Capabilities of monocentric objective lenses

06/25/2013
Igor Stamenov, Ilya Agurok, Joe Ford

Outline:

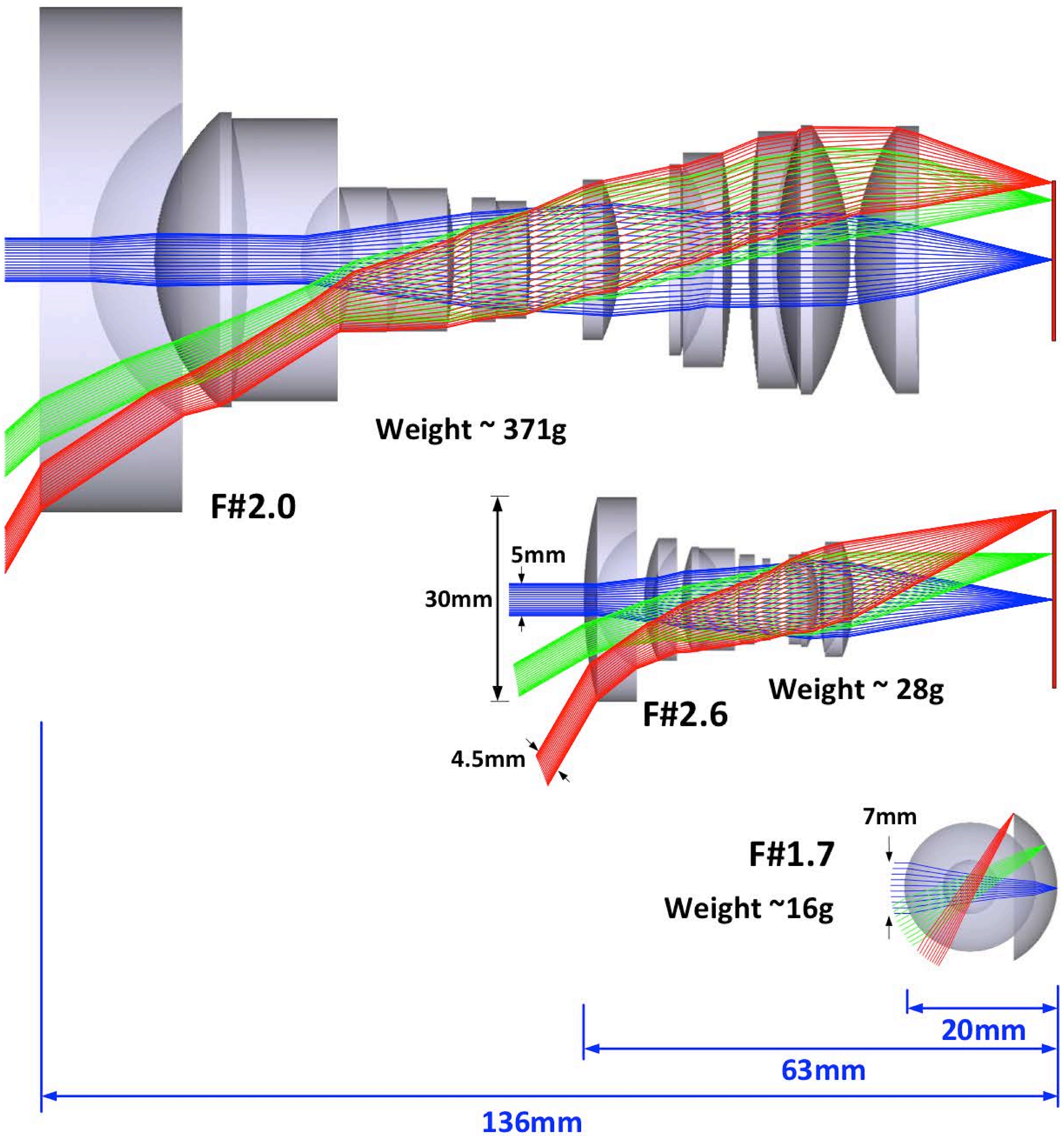
- Motivation and latest applications of monocentric objective lenses
- How to get to top designs of monocentric lenses in simple geometries
- How to push the lens performance and do the designs even better
- Tradeoffs between spectral band, F/#, and lens complexity

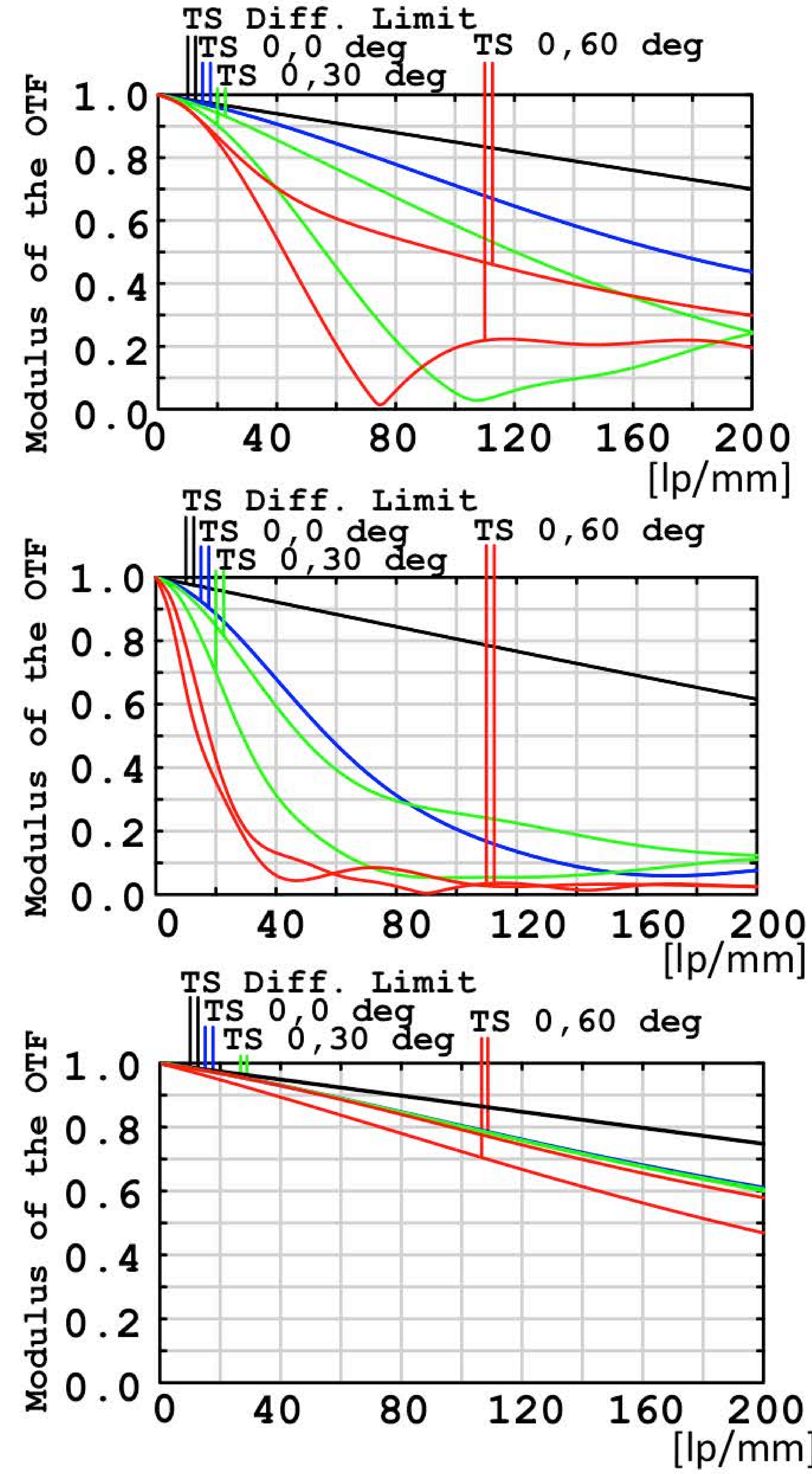
Monocentric imager vs single flat-focus lens

UCSD Photonics

SCENICC CEV imager design results:

f=12 mm large NA lenses implemented with convention retro-telephoto vs monocentric lens





Monocentric lenses offer compact wide-angle imaging with extraordinary light collection...

Given spherical image sensors with angle-selective coatings (or their equivalent).

Monocentric imagers in the standard lens taxonomy

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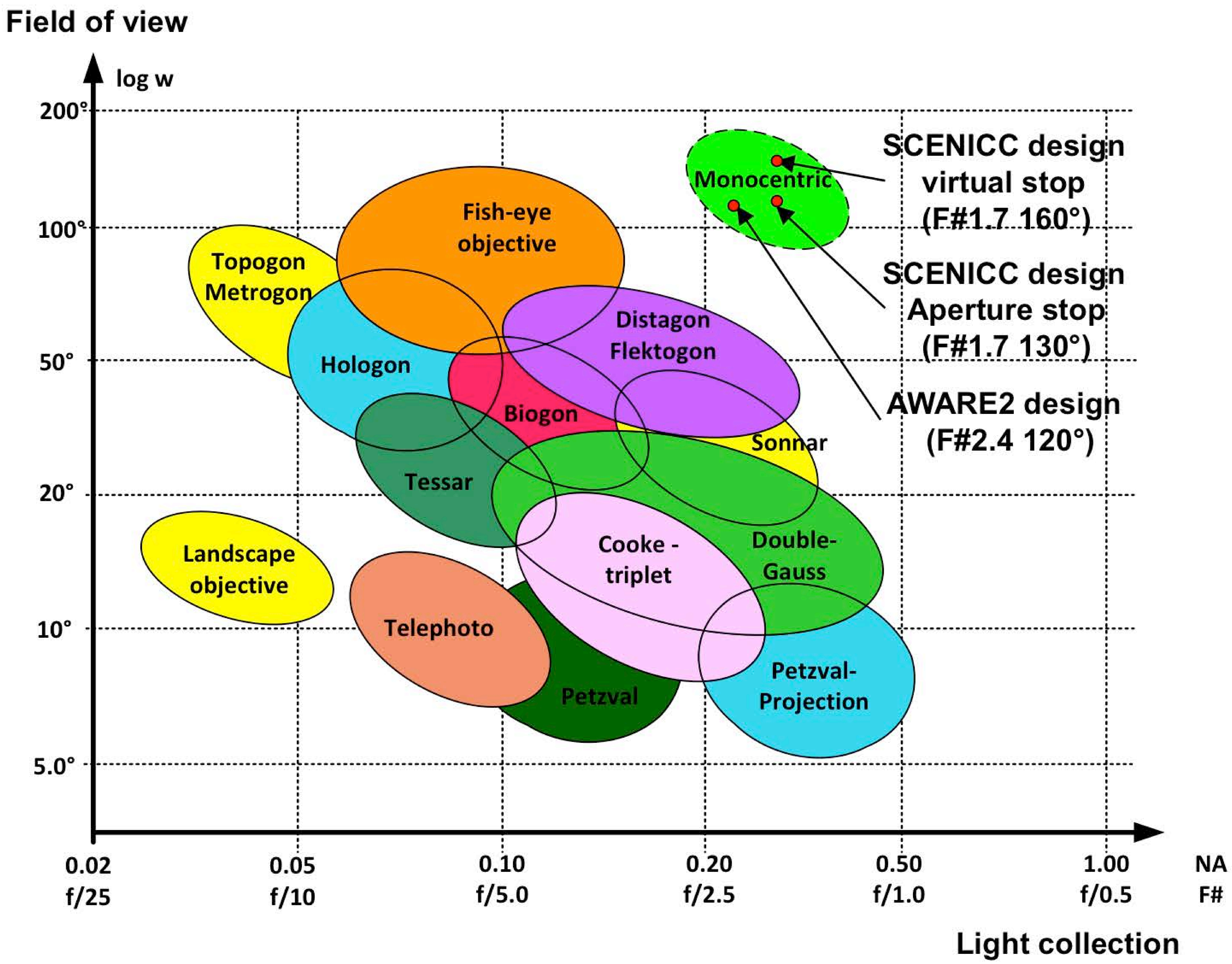
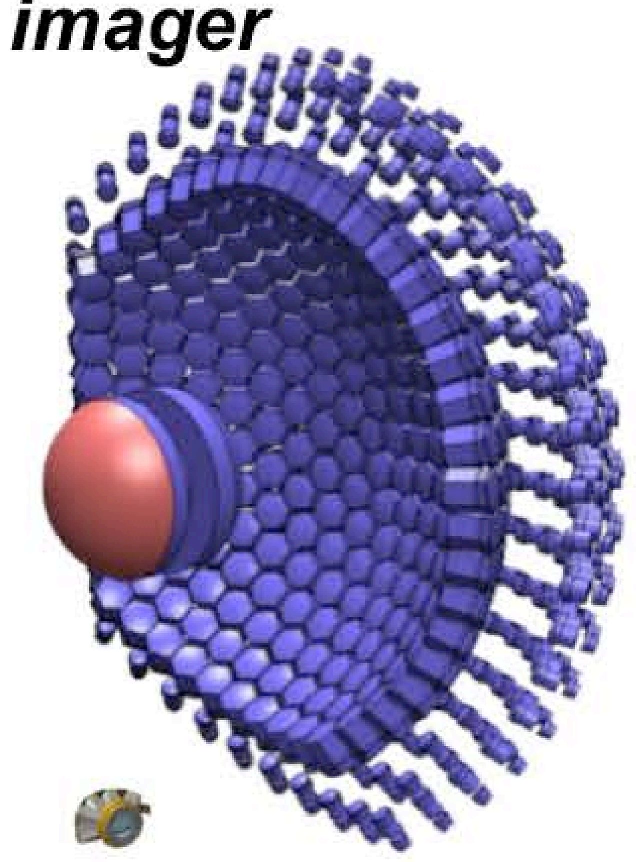
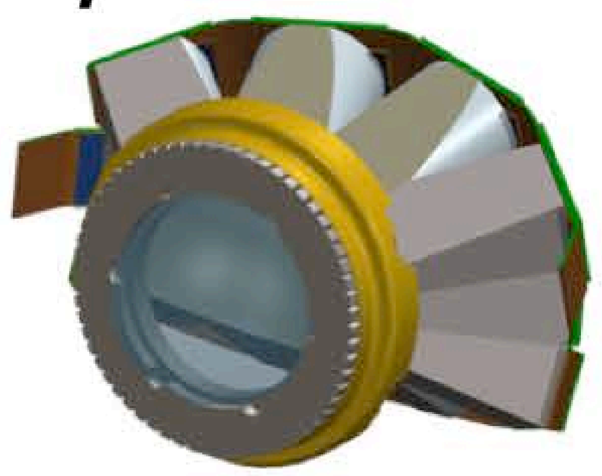


MOSAIC / AWARE-2 Monocentric multiscale prototype imager



SCENICC CEV Monocentric fiber-coupled imager optics



Conventional lenses fall into a standard lens taxonomy of field of view and F/#

Figure adapted from H. Gross, Handbook of Optical Systems 4 – Survey of Optical Instruments, Wiley 2008

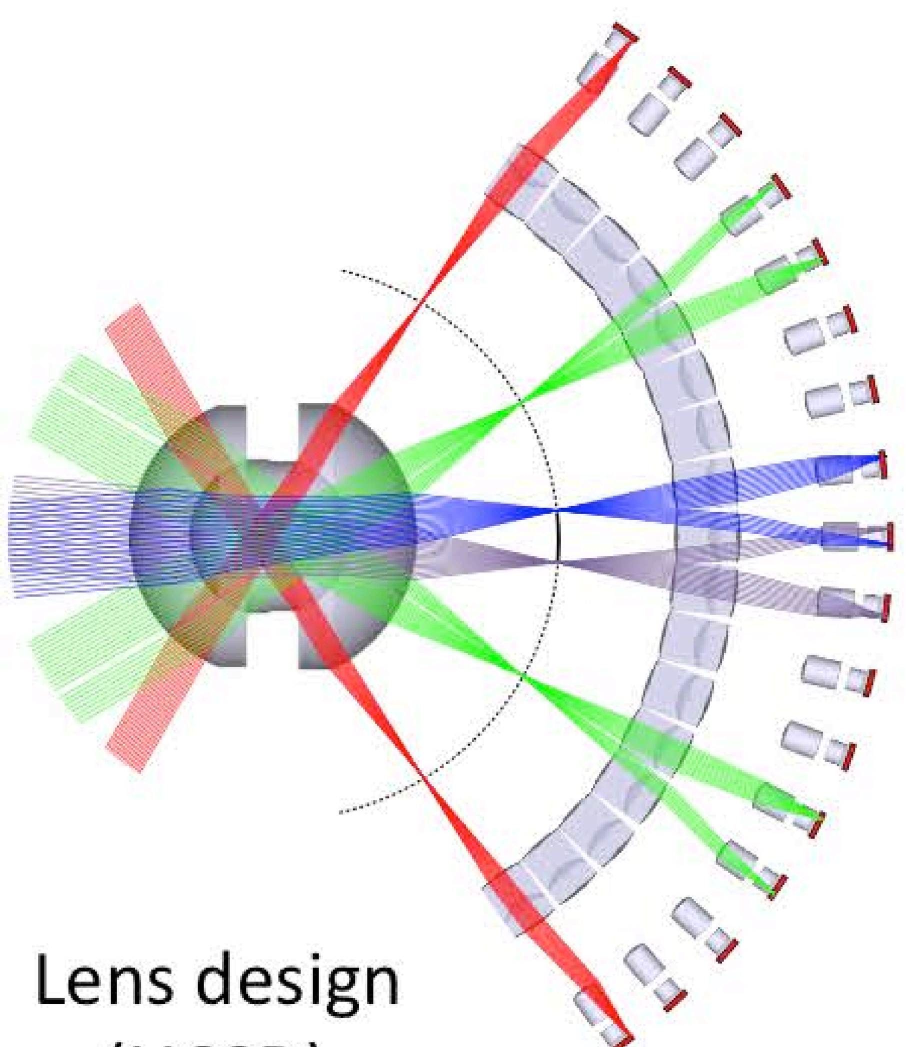
Monocentric systems (large & small) can provide excellent wide-angle performance

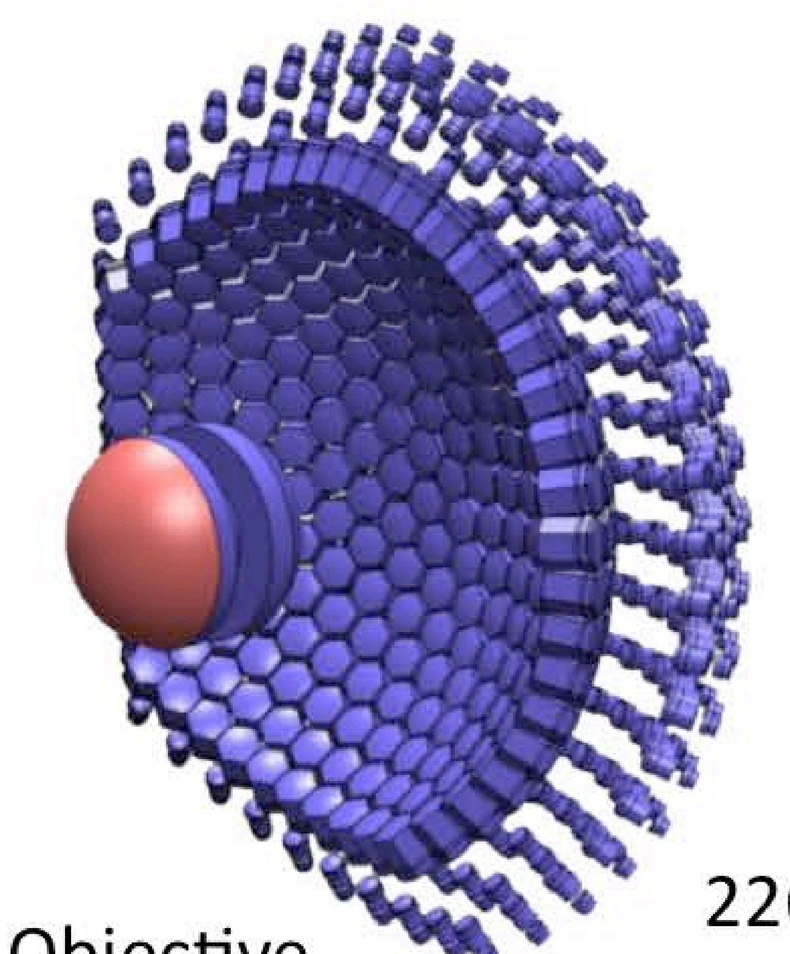
Significant improvement in light collection and physical volume relative to single-aperture, flat image plane objective lenses

DARPA's "AWARE" Wide Field Imaging Project (MOSAIC)

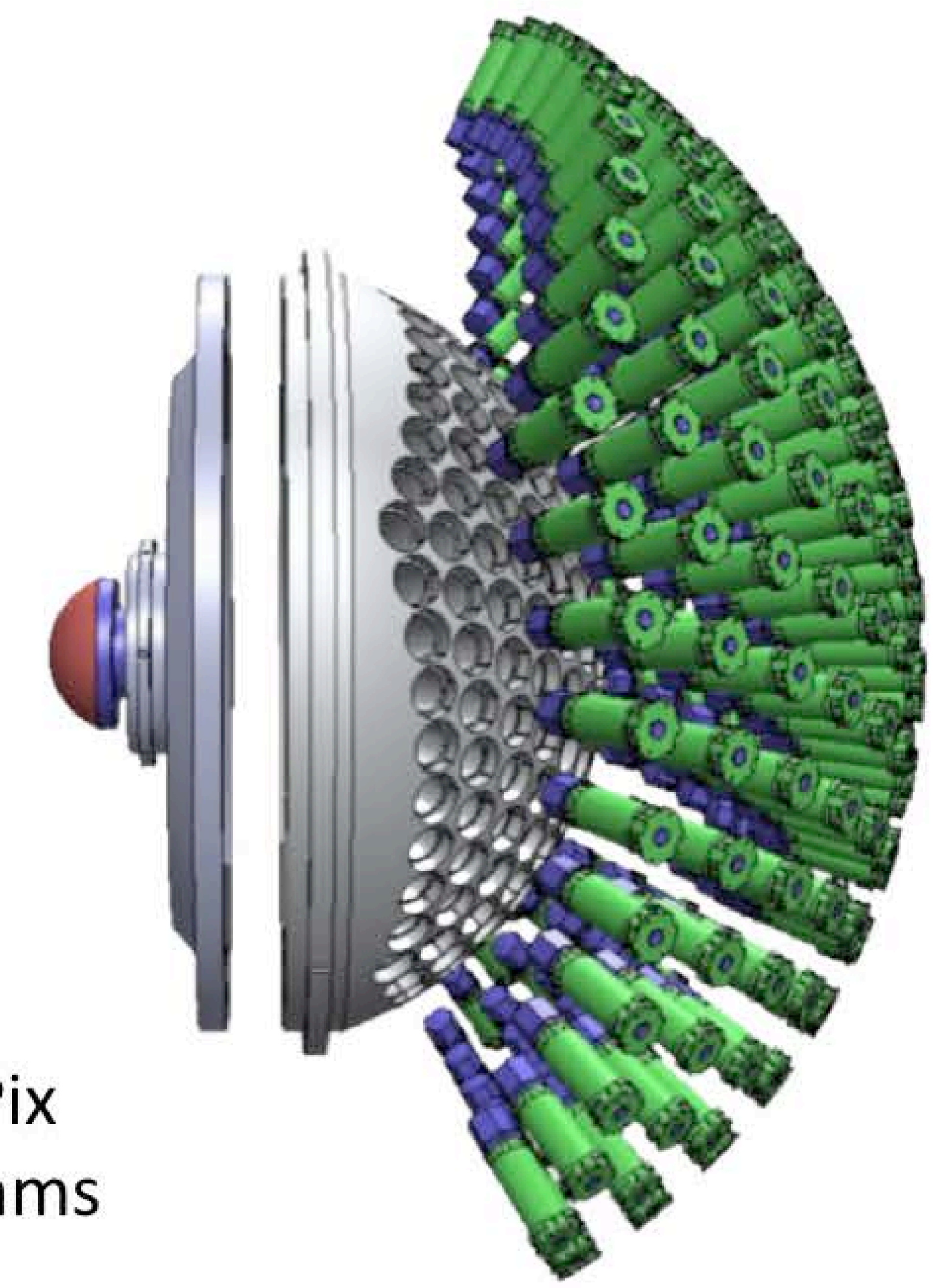
Duke University · Aptina · MIT · RPC Photonics · Distant Focus Corporation · Teledyne Scientific & Imaging · Raytheon · SAIC · UCSD · MTO DARPA Microsystems Technology Office

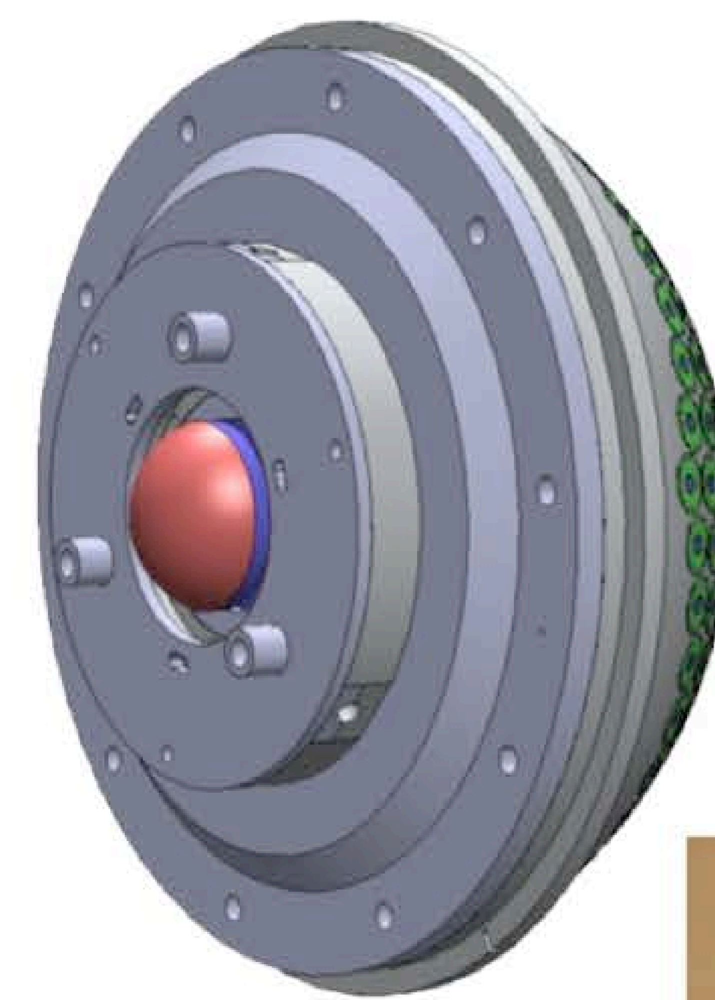
Multi-scale monocentric imager: 2400 Megapixels per image at up to 10 fps

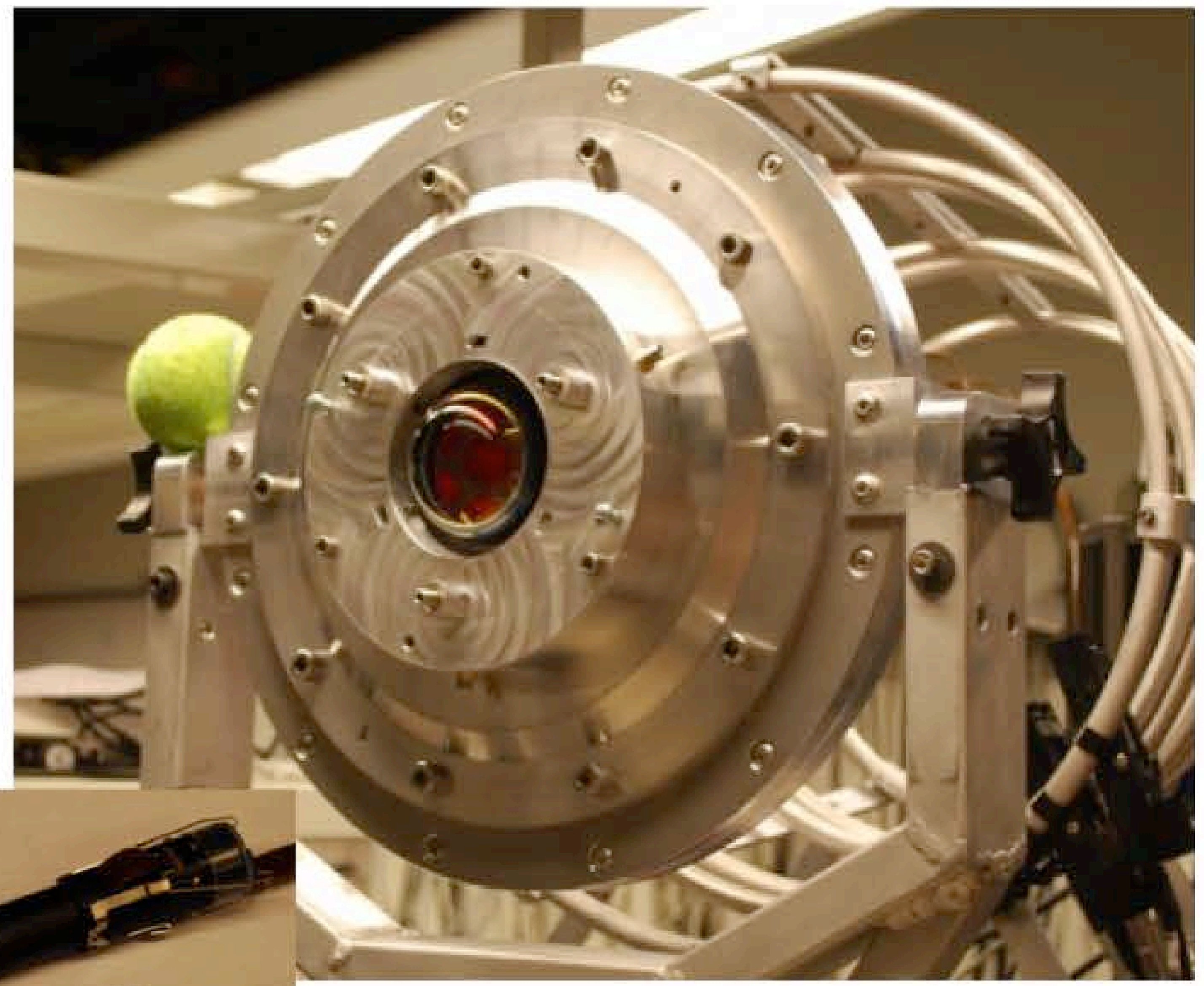

Lens design (UCSD)

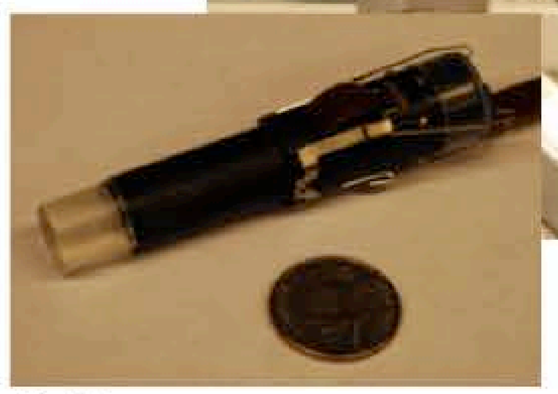

Objective Lens

226 14 MPix microcams

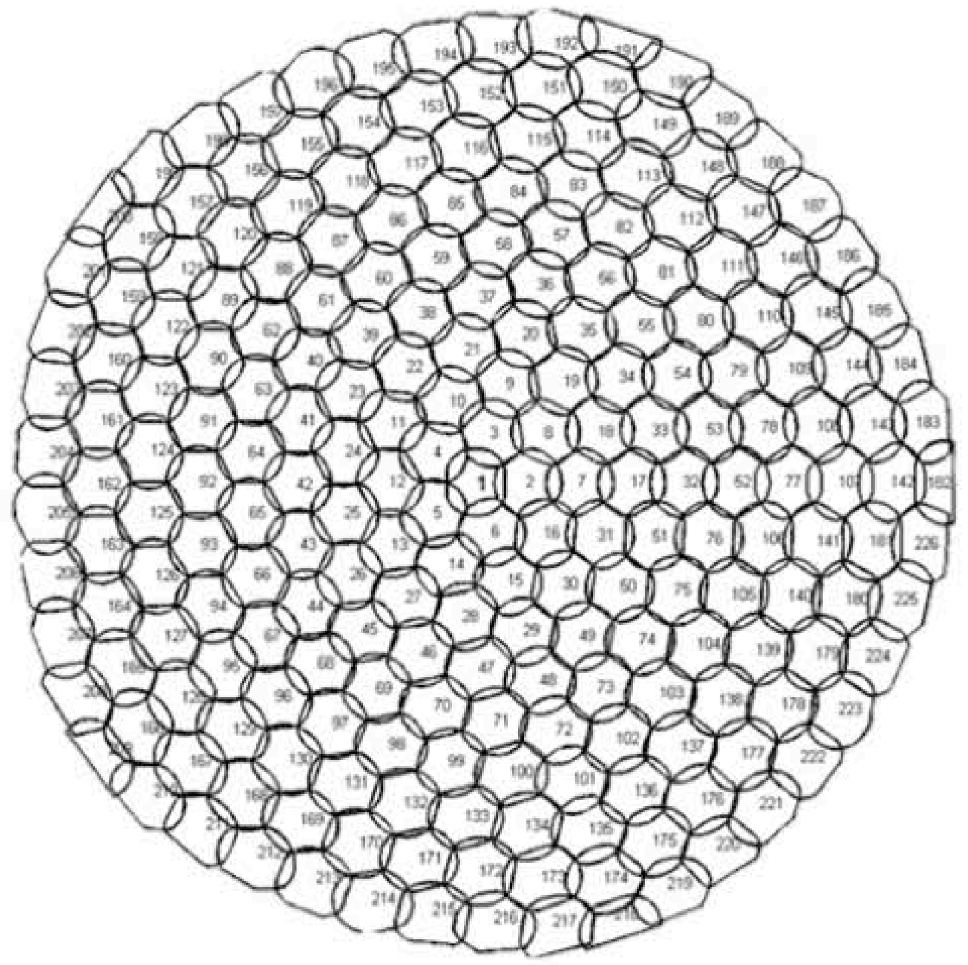





Optomechanics (Jungsang Kim)


Microcamera


David Brady (PI & technical lead)




Partial image captured Nov 2011

Soldier-Centric Imaging with Computational Cameras

SCENICC Computer-Enhanced Vision

SCENICC Performance Metrics		3D Optics Approach
Weight	<250g	Eye-Borne Optic w/ holographic/spectral filtering for lightweight wide-field HMD
Battery Life	24 hours	Multi-mode pixel and focal plane architectures for 100-1000x less power
%Shannon # Limit	>90%	Rapid eye tracker (10 ms) activation to full-resolution and data transfer
Resolution (foveal)	≤0.2mrad	8x less weight & 2000x less power than Nikon D3X DSLR w/ 14 mm f/2.8 lens
% Diffract Limit MTF	>75%	
Full / Zoom FOV	120° / 13°	
IFOV Latency	≤10ms	

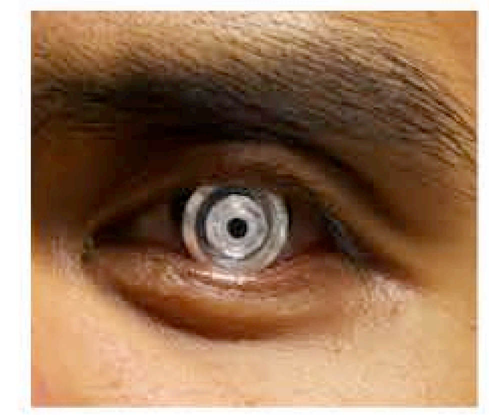
(1) Eye-tracked object-of-gaze brightness/contrast enhancement

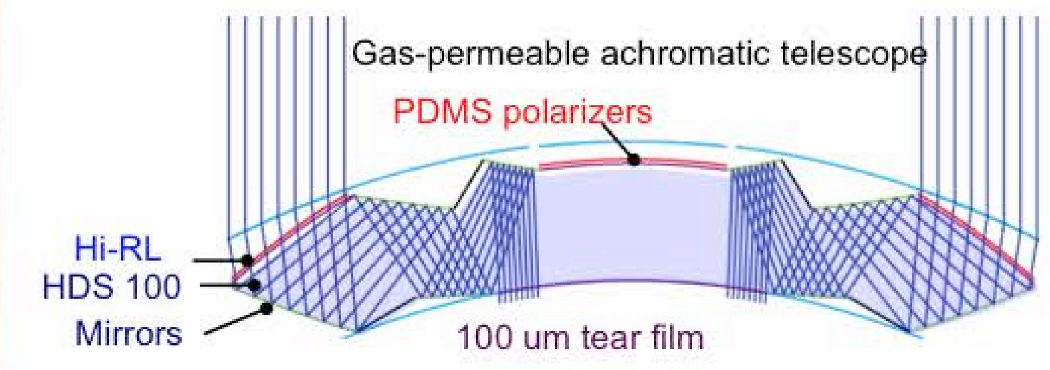
(2) Eye-tracked or object-tethered 3x-10x magnification

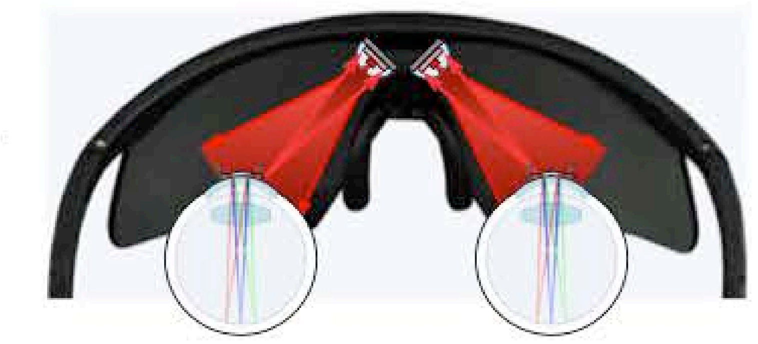
(3) High-level image processing

Eye-Borne Optics (Hands-Free Zoom and CEV display)

Precision eye tracking via optics embedded in scleral contact lens

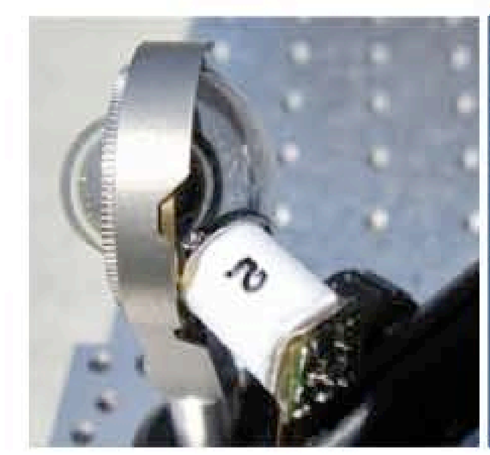


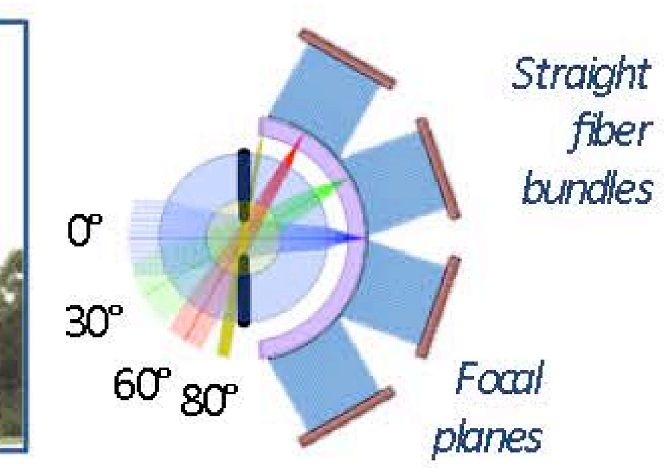


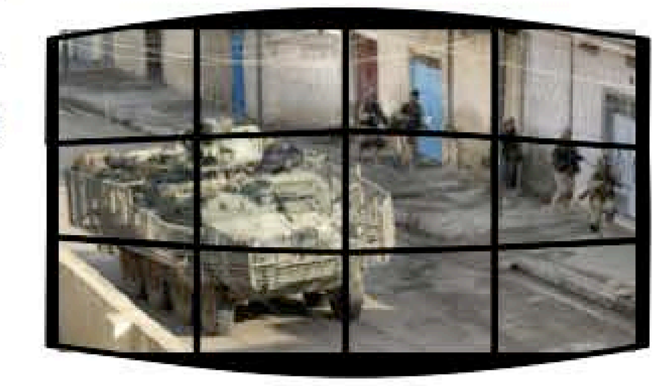


Computational Imaging

Foveated wide-field imager, 3D optics & multimodal focal planes

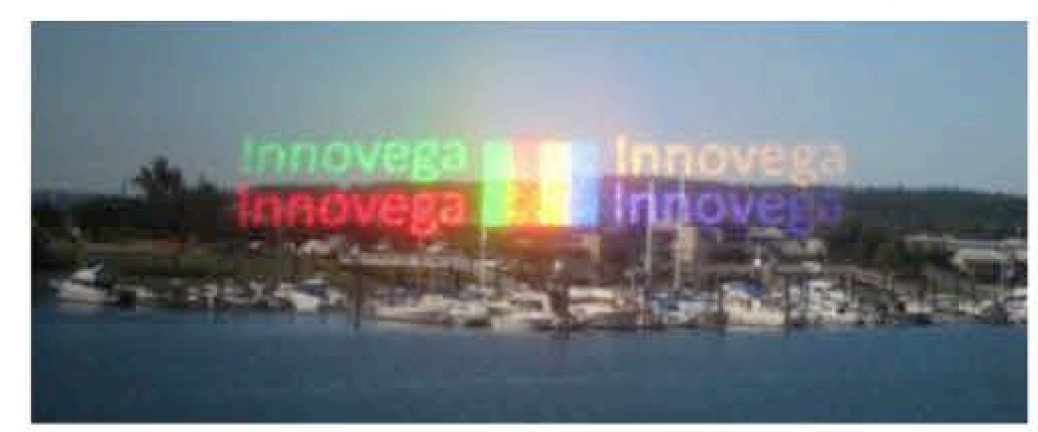


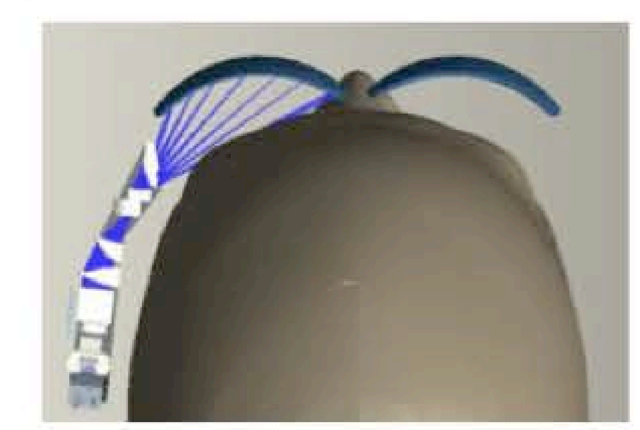


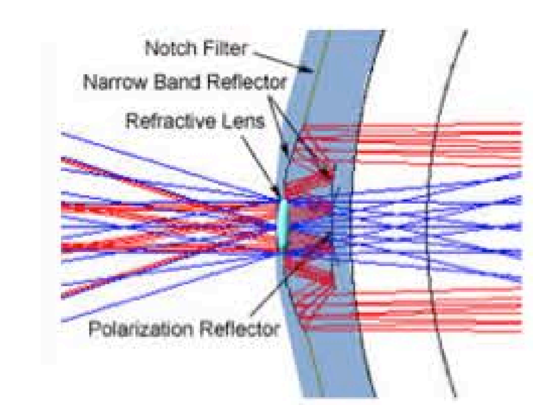


Human Interface

Dual-HD Head-Mounted Display projecting on transflective lenses







3DOptics Research:

(1) 3D Optical elements using fully 3-D structures at the macro / micro / nano-scale

(2) 3D Joint Optimization spanning the optical / electronic / computational domain.

(3) Foveation & eye-borne optics to minimize data flow and reduce system SWaP.

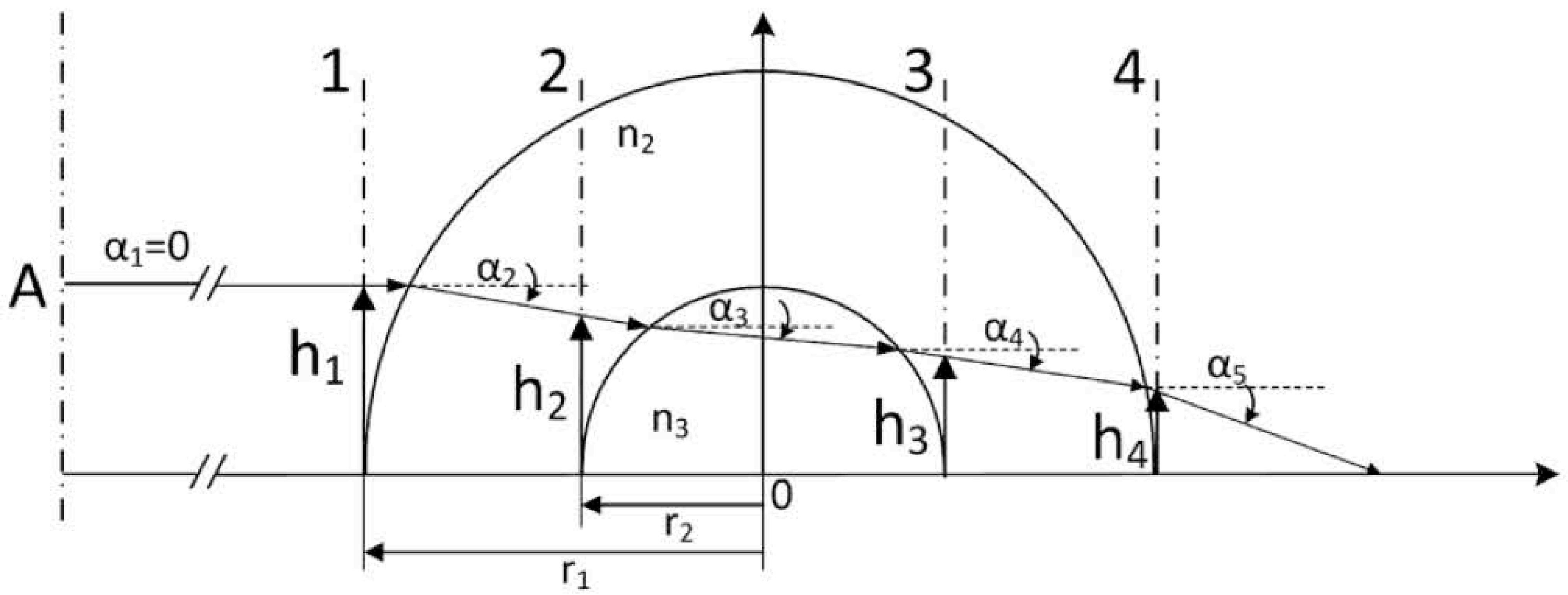
(4) Human Factors as the fundamental drivers of overall system interface & function.

Rockwell Collins · EPFL École Polytechnique Fédérale de Lausanne · FORZA · Draper Laboratory · Pacific Science & Engineering · Michigan · Distant Focus Corporation · innovega · Paragon Vision Sciences · MIT · AQT · Ascentia Imaging · CU · Lockheed Martin · UCSD

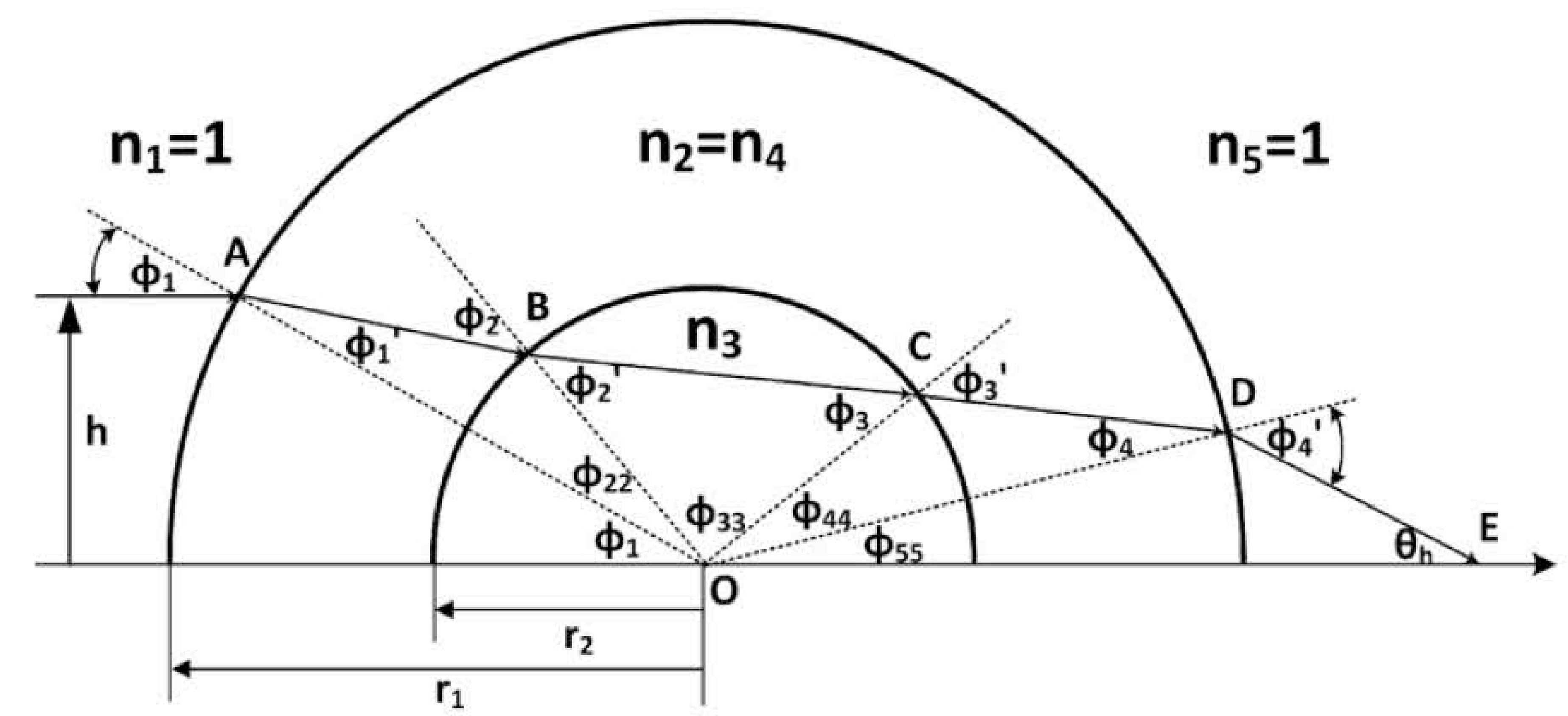
Initial approach: Monocentric 2 glass symmetric (2GS) geometry (3λ UCSD global search algorithm)

UCSD Photonics

1st step: 1st and 3rd order analysis



Exact raytracing analysis (3 wavelengths, multiple ray heights)



1st order approximation

$$\frac{1}{f}=\frac{2}{r_1}\left(1-\frac{1}{n_2}\right)+\frac{2}{r_2}\left(\frac{1}{n_2}-\frac{1}{n_3}\right)$$

$$B=\frac{1}{2}\sum_{s=1}^{4}h_s\left(\frac{\alpha_{s+1}-\alpha_s}{\frac{1}{n_{s+1}}-\frac{1}{n_s}}\right)^2\left(\frac{\alpha_{s+1}}{n_{s+1}}-\frac{\alpha_s}{n_s}\right)$$

$$W_{040}=\frac{1}{4}B\rho^4\overset{\rho=1}{=}\frac{1}{8}\sum_{s=1}^{4}h_s\left(\frac{\alpha_{s+1}-\alpha_s}{\frac{1}{n_{s+1}}-\frac{1}{n_s}}\right)^2\left(\frac{\alpha_{s+1}}{n_{s+1}}-\frac{\alpha_s}{n_s}\right)$$

$$W_{040}=h_1^4\left(\begin{array}{l}-\frac{\left(n_2^2-3n_2n_3+n_3^2\right)}{32f^3\left(n_2-n_3\right)^2}-\frac{\left(n_2-1\right)\left(n_2^2-n_3\right)\left(n_3-1\right)}{4n_2^2\left(n_2-n_3\right)^2r_1^3}+\\ +\frac{\left(n_2-1\right)^2\left(n_2^2+n_2n_3+n_3^2\right)}{8fn_2^2\left(n_2-n_3\right)^2r_1^2}-\frac{\left(n_2-1\right)\left(n_2^2+n_2n_3+n_3^2\right)}{16f^2n_2\left(n_2-n_3\right)^2r_1}\end{array}\right)$$

$$L_0=-2W_{020}=h_1^2\left(\frac{\left(n_3-1\right)\left(2f\left(1-n_2\right)+n_2r_1\right)}{f\left(n_2-n_3\right)r_1n_3v_3}-\frac{\left(n_2-1\right)\left(2f\left(1-n_3\right)+n_3r_1\right)}{f\left(n_2-n_3\right)r_1n_2v_2}\right)$$

$$\overline{OE}=S=\frac{h}{\sin\left\{2\left[\arcsin\left(\frac{h}{r_1}\right)-\arcsin\left(\frac{h}{r_1n_2}\right)+\arcsin\left(\frac{h}{r_2n_2}\right)-\arcsin\left(\frac{h}{r_2n_3}\right)\right]\right\}}$$

$$\Delta S\left(h_i\right)=S\left(h_i\right)-f$$

$$Q=\sum_{i=1}^{3}Abs\left(\Delta S\left(h_i,\lambda\right)\right)+\sum_{j=1}^{3}\sum_{k\neq j}Abs\left[\Delta S\left(h_j,\lambda\right)-\Delta S\left(h_k,\lambda\right)\right]$$

$$\left(\Delta\Phi\right)^2=\overline{\Phi^2}-\left(\overline{\Phi}\right)^2=\frac{1}{2}\sum_{i=1}^{3}\left\{\frac{\left[C_{20}^{new}\left(\lambda_i\right)\right]^2}{3}+\frac{\left[C_{40}\left(\lambda_i\right)\right]^2}{5}+\frac{\left[C_{60}\left(\lambda_i\right)\right]^2}{7}+\frac{\left[C_{80}\left(\lambda_i\right)\right]^2}{9}\right\}$$

Brute force algorithm runs within minutes:
Computation of 312.000 glass combinations from existing catalogs.

LIMITATION: narrow wavebands with close to linear glass dispersion

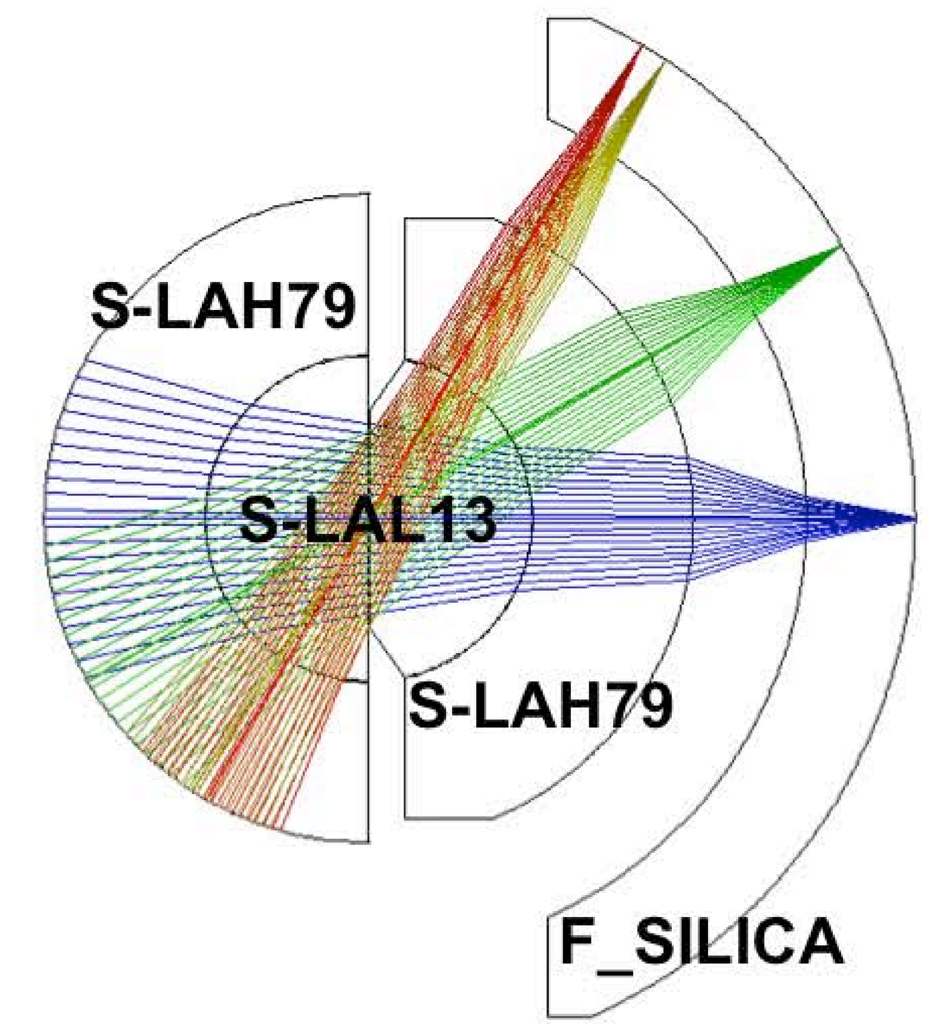
Igor Stamenov, Ilya P. Agurok, Joseph E. Ford,
"Optimization of two-glass monocentric lenses for compact panoramic imagers: general aberration analysis and specific designs," Appl. Opt. **51**,7648-7661 (2012);

Lens fabricated for SCENICC Y1 demo (3λ search algorithm)

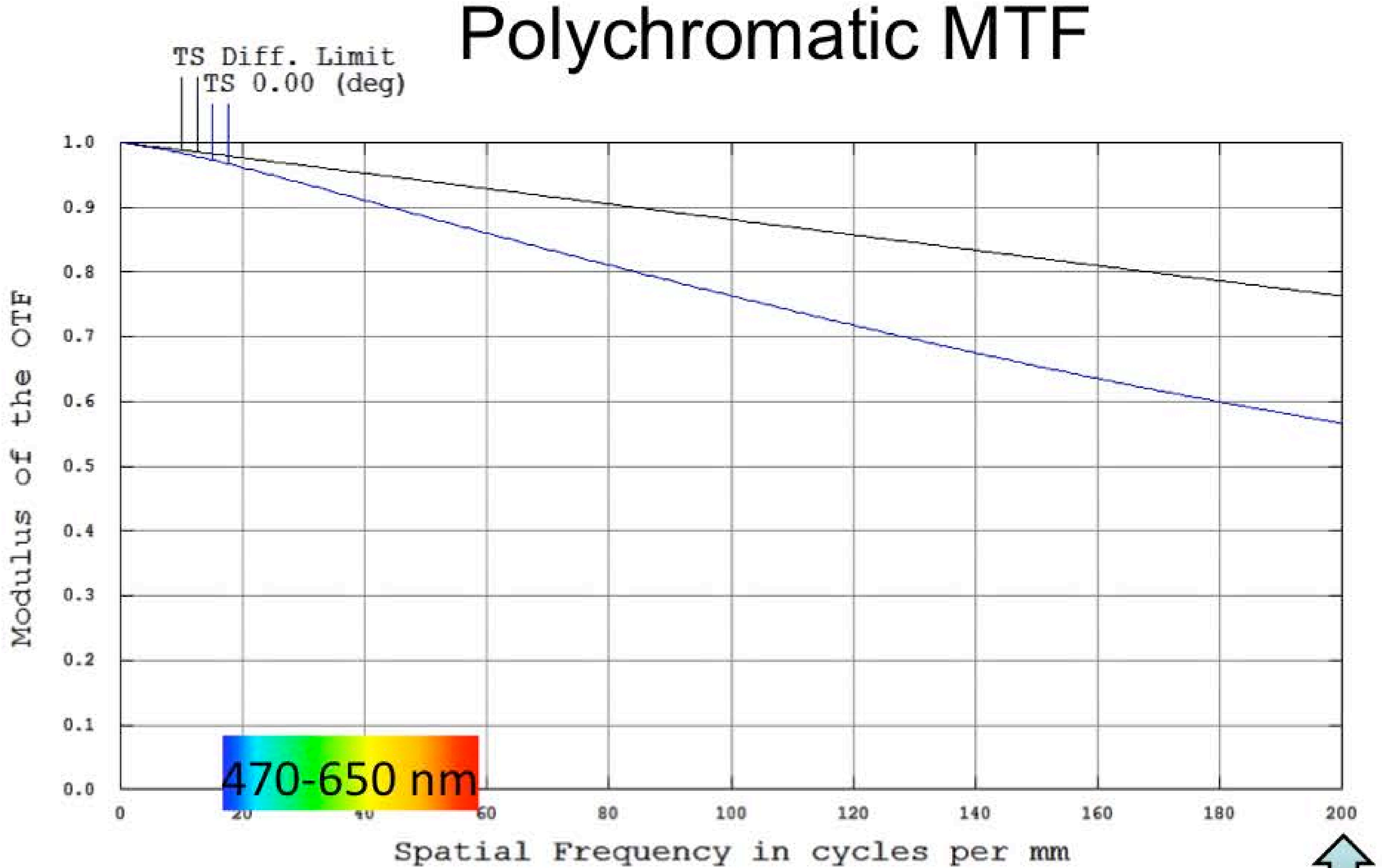
UCSD Photonics

470-650nm CEV F1.715 f=12mm, fused silica meniscus present for mounting purposes

Surf	Type	Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				Infinity	
1*	Standard		7.15000		3.54539		S-LAH79		7.15000	U
2*	Standard		3.59900		1.0000E-002		1.56,43.0		3.59900	U
3*	Standard		3.58900		3.58900	P	S-LAL13		3.58900	U
4	Standard		Infinity		5.0000E-003		1.56,43.0	P	2.41641	
STO	Standard		Infinity		5.0000E-003		1.56,43.0	P	2.39185	
6*	Standard		Infinity		3.58900	P	S-LAL13	P	2.38000	U
7*	Standard		-3.58900	P	1.0000E-002	P	1.56,43.0	P	3.50000	U
8*	Standard		-3.59900	P	3.54539	P	S-LAH79	P	3.51000	U
9*	Standard		-7.15000	P	2.48990	V			6.60000	U
10*	Standard		-9.63500		2.40000		F_SILICA		8.80000	U
11*	Standard		-12.03400		0.00000				11.00000	U
IMA	Standard	final im	-12.03400	P	-				10.42840	



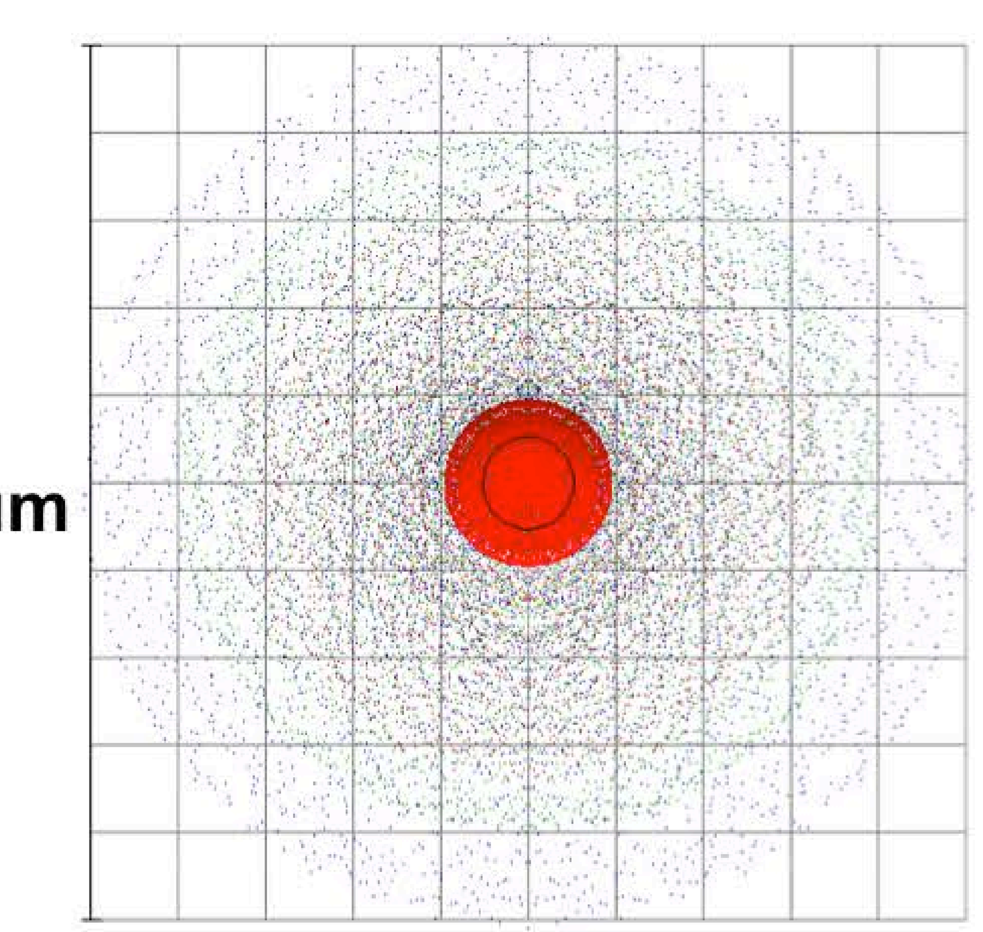
Polychromatic MTF



200cyc/mm

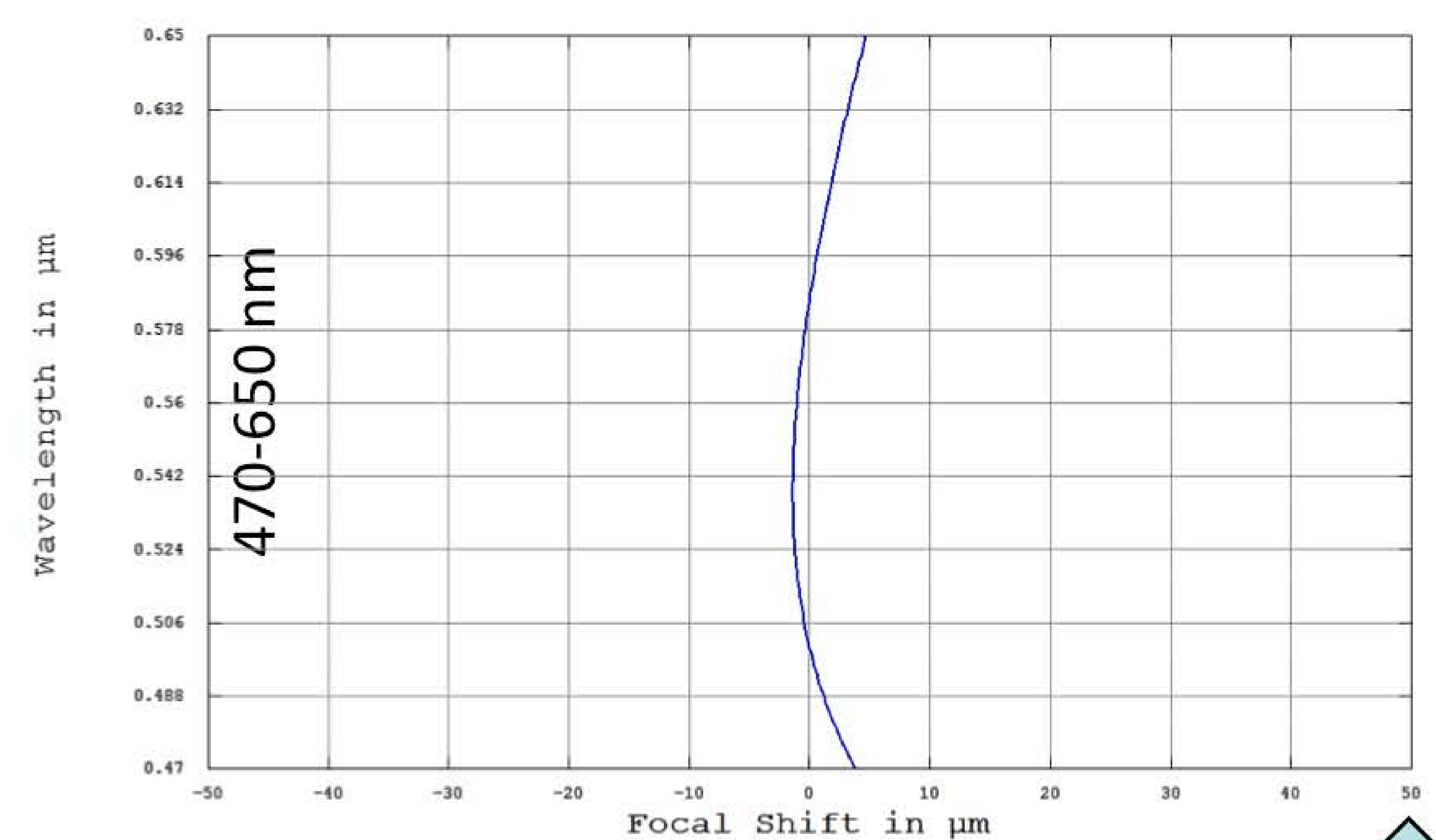
Spot size

20um



RMS 2.41um

Chromatic focal shift



50µm

DARPA's SCENICC Project : CEV camera

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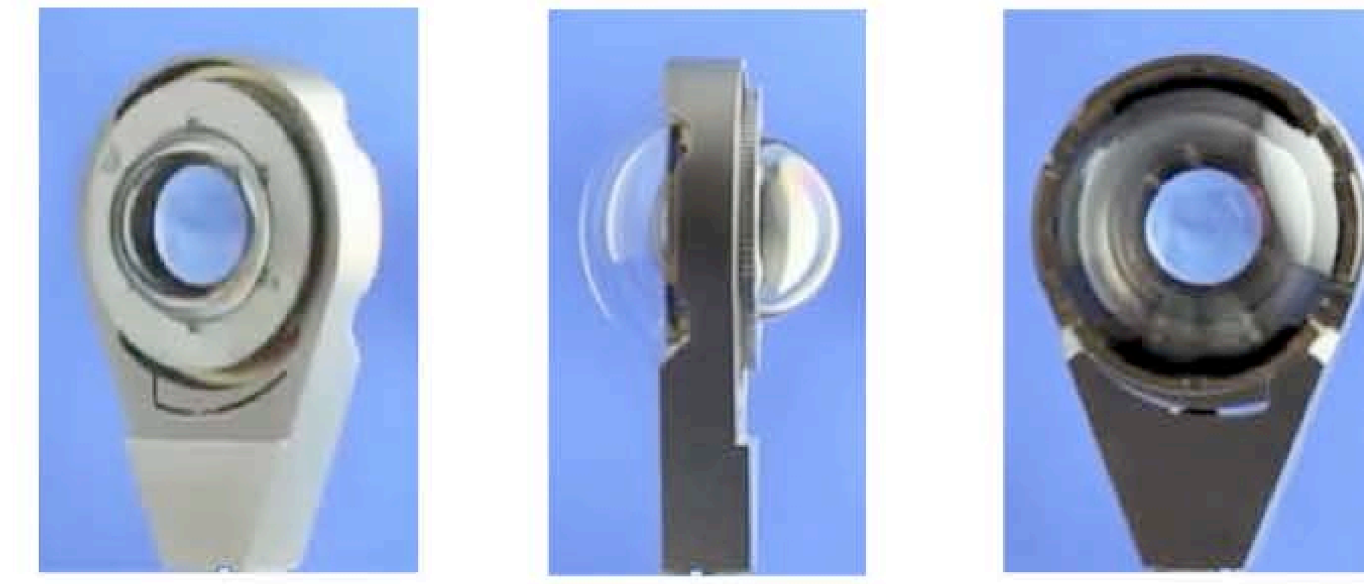
CEV: 12mm EFL F1.7 wide FOV imager

2-glass ball objective lens

12 mm radius meniscus lens (fiber bundle mounting surface)



Optomechanical mount (with mechanical focus)

Canon F/4 "fisheye" lens -60˚ field

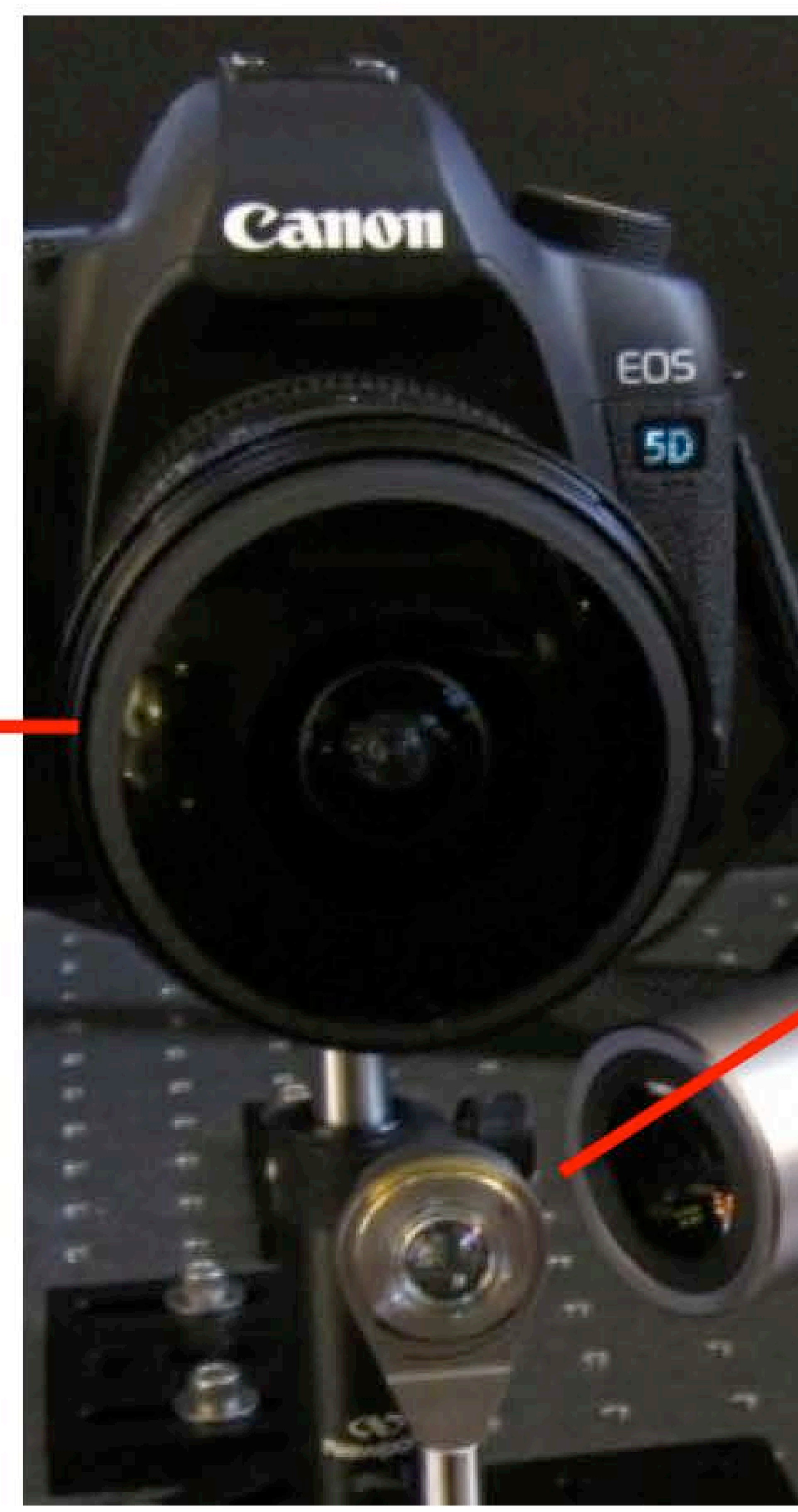
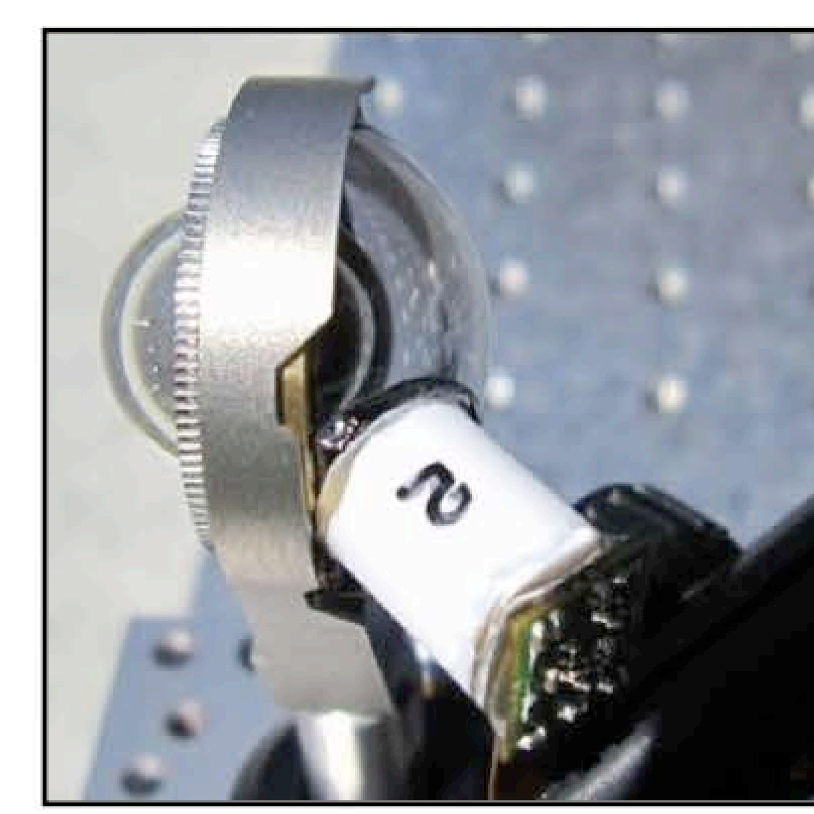


Image taken with Canon DSLR Fisheye lens : low resolution, visible chromatic aberration and distortion.

SCENICC F/2 CEV: -60° field

Microscope imaging of monocentric lens image surface indicates high resolution even at full 60° field at 10X smaller weight and volume with 4X light energy collection.

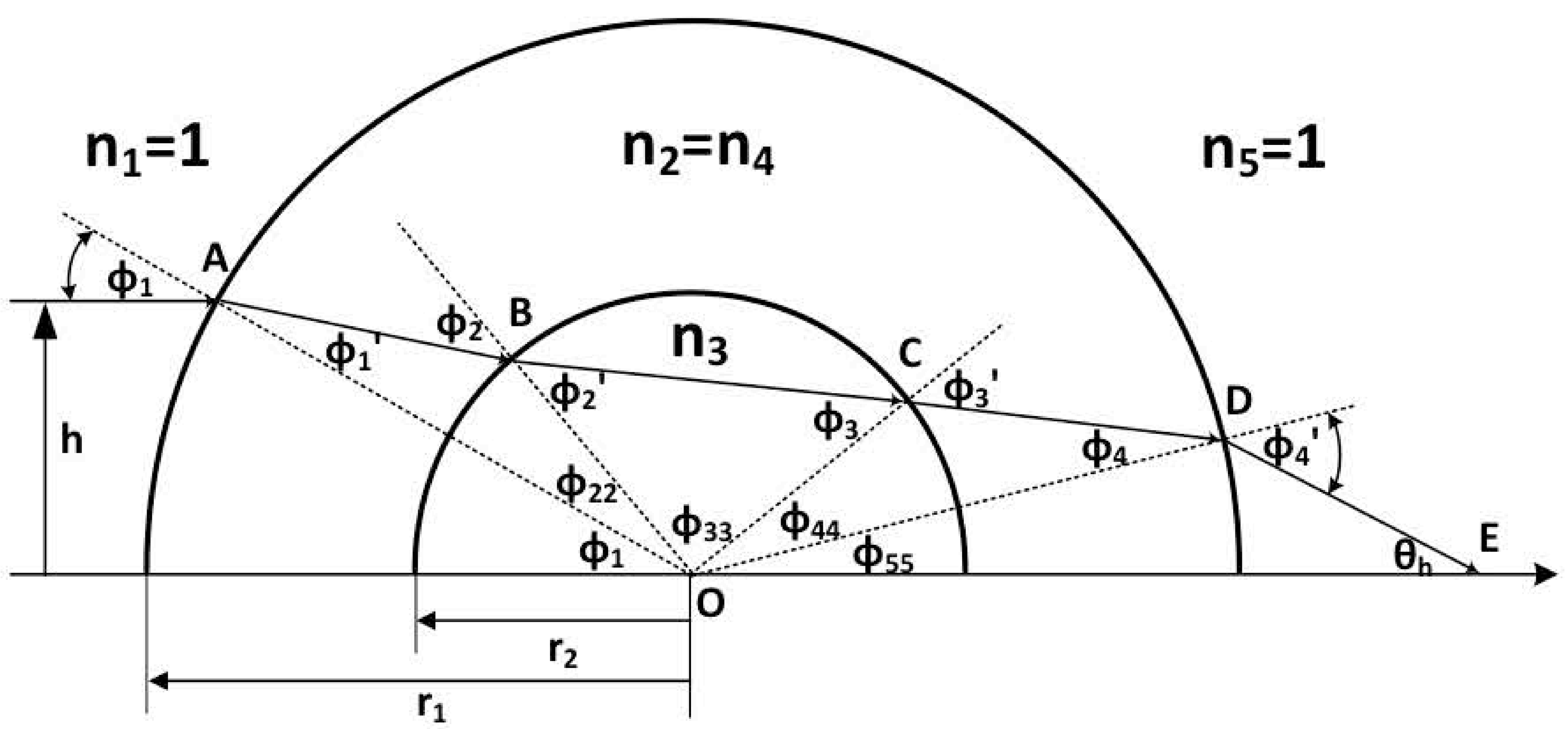


Initial result of fiber coupled imager.

1st improvement: 2&3-glass global optimization algorithm (5λ)

Symmetric 2 glass geometry

Exact raytracing analysis (5 wavelengths, multiple ray heights)
Modified 3λ algorithm with aim to address wider wavebands.



1st order approximation $\frac{1}{f}=\frac{2}{r_1}\left(1-\frac{1}{n_2}\right)+\frac{2}{r_2}\left(\frac{1}{n_2}-\frac{1}{n_3}\right)$

$$\overline{OE}=S=\frac{h}{\sin\left\{2\left[\arcsin\left(\frac{h}{r_1}\right)-\arcsin\left(\frac{h}{r_1 n_2}\right)+\arcsin\left(\frac{h}{r_2 n_2}\right)-\arcsin\left(\frac{h}{r_2 n_3}\right)\right]\right\}}$$

$$\Delta S(h_i)=S(h_i)-f$$

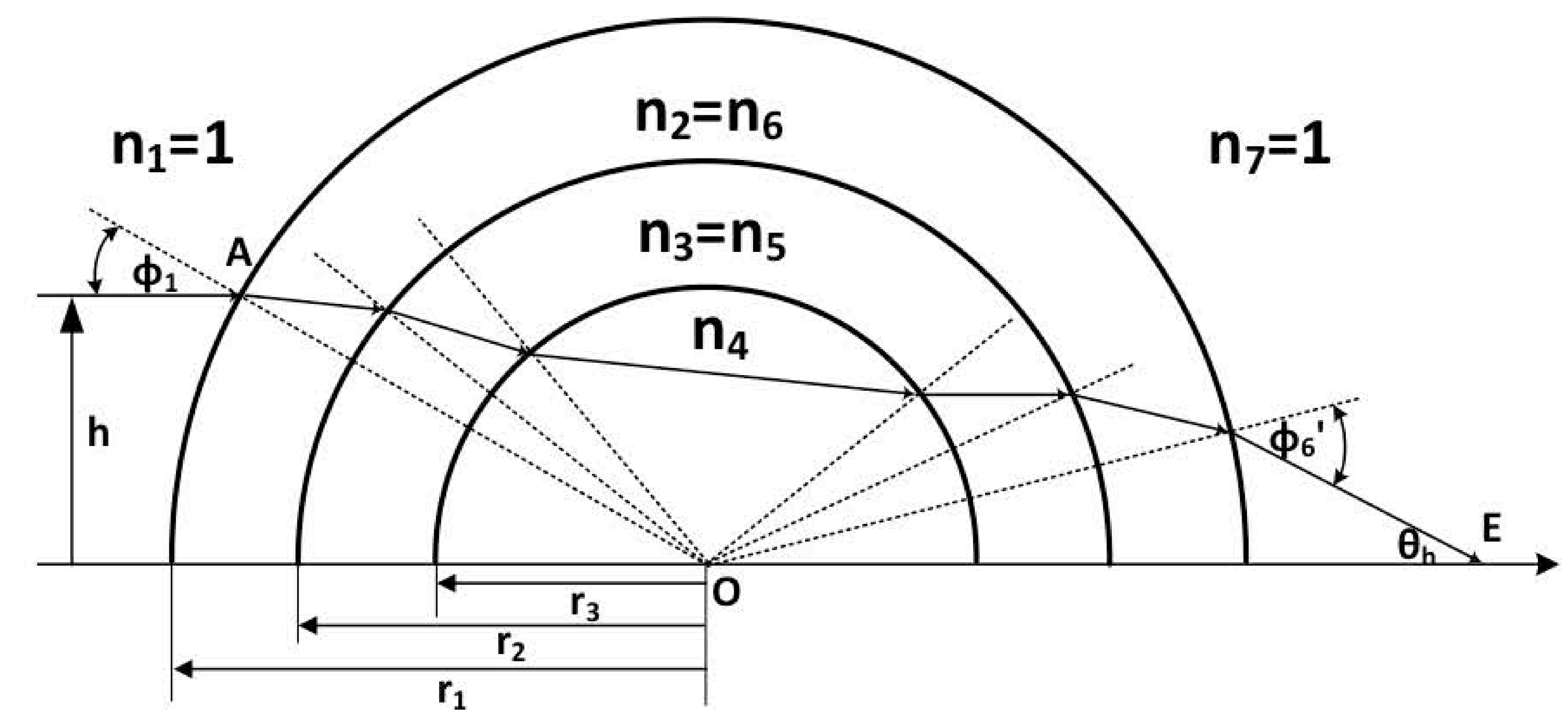
$$Q=\sum_{i=1}^{5}Abs\left(\Delta S(h_i,\lambda)\right)+\sum_{j=1}^{5}\sum_{k\neq j}Abs\left[\Delta S(h_j,\lambda)-\Delta S(h_k,\lambda)\right]$$

$$(\Delta\Phi)^2=\overline{\Phi^2}-(\overline{\Phi})^2=\frac{1}{2}\sum_{i=1}^{5}\left\{\frac{\left[C_{20}^{new}(\lambda_i)\right]^2}{3}+\frac{\left[C_{40}(\lambda_i)\right]^2}{5}+\frac{\left[C_{60}(\lambda_i)\right]^2}{7}+\frac{\left[C_{80}(\lambda_i)\right]^2}{9}\right\}$$

(runs 8min on 12 physical CPU cores)
(2 x Intel 3.1GHz Xeon E5-2687W)

Symmetric 3 glass geometry

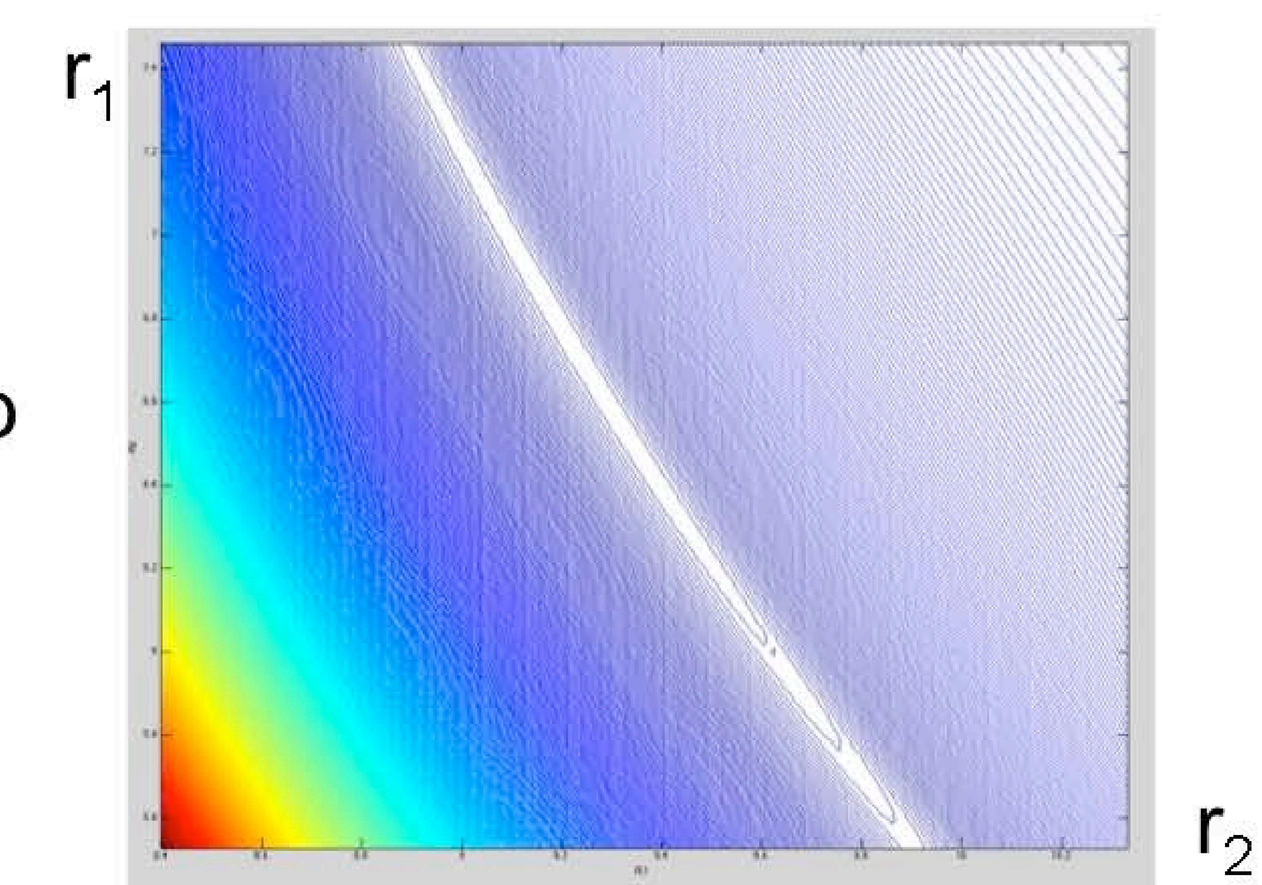
Exact raytracing analysis (5 wavelengths, multiple ray heights)
Extension of 2 glass global search algorithm as an attempt to improve designs over large scales and broader wavebands.
Air is one of the materials consider -> 2-glass symmetric air gap.



1st order approximation $\frac{1}{f}=\frac{2}{r_1}\left(1-\frac{1}{n_2}\right)+\frac{2}{r_2}\left(\frac{1}{n_2}-\frac{1}{n_3}\right)+\frac{2}{r_3}\left(\frac{1}{n_3}-\frac{1}{n_4}\right)$

$$\overline{OE}=S=\frac{h}{\sin\left\{2\left[\arcsin\left(\frac{h}{r_1}\right)-\arcsin\left(\frac{h}{r_1 n_2}\right)+\arcsin\left(\frac{h}{r_2 n_2}\right)-\arcsin\left(\frac{h}{r_2 n_3}\right)+\arcsin\left(\frac{h}{r_3 n_3}\right)-\arcsin\left(\frac{h}{r_3 n_4}\right)\right]\right\}}$$

One radius is predetermined by the focal length. For a viable glass choice other two form a close to linear ravine in merit function optimization space.



(runs 24h on 32 physical/64 logical CPU cores)
(4 x Intel 2.7GHz Xeon E5-4650)

Extended Spectrum operation of CEV (f=12mm F1.7 120° FOV)
Symmetric geometries (2GS, 3GS)

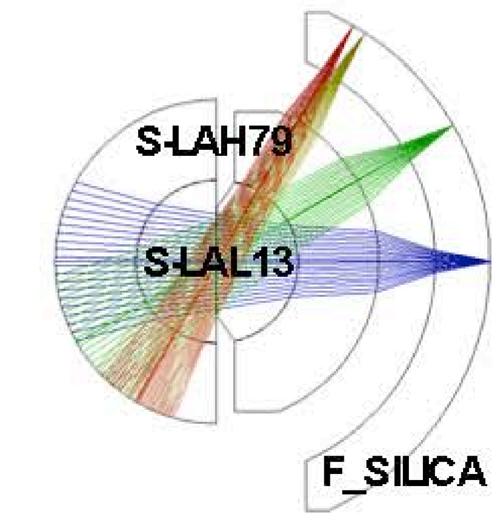
UCSD Photonics

Layout | Polychromatic MTF | Spot size | Chromatic focal shift

Extended Spectrum operation of CEV (f=12mm F1.715 120° FOV) Symmetric geometries (2GS, 3GS)

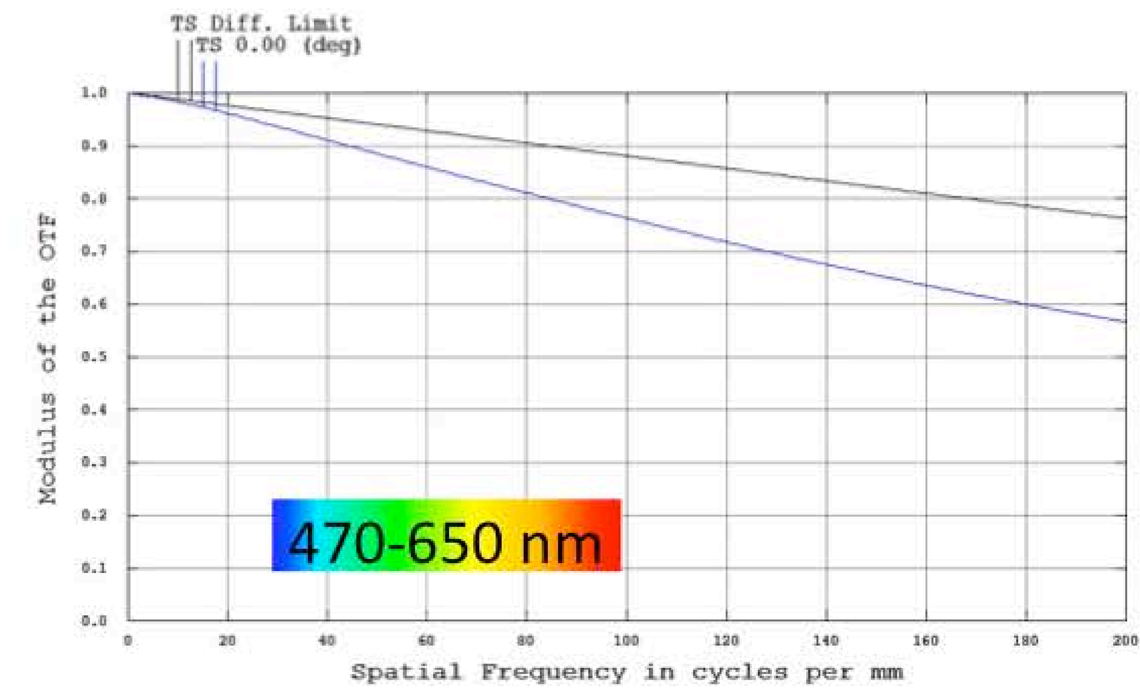
UCSD Photonics

Layout	Polychromatic MTF	Spot size	Chromatic focal shift

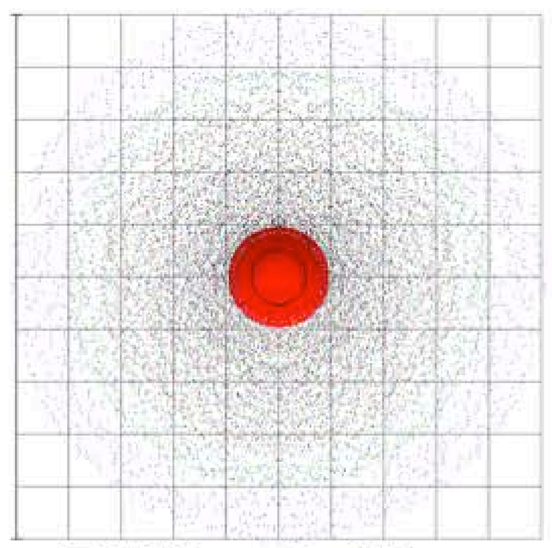


R1=7.15mm
R2=3.58mm

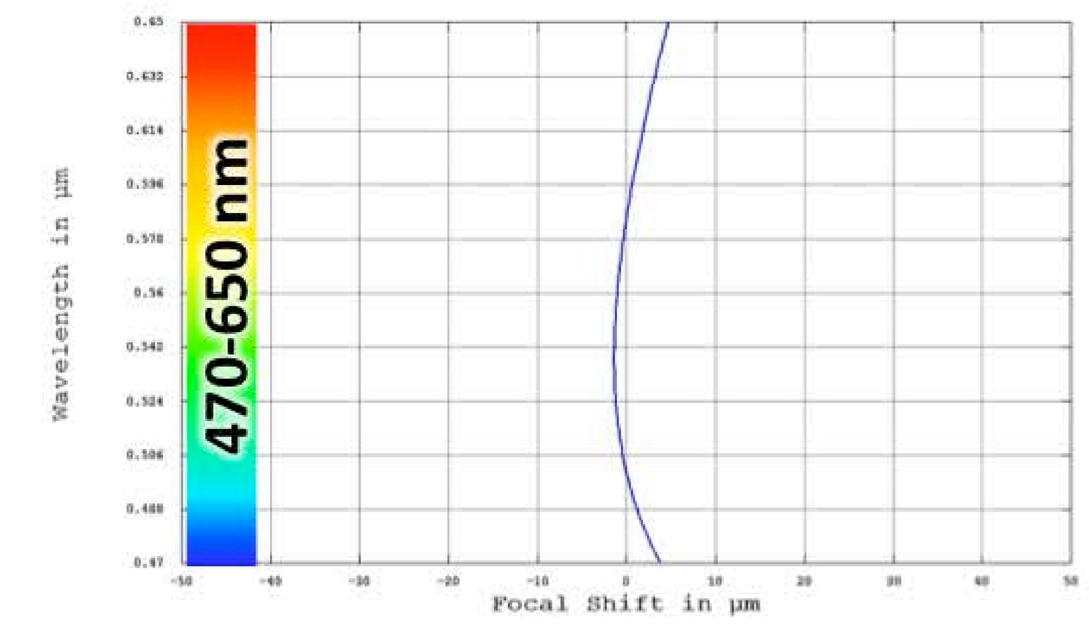
Fabricated 2G VIS



20um

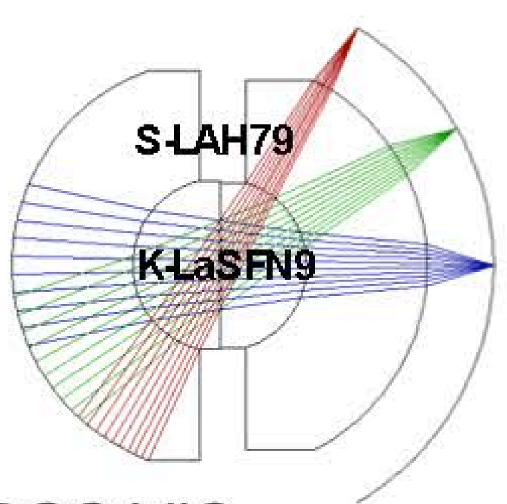


RMS = 2.41um



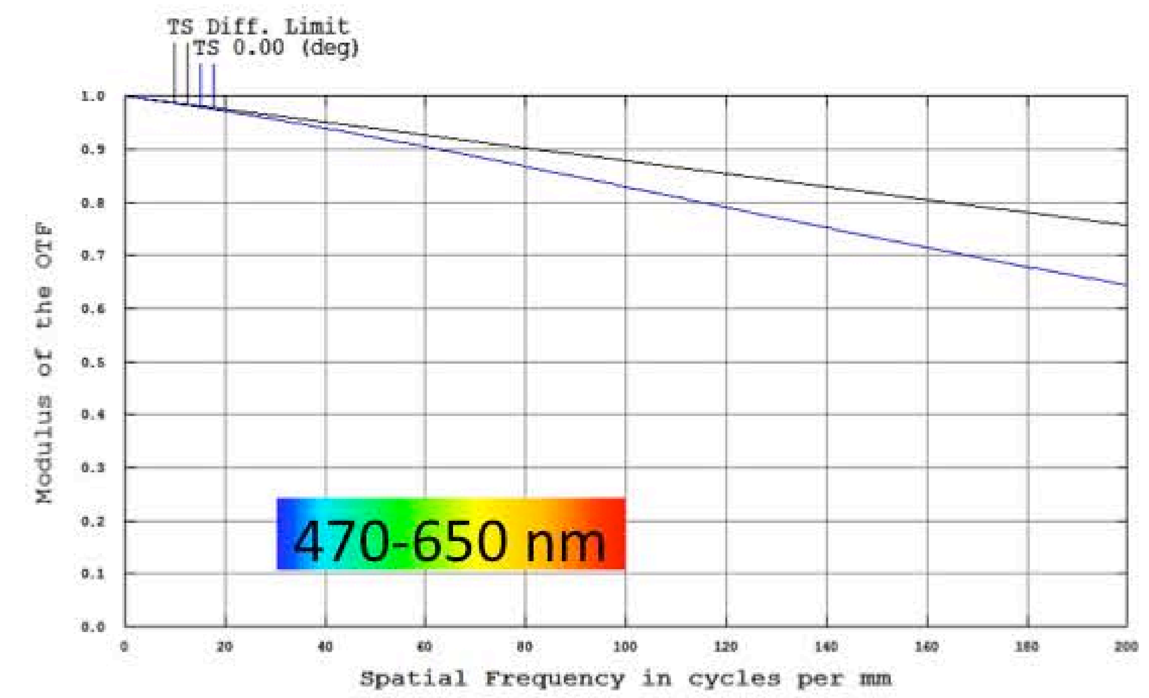
650nm

470nm

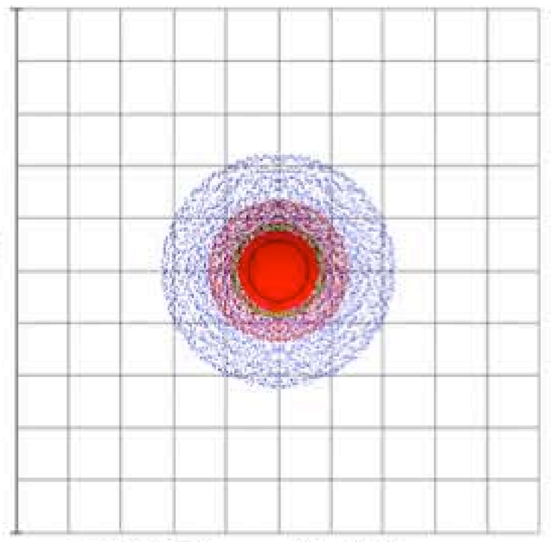


R1=9.07mm
R2=3.79mm

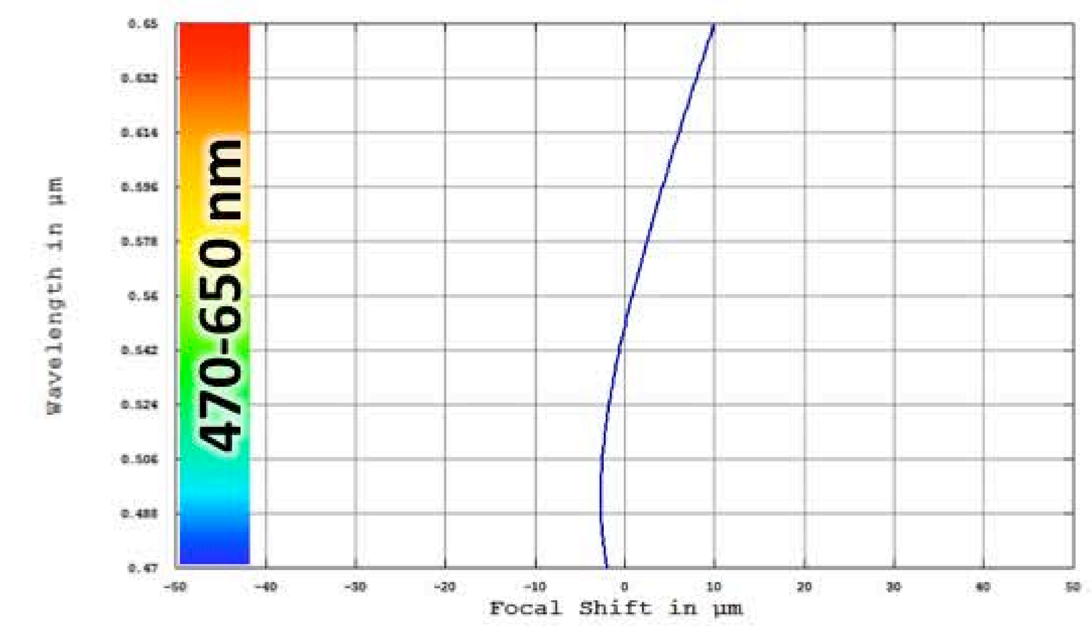
Top 2GS VIS



20um

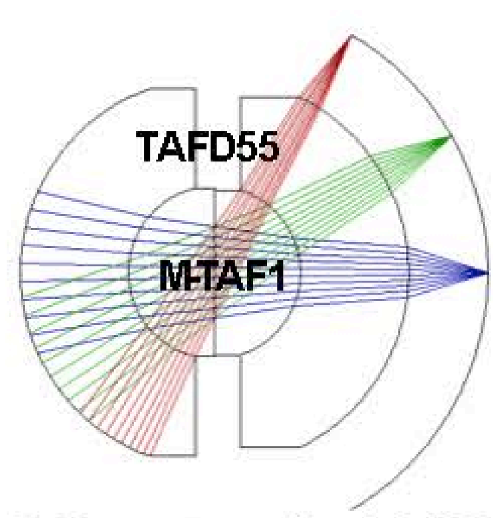


RMS = 1.11um



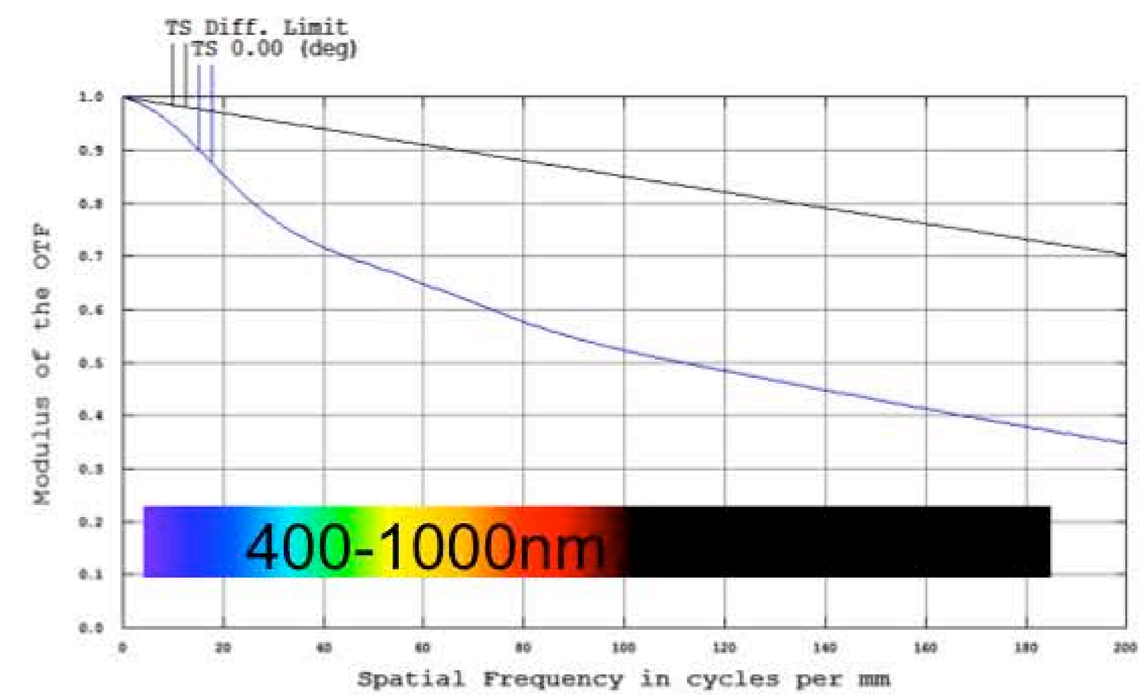
650nm

470nm

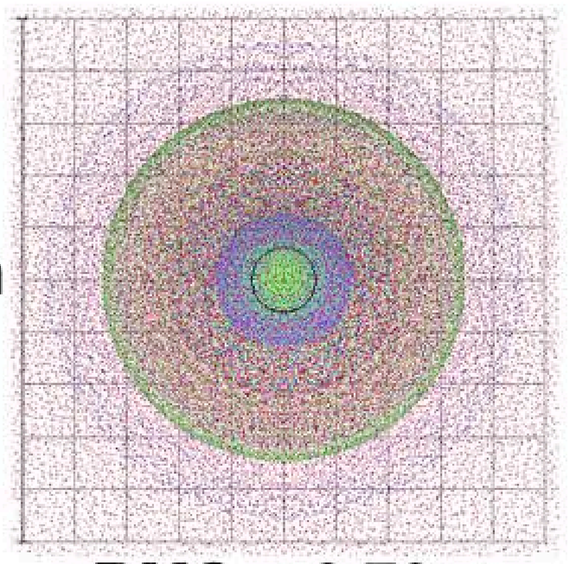


R1=8.52mm
R2=3.72mm

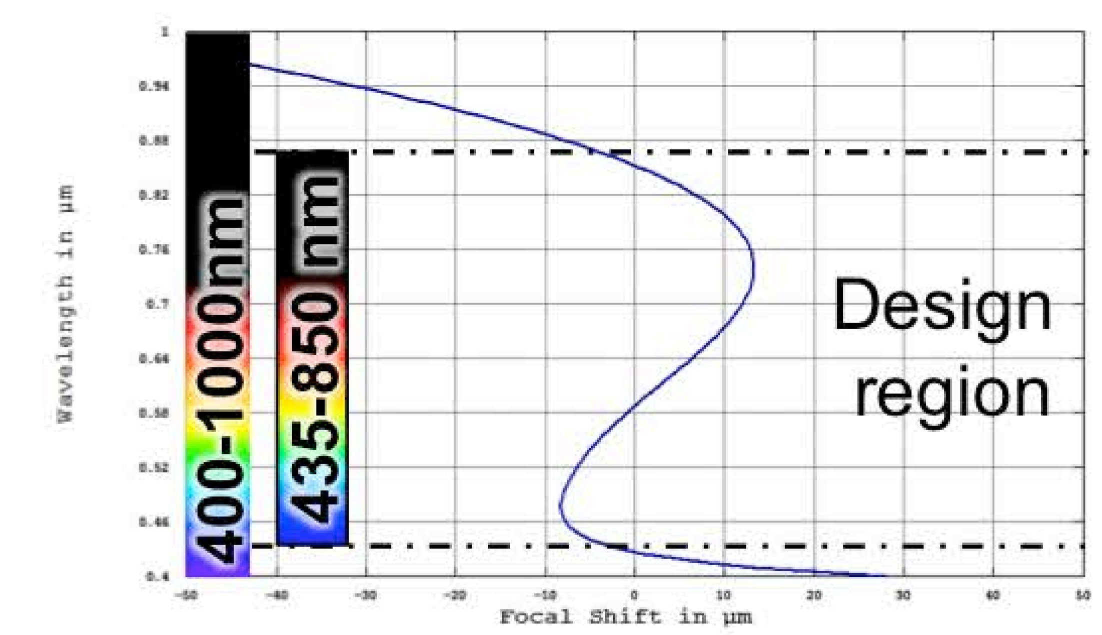
Top 2GS extended VIS @ 400-1000nm



20um

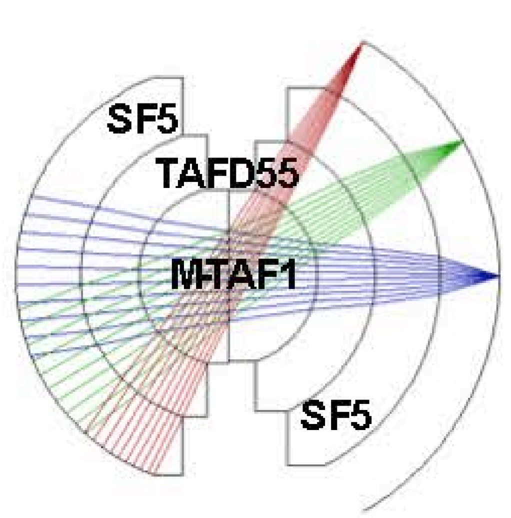


RMS = 6.70um



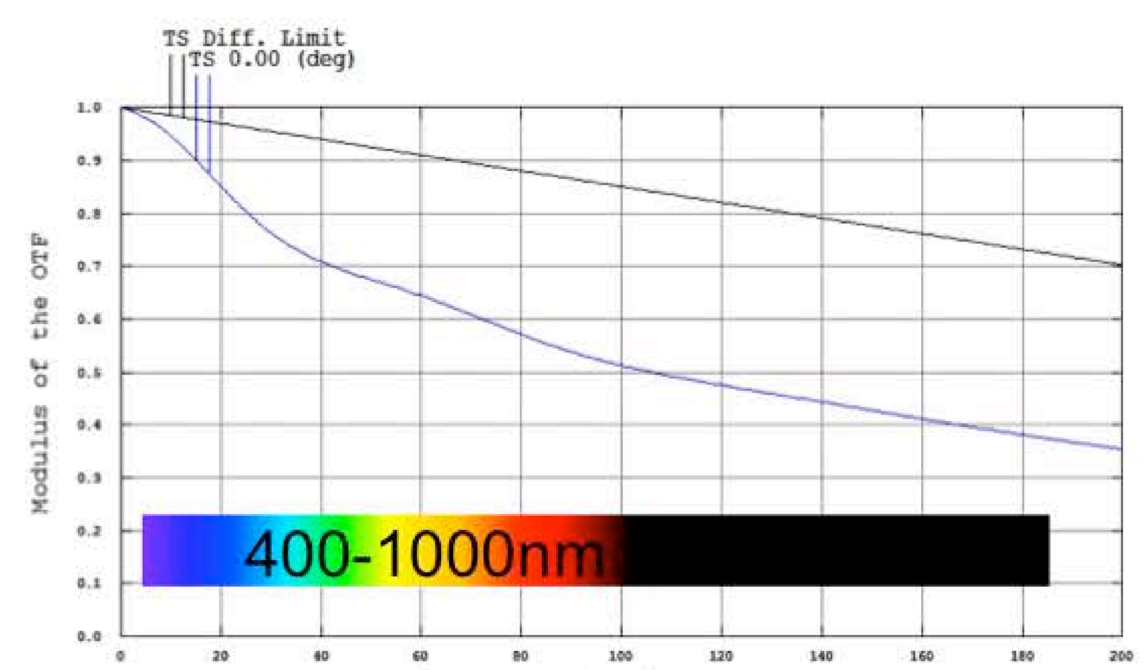
1000nm

400nm



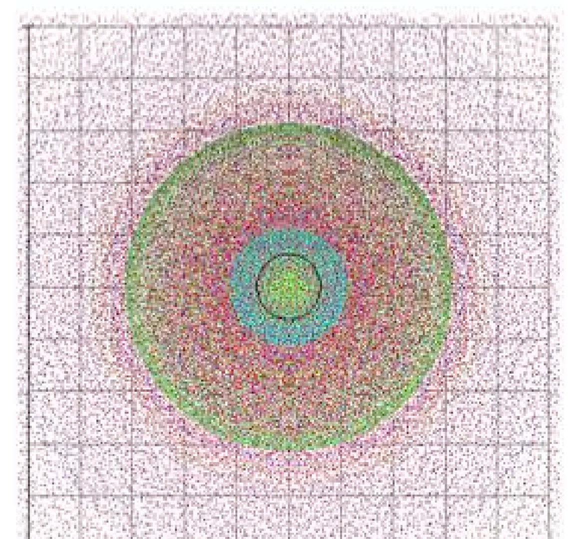
R1=9.37mm
R2=6.50mm
R3=3.95mm

Top 3GS extended VIS @ 400-1000nm

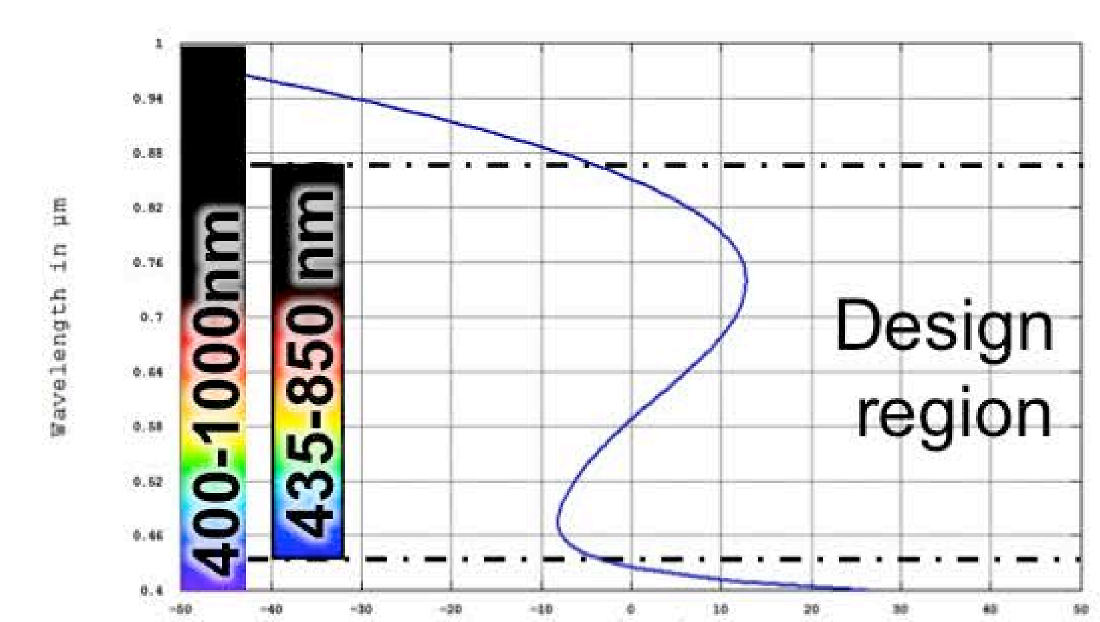


200cyc/mm

20um



RMS = 6.72um



1000nm

400nm

50µm

Towards extended waveband and larger aperture: exploration of monocentric lens geometries

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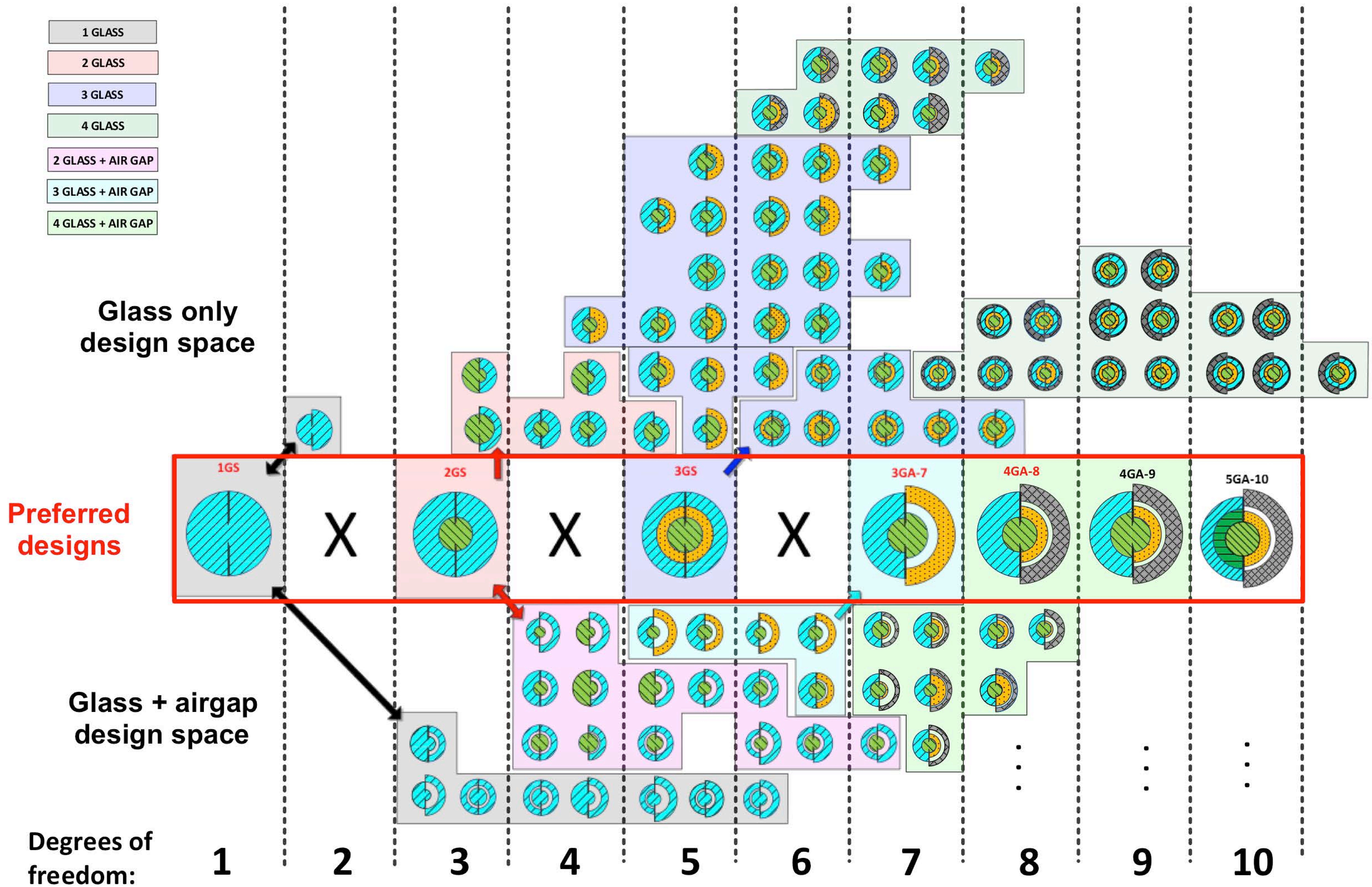
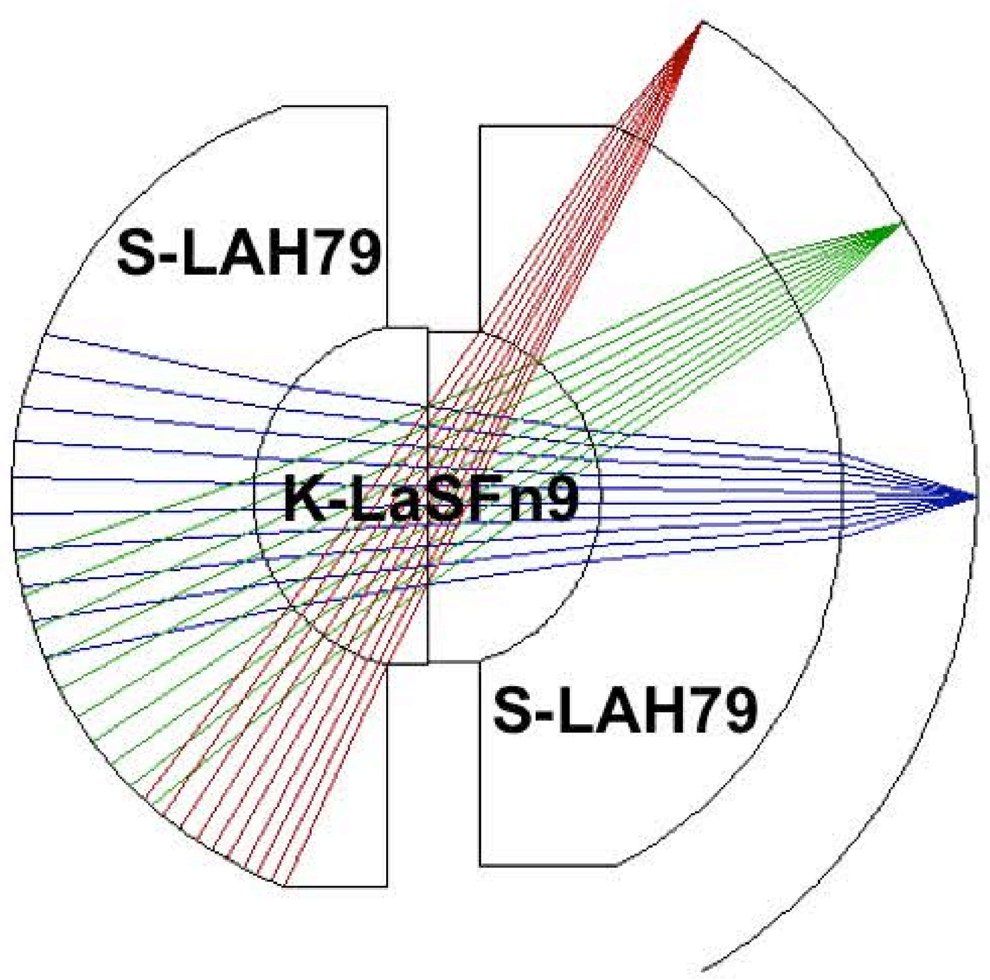
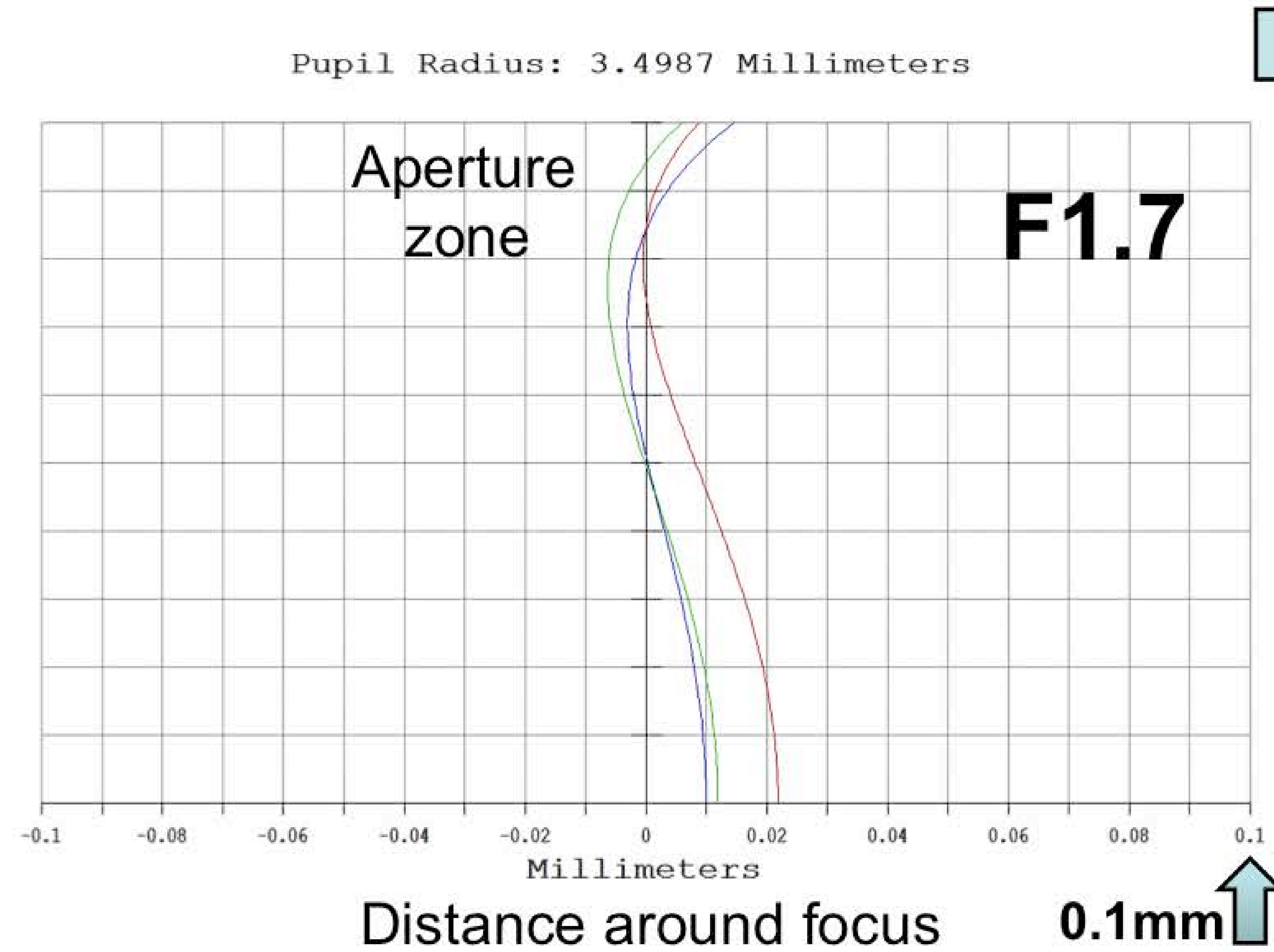


4-glass asymmetric geometry with air-gap (4GA)

470-650nm CEV F1.7 f=12mm
top design **2GS** candidate

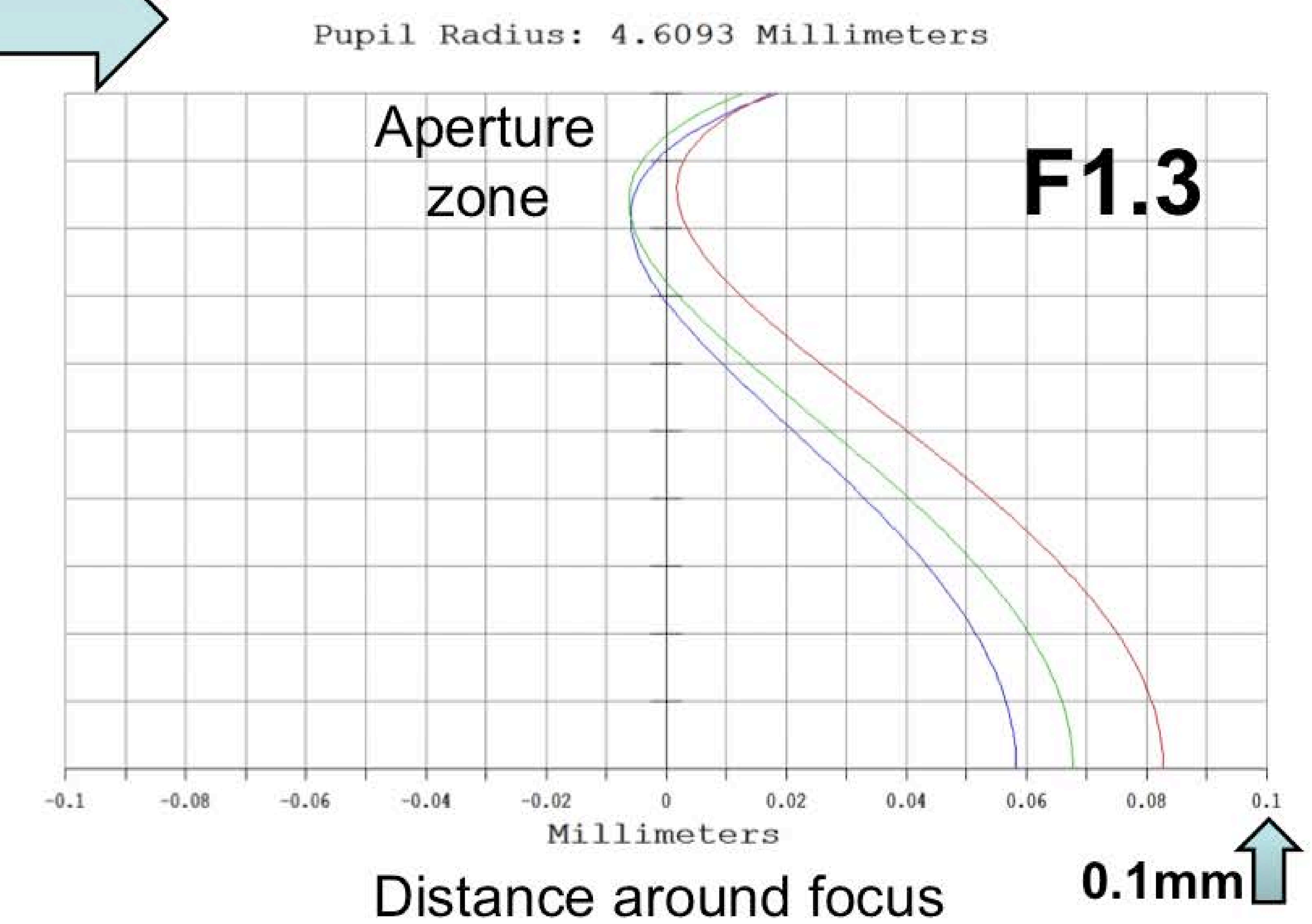


Longitudinal aberration

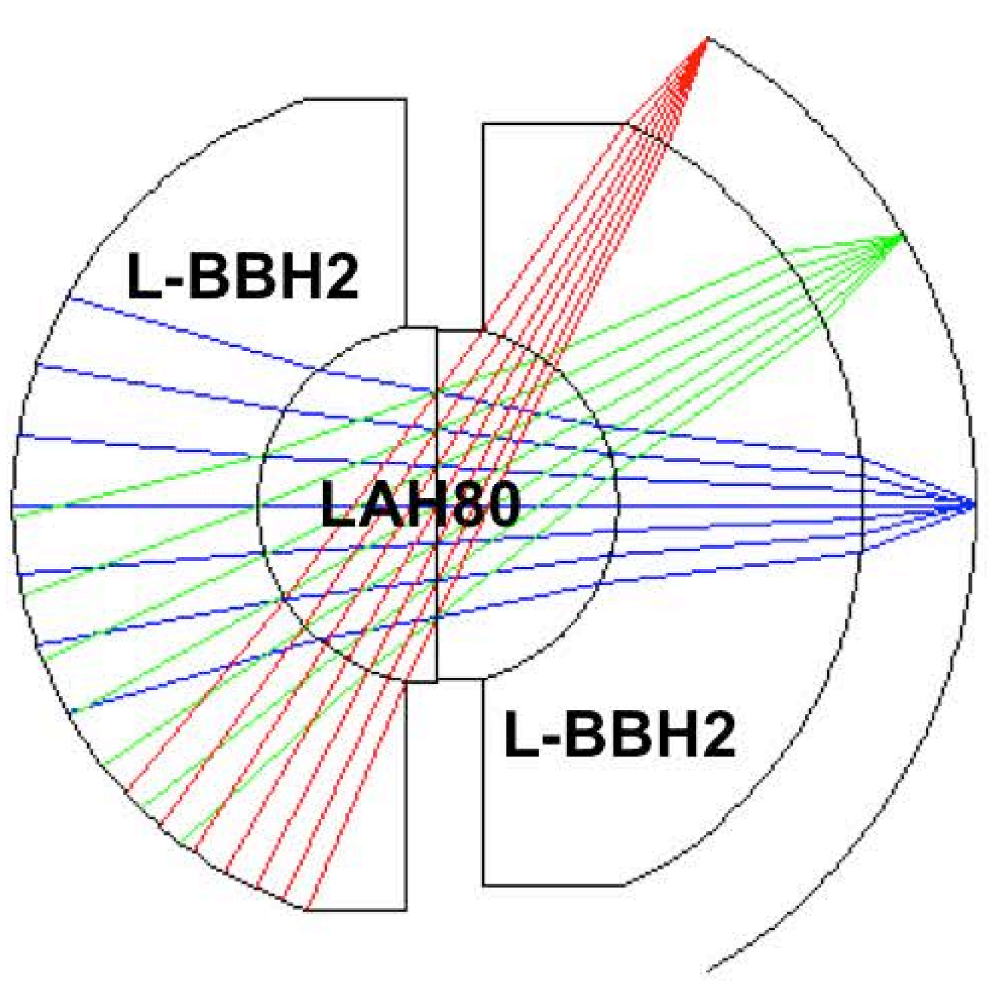


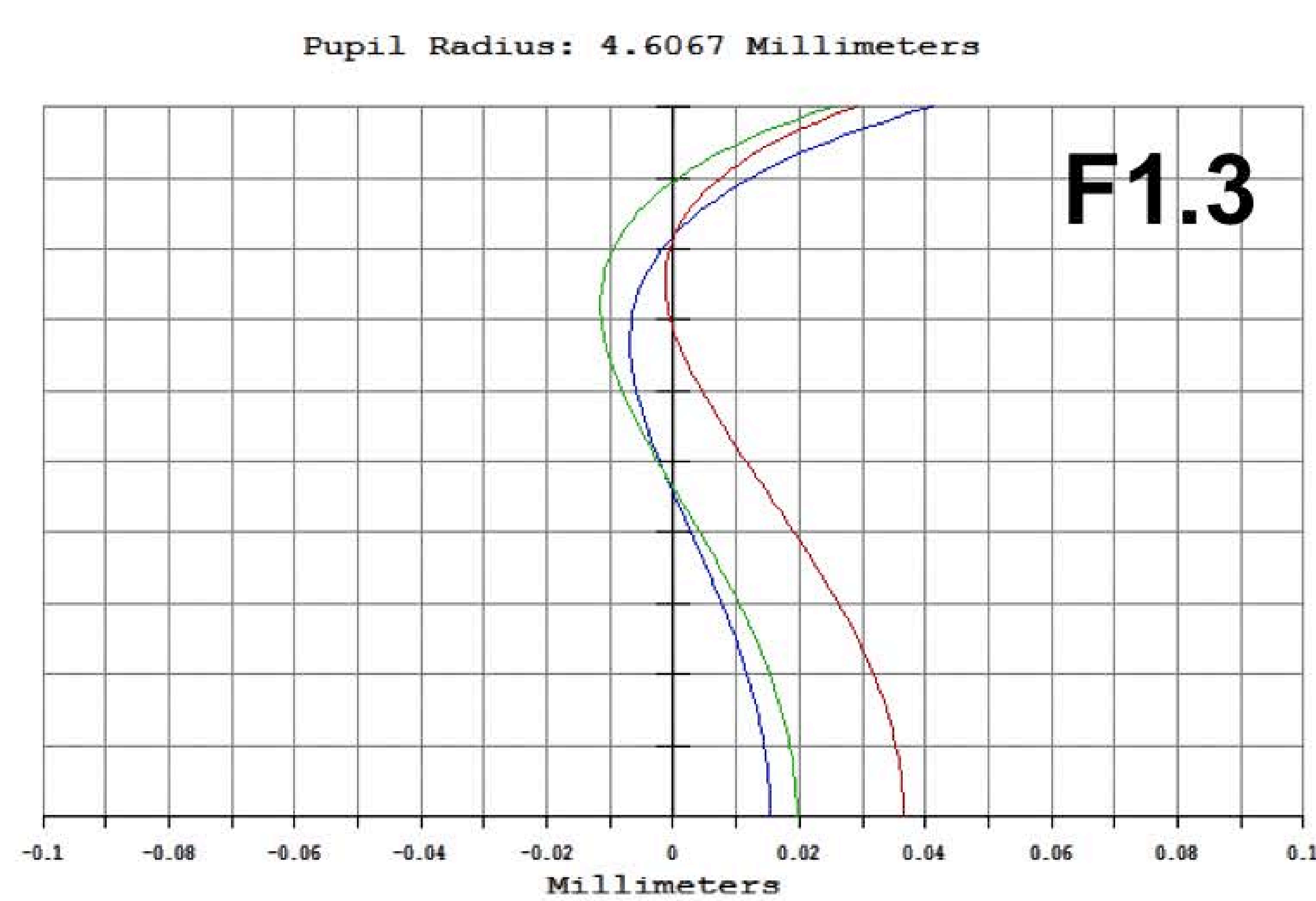
Push F number & optimize

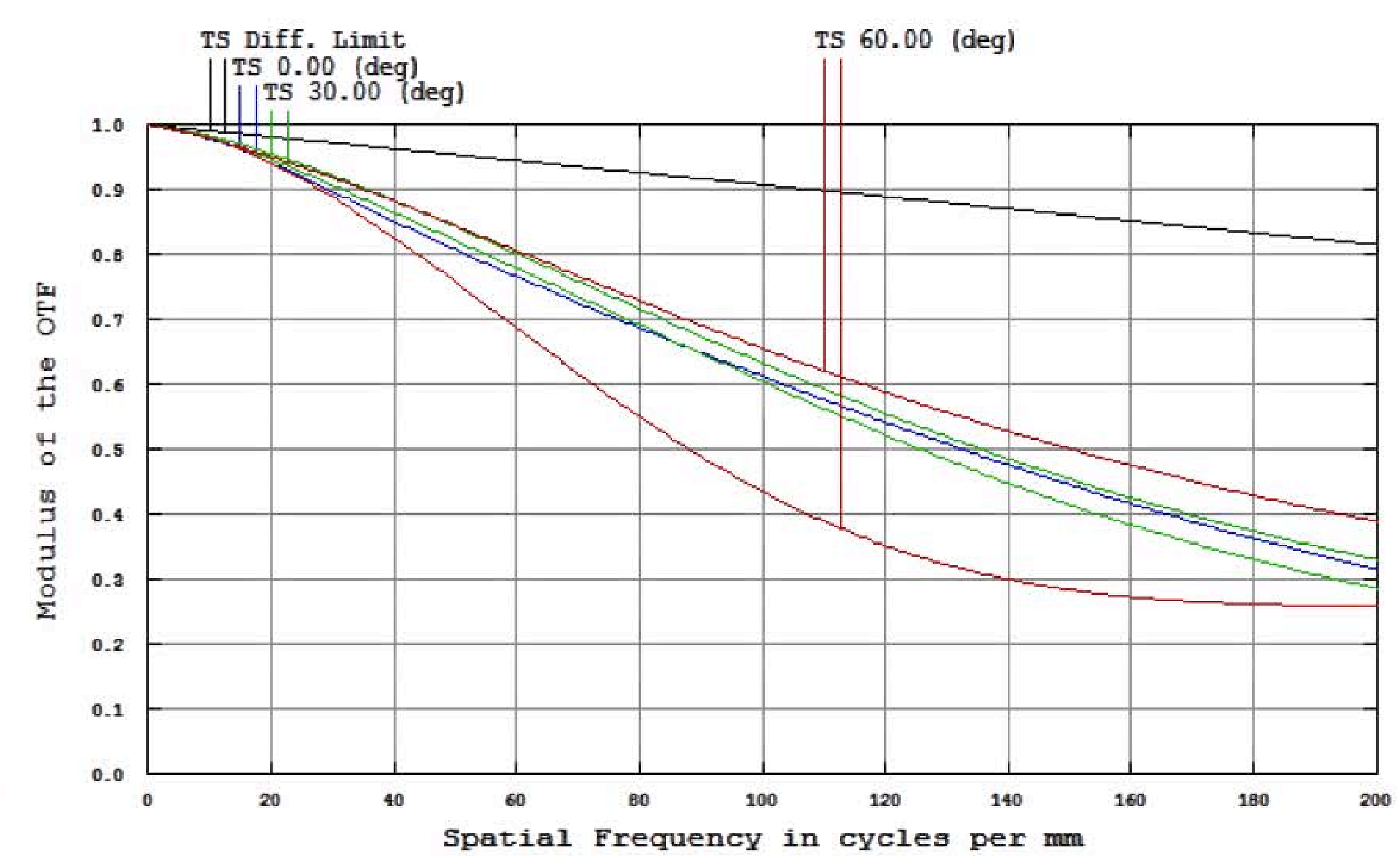
Spherochromatism & zonal aberration



2GS optimization for F/1.3 on 470-650nm spectral band leads to glass L-BBH2 + LAH80 core candidate, but still unsatisfactory result - more degrees of freedom are needed.







Example: Spherochromatism compensation method, introduce air gap between crown & flint glass

Asymmetric air gap lens

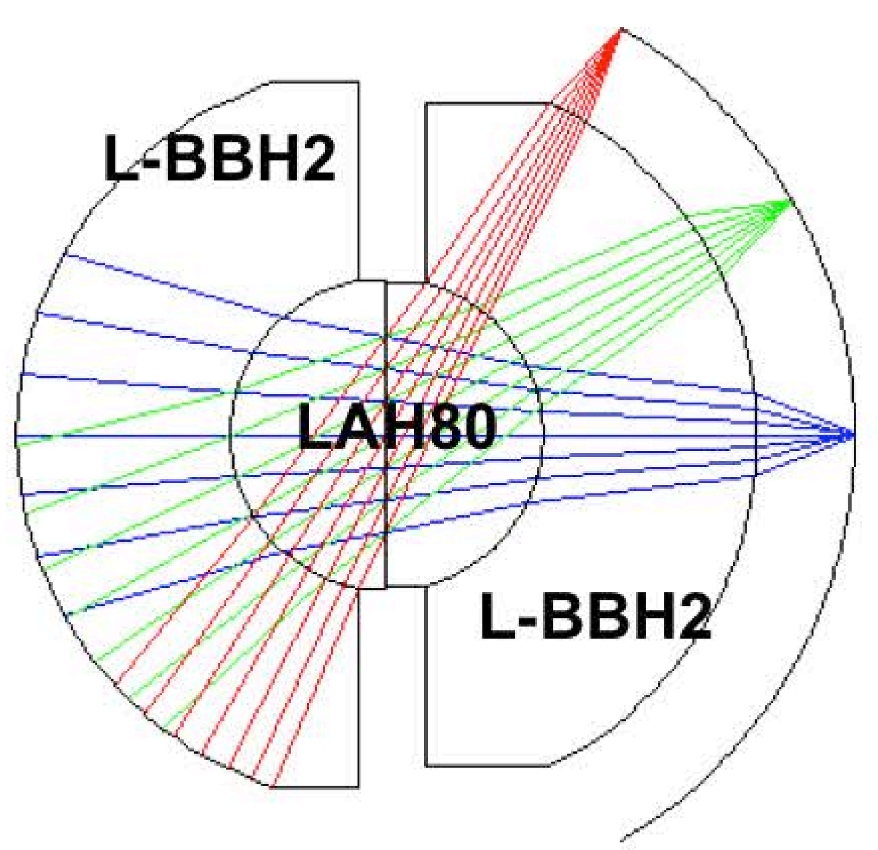
Optimization process 1 (fast)

- Start from the best 2-glass candidate(s)
- Split the right shell and introduce airgap
- Do hammer optimization with glass substitution, but keep the core glass fixed

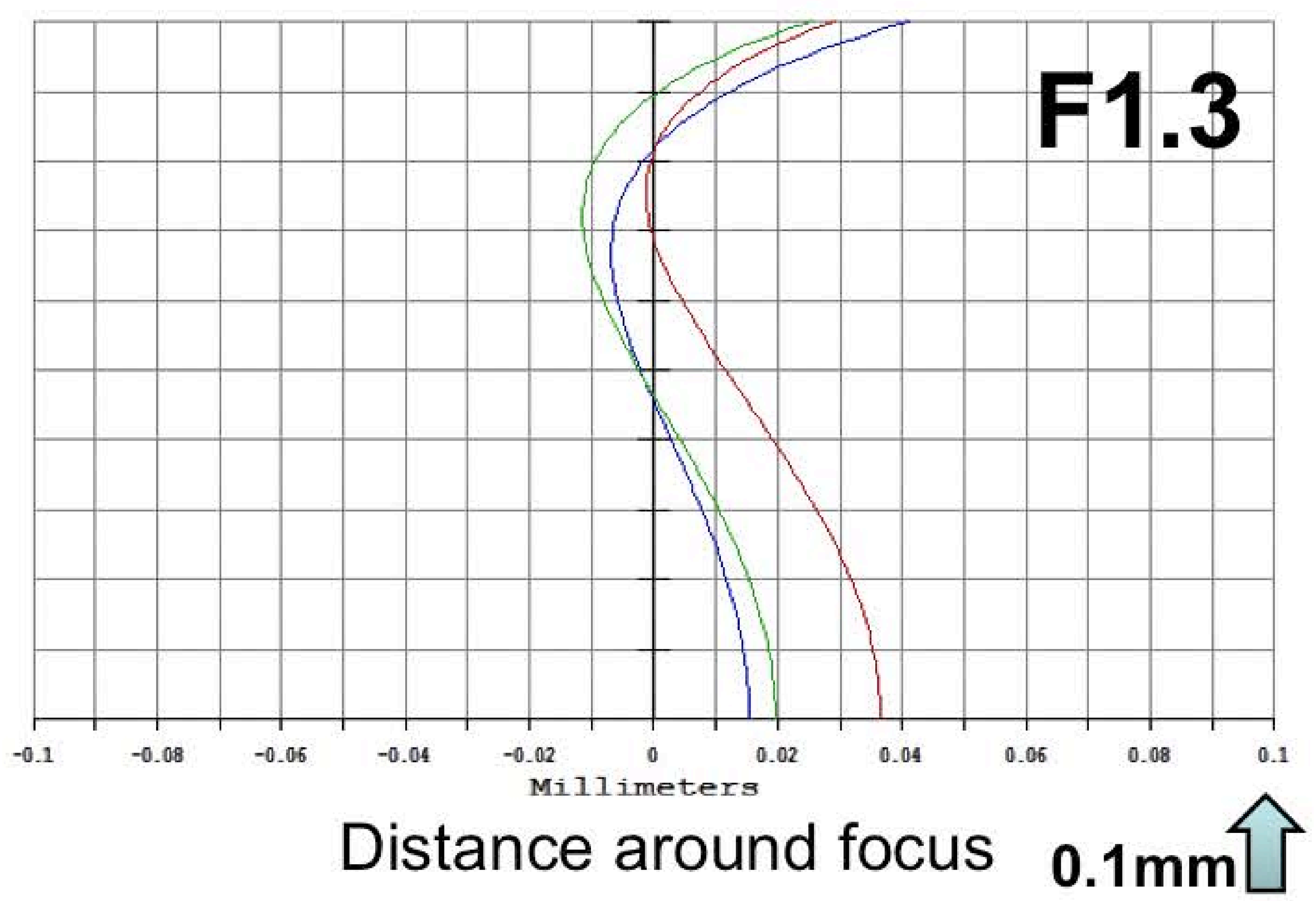
Optimization process 2 (in progress)

- Start from the best 2-glass candidate core
- Perturbate the glass adjacent to the core and try all glasses for the meniscus material.
(5-dimensional systematic (not global) search)

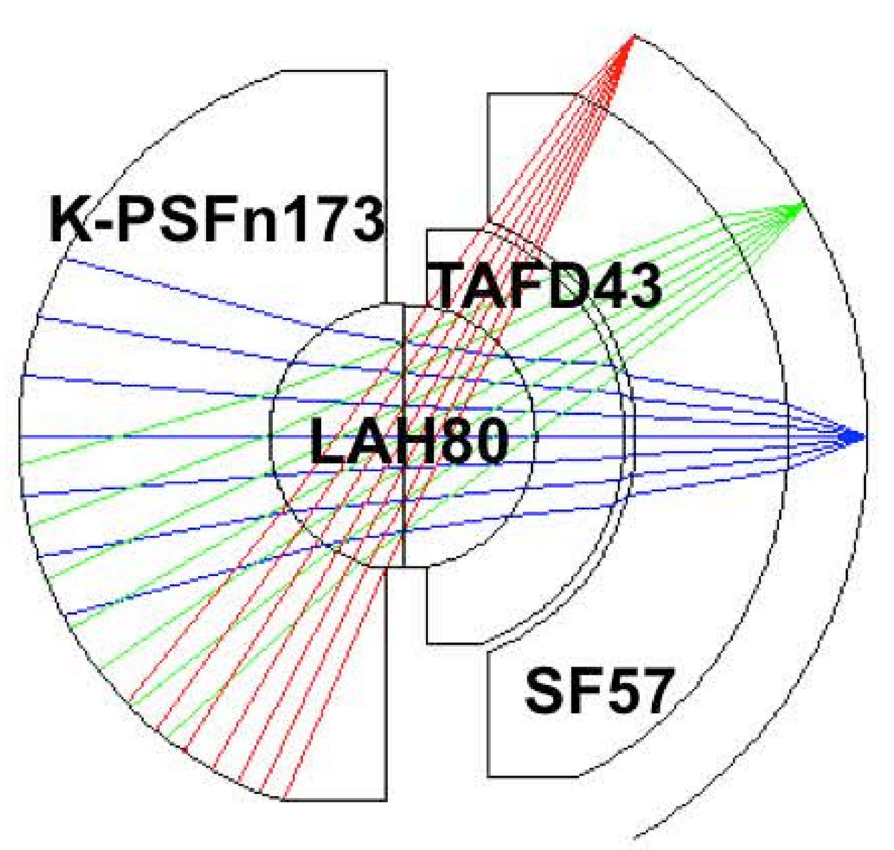
470-650nm CEV F1.3 f=12mm
seed **2GS** candidate

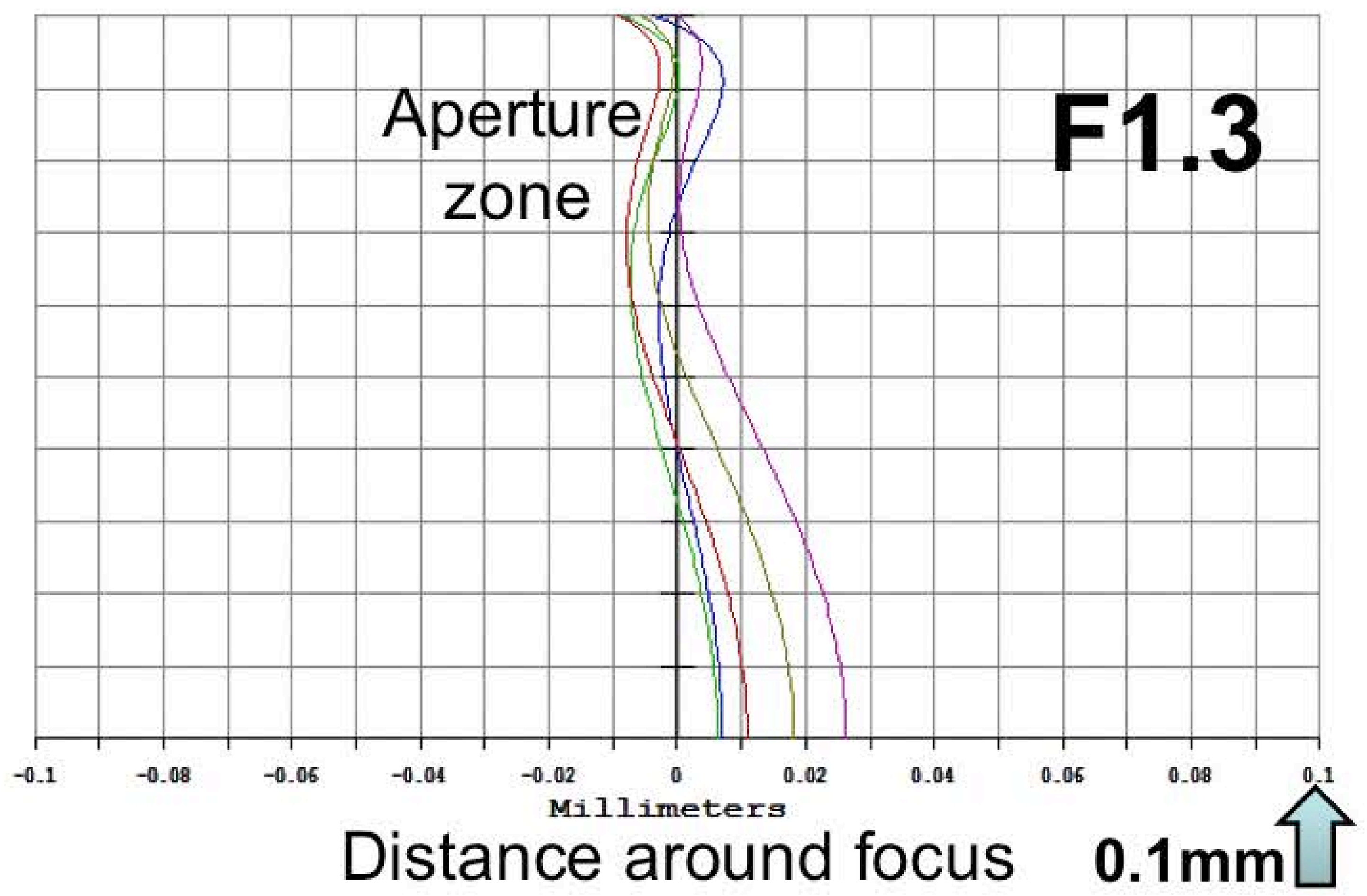


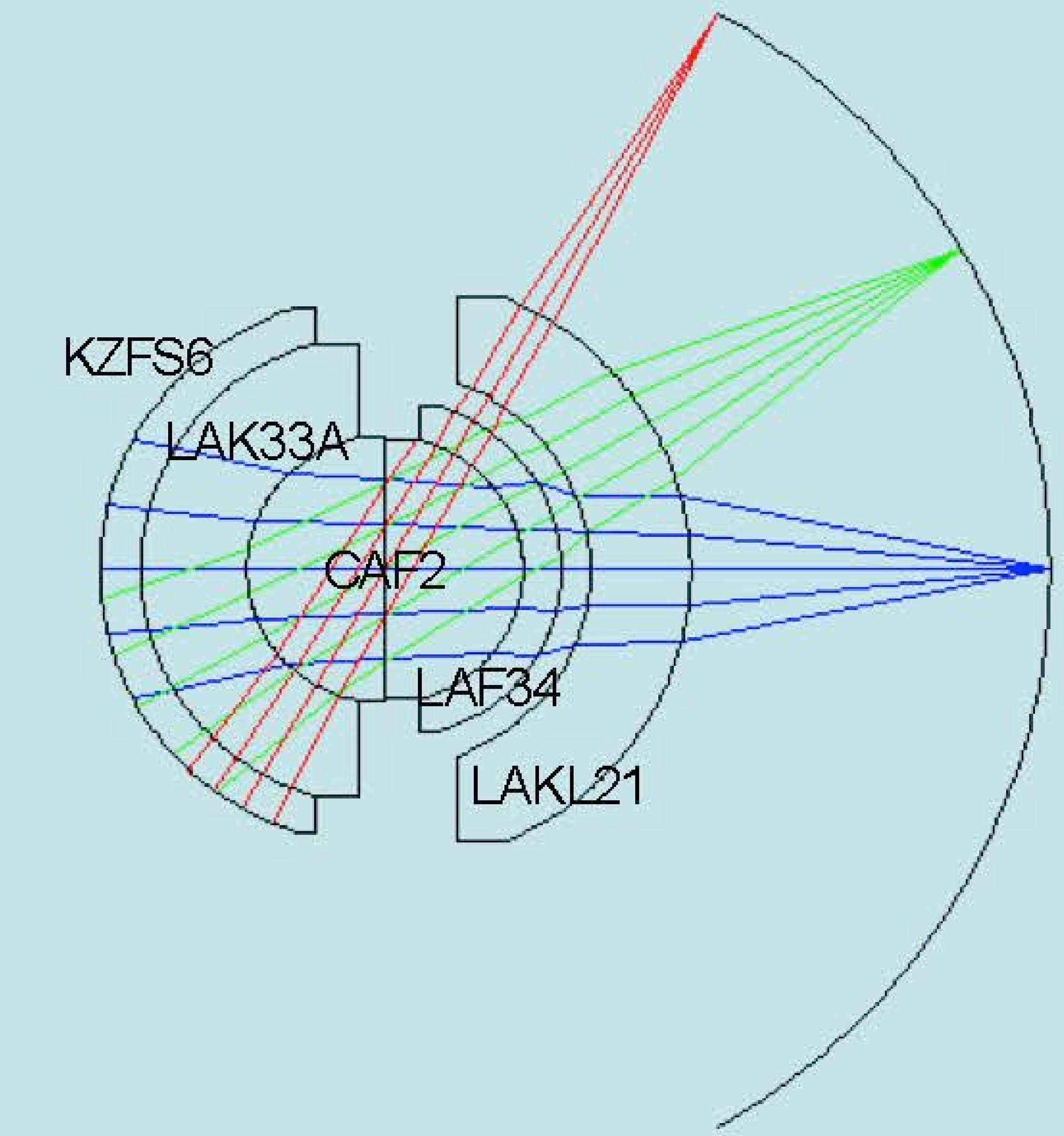
Longitudinal aberrations



470-650nm CEV F1.3 f=12mm
4 glass + air gap (**4GA**) candidate







D. Marks and D. Brady, "Gigagon: A Monocentric Lens Design Imaging 40 Gigapixels," in Imaging Systems, OSA technical Digest (CD) (Optical Society of America, 2010), paper ITuC2.

CEV (f=12mm F1.715 120° FOV) optimized candidates comparison
Asymmetric geometries (3GA, 4GA) derived from 2GS

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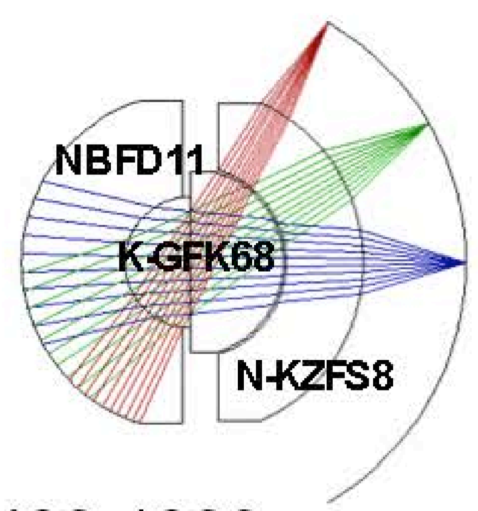
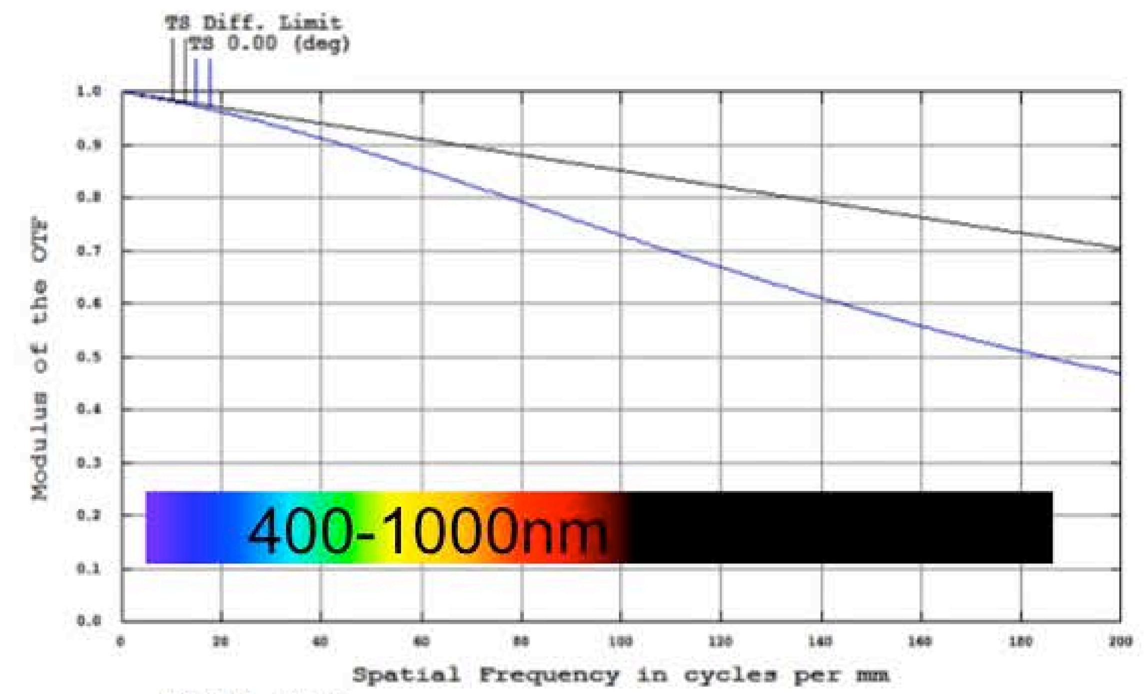
Layout		Polychromatic MTF	Spot size	Chromatic focal shift

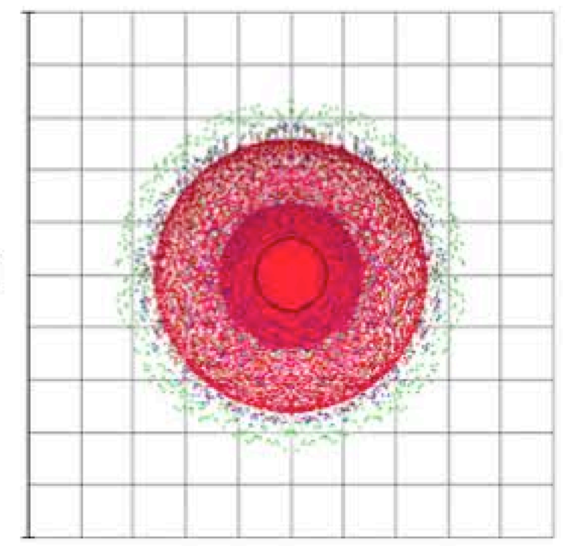


R1=7.17mm
R2=2.82mm
R3=-4.04mm
R4=-4.16mm
R5=-7.65mm

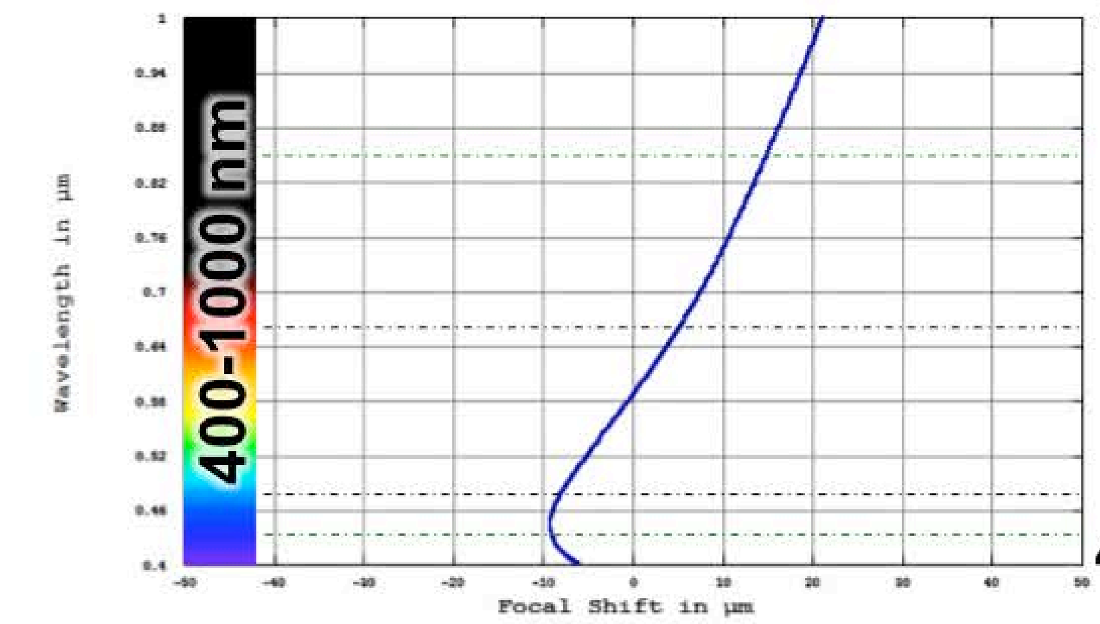
3GA 400-1000nm



20um

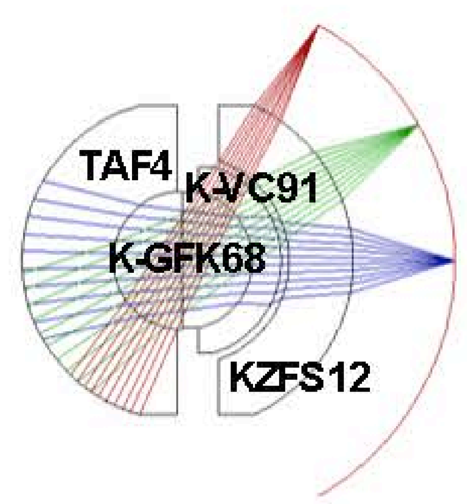


RMS = 1.61um



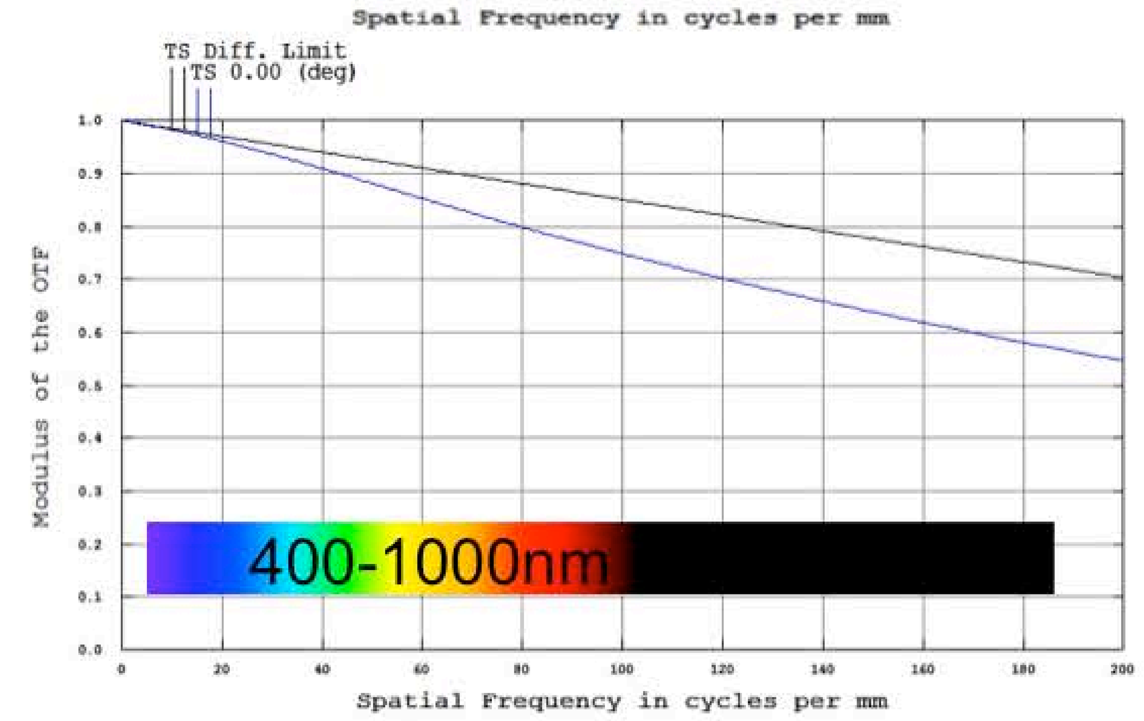
1000nm

400nm

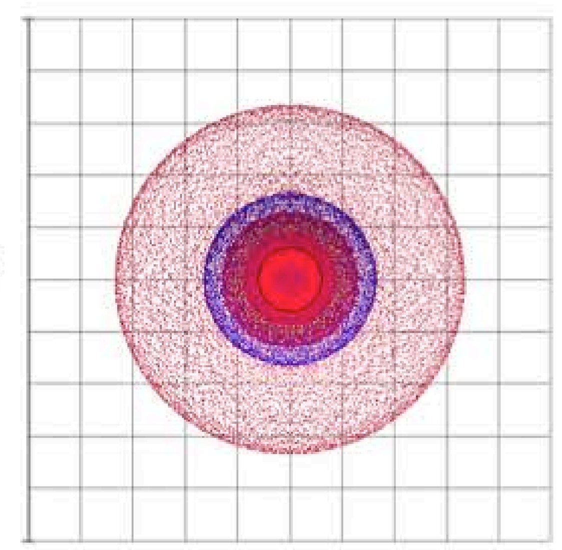


R1=7.07mm
R2=3.05mm
R4=-4.32mm
R5=-4.67mm
R6=-7.49mm

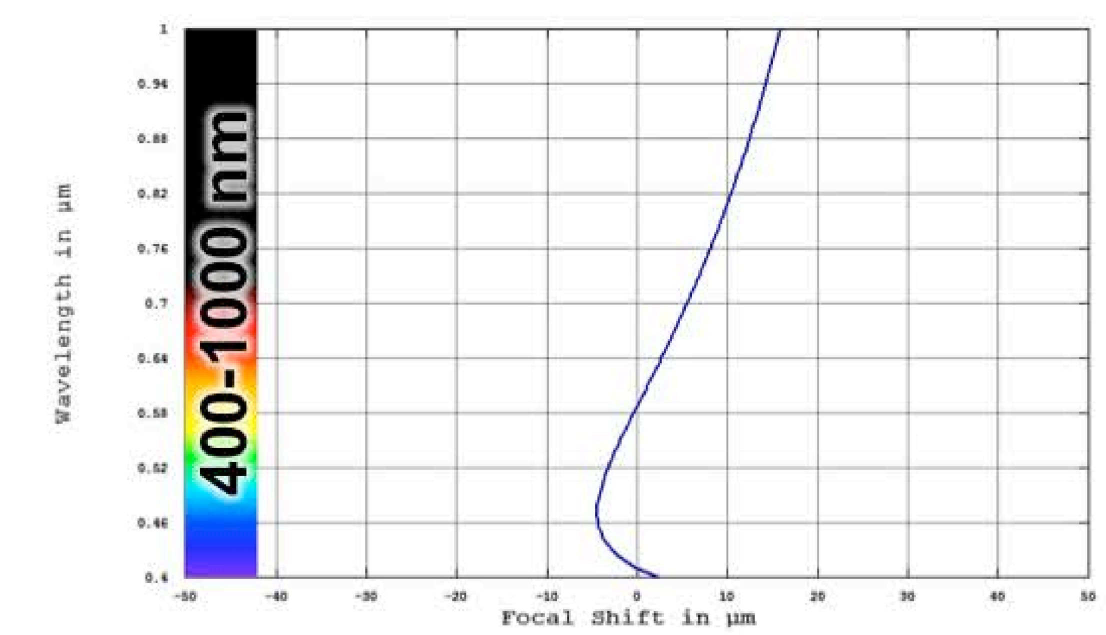
4GA 400-1000nm



20um

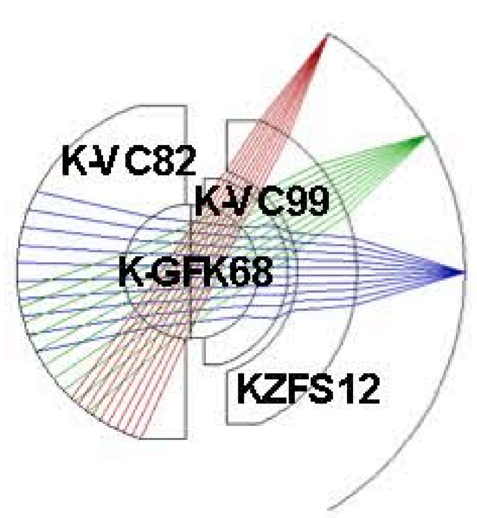


RMS = 1.55um



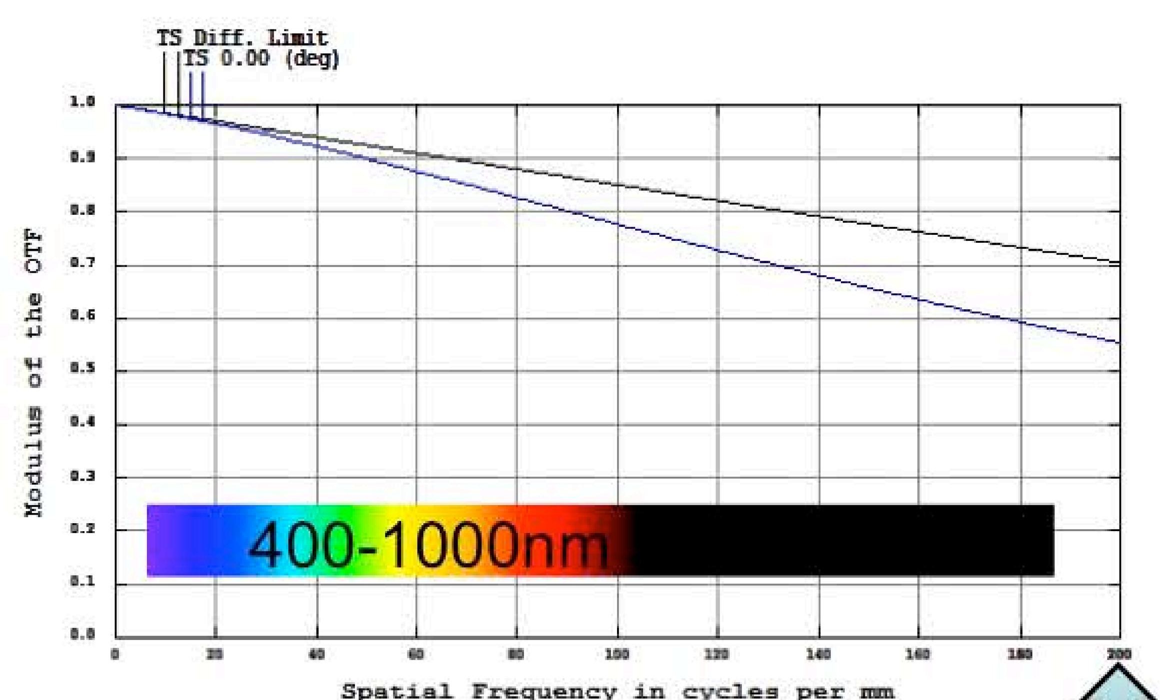
1000nm

400nm



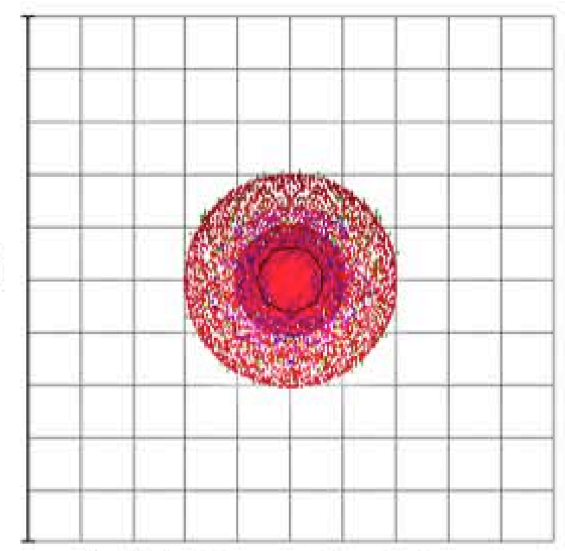
R1=7.37mm
R2=3.01mm
R4=-4.28mm
R5=-4.61mm
R6=-7.44mm

4GA 400-1000nm

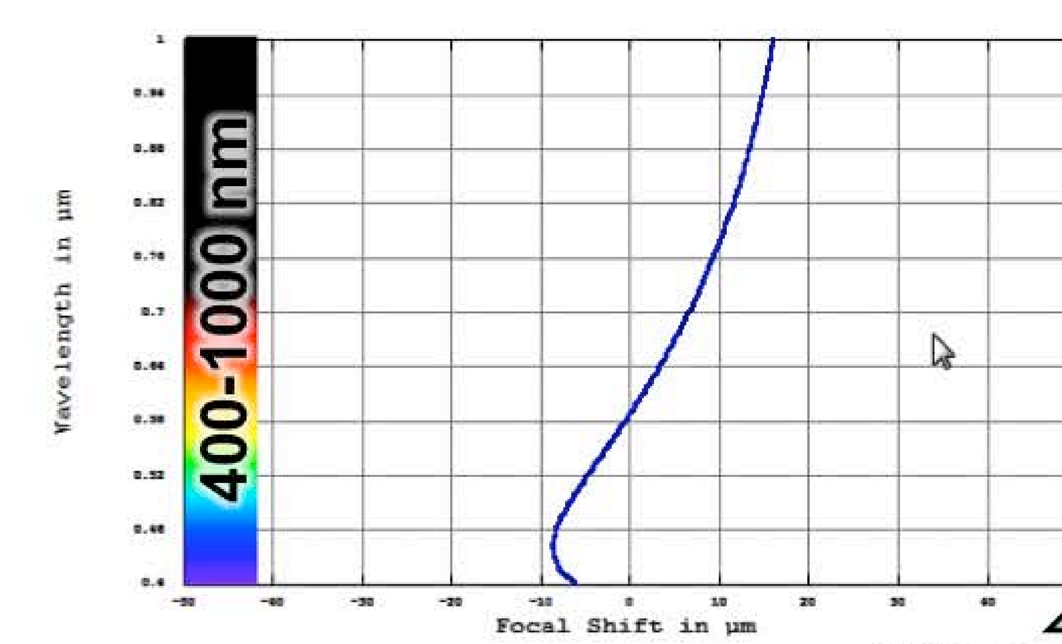


200cyc/mm

20um



RMS = 1.18um

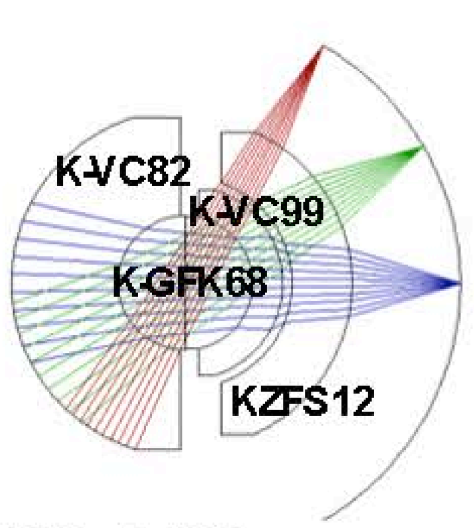


1000nm

400nm

50µm

VNIR Candidate

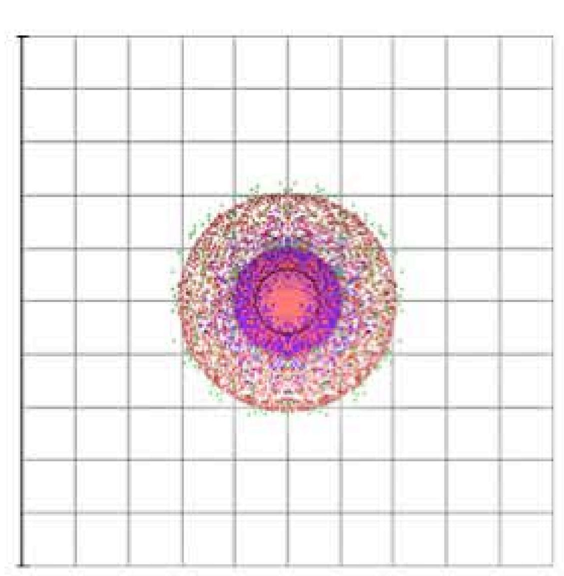


R1=7.40mm
R2=3.00mm
R4=-4.27mm
R5=-4.60mm
R6=-7.40mm

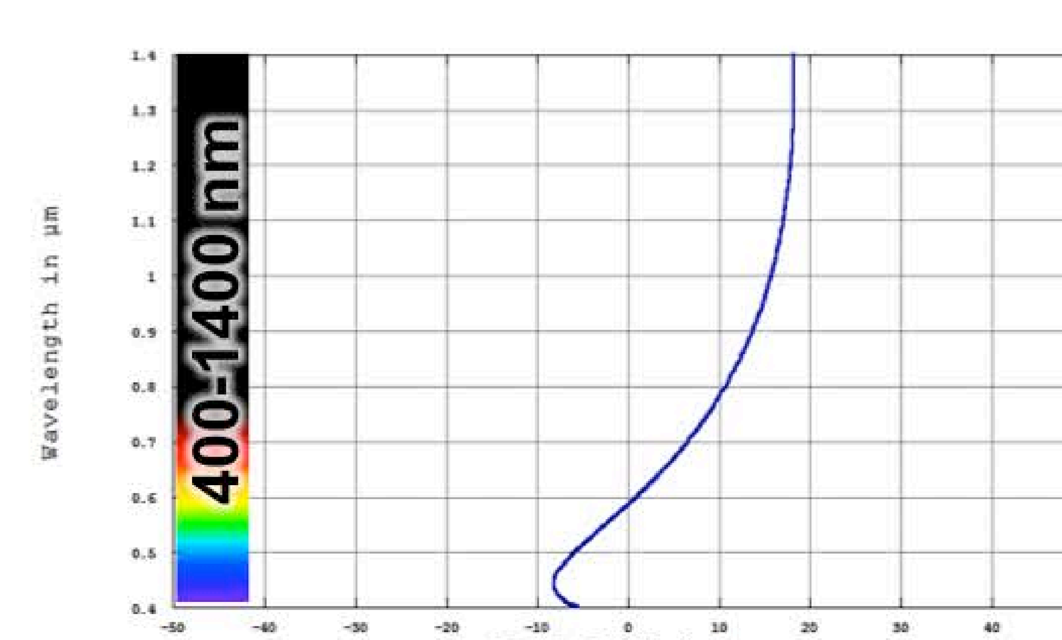
4GA 400-1400nm

200cyc/mm

20um



RMS = 1.18um



1400nm

400nm

50µm

AWARE10 (f=112mm F2.33 120° FOV)

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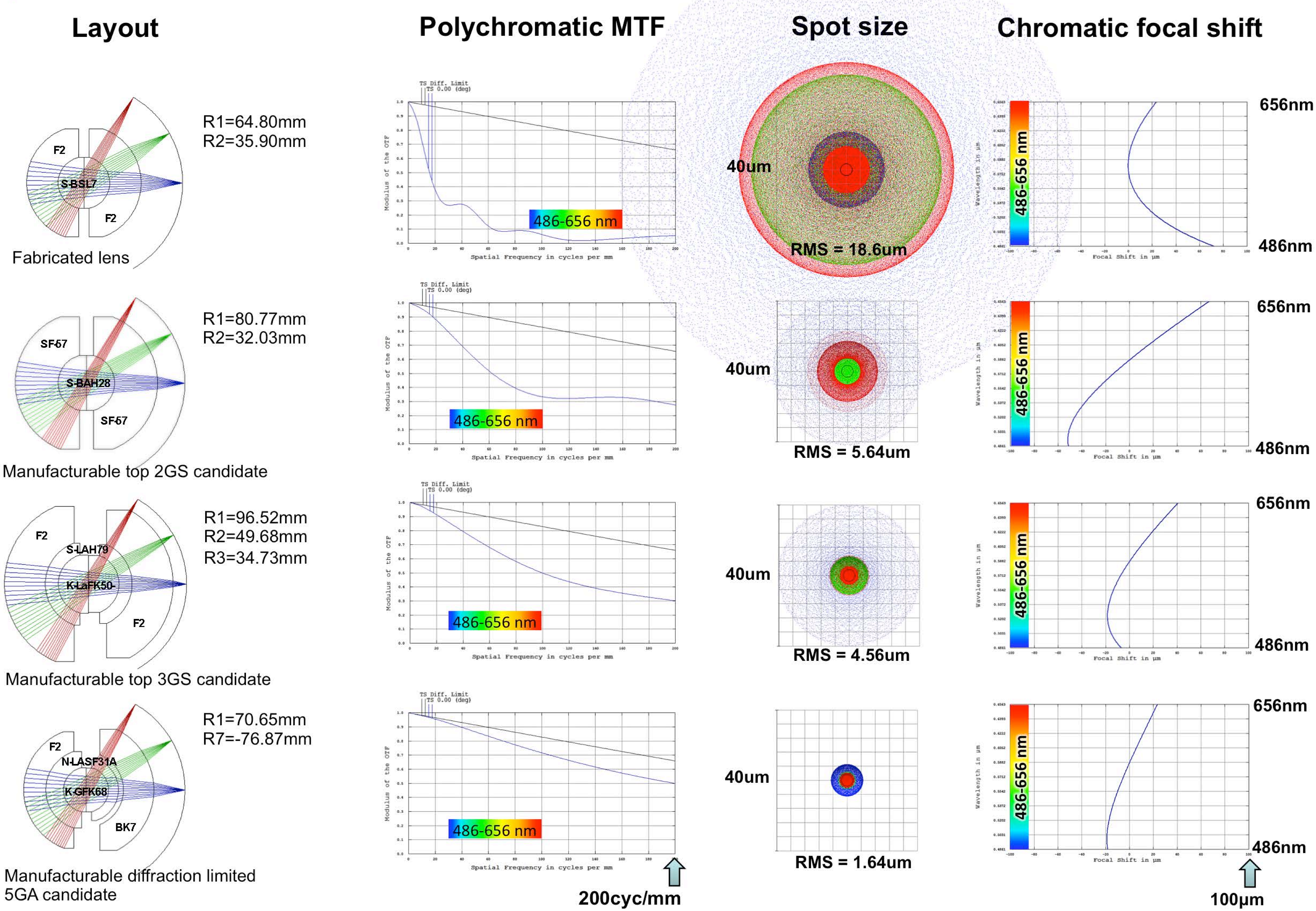

Lens complexity vs F/# for visible light

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Optimal solutions found by global search

Ill chosen geometries which converge to simpler ones.

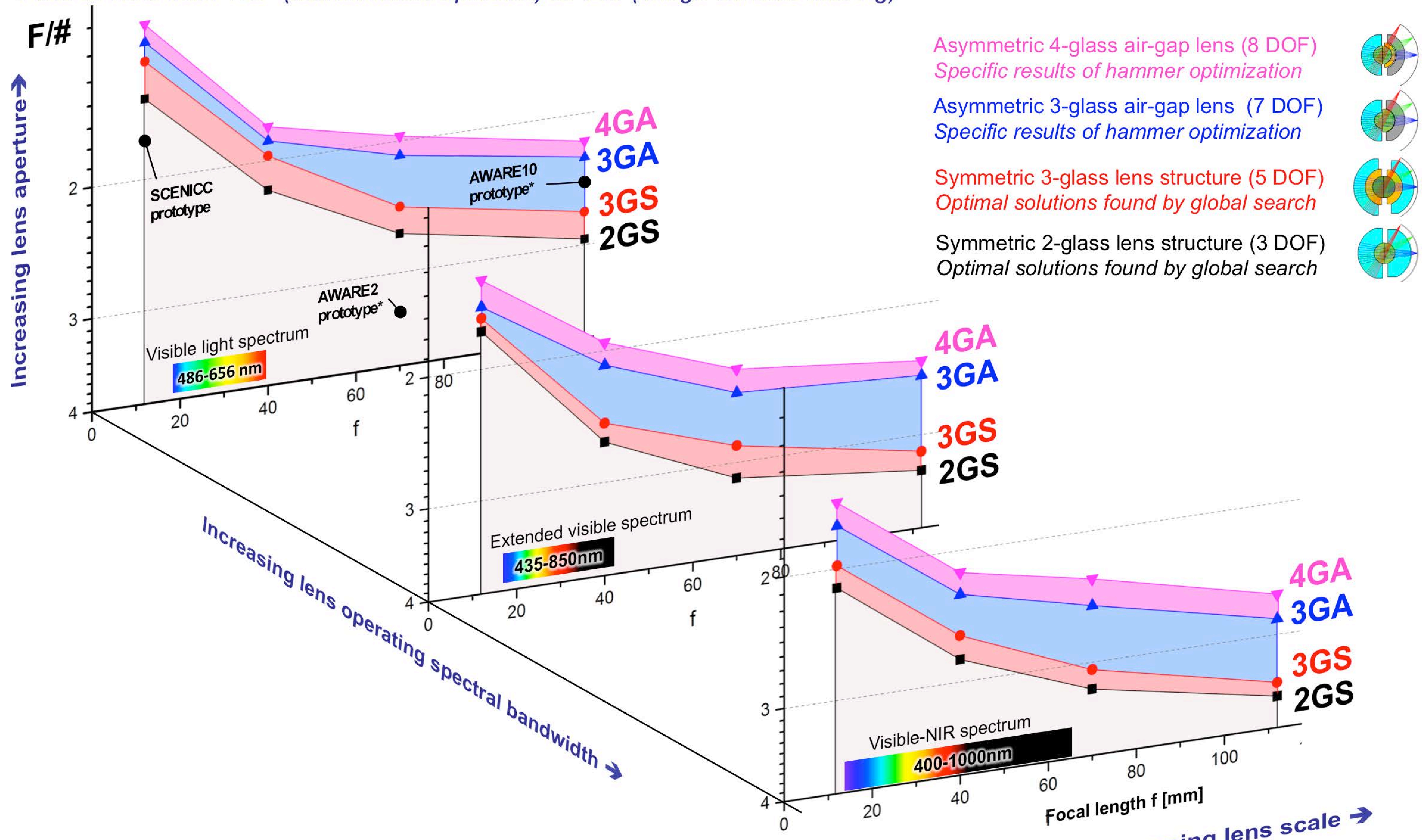
Specific results of hammer/systematic optimization

Increasing degrees of freedom

Summary: Monocentric Objective Performance

Define performance constraint: MTF at least 70% of diffraction limit @ 200lp/mm & RMS spot radius <1.5 Airy

- *Continuous function of lens F/# (energy collection) and physical scale (focal plane area)*
- *Three selected wavelength ranges: VIS, Extended VIS and Visible to NIR*
- *Field of view from 120˚ (conventional aperture) to 160˚(image-surface filtering)*



* AWARE prototype objectives alone (not including relay optics) were not designed to satisfy MTF performance constraint

Thank you for your attention