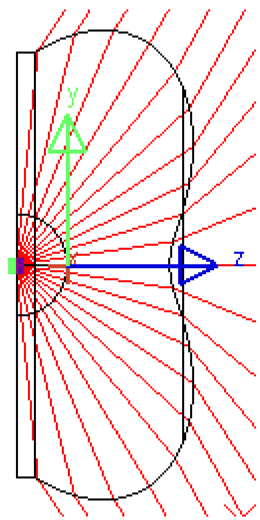


Freeform Lenses

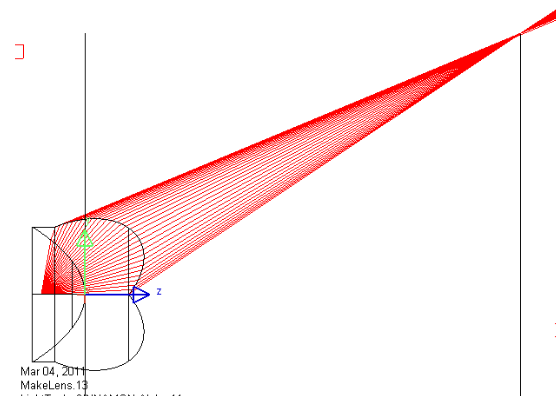






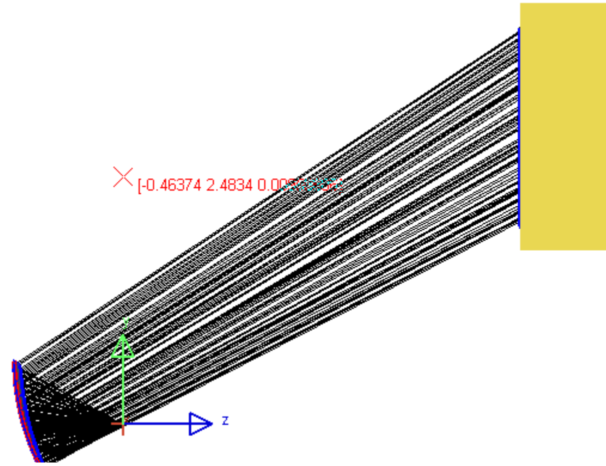


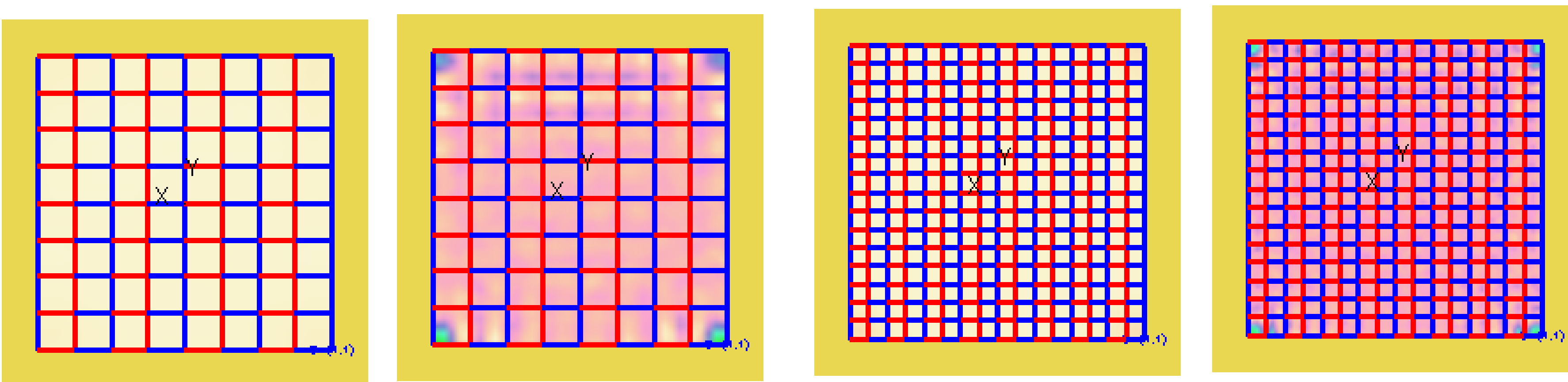
- Freeform lenses may not be monotonic in Z or Y



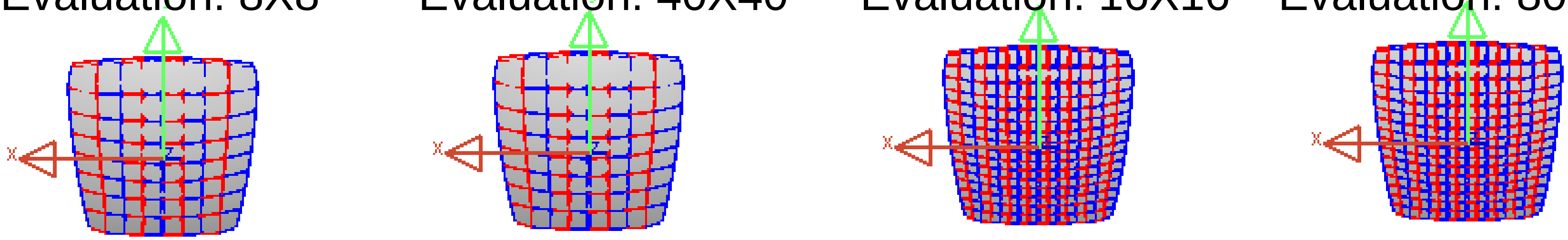
Freeform

- Freeform algorithms generally specify the number of computed points.
- Care must be taken to ensure that the resolution of the result is sufficient



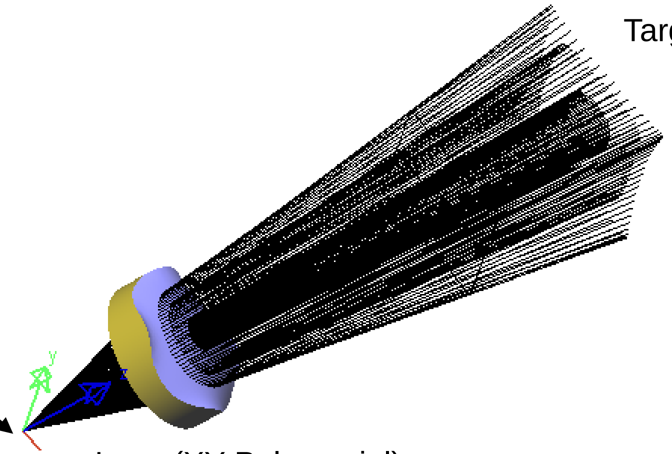


Design: 8X8	Design: 8X8	Design: 16X16	Design: 16X16
Evaluation: 8X8	Evaluation: 40X40	Evaluation: 16X16	Evaluation: 80X80



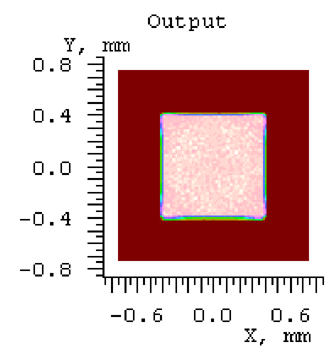
Aimed Rim Rays + Central Flux Tubes: Works for Asymmetric Source and/or Target

Rotationally symmetric source

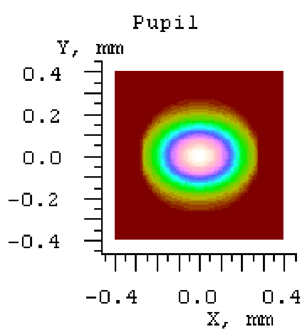


Target

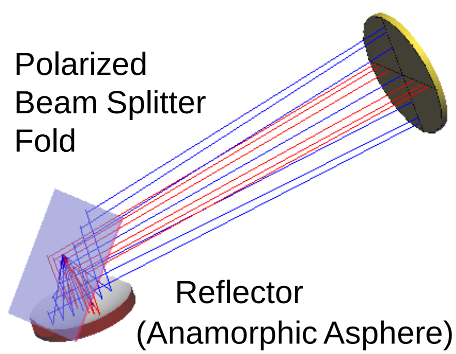
Lens (XY Polynomial)



Asymmetric source angular distribution

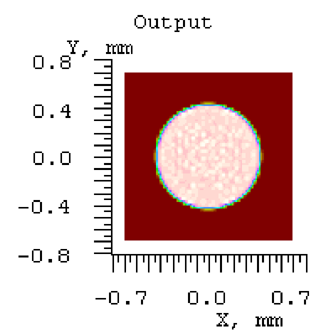


Polarized Beam Splitter Fold



Target

Reflector (Anamorphic Asphere)

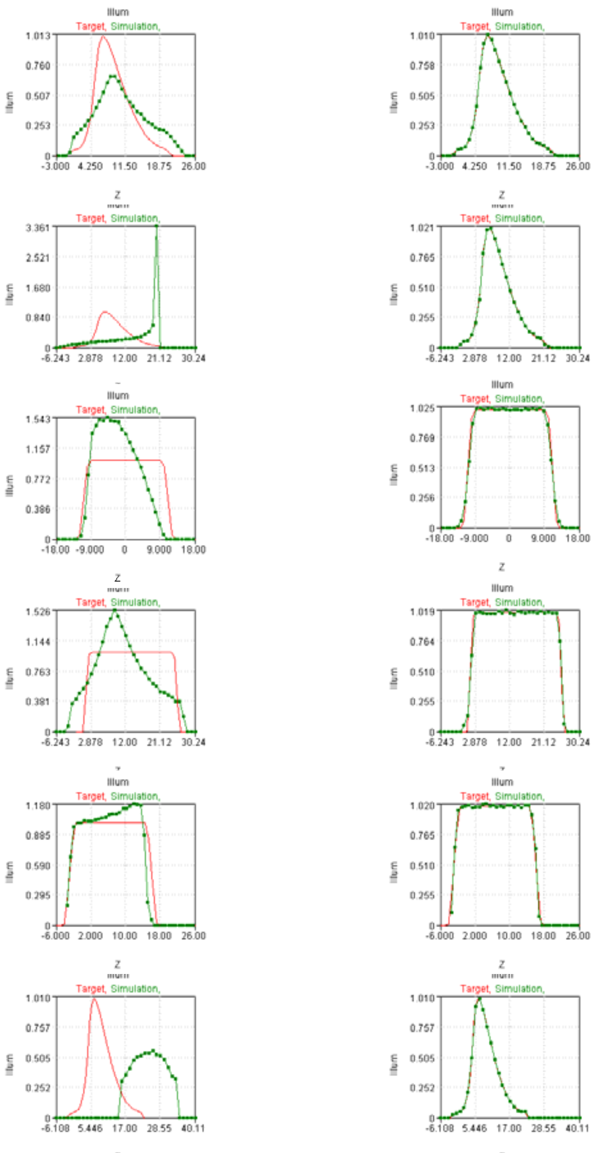


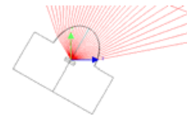
Optimized Output

SYNOPSYS®
Predictable Success

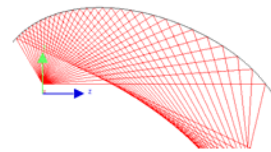
Compensation Is Robust

BEFORE AFTER

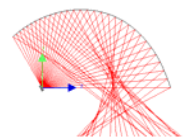




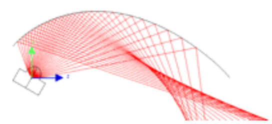
LED with
Extended Source



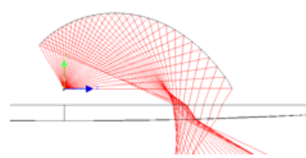
Shifted Source



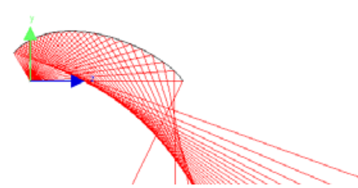
Extended Source with
Surface Scatter



LED with
Point Source

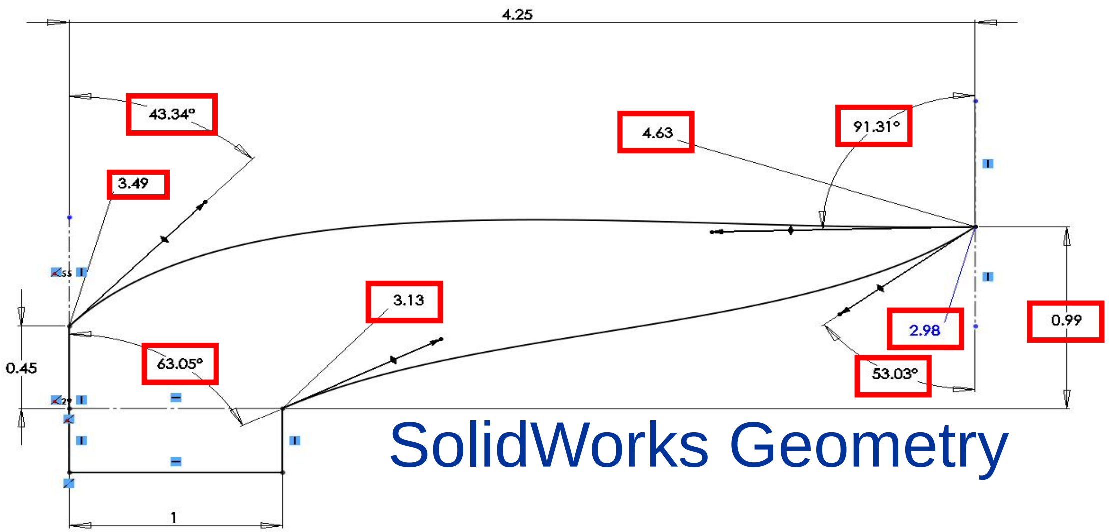


Coverplate

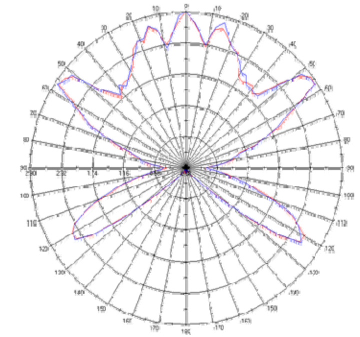


Poor Starting Point

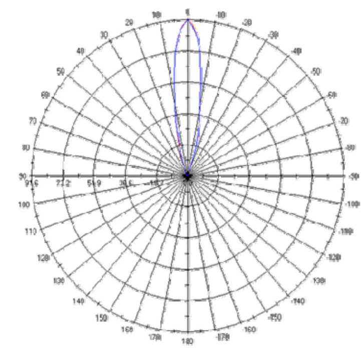
Illumination software can be used with commercial CAD software



SolidWorks Geometry



Before Optimization



After Optimization

- Construction parameters in CAD software can be used as variables in illumination software.
- Two common approaches:
  - Direct link/integration with the CAD software
  - Use of data exchange files
    - Step, IGES, SAT, etc

Conclusions

- Illumination Optimization is routine
  - Current ray trace speed allows use of Monte Carlo simulations
  - Production designs require balancing the tradeoffs
- Choosing effective variables is important
  - Direct surface computation algorithms provide a means to do this that is intuitive to a user.
  - ‘neat’ variables
- Specialized optimization algorithms can be used for some design problems.
- Direct freeform surface algorithms can be integrated with commercial software.

Freeform optics at OSRAM

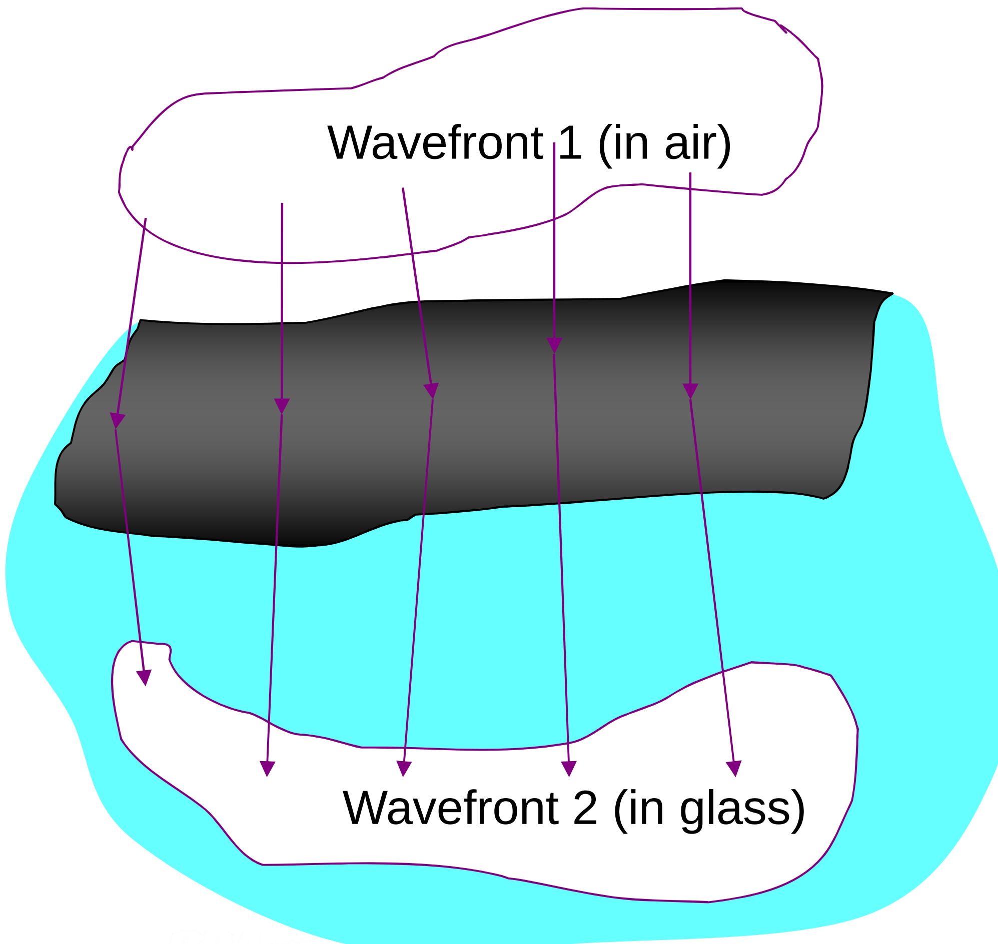
OSA Freeform Optics Incubator
Washington, D.C. Nov. 1, 2011
J. Muschaweck

”WHAT WE NEED THAT WE DO NOT HAVE”

OSRAM

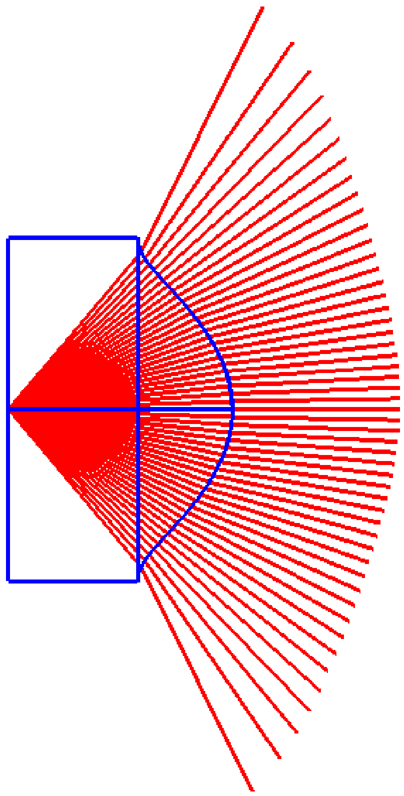
Known methods:
Wavefront matching / Cartesian ovals

- **Given optical surfaces match resulting pairs of wavefronts**
- **Levi-Civita: For any given pair of wavefronts, there is an optical freeform surface (Cartesian Oval) which matches them.**
- **For both refraction and reflection**
- **Commercial software implementation: ?**



Known methods:
"Simple" 2D tailoring

- "Cartesian oval" software in 2D: ray fan to ray fan
- Desired intensity / illuminance from rotationally symmetric wavefront (edge ray tailoring)
- Commercial software implementation: ?



Known methods:
Single surface 3D tailoring for point sources

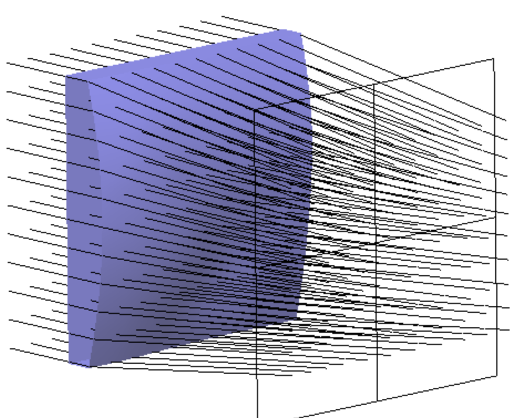
- **Well known method for > 10 years**

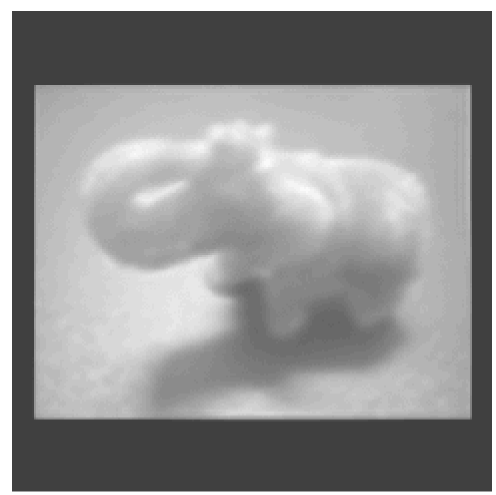
  H. Ries, J. Muschaweck and A. Timinger, "New Methods of Reflector Design", Optics & Photonics News August 2001

- **Implemented by various groups (OEC, Fraunhofer Inst., Univ. Karlsruhe, …)**

- **Commercial implementations: rare**

  "Elephant" designed using software from Fraunhofer ITWM





Known Design/Optimization Methods:
2D / 3D SMS (Simultaneous Multiple Surface)

- Well known method by LPI / Univ. Politecnica de Madrid
- Based on Levi-Civita style matching of multiple pairs of wavefronts
- Commercial software implementation: None

Missing methods:
Double surface 3D tailoring for point sources

- **Single surface 3D tailoring: Full control over illuminance**
- **Double surface 3D tailoring: Full control over illuminance + 1**
  - Color correction?
  - Source intensity incident on 2nd surface?
  - Illuminance on two target planes ("homogeneity with depth of field")?

Missing methods:
“Rigorous“ 3D tailoring for extended sources

- **Point source approximations fail sometimes**

- **“Fully flashed apertures“ in etendue limited systems**
  - Condensers for projection
  - Automotive headlamps
  - Wall washing / cove lights

- **“Considerably flashed apertures“ for “Large source“ systems**
  - Mobile flash
  - Single LED based streetlights

Conclusion

- Freeform surfaces for illumination promise high potential
  - Known for considerable time
  - Don‘t live up to this promise (yet)

- Existing design methods:
  - Few commercially available implementations
  - Some are complex / hard to use
  - „Solutions looking for a problem“? To some extent, yes

- Missing design methods:
  - For many real world problems (e.g. large sources)

- We are just starting …

Freeform optics for a linear field of view:
1. tracking integration in concentrating photovoltaics
2. analytical segmented lens design

Fabian Duerr, Pablo Benítez, Juan C. Miñano, Youri Meuret and Hugo Thienpont

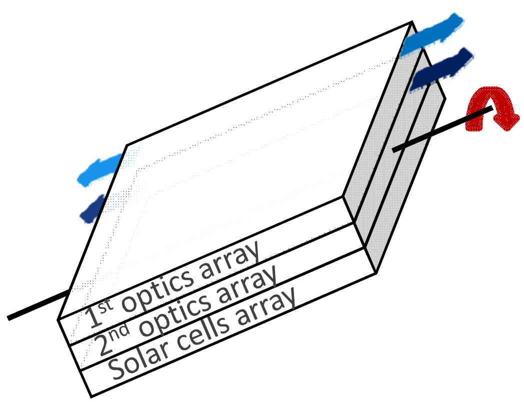
Chosen trade-off:
tracking integration on polar aligned single axis tracker

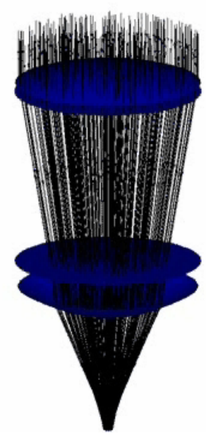
Why polar axis tracking?

- Demonstrate HCPV on single axis trackers (>500x concentration)
- Relatively high yearly insolation (almost comparable with dual axis tracking)
- Minimal aperture angle of ±24° for single axis tracking

System design

- Two laterally moving optics (no vertical movements for the moment)
- Rotational symmetric lens design based on extended SMS2D algorithm [1]

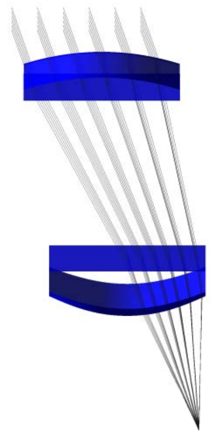




F. Duerr, Y. Meuret, and H. Thienpont, "Tracking integration in concentrating photovoltaics using laterally moving optics," Optics Express 19, A207-A218 (2011)

Rotational symmetric vs. freeform optics design

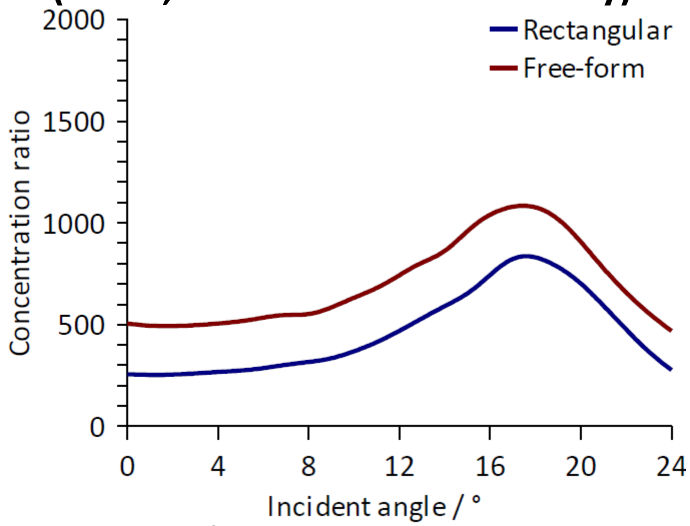
Rotational symmetric design



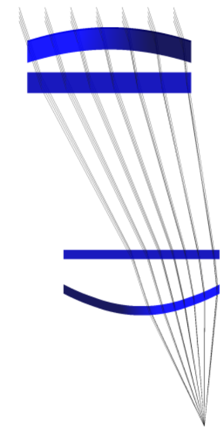
- >500x concentration over ±24° angular range
- Need for squared lens apertures and solar cells

  └> Concentration ratio drops

(n=1.5, 95% collection efficiency)



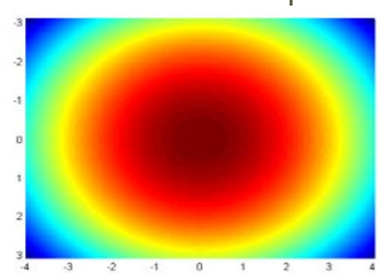
Freeform optics design



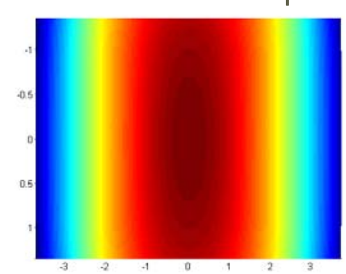
- Based on extended SMS3D [2]
- 1.4 aspect ratio for (x to y)
- Back to >500x concentration
- Non-square solar cells allow even higher values

but …

1st lens contour plot

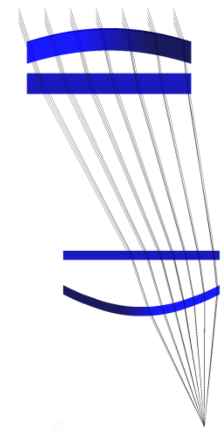


2nd lens contour plot



] F. Duerr, P. Benítez; J.C. Miñano, Y. Meuret, and H. Thienpont, "Integrating tracking in concentrating photovoltaics using non-rotational symmetric optics ," Proc.of SPIE, Vol. 8124 (2011)

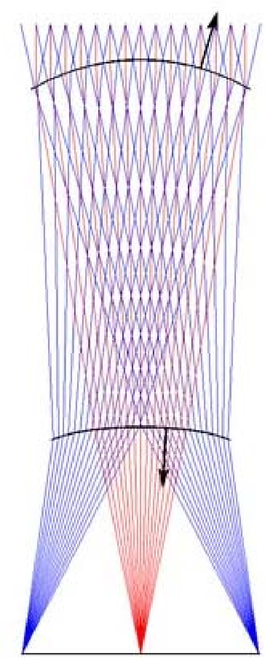
Segmented lens design in two dimensions



Can we do better for wide FOV and/or clearly separated optical surfaces?

- **Thick lens: different incident directions use different portions of the lens (like a field flattener lens or an aperture stop in imaging optics)**

Coupling of three parallel ray sets



- **Fermat's principle leads to set of functional differential equations**
- **Transformation to algebraic (linear) system of equations**
  └> General solution for Taylor series coefficients

- **Solution is fully described by two variables only: directional vectors at convergent points (indicated)**

- **Solutions range from meniscus to biconvex lens shapes**
  └> 15th order Taylor polynomials for lens profiles
  (To be submitted soon)

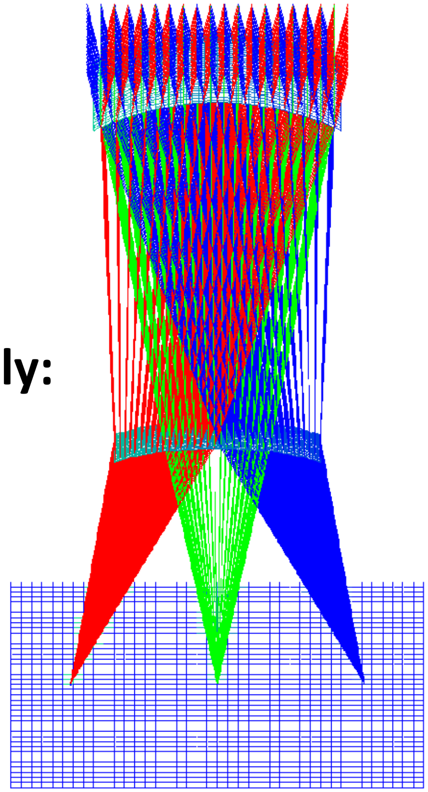
Finally … first three dimensional solution

3D coupling of three parallel ray sets

- **Mathematical framework in analogy to 2D case**
- **Transformation to algebraic (linear) system of equations**

  └> General solution for 2D Taylor series coefficients

- **As before, solution is fully described by two variables only: directional vectors at convergent points**

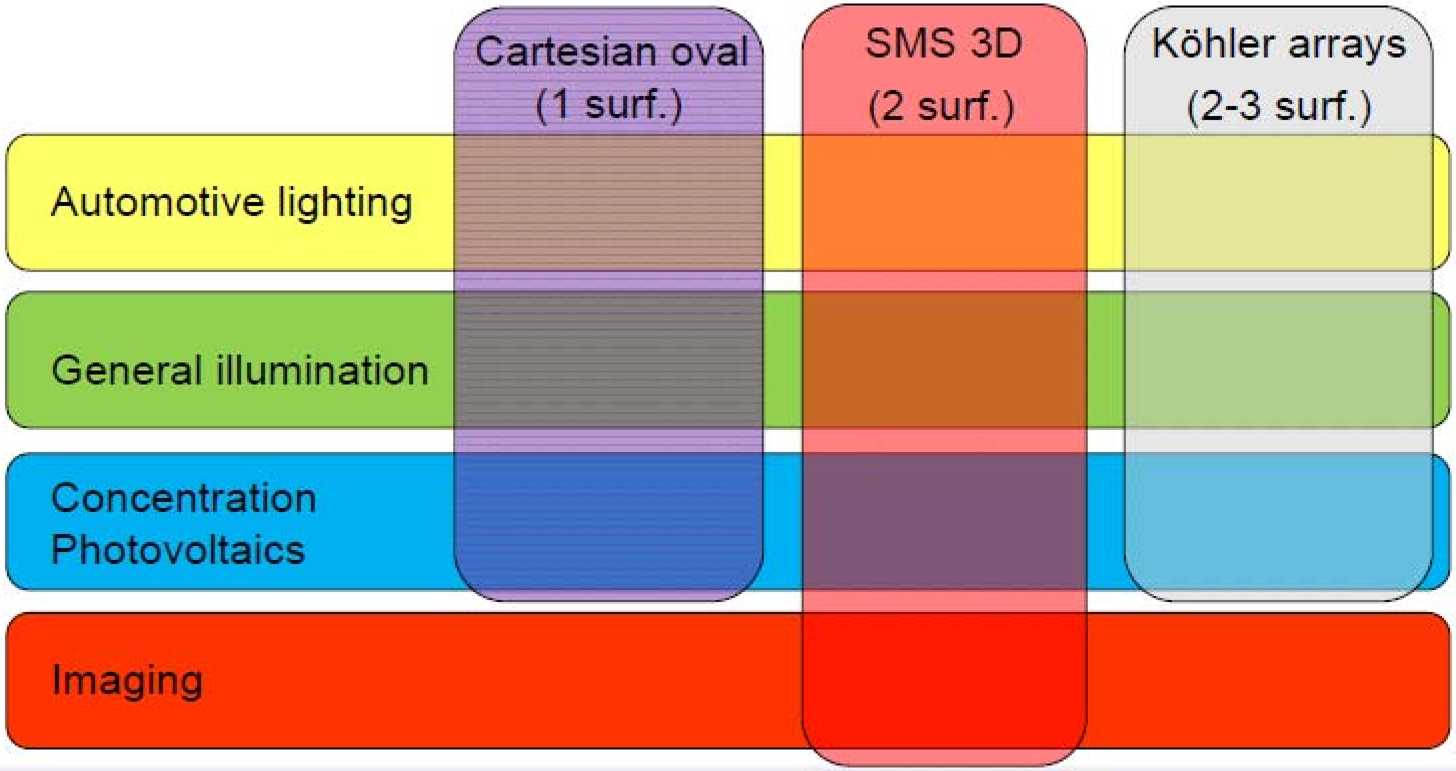


Nonimaging Freeform Optics Applications at LPI

Pablo Benítez, Juan C. Miñano

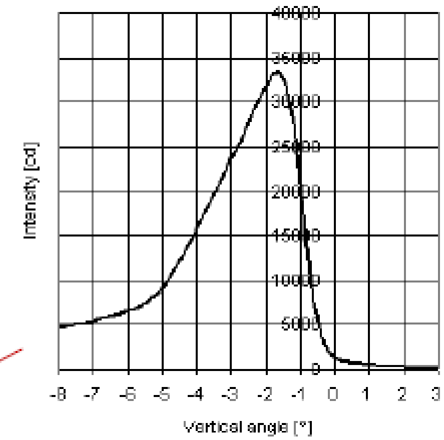
LPI, USA
Universidad Politécnica de Madrid, Spain

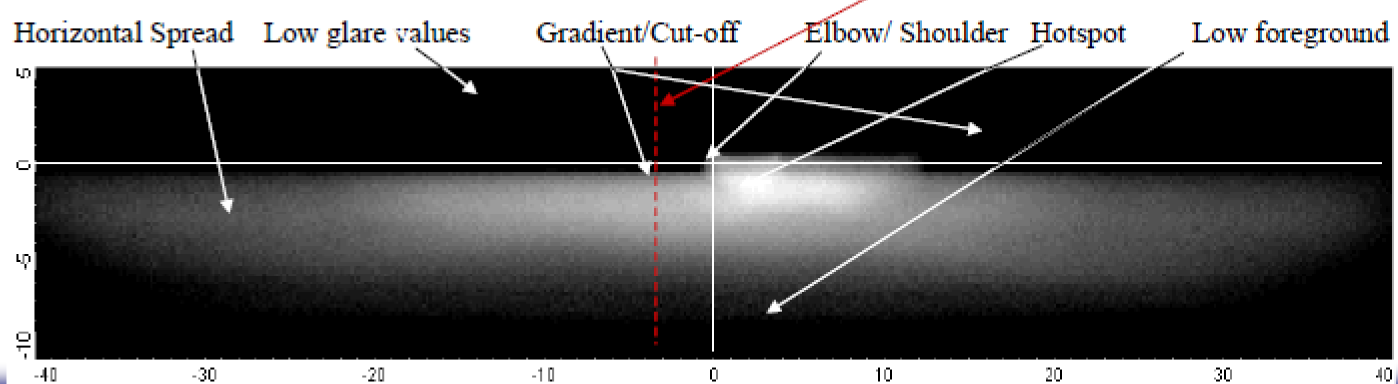
LPI freeform technologies



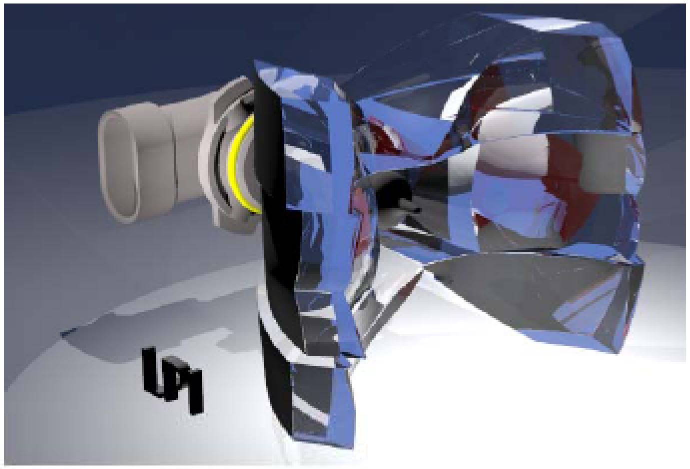
Low beam headlamp specs

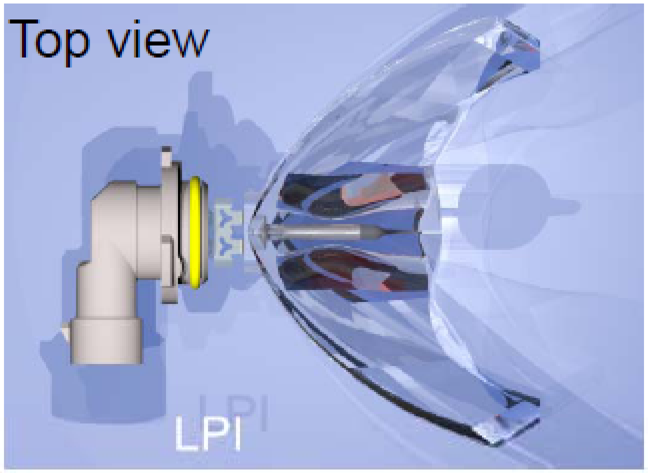
- Defined by ECE and SAE regulations
- Typically 20 min/ max test points/ fields
- Gradient Specifications ($G > 0.13$ USA, $G > 0.22$ EU)
- Homogeneity
- Car producer additional specifications





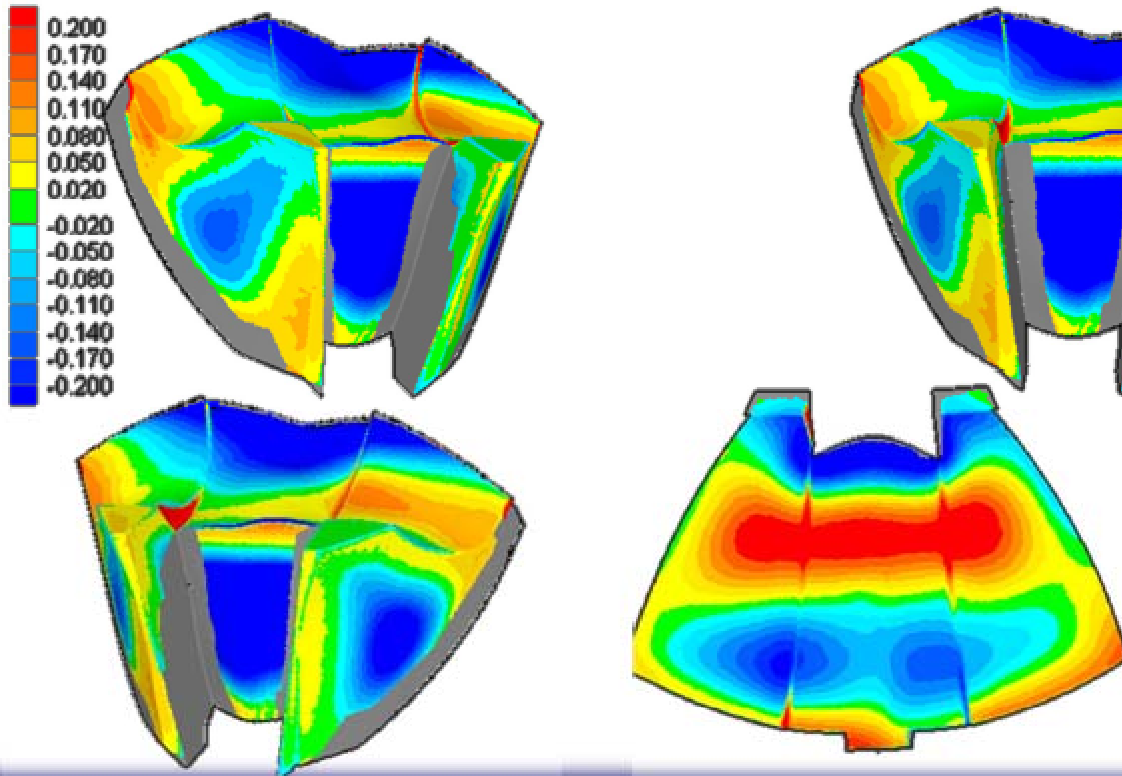
X-beam headlamp



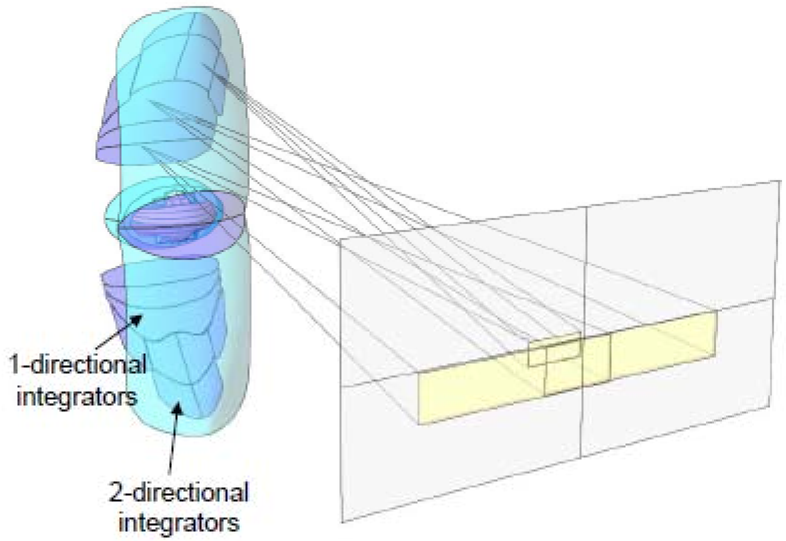


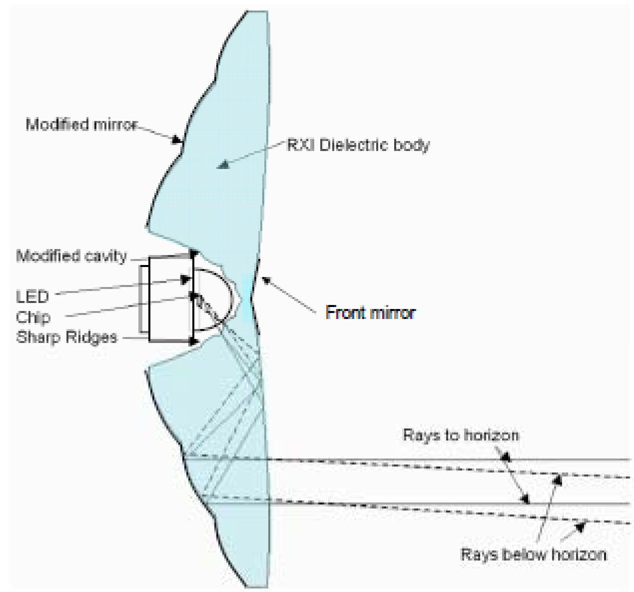
	Conventional	SMS 3D
Aperture	≈140 x 140 mm^2	≈ 80 x 80 mm^2
Flux on the road	350-680 lm	>700 lm
Efficiency	30%-55%	>60%

3D laser scans profilometry



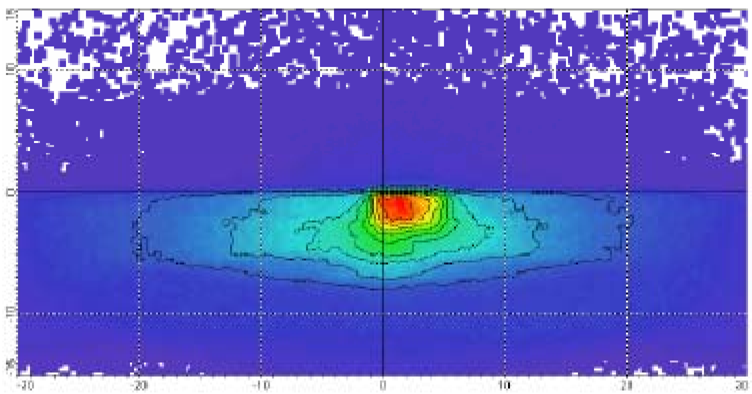
Freeform RXI-Köhler headlamp



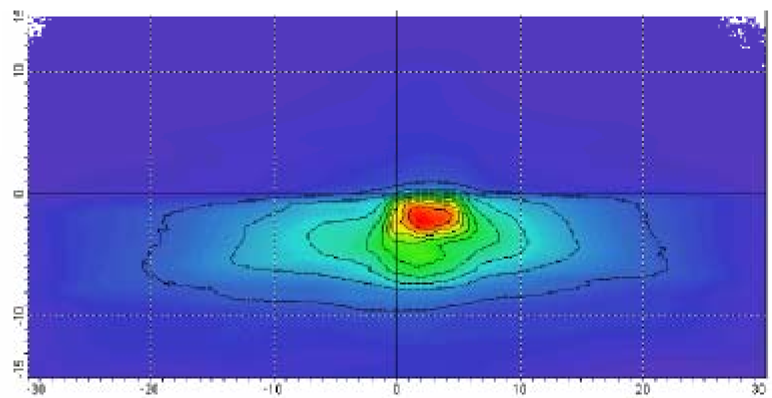


Freeform RXI-Köhler headlamp

Ray trace

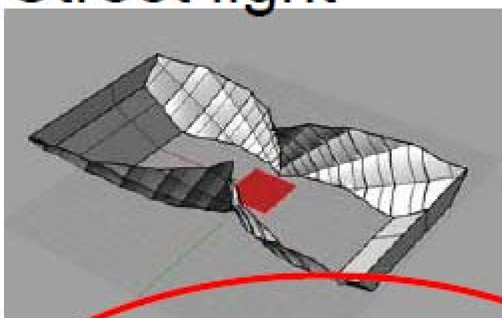


Prototype measurement

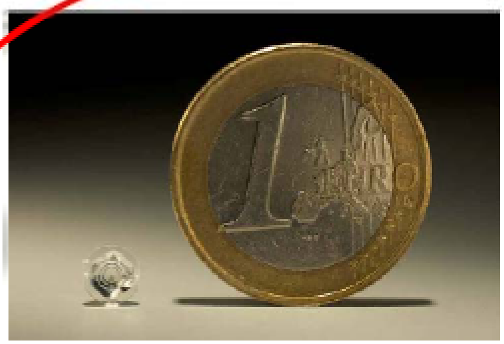


Examples

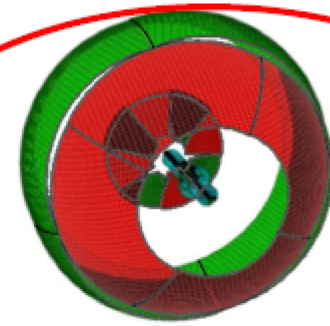
Street light



TIR-RXI collimator

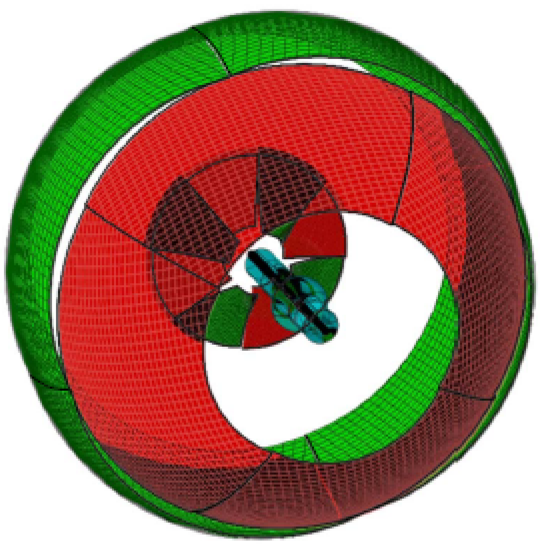


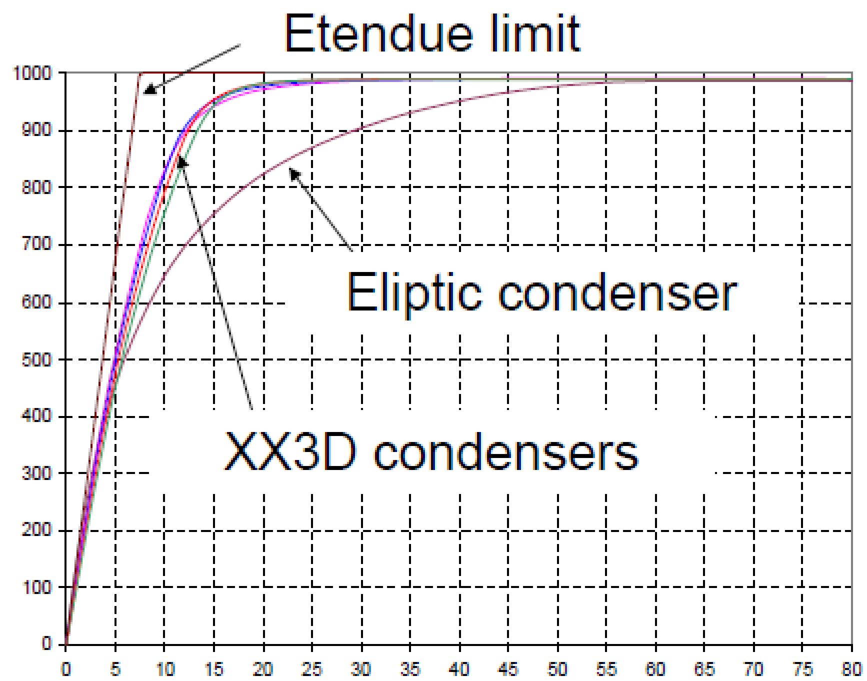
Mobile phone flash



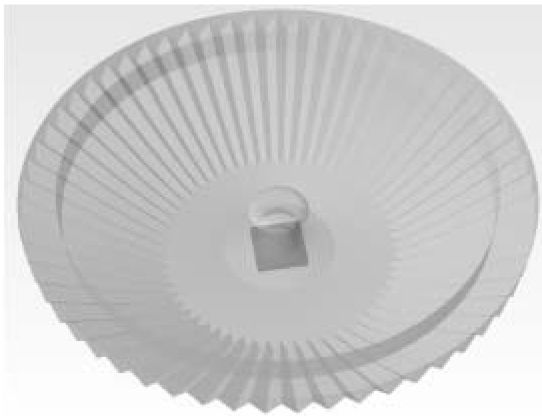
Condenser

Etendue-squeezing condenser

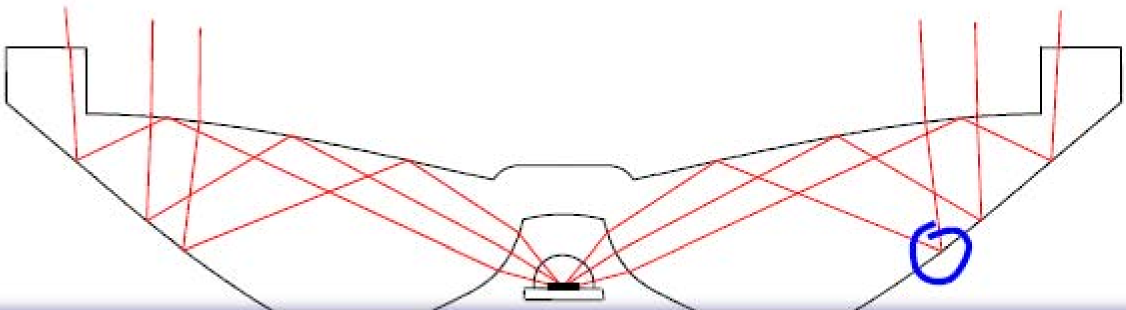




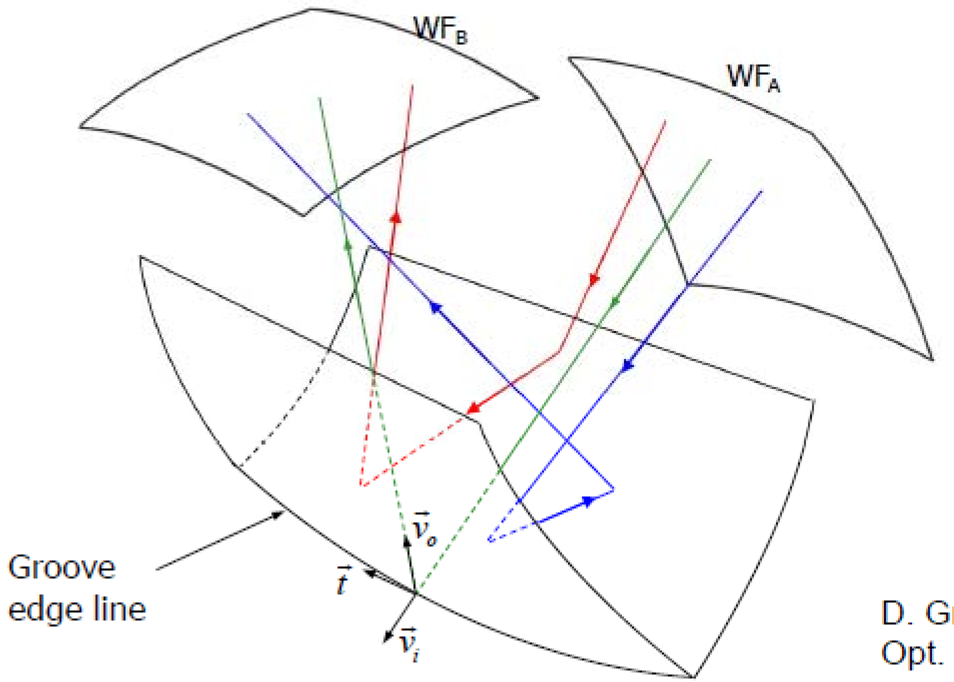
Metal-less TIR-RXI



Two Total internal reflections
at both groove sides

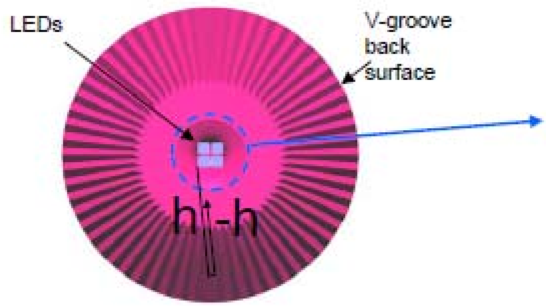


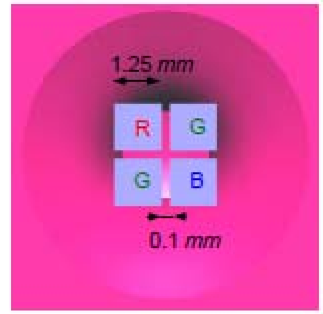
Statement of the problem

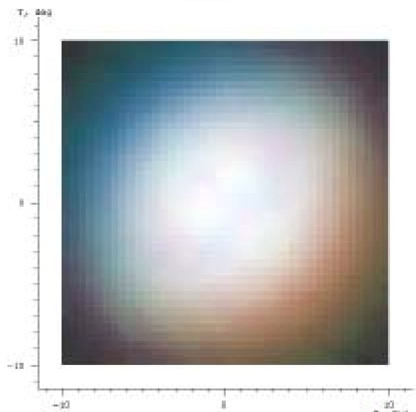


D. Grabovičkić, et al.
Opt. Express 19, (2011)

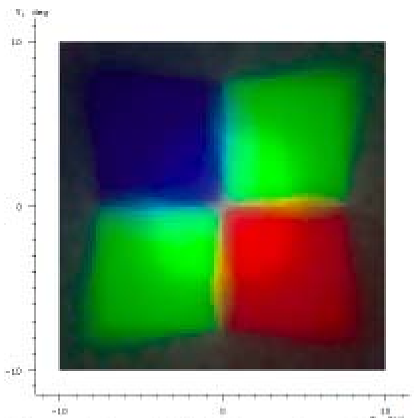
Color Mixing







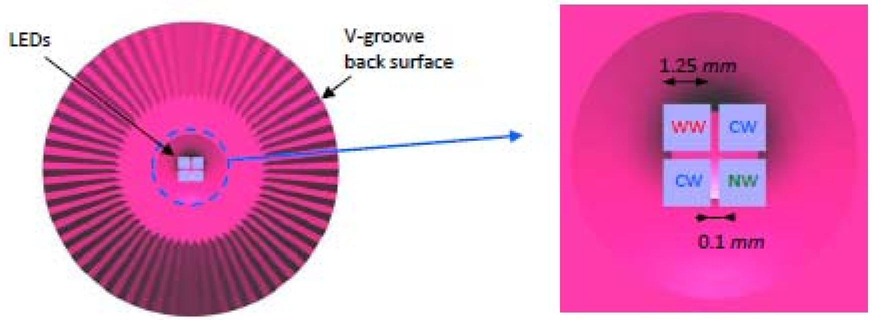
Metal-less RXI, true colour far field pattern

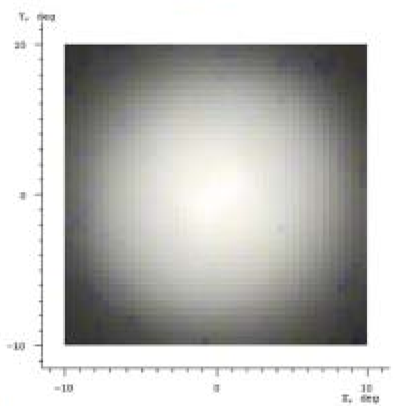


Conventional RXI, true colour far field pattern

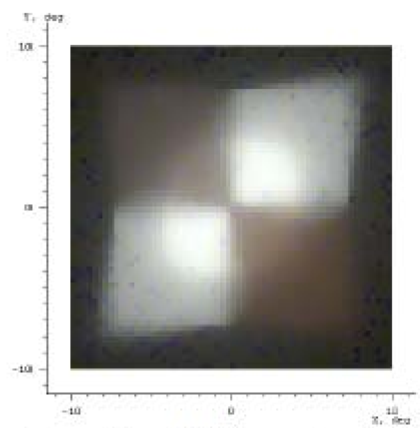
Analysed with

Color Temperature & dimming





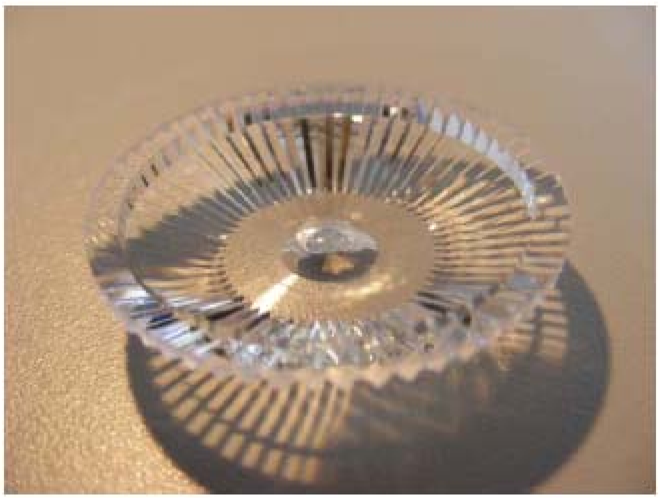
Metal-less RXI, true colour far field pattern



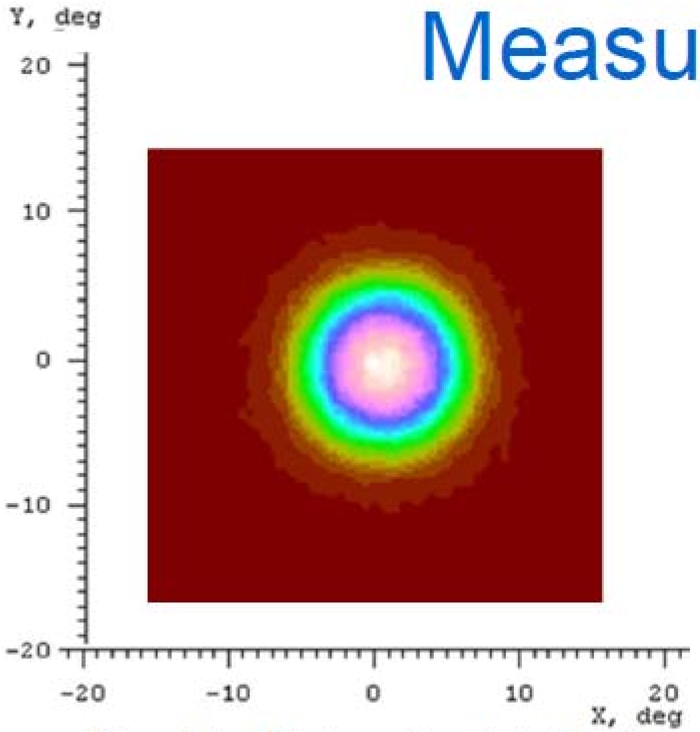
Conventional RXI, true colour far field pattern

Analysed with LightTools SYNOPSYS

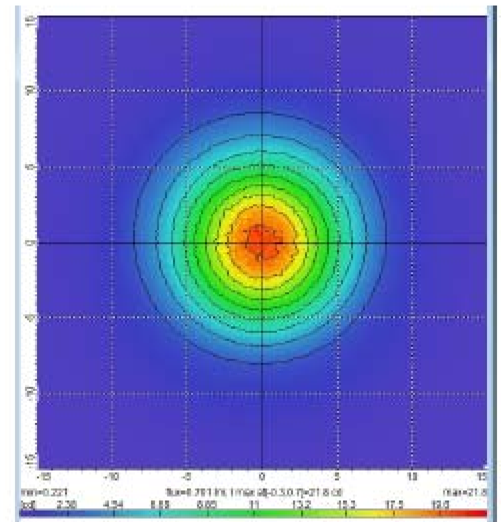
Prototype



Measurements



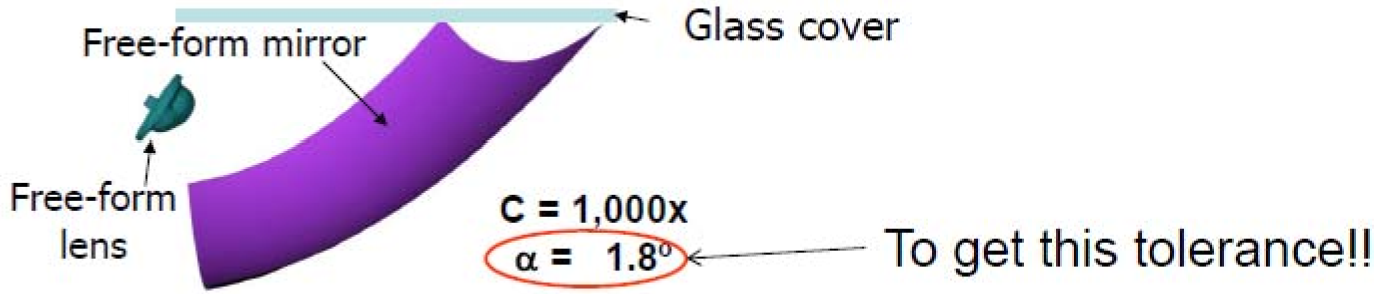
Simulated intensity distribution



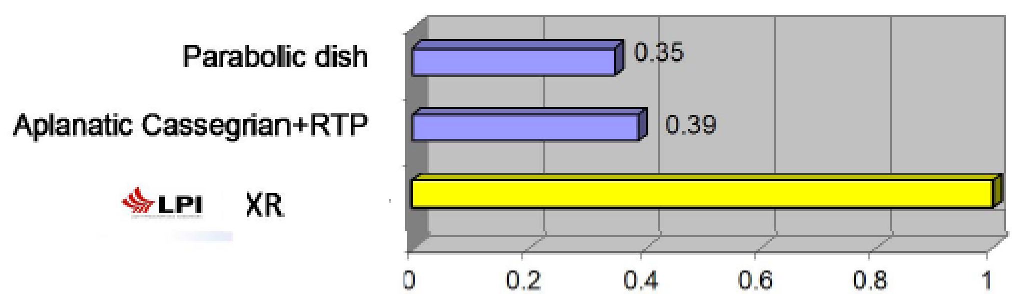
Measured intensity distribution

- Measured maximum intensity 22 cd/lm (29 cd/lm simulated)

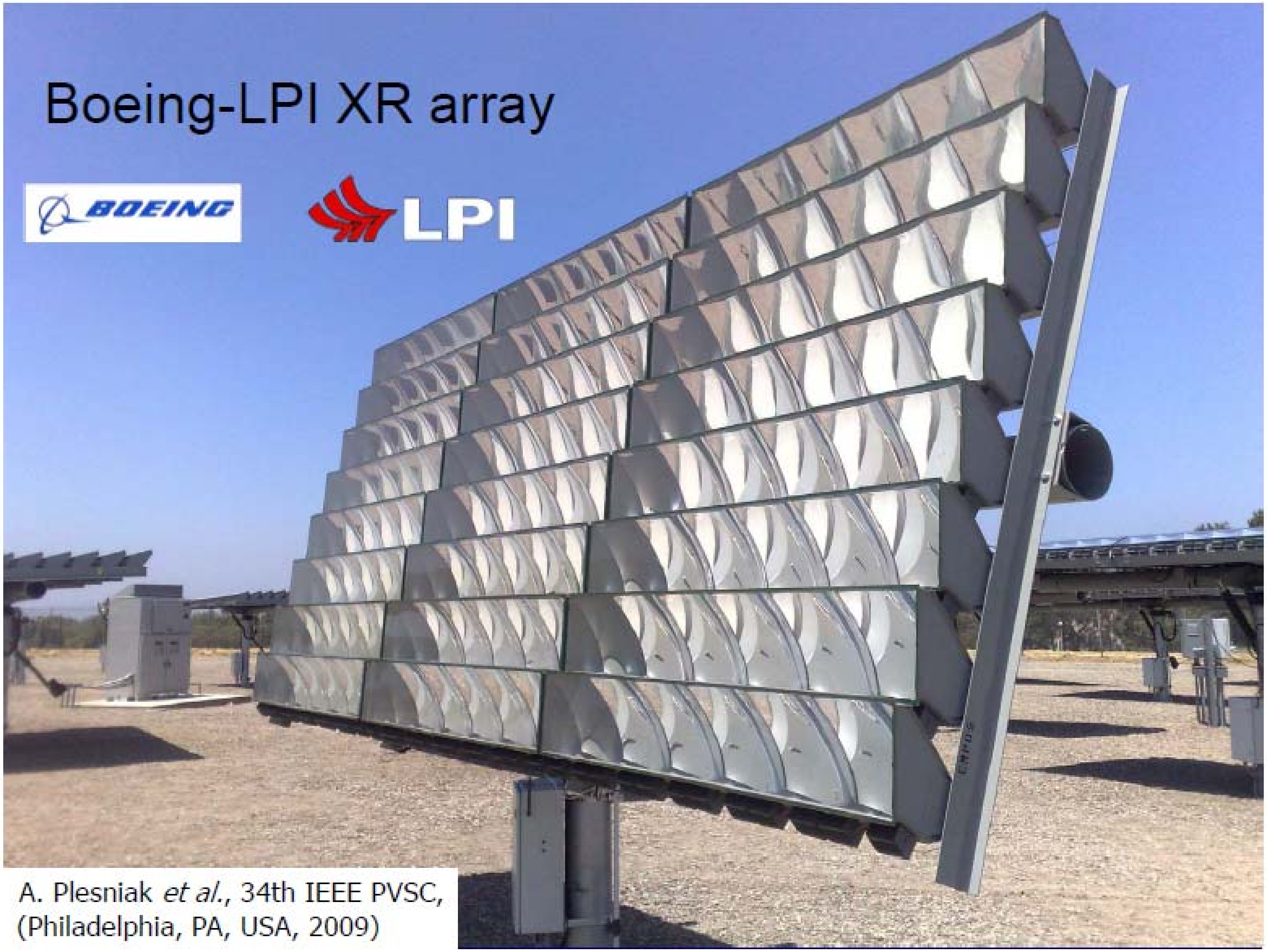
Why freeform is needed?



$$CAP = \sqrt{C} \times \sin\alpha$$

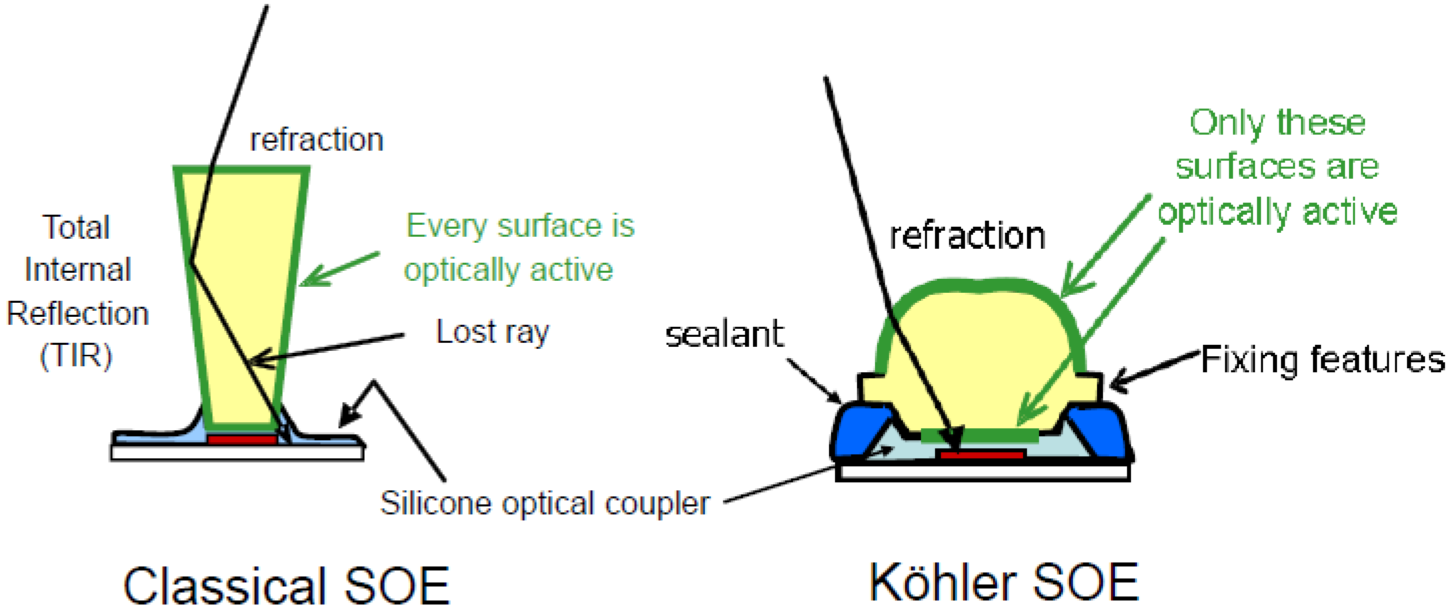


Boeing-LPI XR array

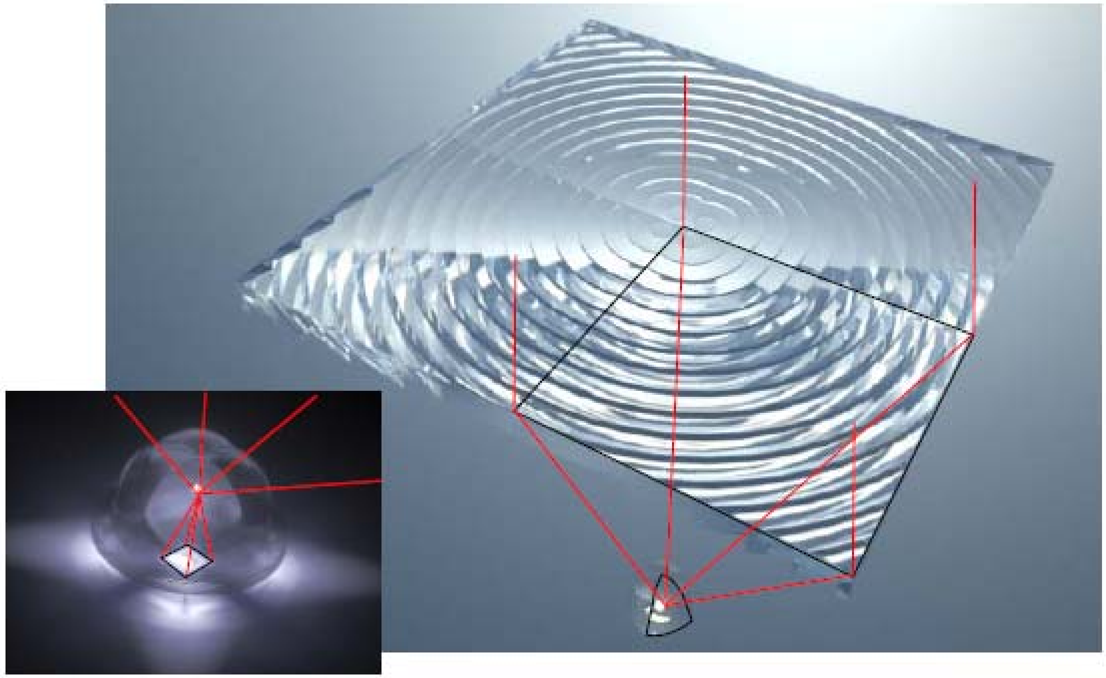


A. Plesniak *et al.*, 34th IEEE PVSC, (Philadelphia, PA, USA, 2009)

Why Kölher PV concentrators?

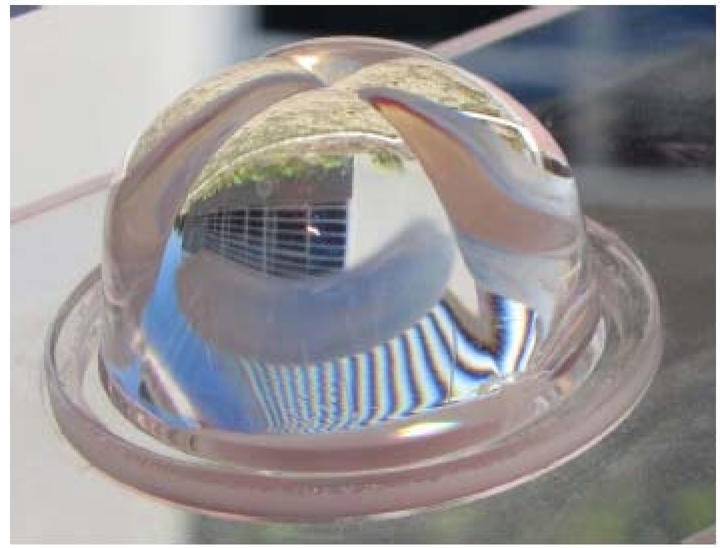


The FK concentrator



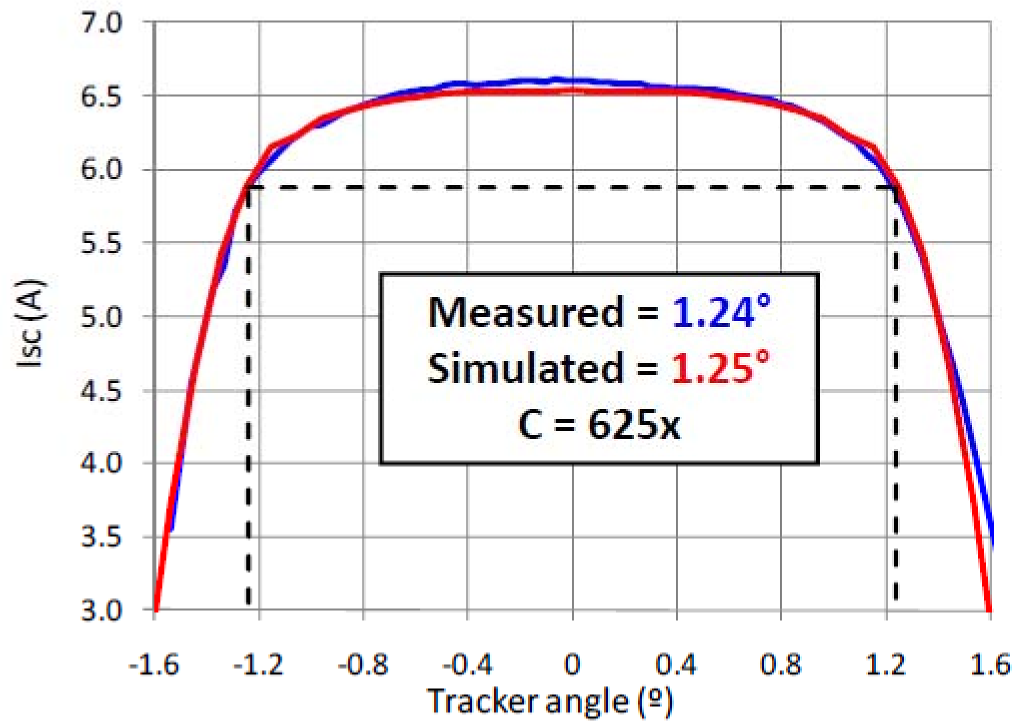
P. Benítez, J.C. Miñano, P. Zamora, R. Mohedano, A. Cvetkovic, M. Buljan, J. Chaves, M. Hernández, Optics Express, Vol. 18, Issue S1 (Energy Express), April 2010

Fresnel LPI-Köhler SOE



International patents pending

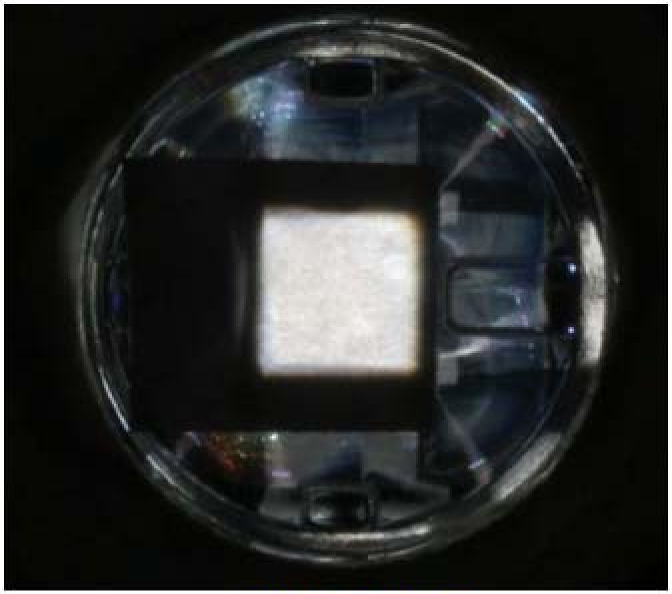
LPI FK concentrator: acceptance angle



* Measured results under DNI = 975 W/m^2

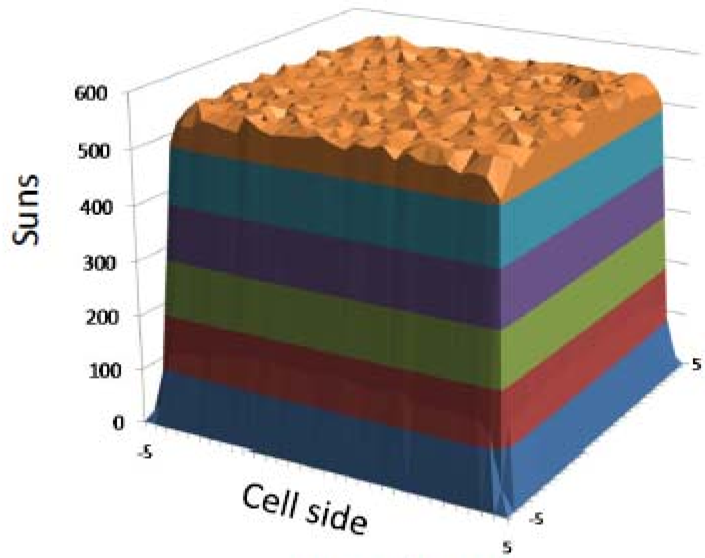
LPI FK concentrator: cell irradiance uniformity

Suns



Measured

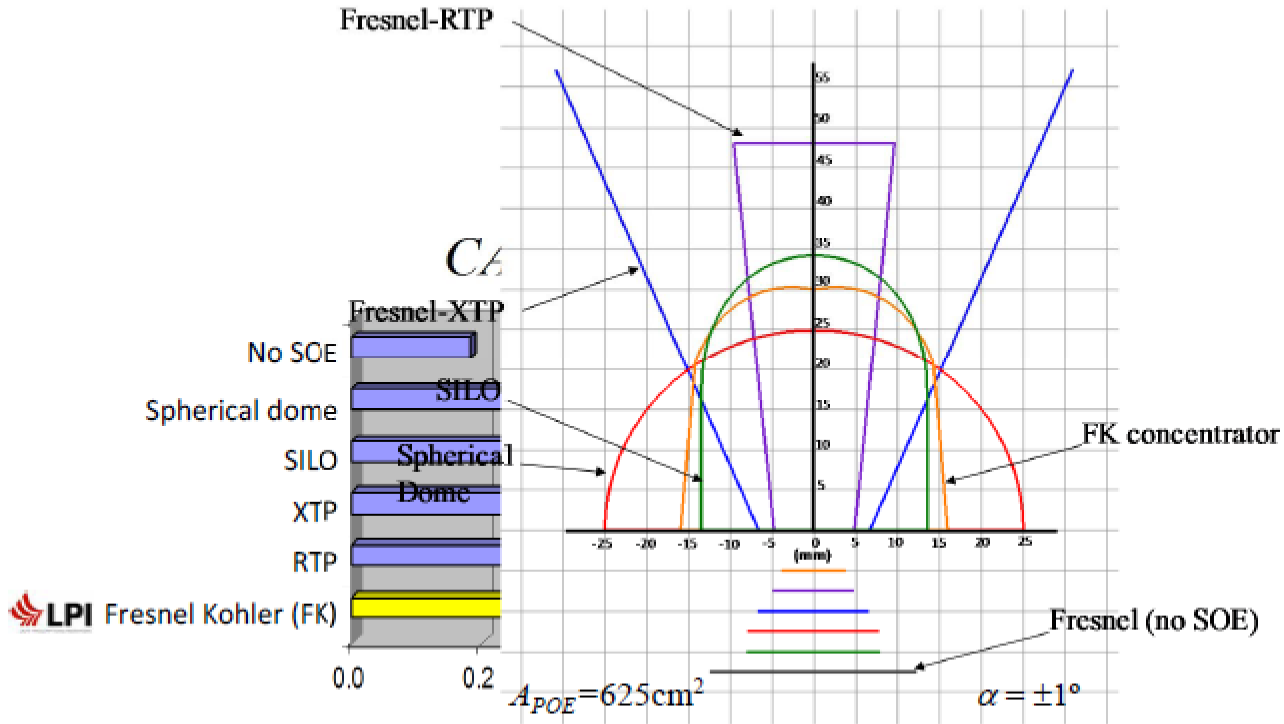
Peak irradiance = 595 suns



Simulated

Peak irradiance = 575 suns

Comparison


Fresnel-RTP
Fresnel-XTP
SILO
Spherical Dome
FK concentrator
Fresnel (no SOE)
No SOE
Spherical dome
SILO
XTP
RTP
LPI Fresnel Kohler (FK)
0.0
0.2
(mm)
A_{POE}=625cm²
$\alpha = \pm 1°$

Summary

- LPI has proprietary tools for freeform optics design, including SMS 3D and freeform Köhler integrators
- LPI is actively developing products in automotive, SSL and CPV
- Freeform imaging development in progress, in collaboration with UPM

F-RXI Photovoltaic Concentrator: a high performance SMS-3D freeform Köhler design

M. Buljan[1], P. Benítez[1,2], R. Mohedano[2], J. C. Miñano[1,2]

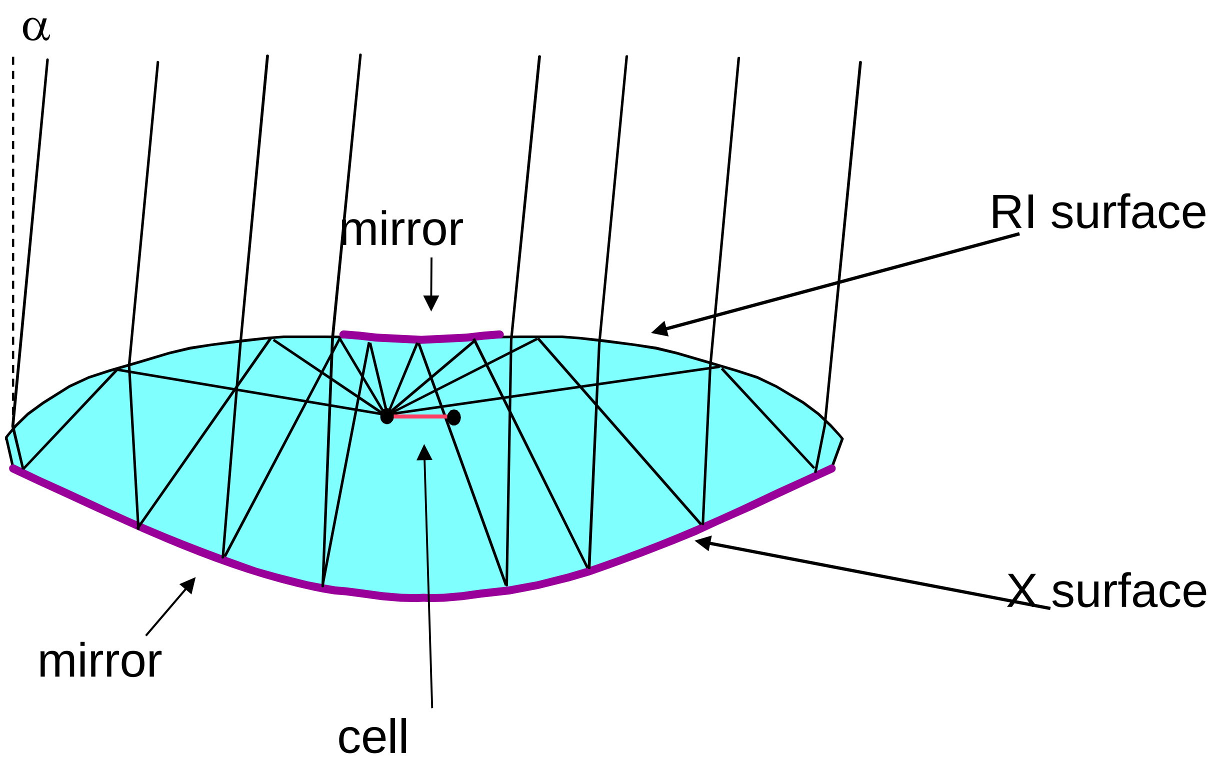
[1]Universidad Politécnica de Madrid (UPM), CeDInt, Spain

[2]LPI-LLC, USA

Why freeforms in advanced HCPV optics?

- New degrees of freedom to the design: A single optical element can perform multiple functions.
- Köhler integration as one of the additional surface functions in order to guarantee superior performance of 3J cells and systems: achromatic, homogeneous and square irradiance distribution with high concentration, high efficiency and wide acceptance angle.
- The **SMS 3D** design method of Nonimaging Optics is the most advanced method to design freeforms.

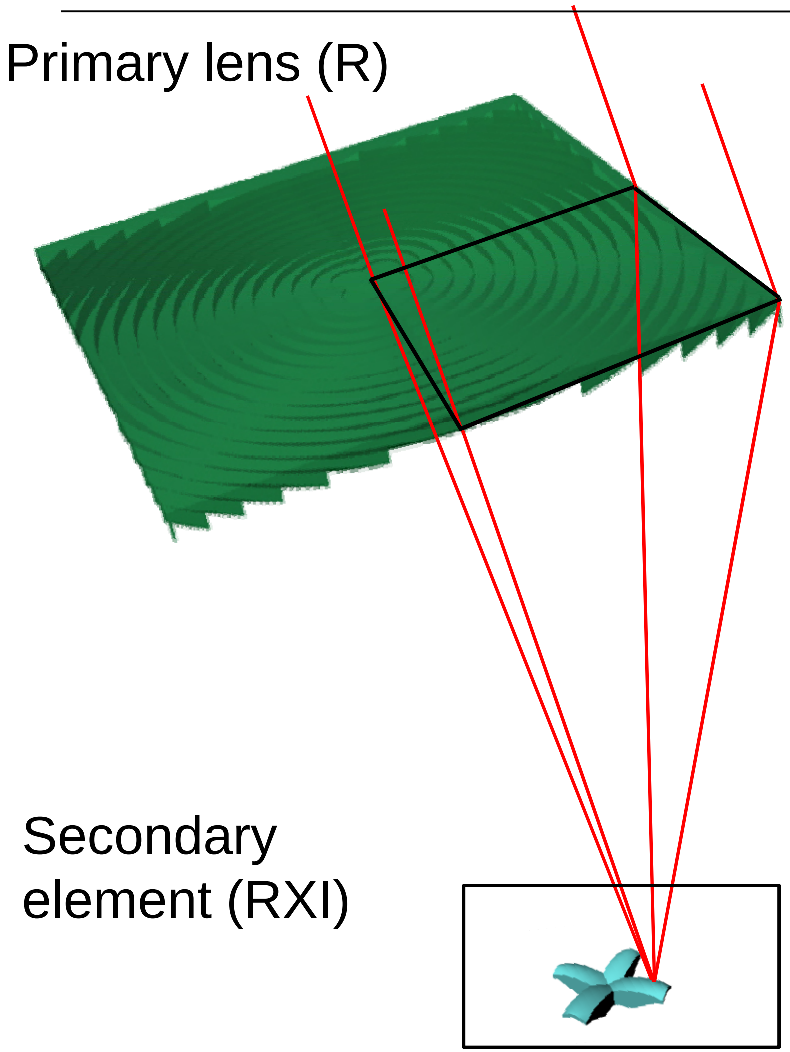
RXI 2D concept

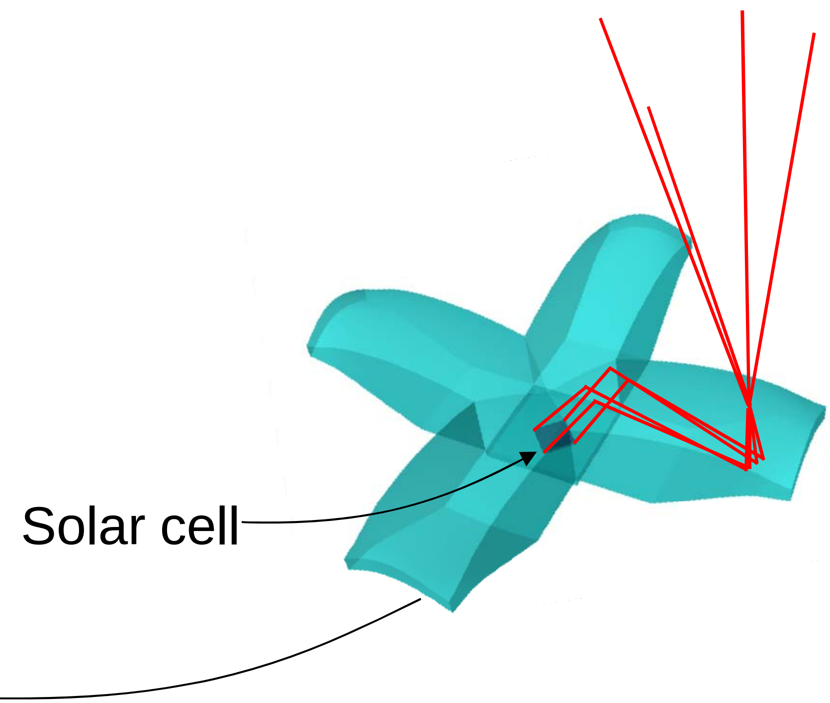


*US patent 6,639,733

HCPV concentrator example: 4-fold F-RXI Köhler

- 3D Köhler integration
- Optical surfaces split into 4 free-form sectors



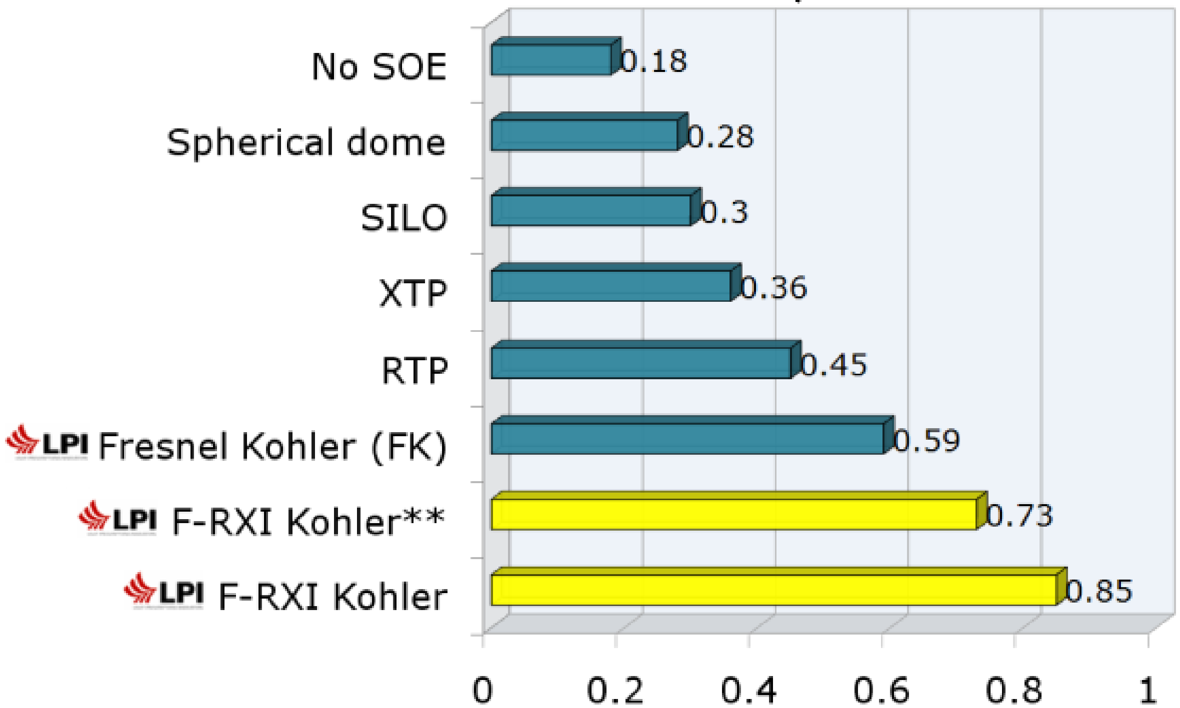


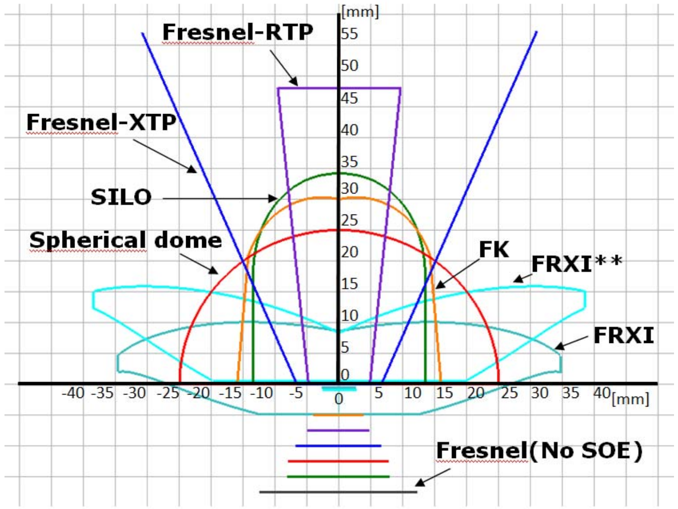
M Buljan, P Benitez, R Mohedano, J C Miñano, "Improving performances of Fresnel CPV system: Fresnel-RXI Kohler concentrator, EU-PVSEC, Valencia(2010)

Merit function: CAP

- The same POE entry aperture area (625 cm²).
- The same acceptance angle (α = ± 1°).

$$CAP = \sqrt{C_g} \times \sin\alpha$$





F-RXI** without frontal metallization

F-RXI with small metalized frontal area

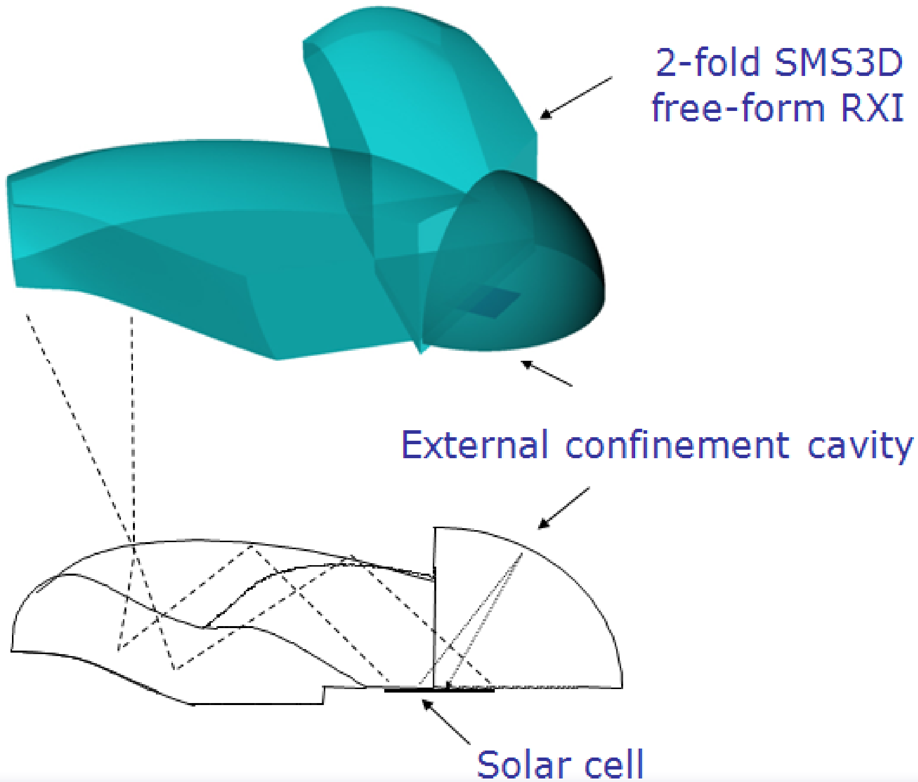
M Bulian, P Benitez, R Mohedano, J C Miñano, "Improving performances of Fresnel CPV system: Fresnel-RXI Kohler concentrator, EU-PVSEC, Valencia(2010)

Advanced features: RXI + confining cavity

- Drop ½ C_g + Light confinement with external cavity.

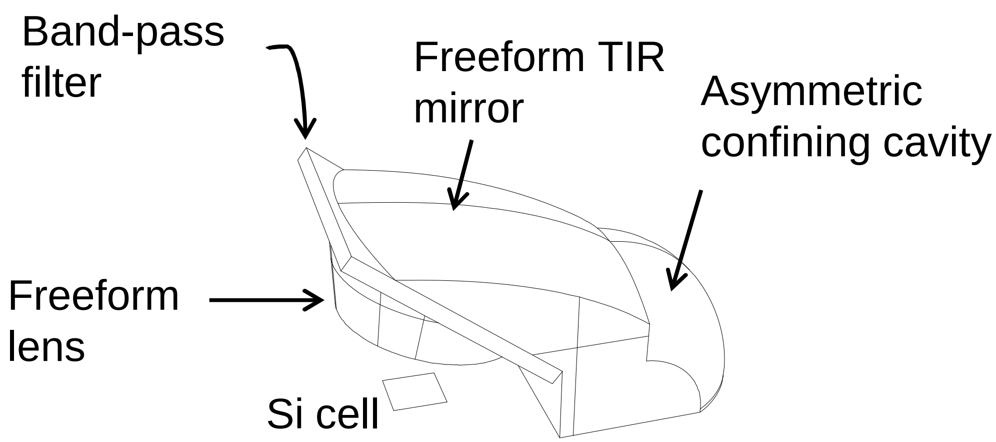
- Demonstrated 6% relative increase of light absorbed by cell (recovered by external confinement cavity).

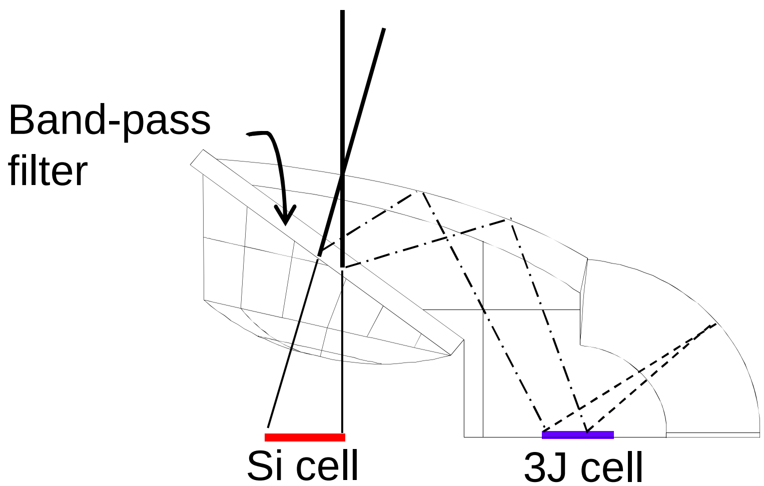
- More dense grid-lines possible
  - Joule losses minimized: lower R_s
  - Higher concentrations.

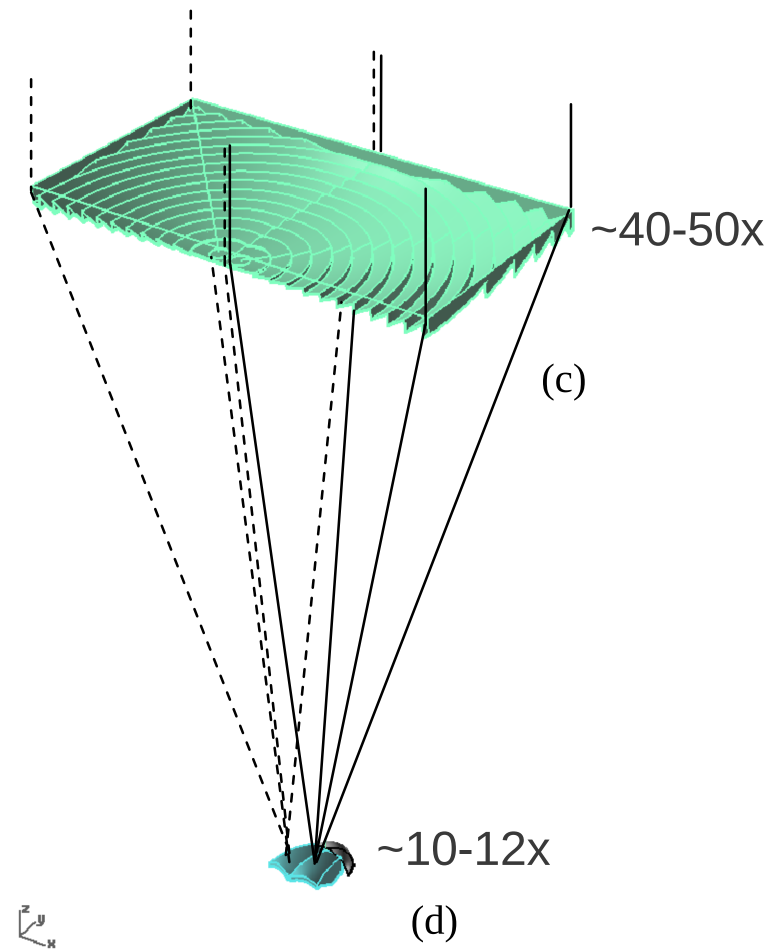


M.Buljan, P.Benitez, R.Mohedano, J.C.Miñano, "Improving performances of Fresnel CPV system: Fresnel-RXI Kohler concentrator, EU-PVSEC, Valencia(2010)

Advanced features: The F-RXI Spectrum Splitting



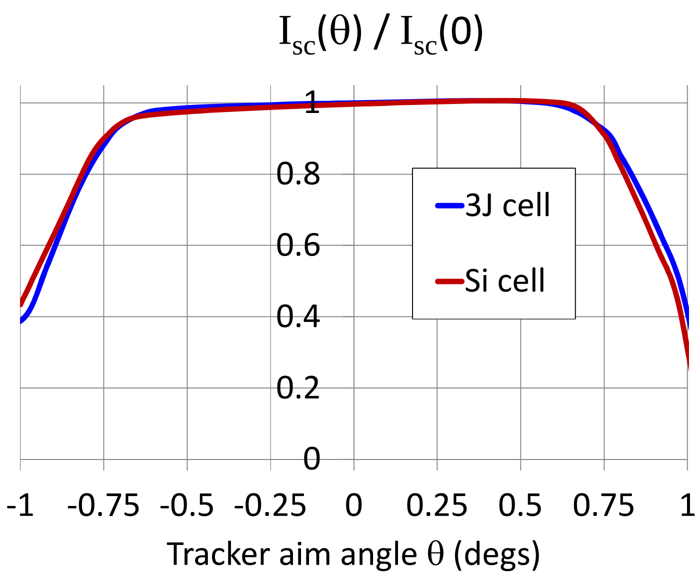


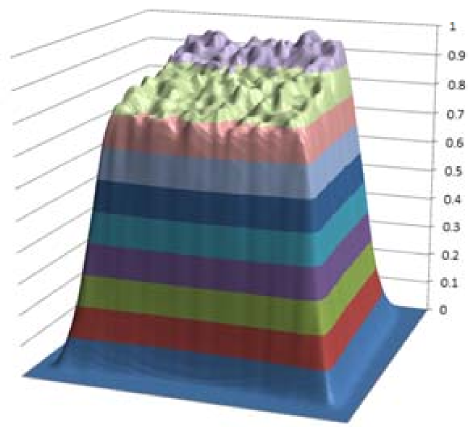


Advanced features: The "Nautilus" SOE (F-RXI-RI^2)

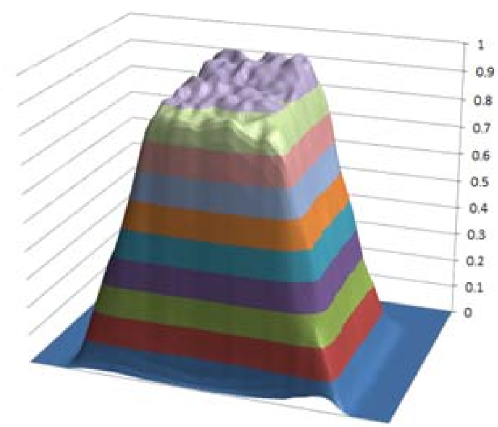
Parameter	3J cell	Si cell
Geometrical concentration	625x	560x
Acceptance angle	0.75º	0.76º
Optical efficiency	85%	85%

CONFIDENTIAL





3J cell



Si cell

Summary

- **SMS 3D** method is the most advanced design method in the field of the Nonimaging Optics.
- Optical surfaces in HCPV concentrators as **freeform Köhler integrating arrays.**
- Potential to obtain devices with acceptance-concentration products approaching the maximum value as derived from the **étendue** conservation theorem.
- Possibility to “invest” half of the system in more **advanced features** and use high tolerance budget we have.

Head Worn Displays

"A Playground for Freeform Surfaces"

Jannick Rolland

Brian J. Thompson Professor of Optical Engineering
The Institute of Optics, University of Rochester, NY

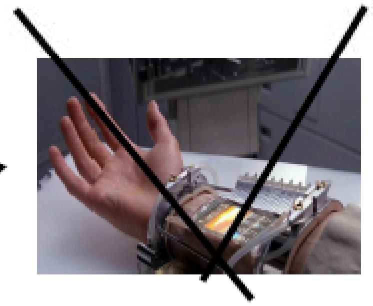
www.odalab-spectrum.org
(Optical Diagnostics and Applications Lab)

rolland@optics.rochester.edu

Research Focused on Optical See-Through

How do we want to Achieve OPTICAL SEE THROUGH

We have envisioned for some time that the future for Augmented Reality

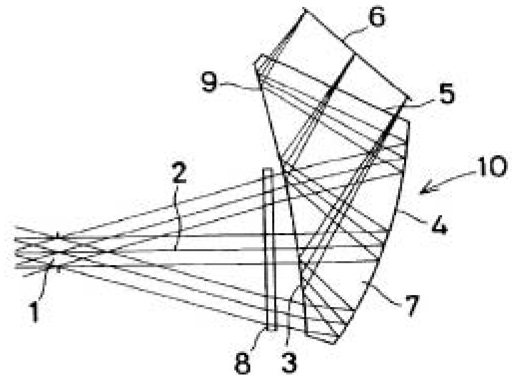


- Is hands-free (not hand-slaved) tech.

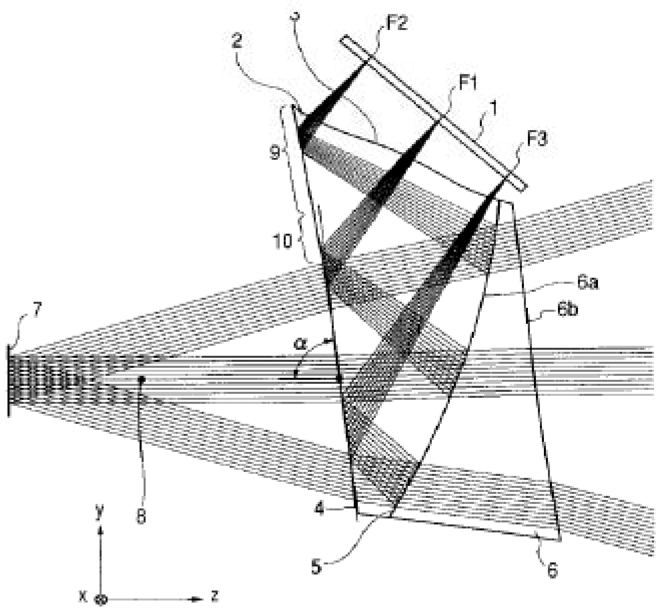
- Will display information in situ

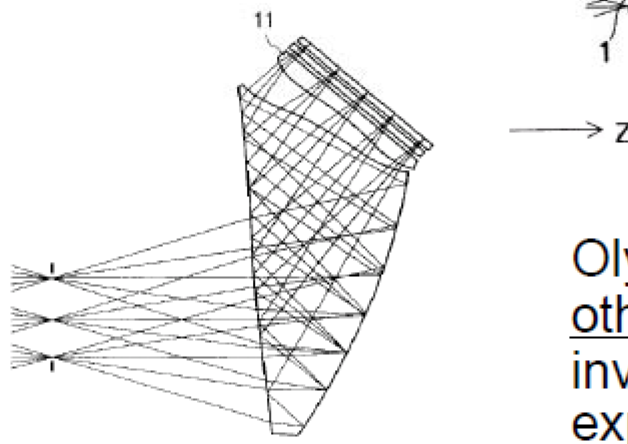
FreeForm Prism

Olympus
6,181,475



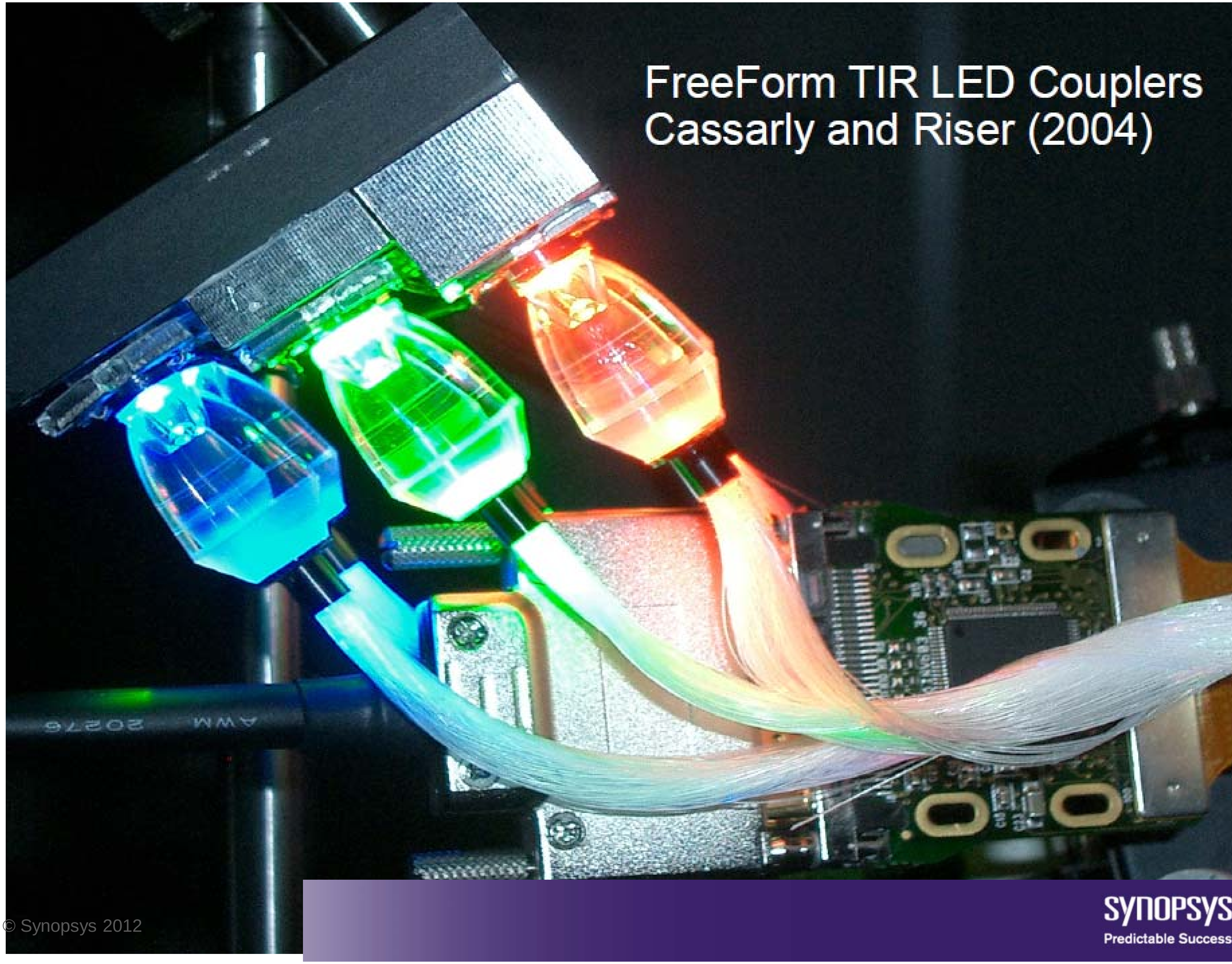
Canon
6,384,983



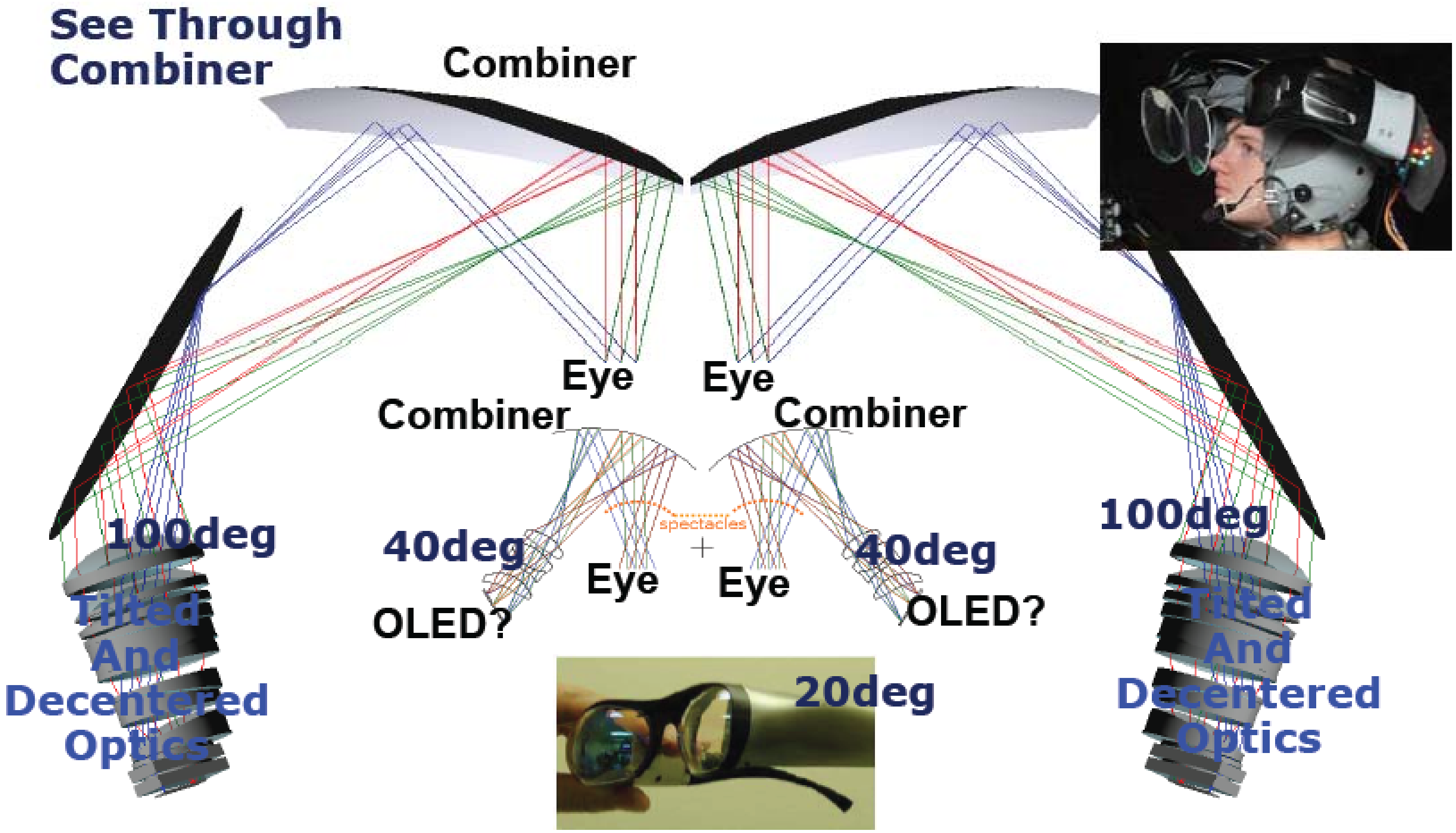


Olympus <u>and many others</u> have investigated and expanded on this design form.

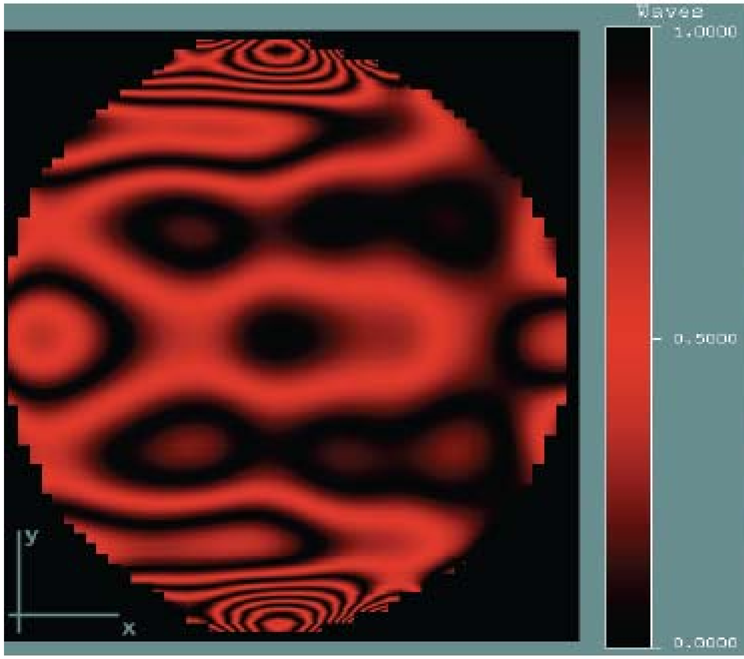
FreeForm TIR LED Couplers
Cassarly and Riser (2004)



Off-Combiner Designs Scalable from 20 to 100 deg.



Towards FreeForm Optics



HEAD-WORN DISPLAYS:

The Future Through **New Eyes**

Jannick Rolland and
Ozan Cakmakci

As display technologies shrink in size and **grow in sophistication**, digital "glasses" represent a **next generation** of mobile devices.

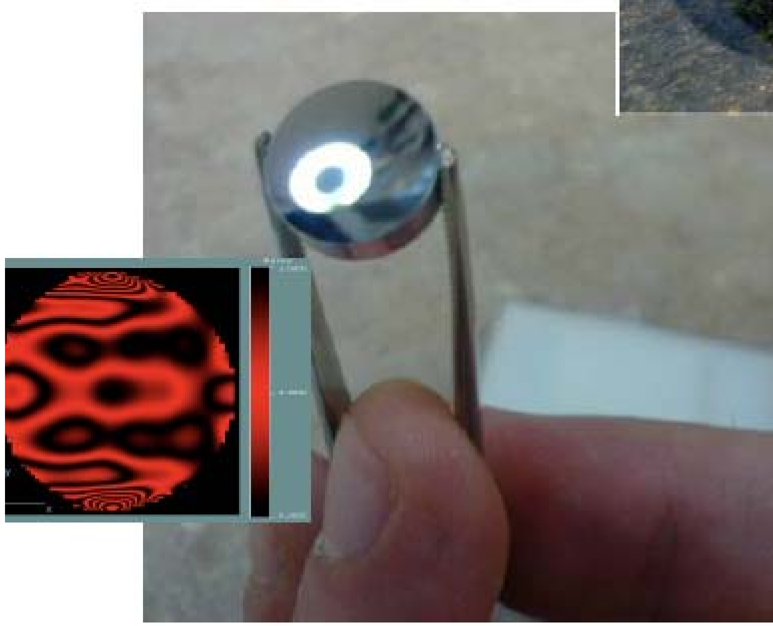
OPN April 2009

Freeform Optical Elements in HWDs

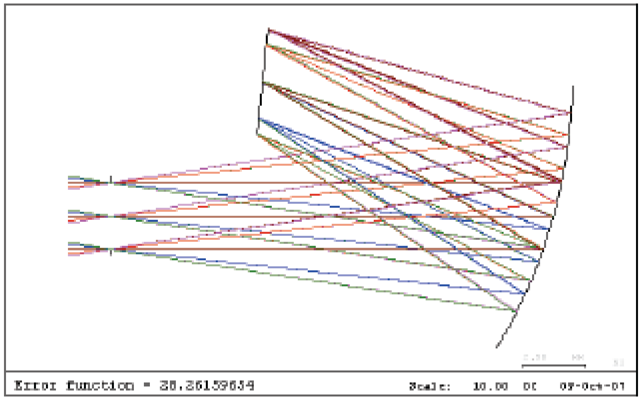
We have designed and also fabricated a first RBF-freeform surface

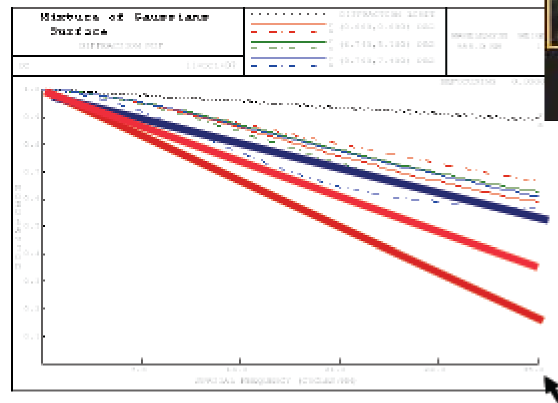
Revision Eyewear

Cakmakci et al., in SPIE **7618** 761803, 2010



Early Findings





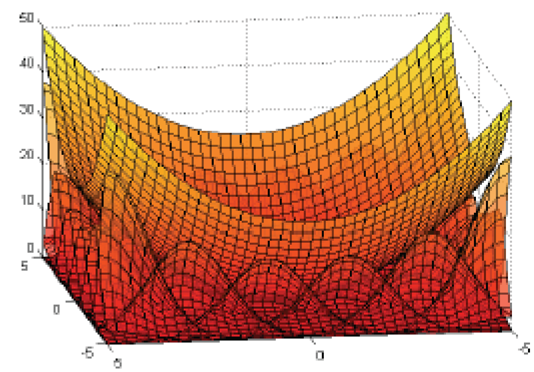
60%

43%

26%

1.5 arcmin

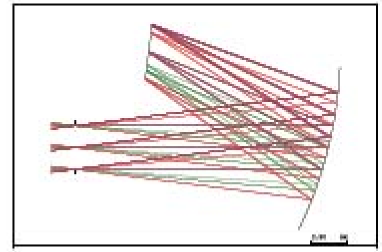
Surface type	Average MTF	Max. Distortion
Anamorphic asphere	26.5%	3.8%
X-Y polynomial	43.6%	2.65%
Zernike polynomial	42%	3.74%
RBFs	60.5%	3.6%

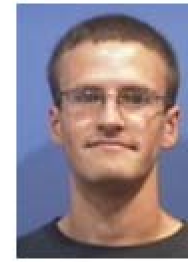


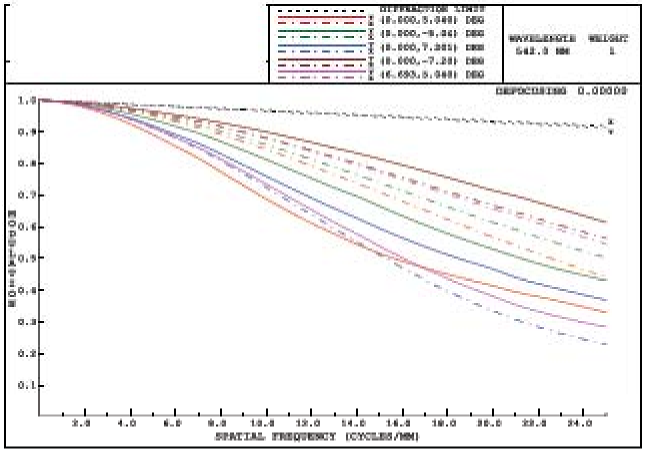
Cakmakci et al., Optics Express 16(3) (2008)

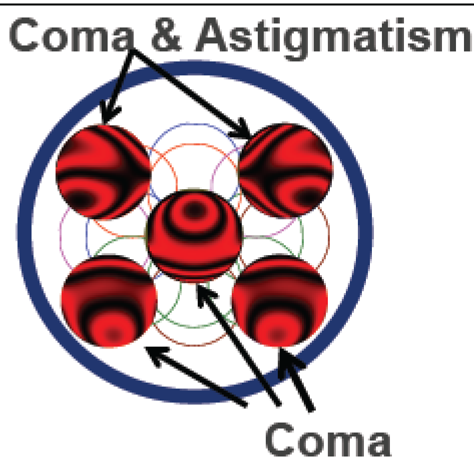
Freeform Optical Surfaces using Radial Basis Functions (RBFs)

(as a Generalization of Multivariate Polynomials)









With RBF Added