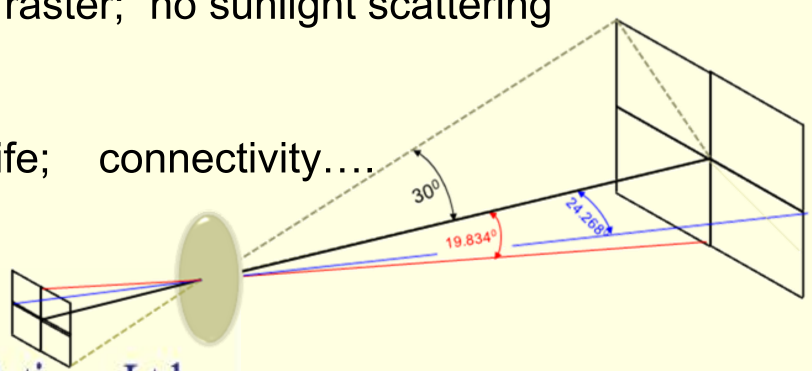
Design of a 60^{0} x 40^{0} Augmented Reality (AR) near to eye display.

- Customer initial requirements
- The requirement "negotiation" process
- Choice of architecture
- The design process- considerations ; issues encountered ; performance
- Non sequential design
- Interface with the mechanical designers
- Performance

What does everyone want? (2013 presentation)

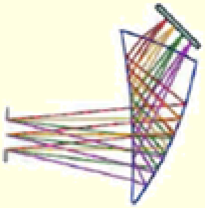
Oakley Thump = Sunglasses+MP3

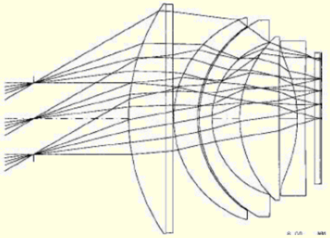
"Oakley look" .	i.e., thin & small optics
Augmented imaging	preferably an optical see-through channel
Low cost	& small image generators (OLED, LCOS, …)
Wide field of view	30^0 deg to 110^0 full diagonal field
Large eye box	~10 mm diameter, for eyeball movement + loose alignment
Large eye relief	> 20 mm, for lash clearance and prescription glasses
High resolution	~ SXGA (1280 x 1024) or higher
Low distortion	< 2%
Bright	hundreds of Cd/m^2
Artifact free;	no "dirty windows" ; no raster; no sunlight scattering
Low weight	
Other:	eye tracking; battery life; connectivity….



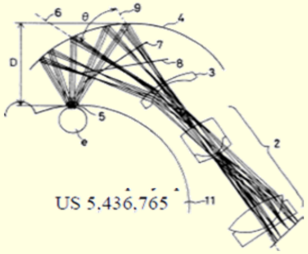
NEDs: categories of optical design forms (2013)

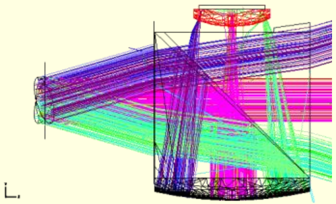
- Magnifiers i.e. eye piece + image generator



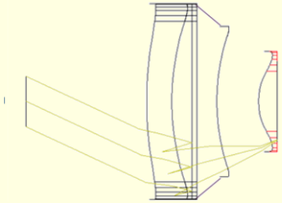


- Relay based NEDs
- Monocentric system

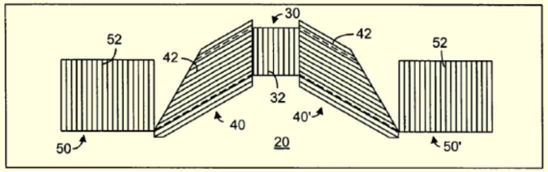




- "Pancake" designs : on axis folded by polarization means



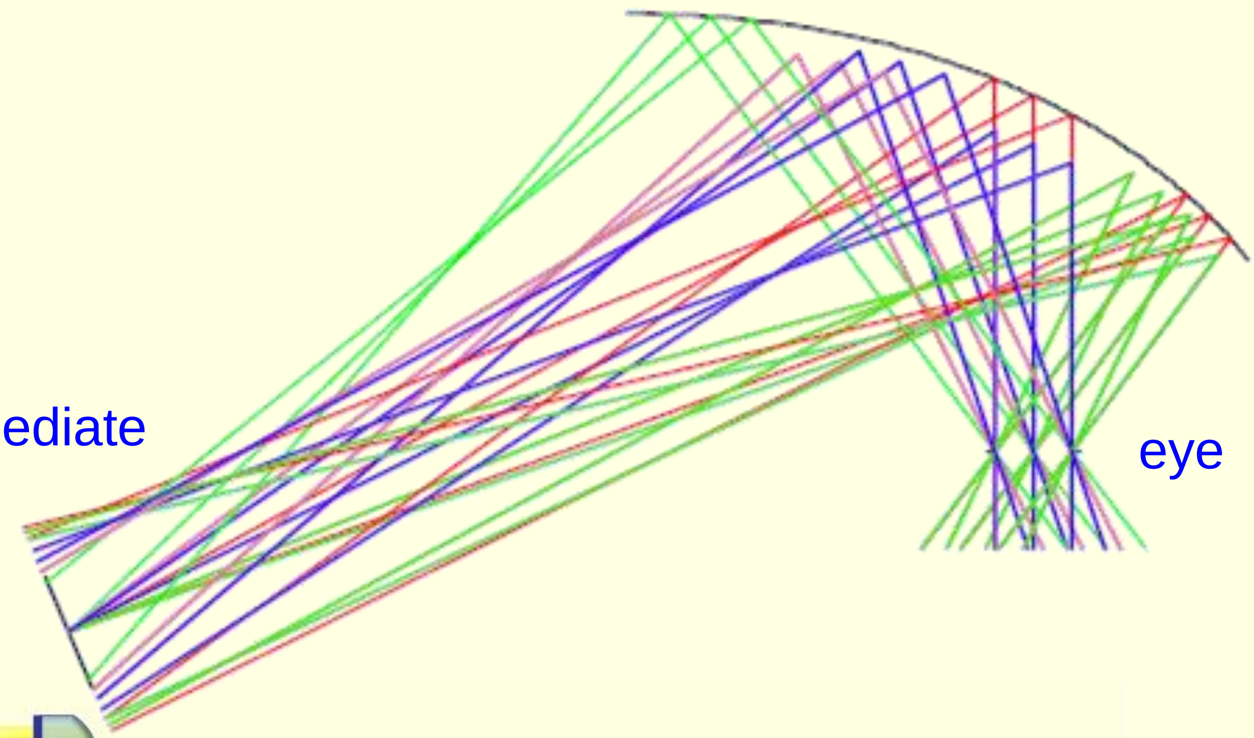
- Pupil splitting :



- Segmented (or tiled) NEDs:
- Other: Foveated; Fiber scanning; Retina scanners; etc.

The core of the design difficulty

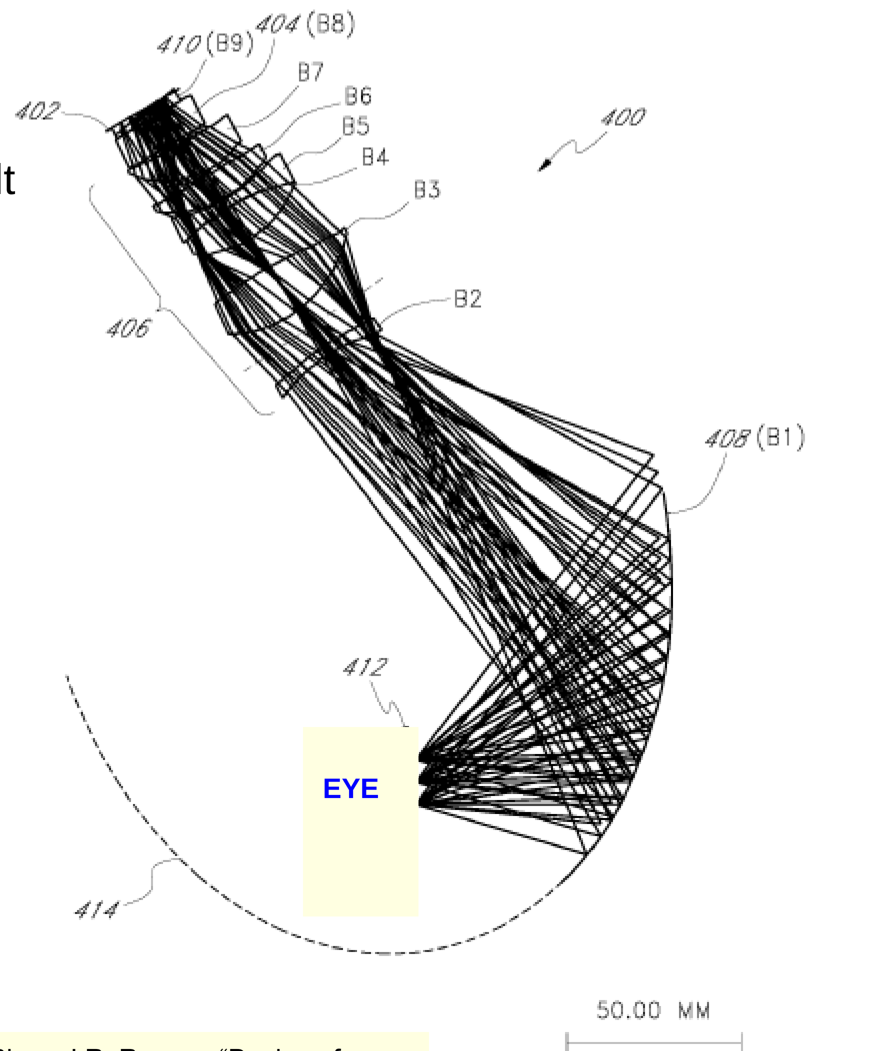
The powered combiner such an ellipsoid can easily relay the **pupils centers** when their centers are at the ellipsoid foci. However, it cannot by itself **maintain the beam collimation** at its power changes over the field and the large off axis aberrations have to be corrected by the remaining optics.



Pilot training HMD using symmetrical elements

The designs are based on the "Nodal Theory" by Thompson and Shack which shows that the aberrations of the tilted combiner can be compensated by a system using tilted symmetrical components which does not result in new aberrations , but just adds new field dependencies.

Eye Relief > 50 mm
Eye Box 15 mm
FOV 65 deg H, 60 deg V
SXGA

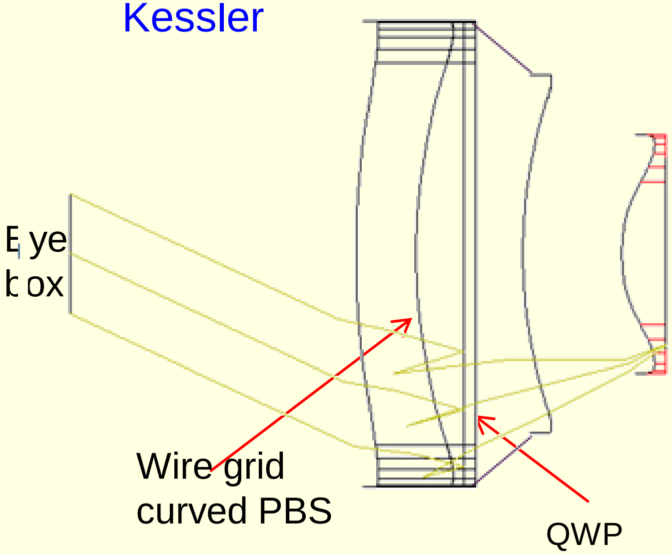


A. Sisodia, A. Riser, J.R. Rogers "Design of an Advanced Helmet Mounted Display " Proc. SPIE Vol. 5801 (2005)

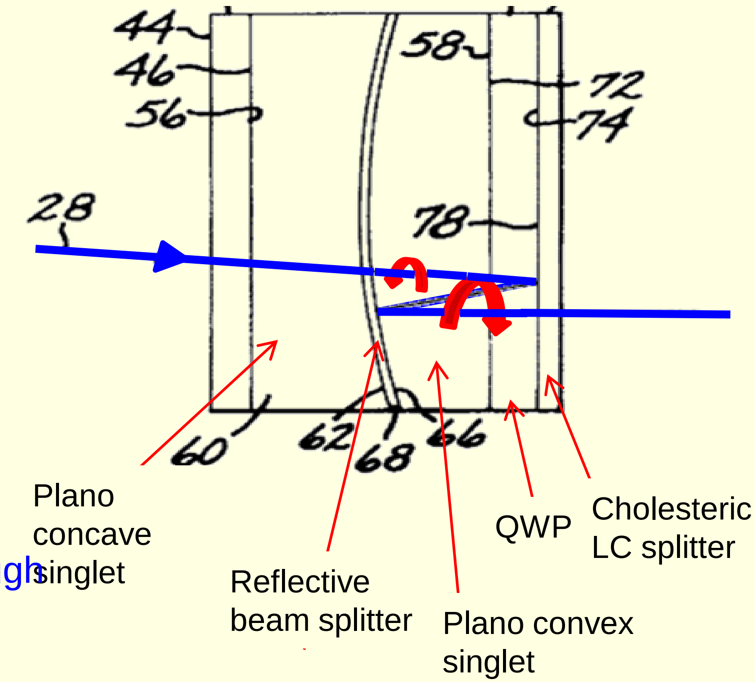
"Pancake " NED designs- the importance of symmetry

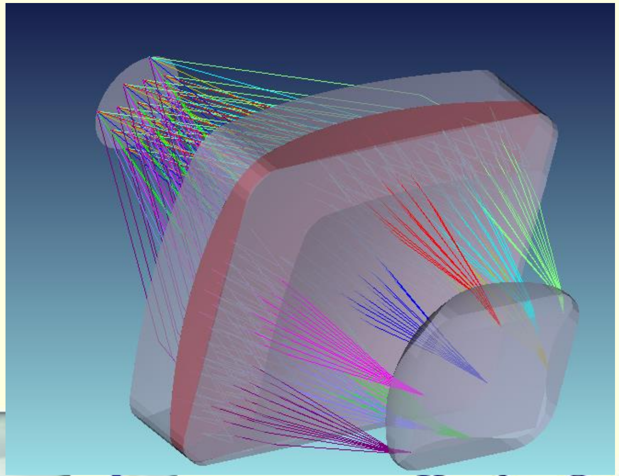
On axis designs folded by polarization means

Kessler



Raytheon US
6,563,638B2





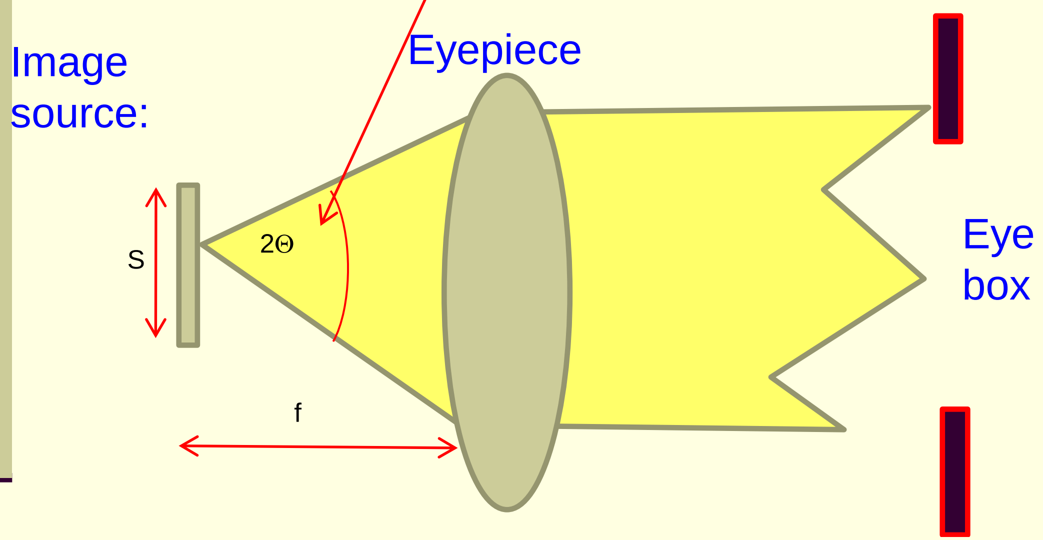
Usually not a see through
SXGA
60^0 FOV
10mm Eye box
24 mm Eye Relief

Main problem : efficiency ~ 6%

Pupil splitting designs
(also: pupil expanders and dilated optics)

We want an optical system to project into the eye with :

* Low F/number (= high Numerical Aperture) for efficiency
* large eye box
* Short focal length for large field and small optics



NA = sin(θ)
(Eye Box) =   2*f * NA
FOV = S / f

However , short focal length means small eye box, so we use a short focal length and get a small exit pupil and then expand it by replication to fill the eye box.

Conservation laws and invariants

Etendue = A Ω

- A = area
- Ω = projected solid angle = $\pi * (NA)^2$

Also: P = B*A*Ω ,

where P = power ,in lumens or Watts

B = luminance in Cd/m^2 or Nits

The three conversion laws (when there is no pupil expansion or diffusion)

P' = P	energy conservation
A' Ω' = A Ω	Etendue invariance,
B' = B	Brightness theorem

When we diffuse at the image or expand the pupil:

P' = P	energy conservation
A' Ω' > A Ω	Etendue is increased
A' > A for pupil splitting	
Ω' > Ω diffusion at an intermediate image	
B' < B	Brightness decreased

Propensity for artifacts have to be considered in designs: The “Dirty windshield” artifact

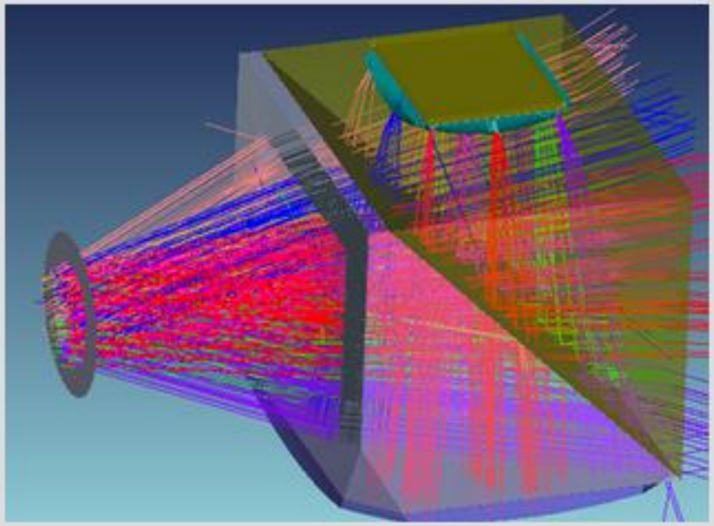
Sunlight scattered off structures and discontinuities on the windshield

This artifact is present in a number of systems with or without windshields.

Correcting for shimmering

See-through: SXGA;   50 degrees diagonal; 10 mm Eye Box ;23mm Eye Relief; 0.78" OLED

Kessler and Bablani , USA 8094377

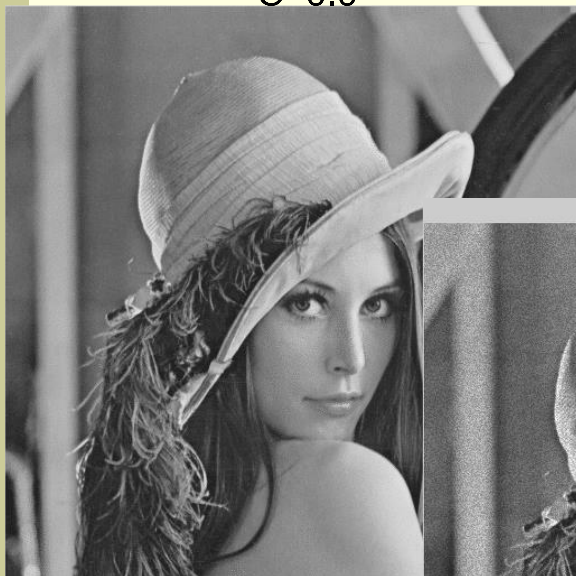


Two ways to design for low shimmering system:

1. to optimize use the full eye box- may be an overkill since the eye is a sub aperture of the eye box at any given position.
2. To use multi configurations for the sub apertures at different location within the eyebox and include chief ray deviations in the merit function.

SPECKLE

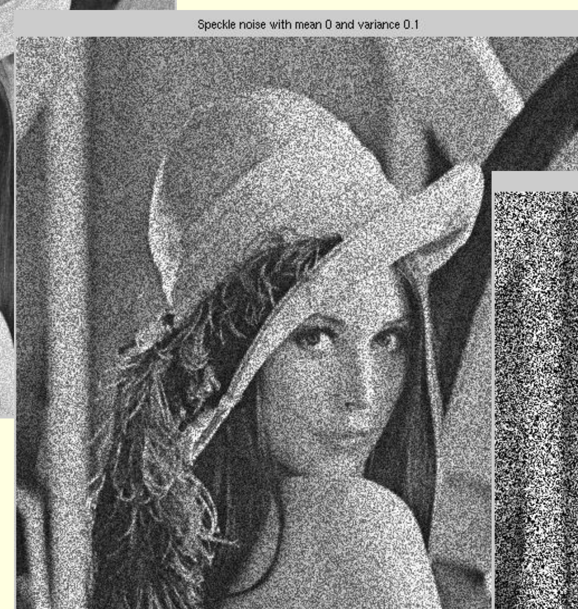
C=0.0



C=0.04

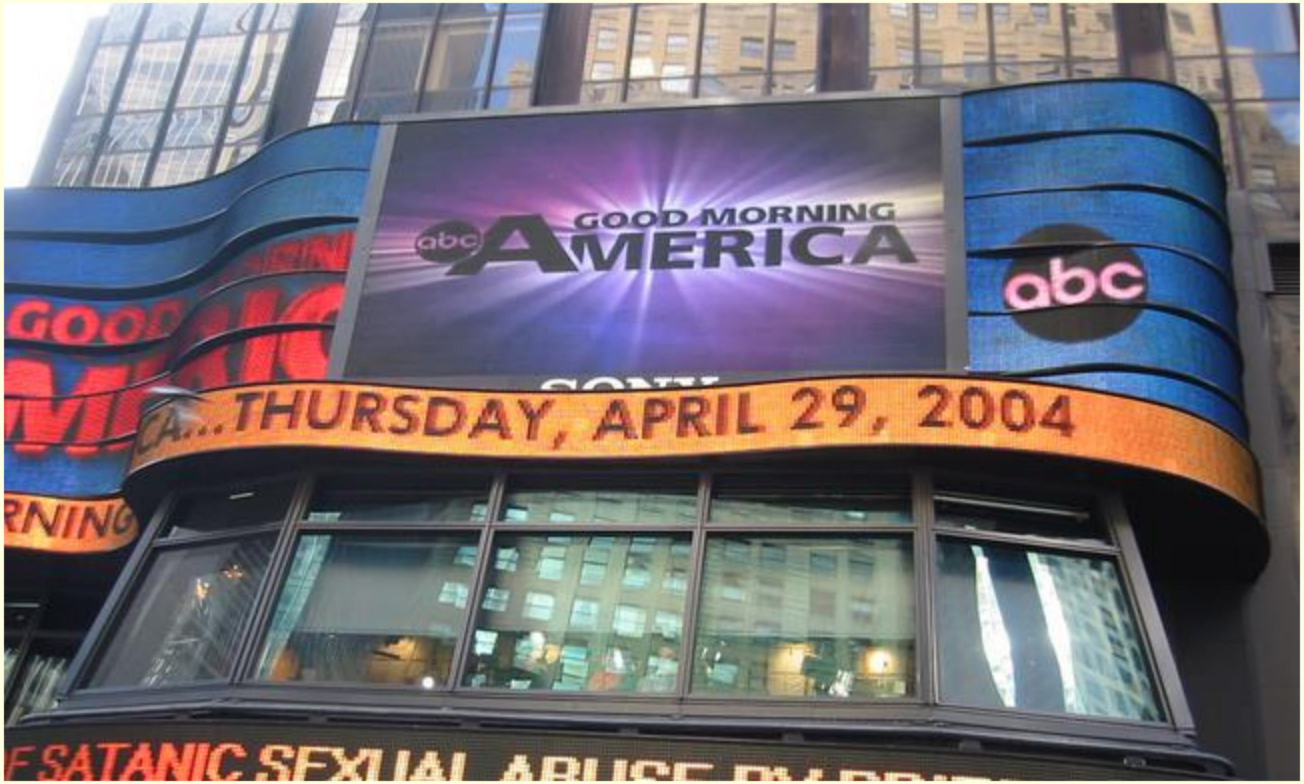
C IS THE SPECKLE CONTRAST

C=0.5



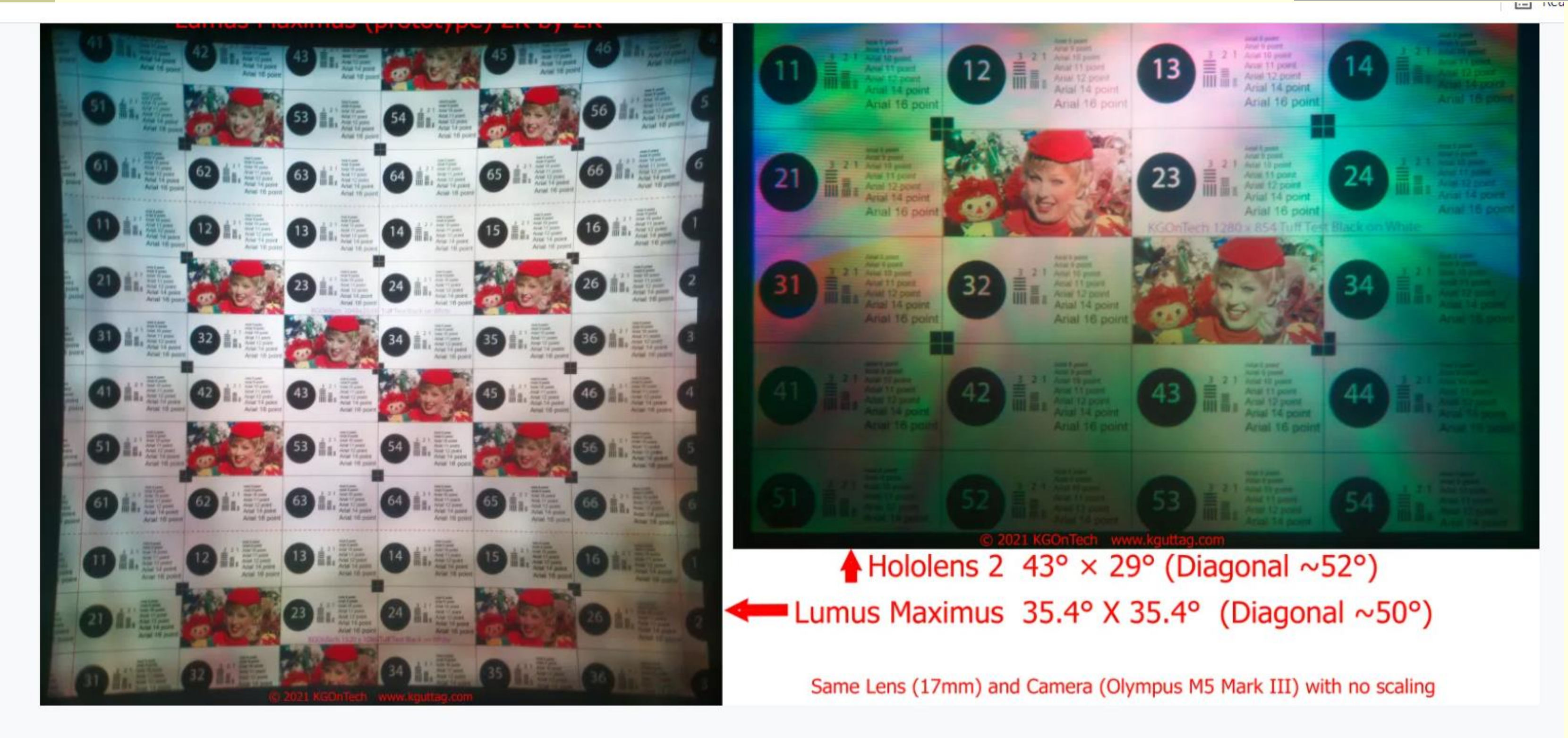
C=0.84

Tiling artifacts



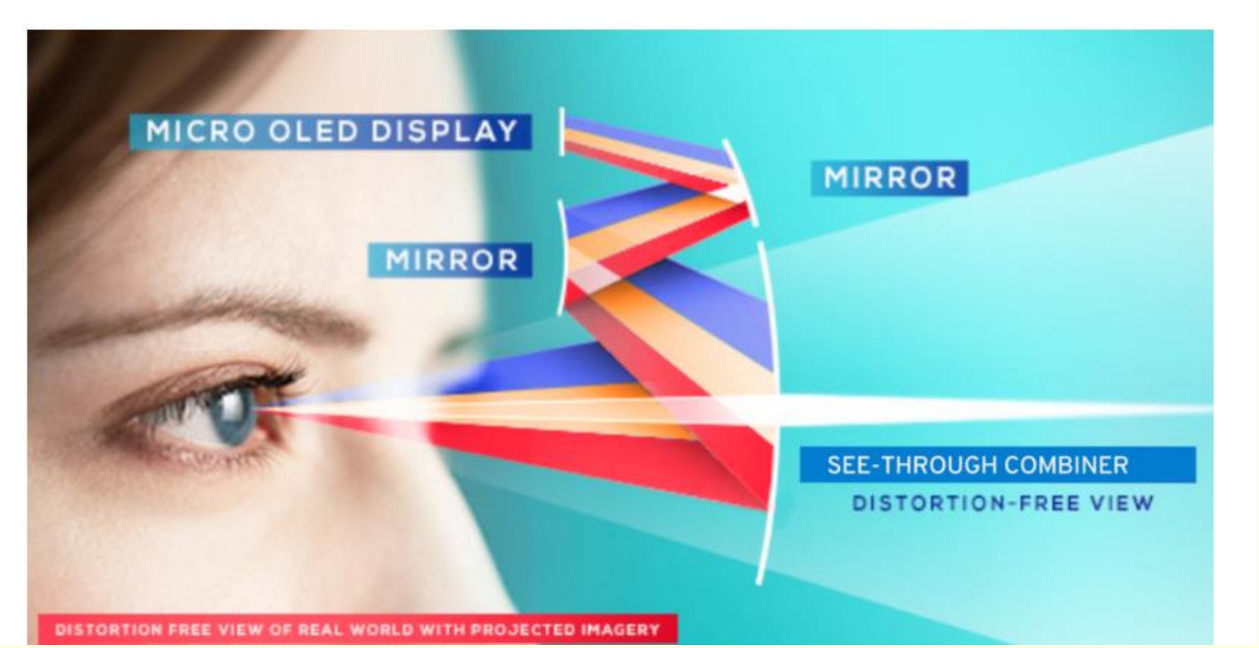
LED displays are usually assembled of 6” x 6“ modules

Color artifacts:
Latest shoot out between Lumus Maximus and Hololens II



From Karl Guttag blog- there are differences in resolution and other attributes but the color artifacts are very present with the Hololens II

A specific recent AR design: Customer original requirements



90 degrees H field obtained by three of the above “blended” by 50 degrees V so each is 30H x 50V

Back to the customer at hand and his requirements:

The main specifications for this design are:

1. The field of view of 60 degrees by 40 degrees (70 deg diagonal)
2. The eyebox of 10 mm diameter
3. Eye relief (from the eye to the closest part of the splitter) > 20 mm
4. Resolution – need to resolve the 7.2 pixels of the OLED*.
5. Maximize brightness in NITS
6. No obscuration of the see through except for looking above the 40 degrees field.
7. Reduced components complexity (no free-forms at least initially) to allow relatively short build.
8. Reasonable esthetics

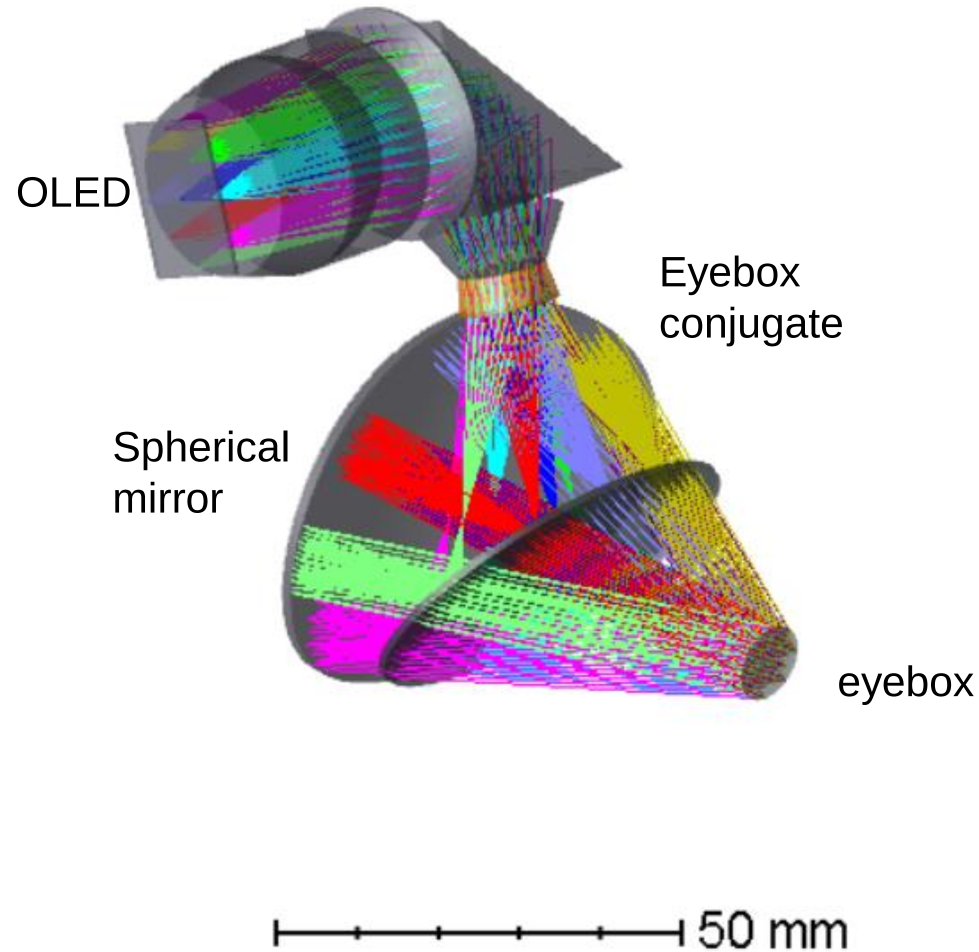
*OLED image generator is 2560 x 2560 pixels with 3000 NITS

Configuration I

This is a "Bird Bath" design with a relay

The center of curvature of the mirror is at the eyebox

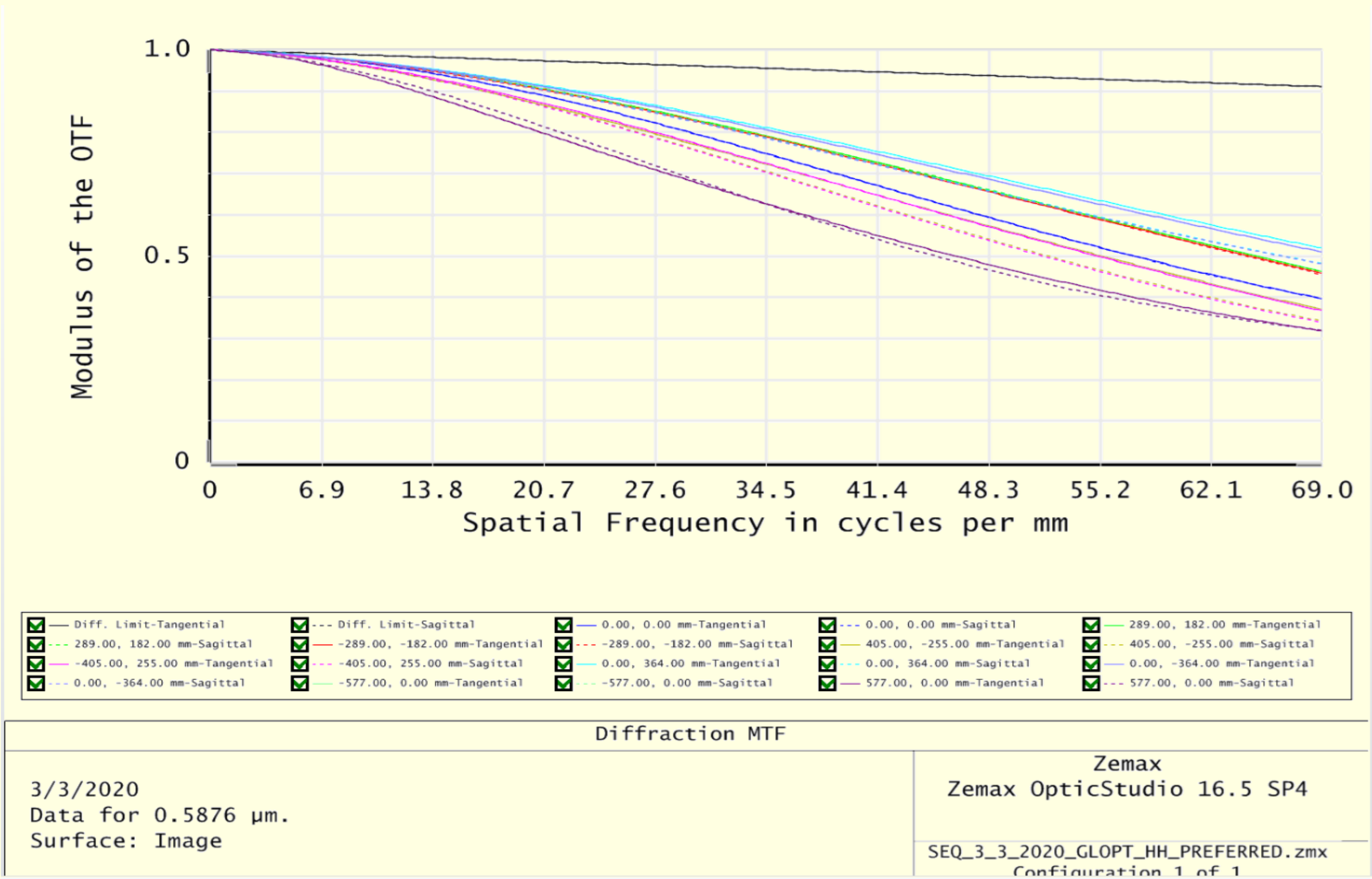
So there are no off axis aberrations from the mirror and its spherical aberration is corrected at the accessible eyebox conjugate with an aspheric



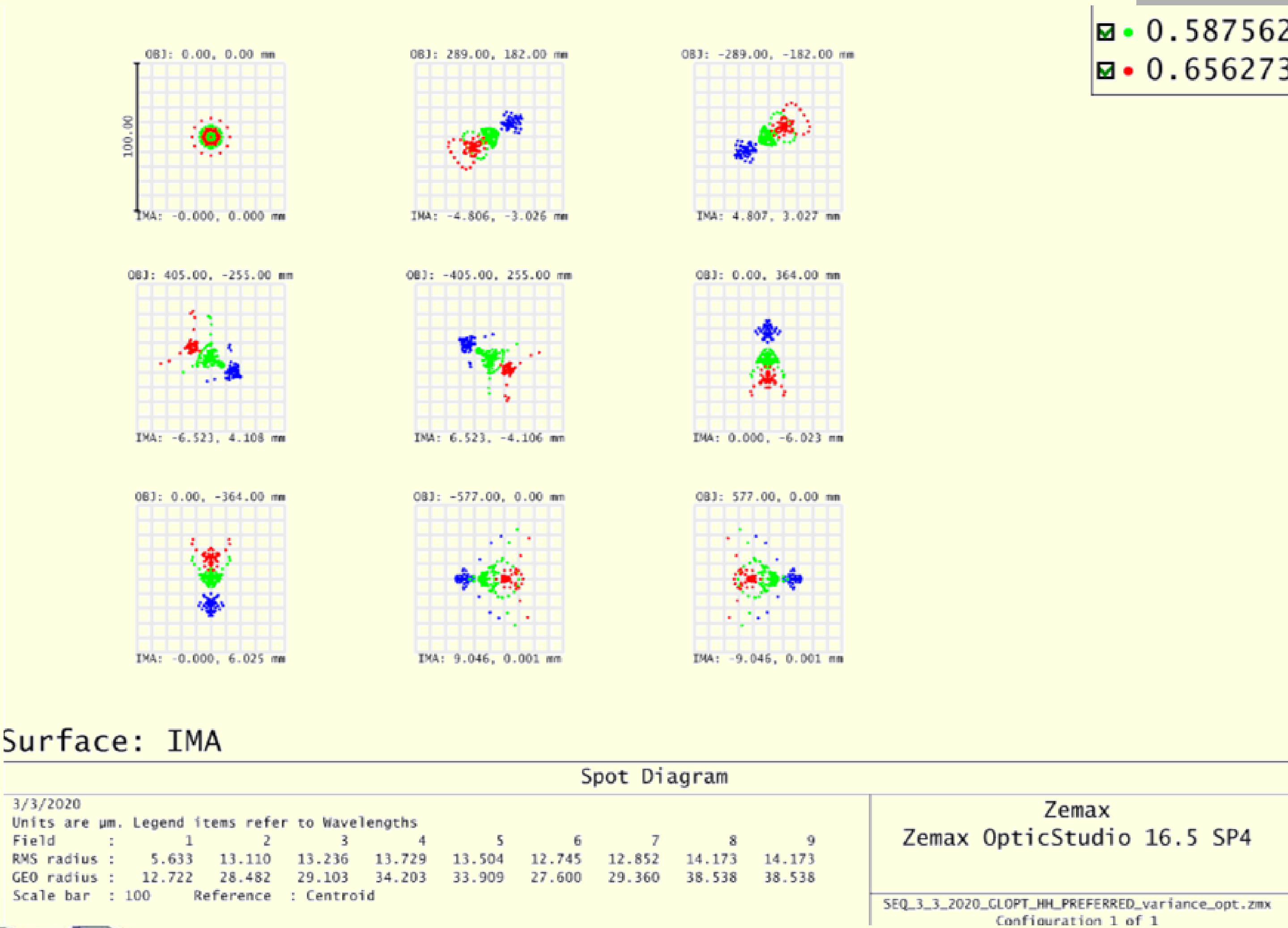
Components:

- 1. Spherical polycarbonate combiner
- 2. S-BSL7 or similar, splitter (silvered mirror or PBS namely wire grid splitter)
- 3. S-NPH2 aspheric singlet
- 4. S-LAH53 aspheric singlet
- 5. S-NPH2/S-LAH53 doublet
- 6. S-BSM4 right angle prism
- 7. S-LAH57 singlet
- 8 IF PBS is used than also: a QWP and a polarizer

Performance- Monochromatic



Lateral color



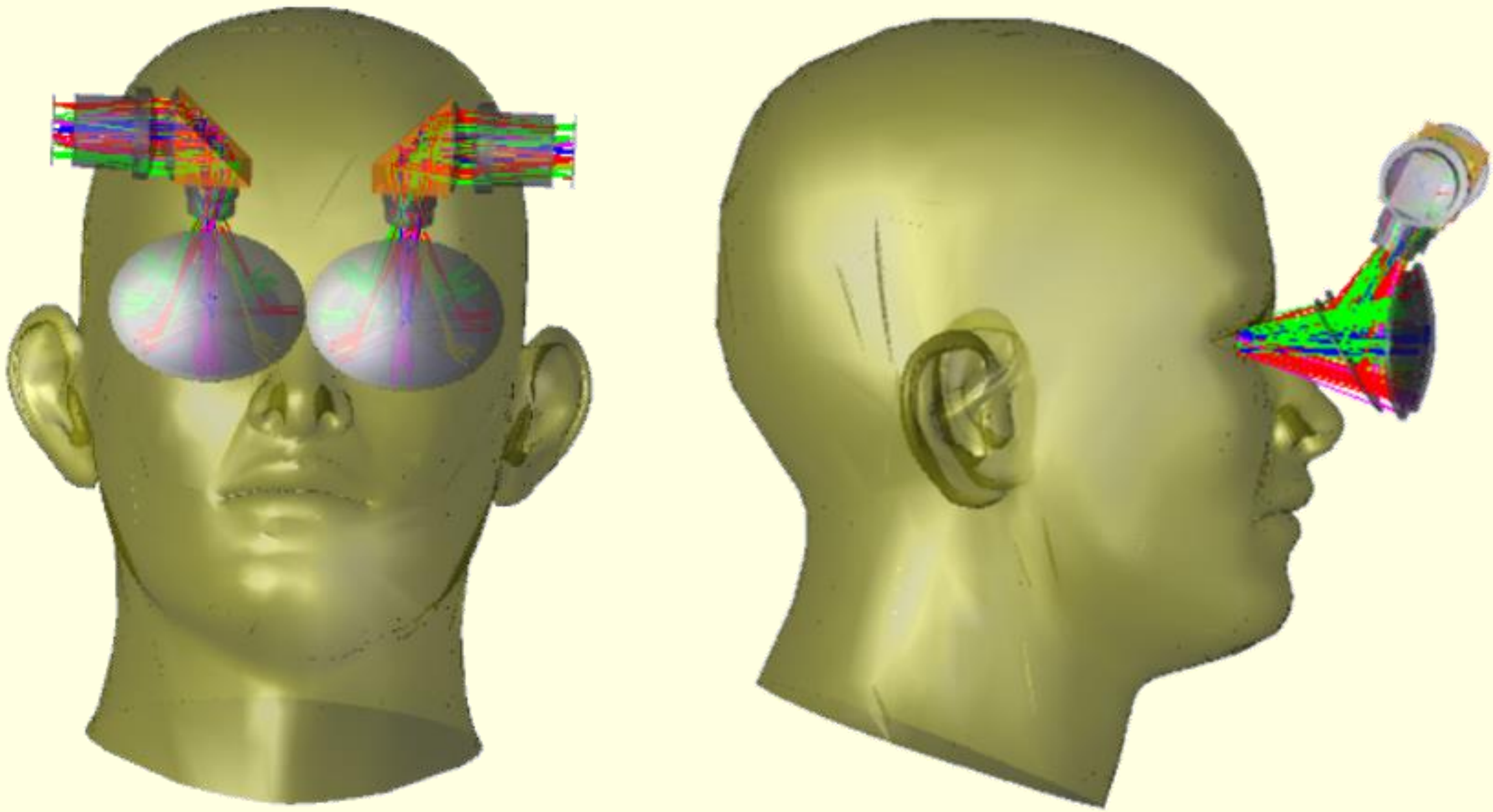
On merit functions

We usually start with RMS spots
We really usually want good MTFs
RMS spot are related to the slope of the MTF curves at MTF origin

As we get closer we switch commonly to wavefront to get better MTFS. This is because the Strehl Ratio is representing the volume under the OTF surface and the Strehl Ratio for a corrected system is related to the wavefront variance through the Marechal relation.

But: if the system final system SR is not going to be better than about .8 then the Marechal relation may not hold and using the wavefront may not result in improved MTFs so we may have to add say some MTF operands or just use the SR operand.

Non-sequential model
Configuration I: where the relay is folded sideways



Well- the customer likes the performance but not the size/look.

- Generally, the conversion is easy either by using the Zemax utility “convert to NSC group”
- How to model wire grid polarizer in NS?
- How to curve a Jones element?
- How to convert Q polynomials to NS

Modeling of a wire grid polarizer on Zemax

How do I model the wire grid splitter on Zemax?

1.DBEF is not good as the manual says at my plus minus 30 degrees in x or more in skew

2.The usual S and P definition do not work either since S and P are local coordinates for a specific incident angle and the wire grid works on the global x and y coordinates

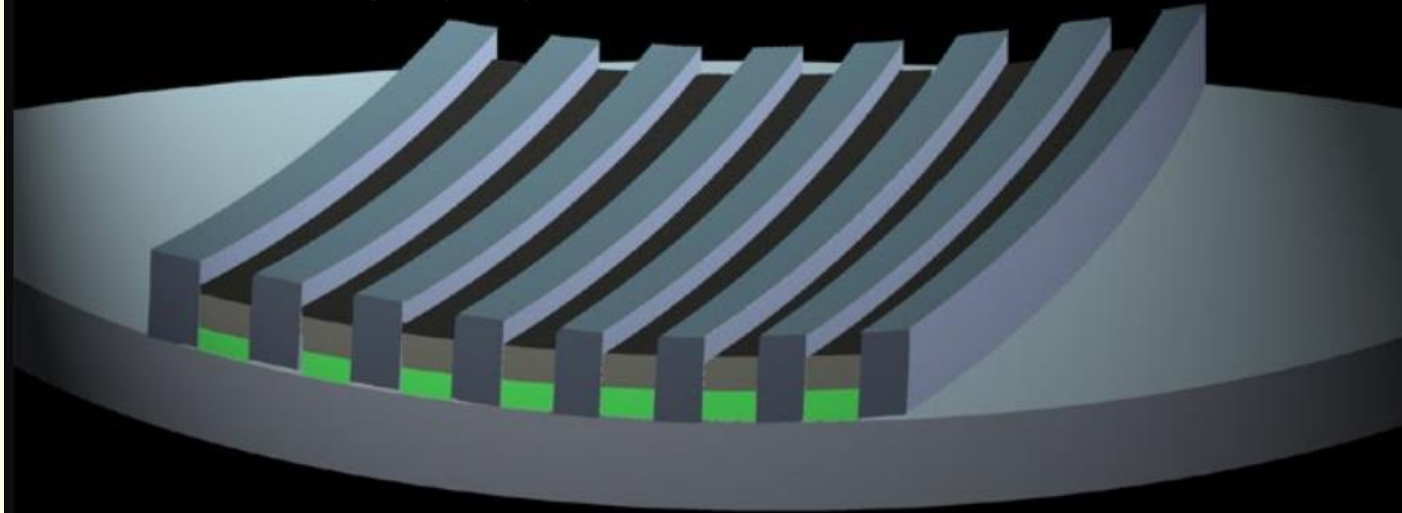
3.Lumerical and the **Zemax_interoperability_metalens_initial.lsf**
I don't design meta lenses or wire grids . I buy and use them and have their specification say from Moxtek. I want to plug the specifications as I do with coating tables when I get a coating specs.   When I design Wire Grid polarizers I happen to use GSOLVER not Lumerical

4. My solution: verify the NS design with a lab set up

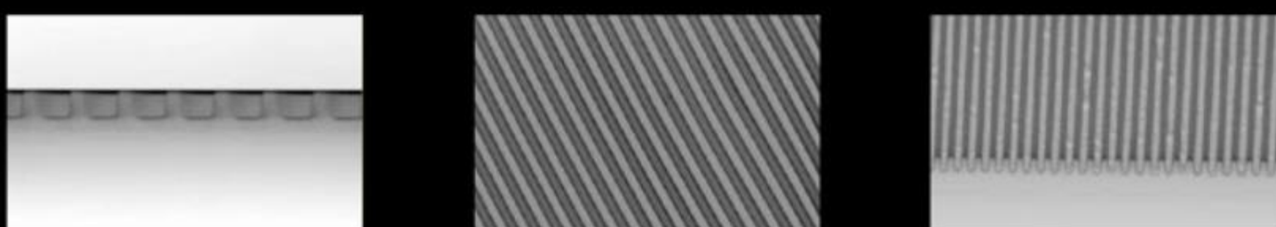
THE FUTURE OF POLARIZED EYEWEAR
SOL-GRID

Sol-Grid Nano-Structure

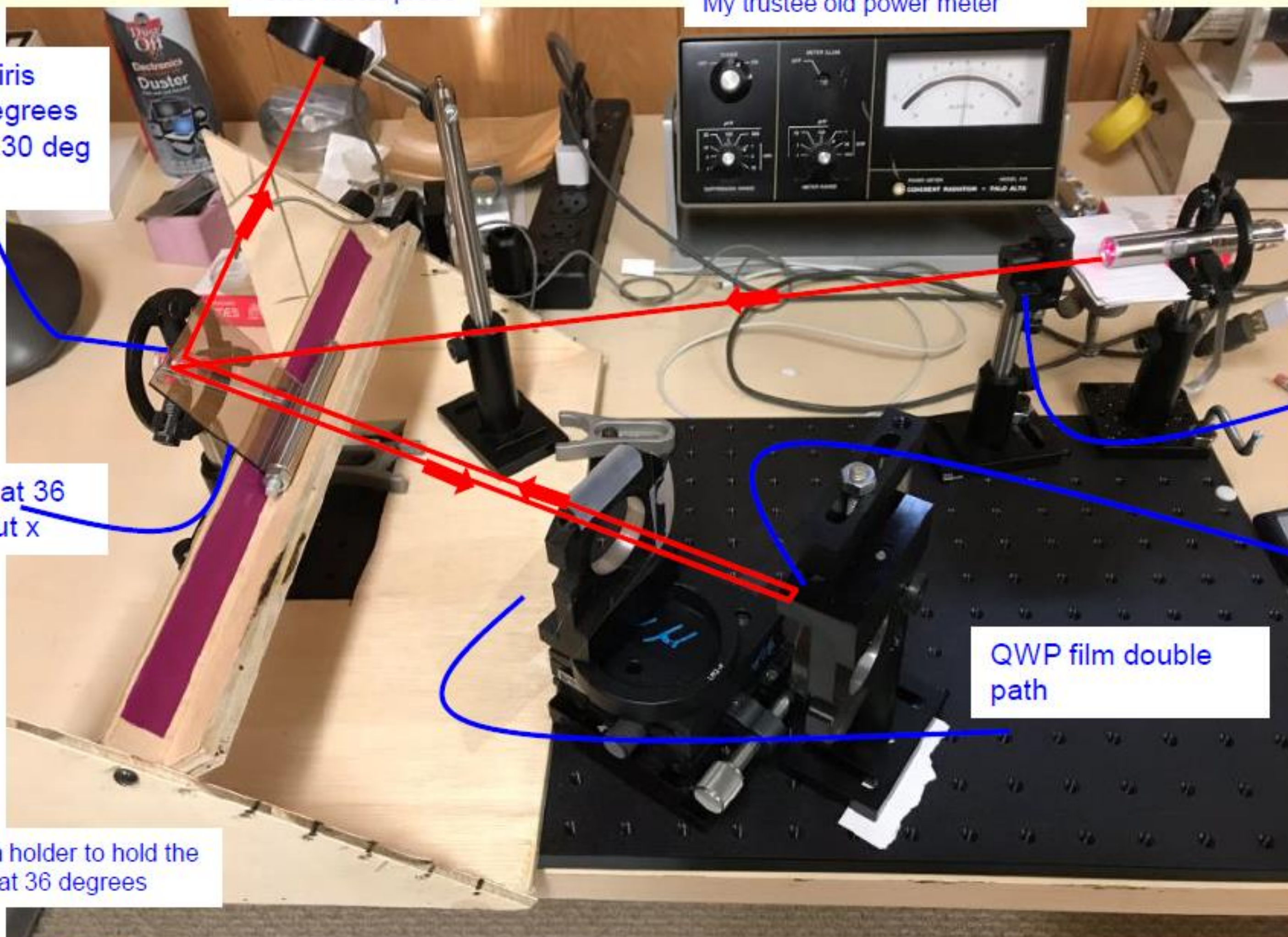
Shown here on the *concave* surface of a lens substrate with both Polarization (green) and Anti-Reflective layers (black).



Electron Micrograph images of actual Nano Grid Structures

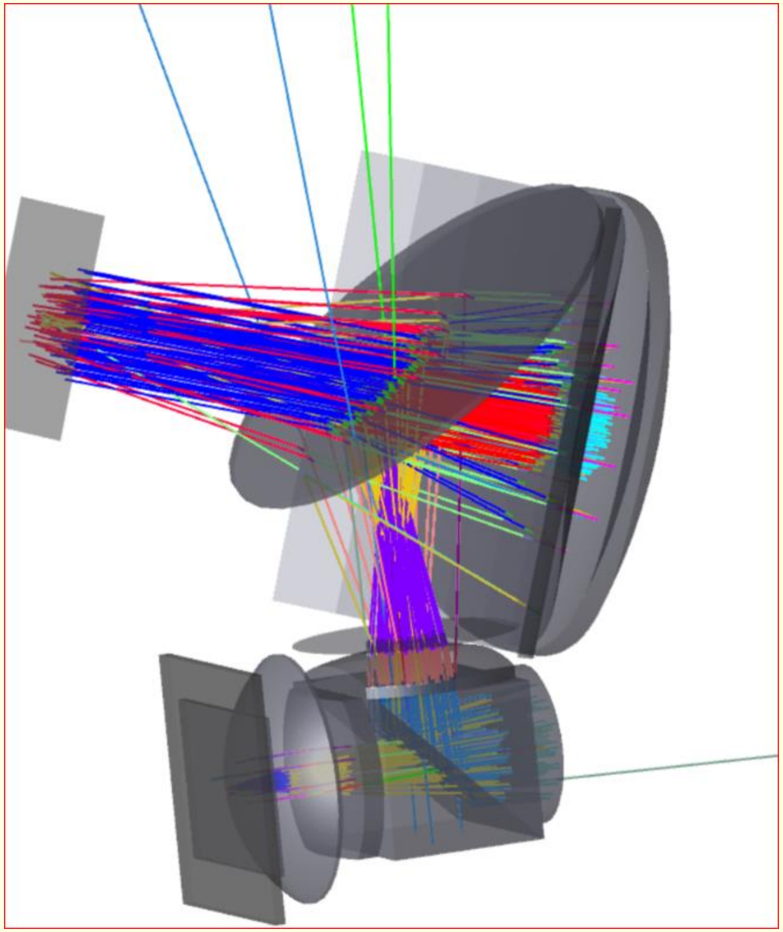


Breadboard


Power meter probe
My trustee old power meter
Mirror at the iris rotated 15 degrees to obtain the 30 deg FOV in x
laser
Glan-Thompson polarizer allowing polarization in the y direction
Moxtek PBS at 36 degrees about x
Mirror simulating the combiner
QWP film double path
Wooden holder to hold the moxtek at 36 degrees

Cylindrically curving the Jones quarter wave plate

Using a ring array of Jones plates



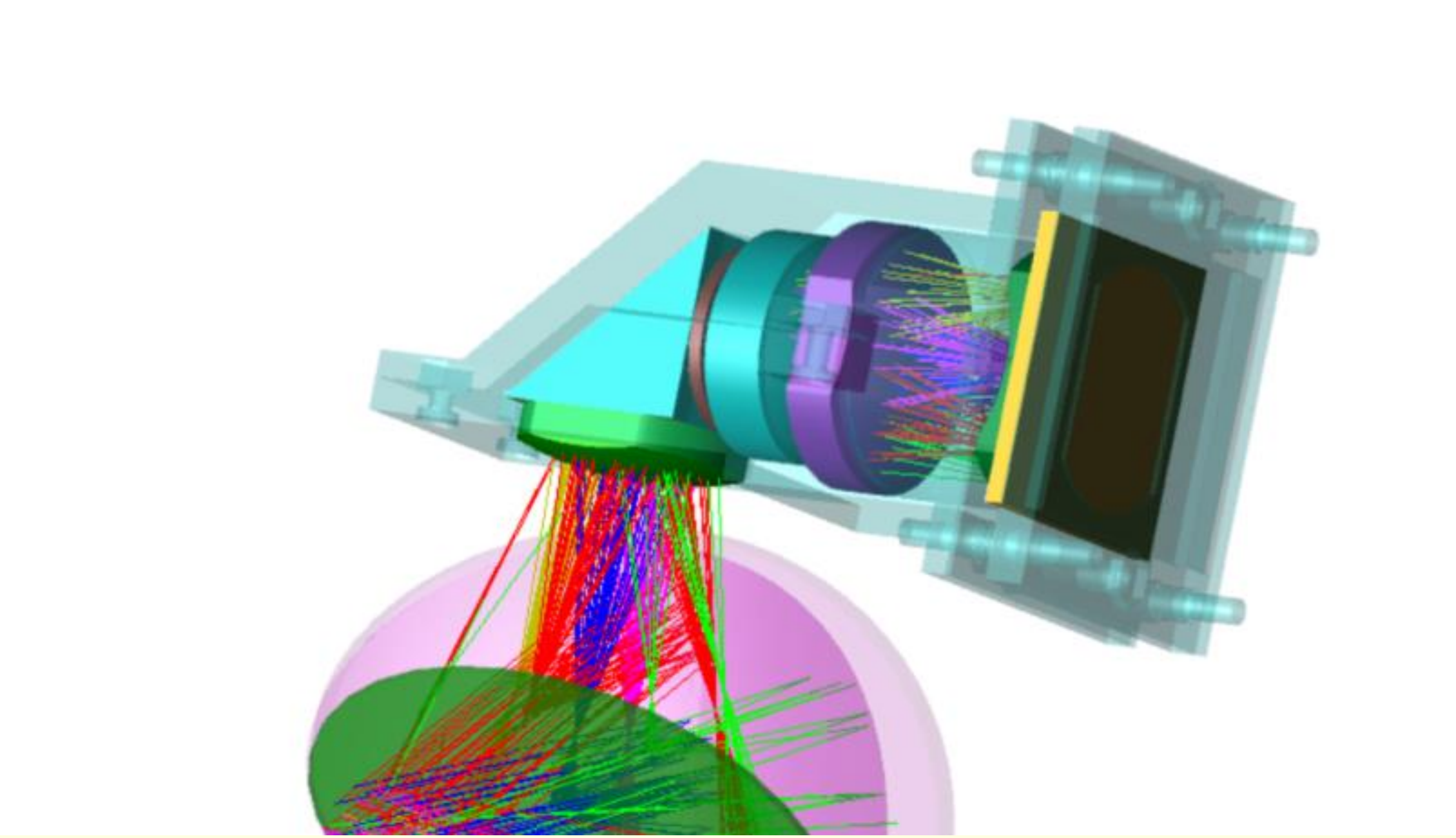
Q aspherics on non sequential model

* The latest update has added Q-Surface not a lens though
* Use the aspheric tool in sequential to convert from the sequential Q to the standard
* Use these coefficients with the even aspheric lens object.
* If more then 16 coefficients are needed - use the Odd Extended Aspheric Lens and kill the odd terms.

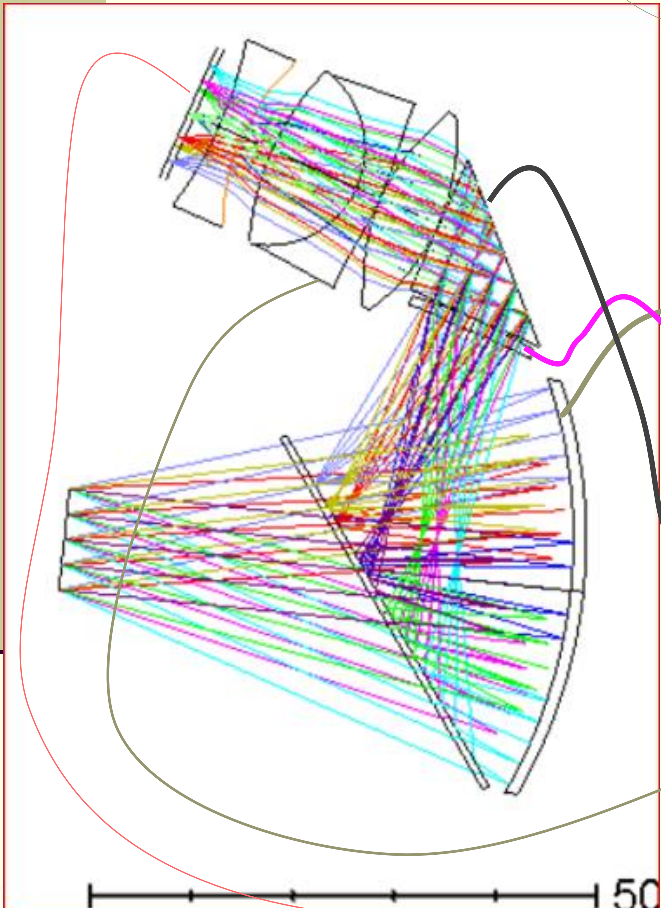
Interfacing with the mechanical designers

- I am not currently using the LensMechanix on Zemax- I am a bit more old fashioned and create the STP or IGES files and send to the mechanical designers and then import etheir designs in my non sequential and look for say ghosts

Initial Mechanical design for the relay



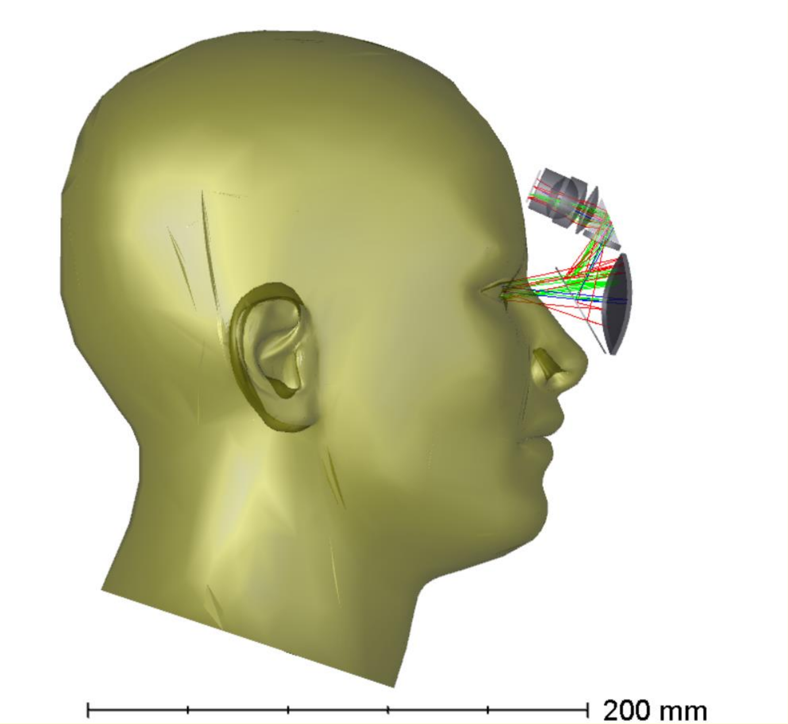
Configuration II: where the relay is folded up- the prism is smaller

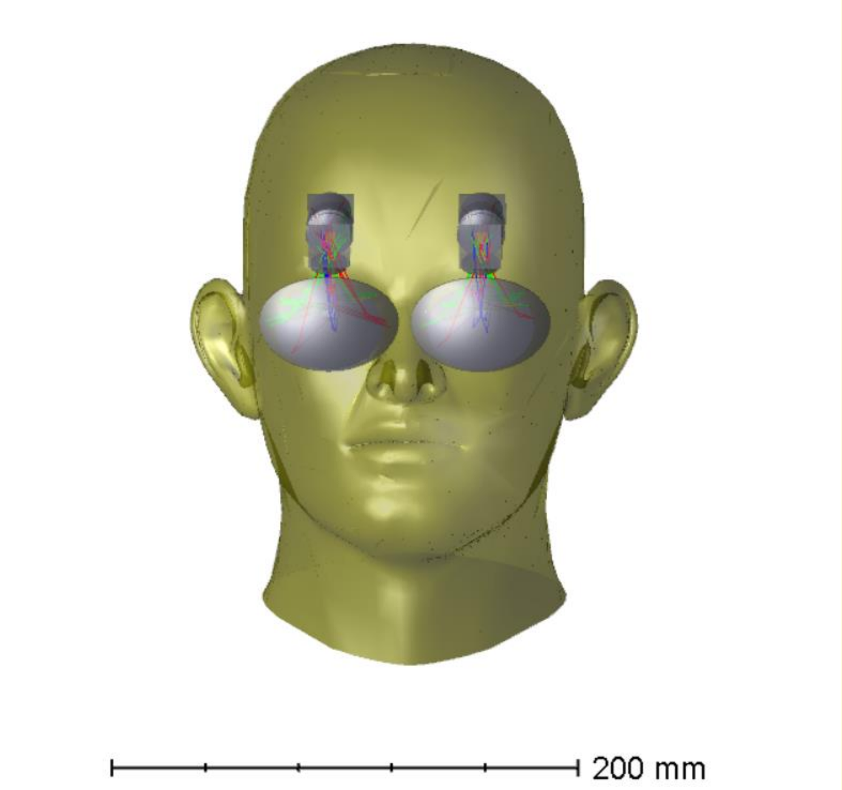


SUMMARY:

Surf	Type	Radius	Thickness	Glass c	Comment
OBJ	STANDARD	Infinity	-1000		
STO	STANDARD	Infinity	29		
2	COORDBRK	-	0		NOTE: DELTAY
3	STANDARD	Infinity	0.7	1.590000, 64.142022	splitter through
4	STANDARD	Infinity	-0.7		
5	COORDBRK	-	0		
6	STANDARD	Infinity	0.729		BACK TO front
7	COORDBRK	-	0		deltay
8	STANDARD	Infinity	20.55		
9	STANDARD	-50	-20.55	MIRROR	primary
10	COORDBRK	-	0		
11	STANDARD	Infinity	0	MIRROR	splitter reflect
12	COORDBRK	-	24.33874		
13	EVENASPH	39.3312	3.001186	N-LASF46A	asphere
14	STANDARD	-1308.378	0.1735078		
15	STANDARD	Infinity	7	S-LAH53	prism in
16	COORDBRK	-	0		
17	STANDARD	Infinity	0	MIRROR	fold
18	COORDBRK	-	-7		
19	STANDARD	Infinity	-0.1142065		prism out
20	STANDARD	-19.39191	-5.232776	S-LAL8	asph cemented
21	EVENASPH	24.07796	-0.07469497		second asphere
22	STANDARD	-24.06514	-2.486024	S-NPH2	field lens flint
23	STANDARD	-9.157246	-10.13038	S-LAH64	field lens crwon
24	STANDARD	23.02939	-1.927573		
25	STANDARD	12.68869	-5.037447	S-NPH2	
26	STANDARD	-86.12759	-1.45065		
27	STANDARD	Infinity	-0.7	SILICA	oled cover
IMA	STANDARD	Infinity			

Non-sequential model
Configuration II: where the relay is folded up

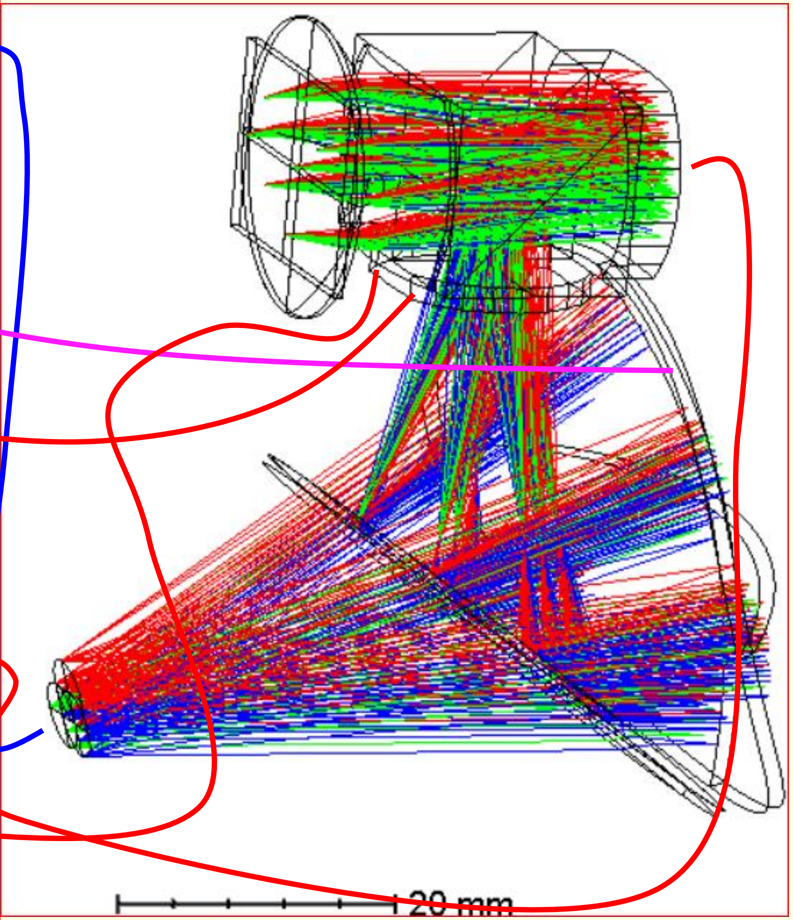




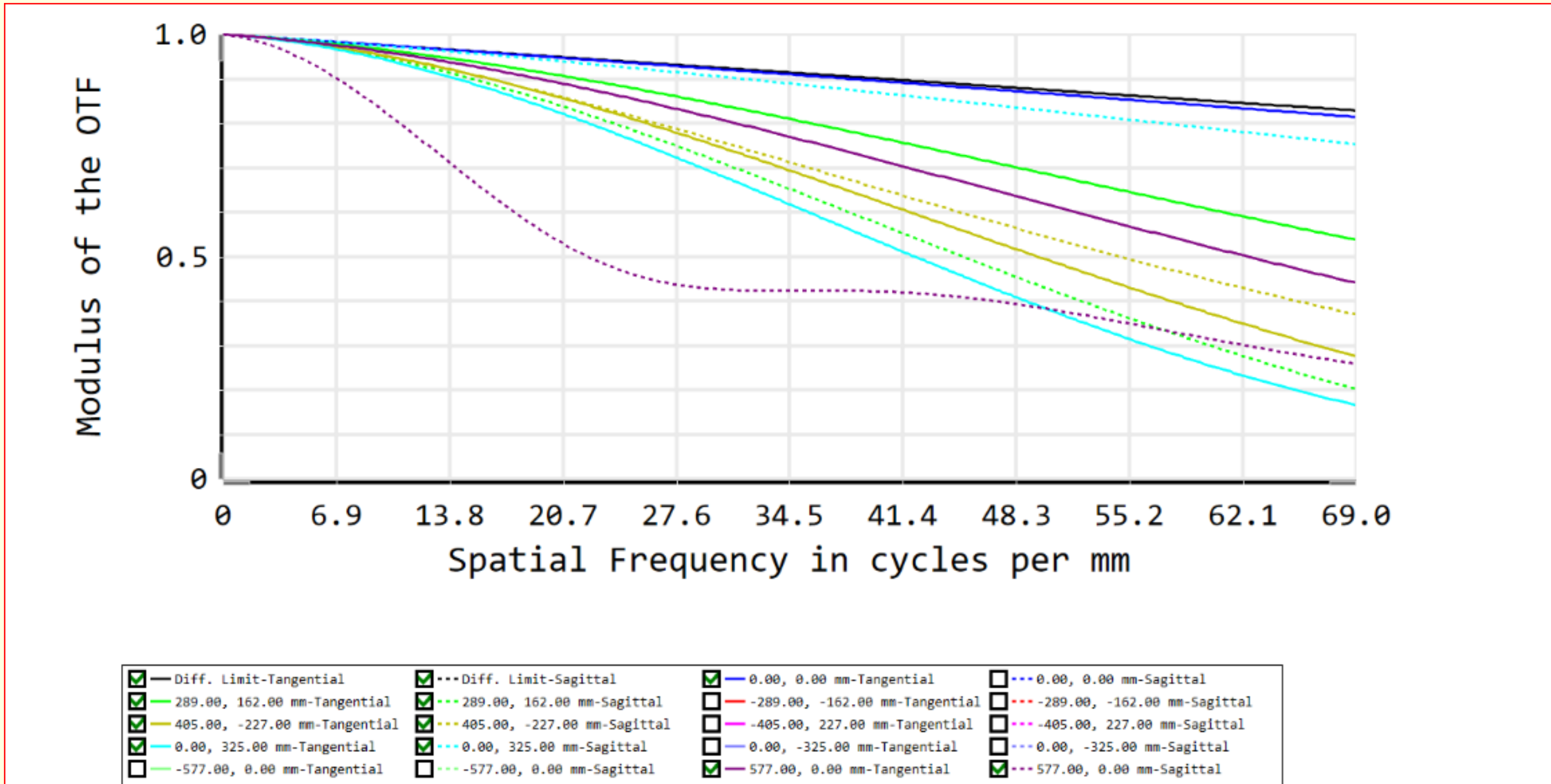
Somewhat smaller than Configuration I but the customer still not happy – also concerned about forehead clearance

Configuration III: reflective relay and a PBS
Y fold – good forehead clearance

Surf	Type	Radius	Thickness	Glass	:	Comment
OBJ	STANDARD	Infinity	-1000			
STO	STANDARD	Infinity	29			
2	COORDBRK	-	0			NOTE: DELTAY
3	STANDARD	Infinity	0.7	1.590000, 64.142022		splitter through
4	STANDARD	Infinity	-0.7			
5	COORDBRK	-	0			
6	STANDARD	Infinity	0.729			BACK TO front
7	COORDBRK	-	0			deltay
8	STANDARD	Infinity	20.55			
9	STANDARD	-50	-20.55	MIRROR		primary
10	COORDBRK	-	0			
11	STANDARD	Infinity	0	MIRROR		splitter reflect
12	COORDBRK	-	21.98213			
13	EVENASPH	20.14045	3.001006	S-LAM60		asphere
14	STANDARD	Infinity	0			
15	STANDARD	Infinity	7	S-LAL9		prism in
16	COORDBRK	-	0			
17	STANDARD	Infinity	0	MIRROR		fold
18	COORDBRK	-	-7			
19	STANDARD	Infinity	0			prism out
20	STANDARD	Infinity	-4.917126	S-PHM53		cemented mangin
21	EVENASPH	44.25724	4.917126	MIRROR		mangin mir asphere
22	STANDARD	Infinity	0			
23	STANDARD	Infinity	14	S-LAL9		
24	STANDARD	Infinity	0			cement topost prism
25	STANDARD	Infinity	1.88416	S-BSM16		second asphere
26	EVENASPH	181.7979	0.4999938			focus gap
27	STANDARD	14.26355	5.474755	S-LAL9		field lens
28	STANDARD	Infinity	0			cement
29	STANDARD	Infinity	0.7	SILICA		oled cover
IMA	STANDARD	Infinity				



Using floating sub apertures within the eyebox MTF, green, 5 mm pupil centered on the eyebox



Diffraction MTF

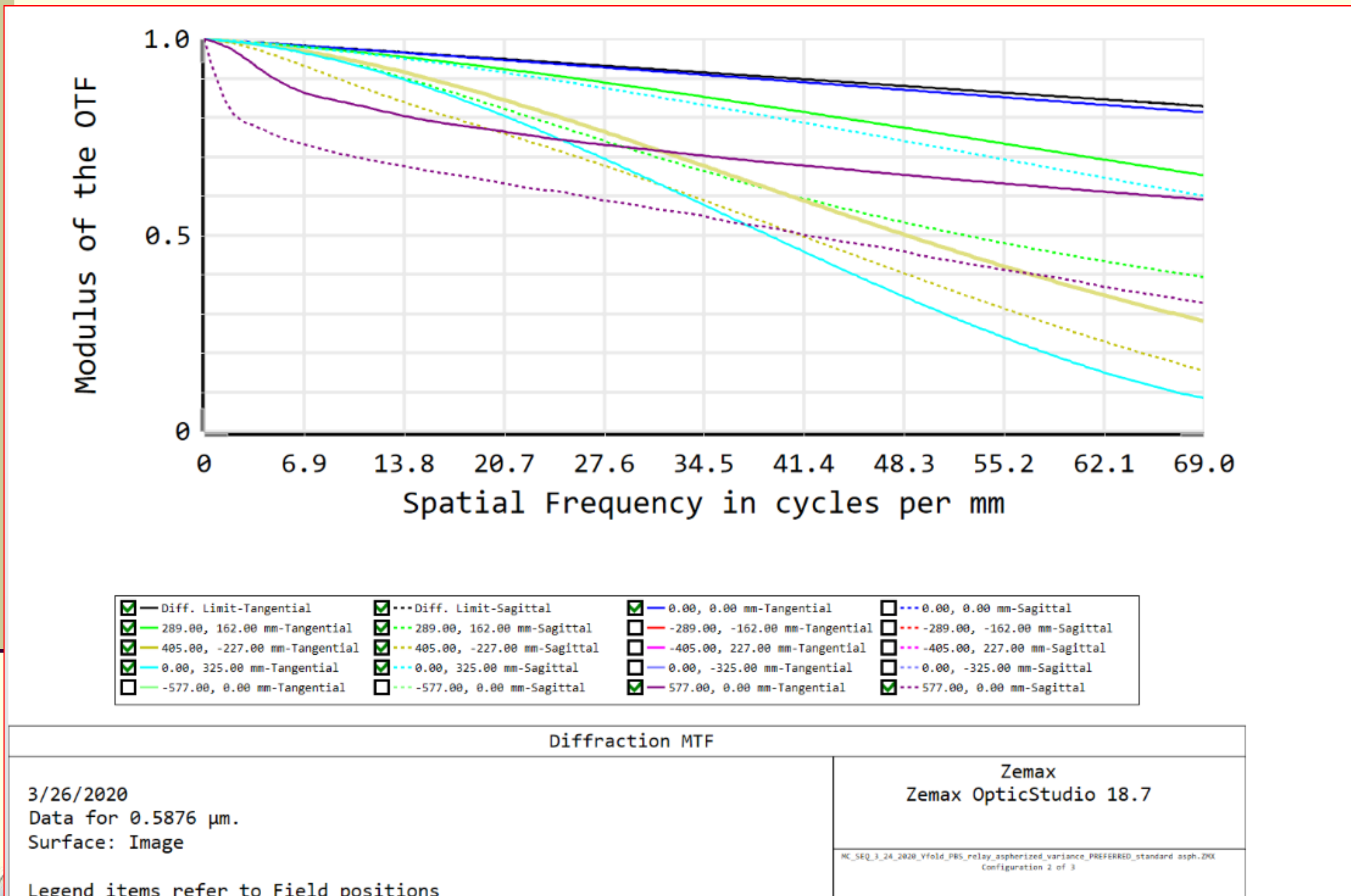
3/26/2020
Data for 0.5876 µm.
Surface: Image

Legend items refer to Field positions

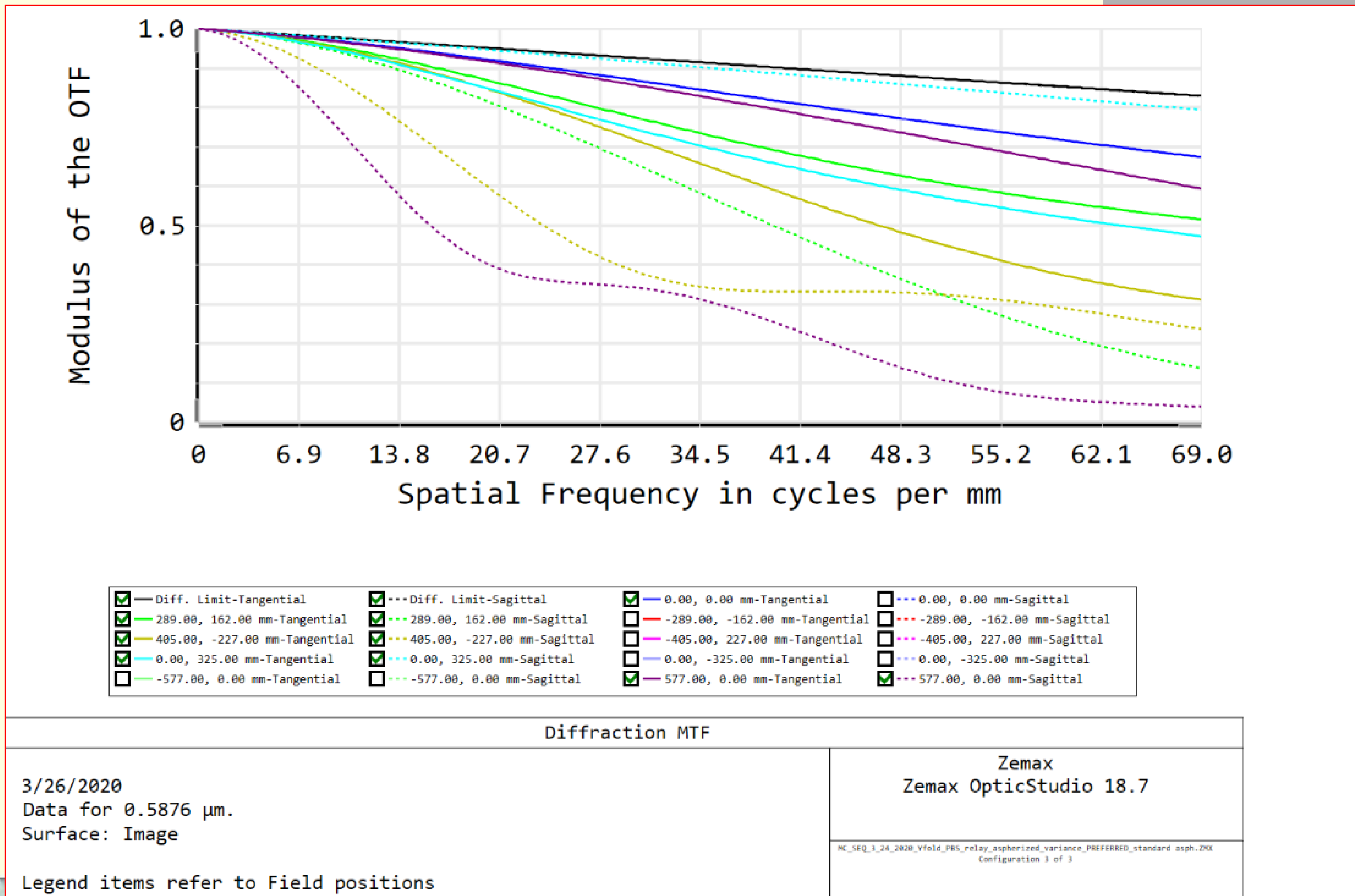
Zemax
Zemax OpticStudio 18.7

MC_SEQ_3_24_2020_Yfold_PBS_relay_aspherized_variance_PREFERRED_standard asph.ZMX
Configuration 1 of 3

MTF, green, 5 mm 2.5 mm x decentered

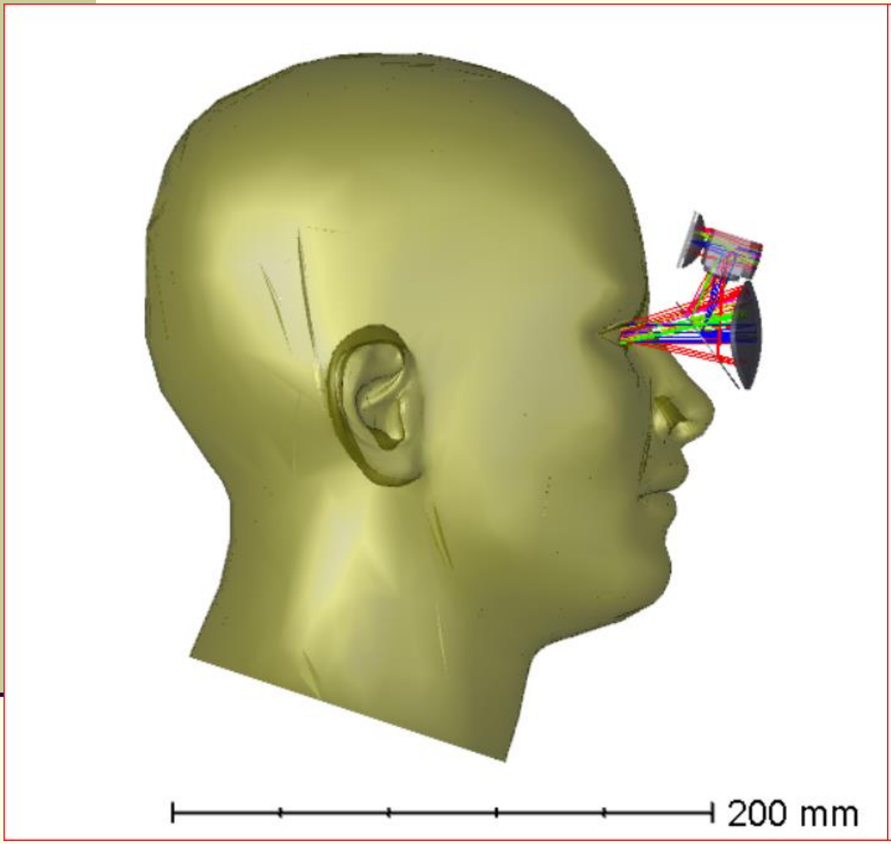


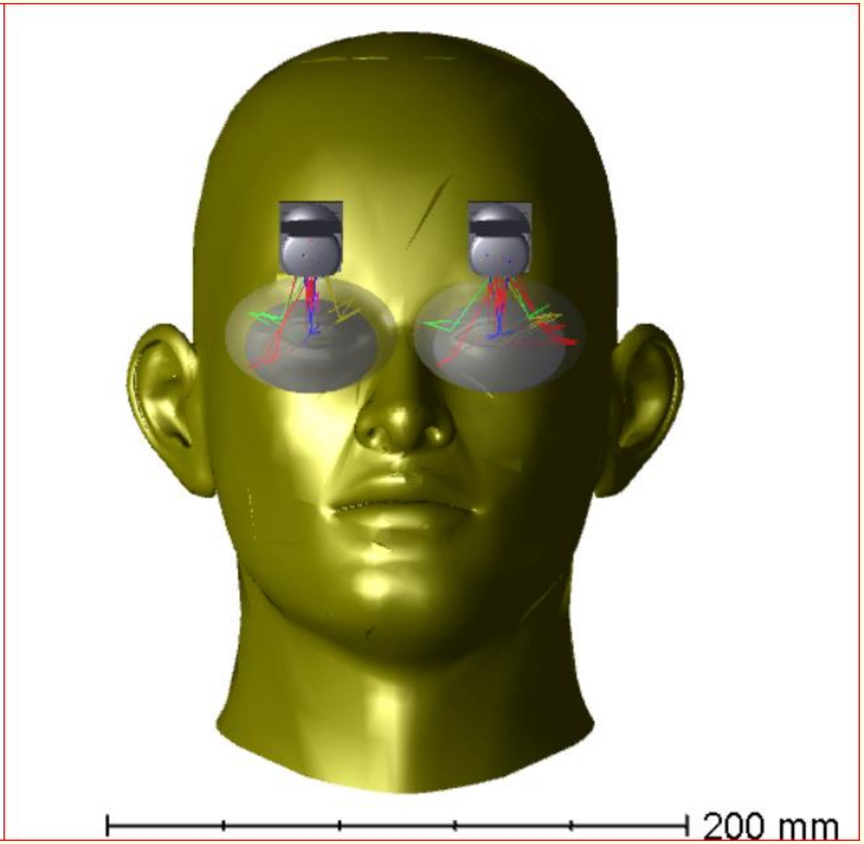
MTF, green, 5 mm 2.5 mm y decentered



Kessler Optics & Photonics Solutions, Ltd.
www.kessleroptics.com

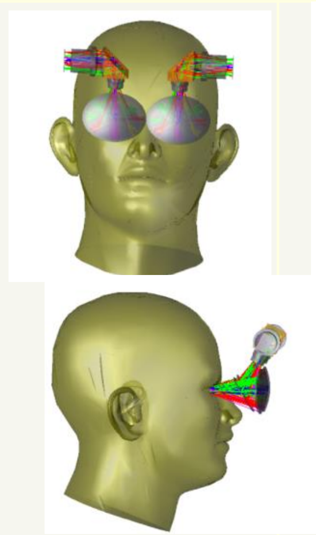
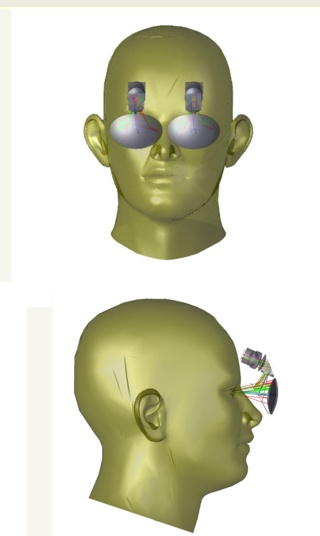
Config III Non-Sequential model





Good performance and good forehead clearance

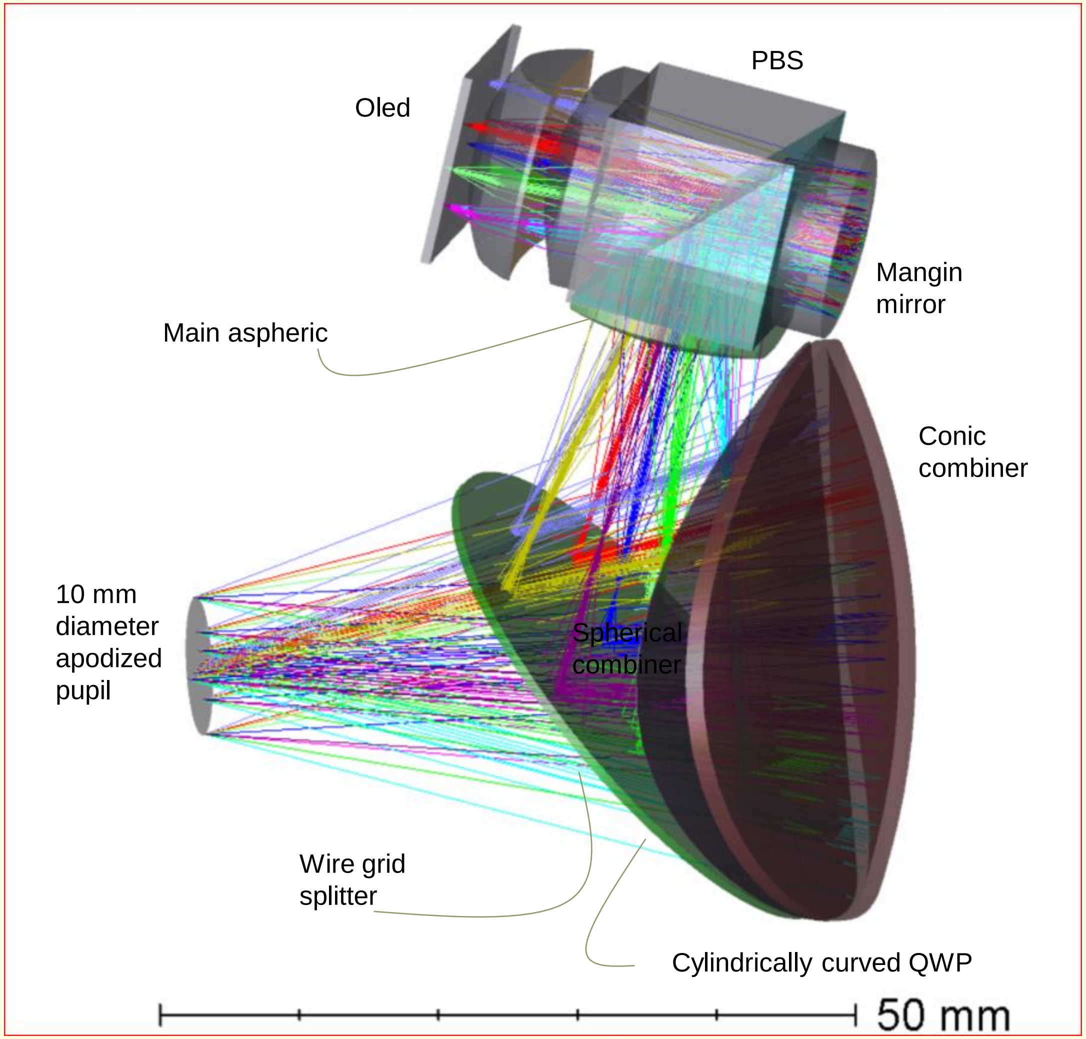
Pugh chart

Configuration:	I	II	III
description	Shown before-using a X fold refractive relay	Using a Y fold refractive relay	Using a reflective Y fold +PBS relay
field	60^0 x 40^0	60^0 x 36^0	60^0 x 36^0
size	large	medium	compact
concerns	large	Forehead clearance 10 pix lateral color	A bit more risky due to PBS
Brightness	1	1	~.8
			

Configuration IV- improving on Conf.III

Pupil is modeled not by floating sub apertures but gaussian apodised 10 mm eyebox
Combiner is conic

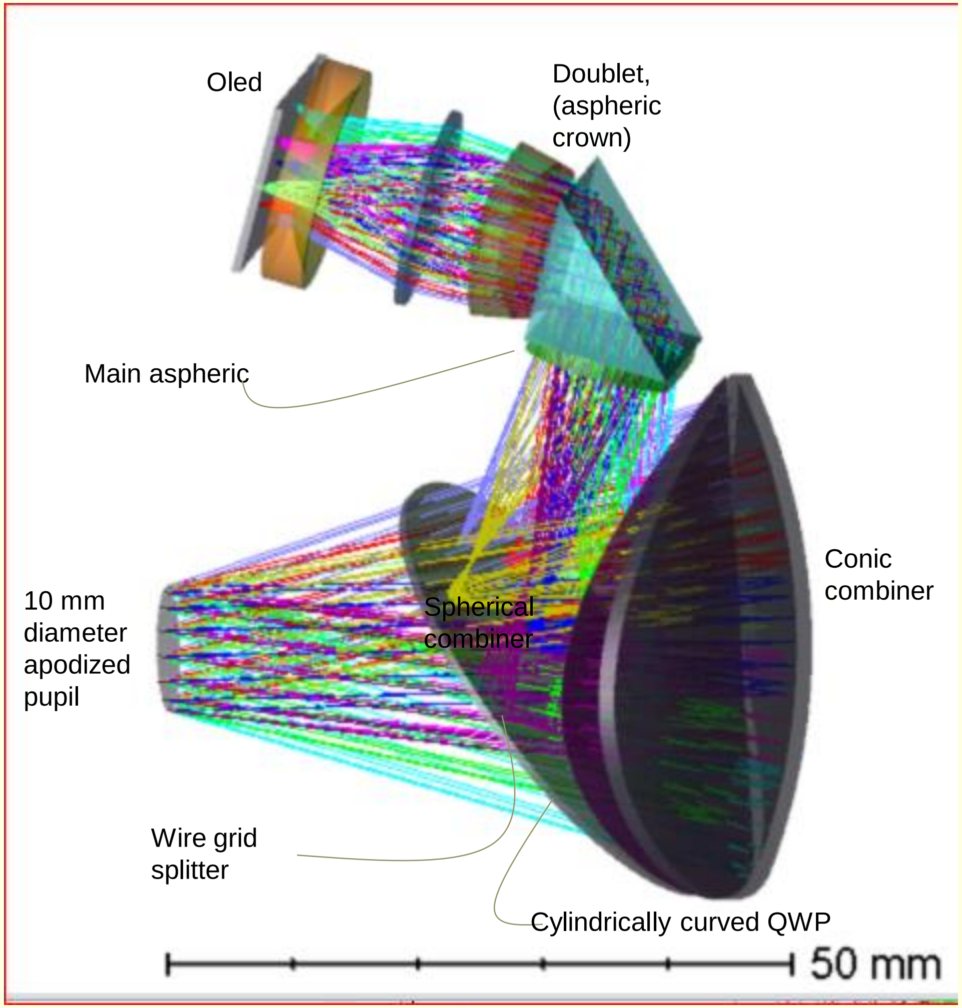
PBS has a bit higher risk- it is Confit quite fast and may present delays in purchasing. Also- maybe about 20% brightness cost



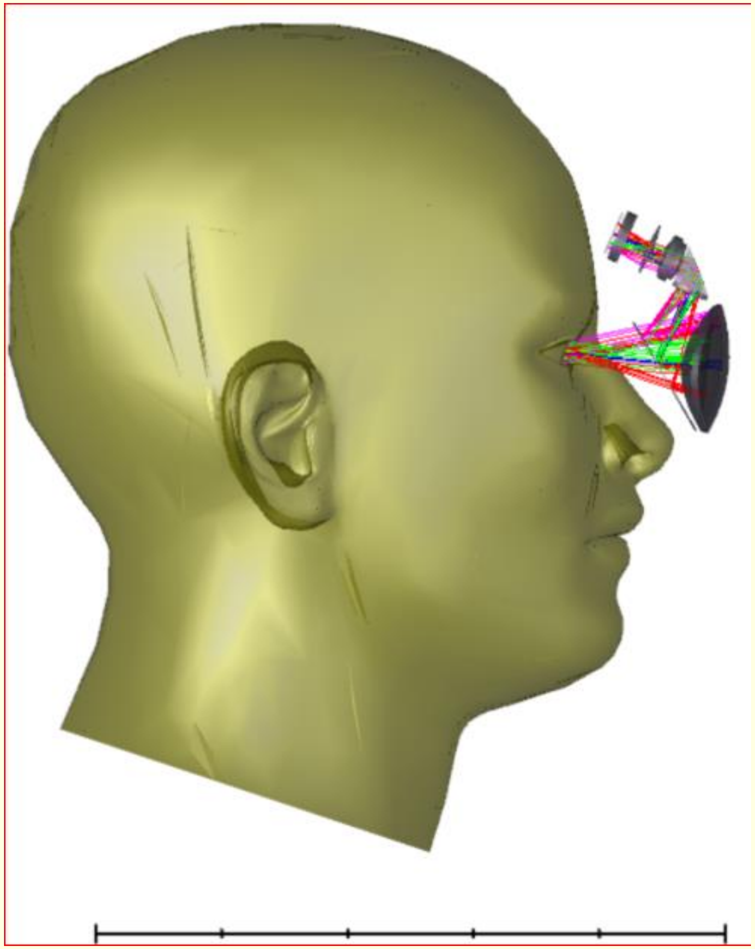
Configuration V: back to right angle prism and Y fold – can the forehead clearance be improved compared to config II?

Compared to II- the combiner is conic, the eyebox is 10 mm diameter , gaussian apodization Clearance increased by also tilting the system 6 degrees forward (pantoscopic tilt)

We also achieve low distortion and lateral color correction



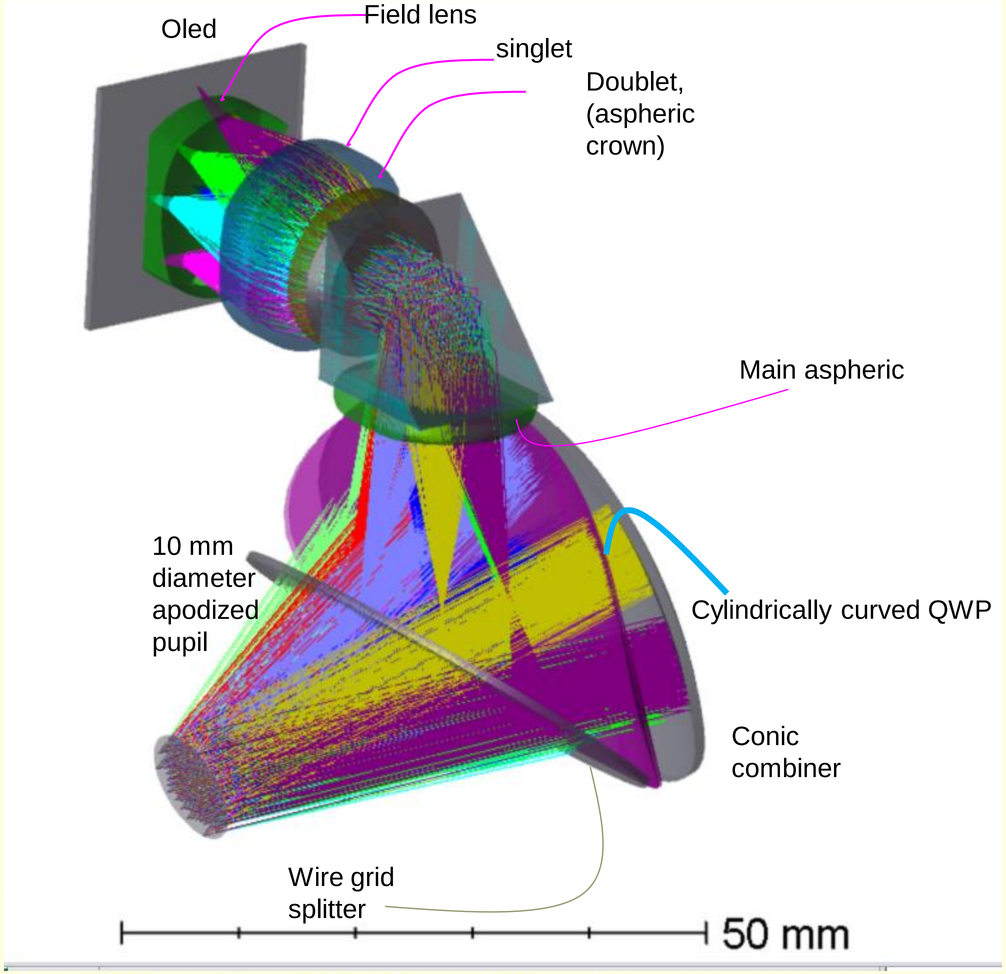
Conf. V non sequential



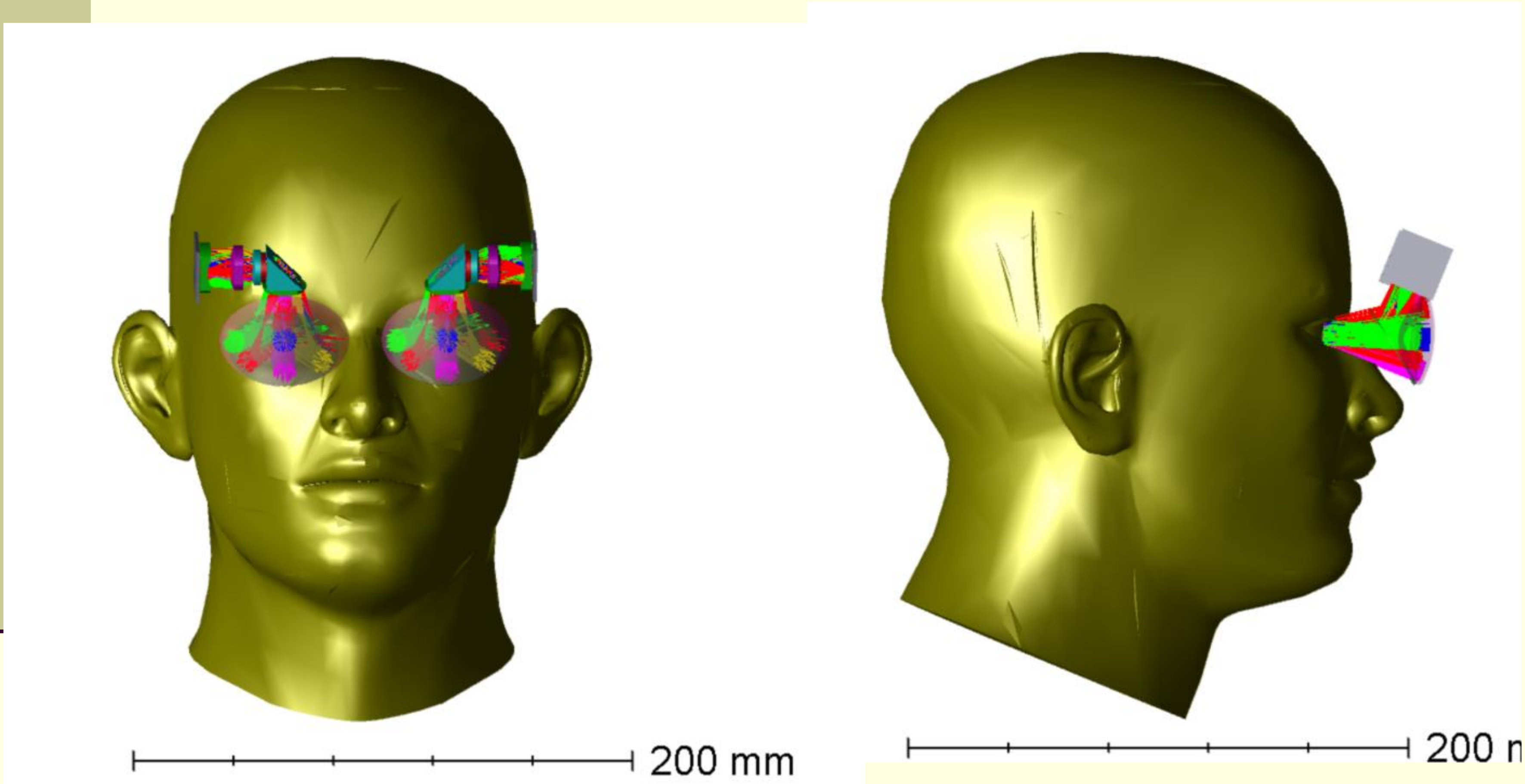
Question: should we do this for the low risk and later come back to the reflective relay? Well- customer really wants x fold with the size of a Y fold.

Configuration VI X fold

10 mm gaussian apodised eyebox,
Conic combiner
Stop moves to the prism hypotenuse to make the prism smaller.



Conf. VI

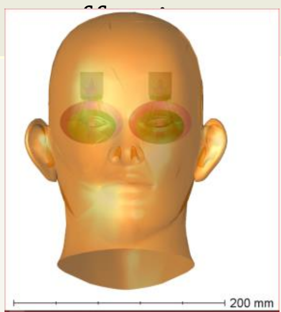


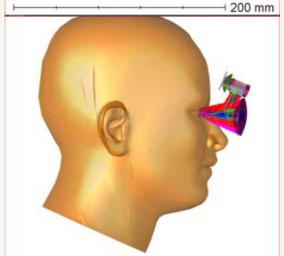
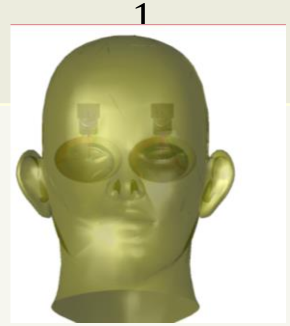
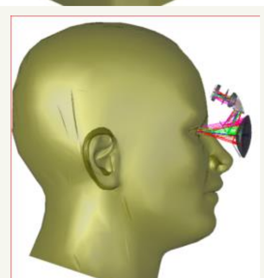
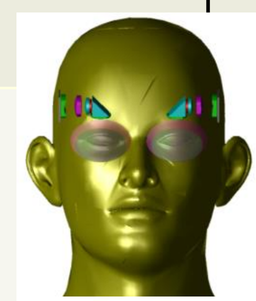
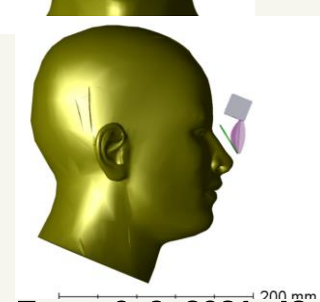
System height is good and no forehead clearance issues

Pugh chart Cont.

Design FREEZE

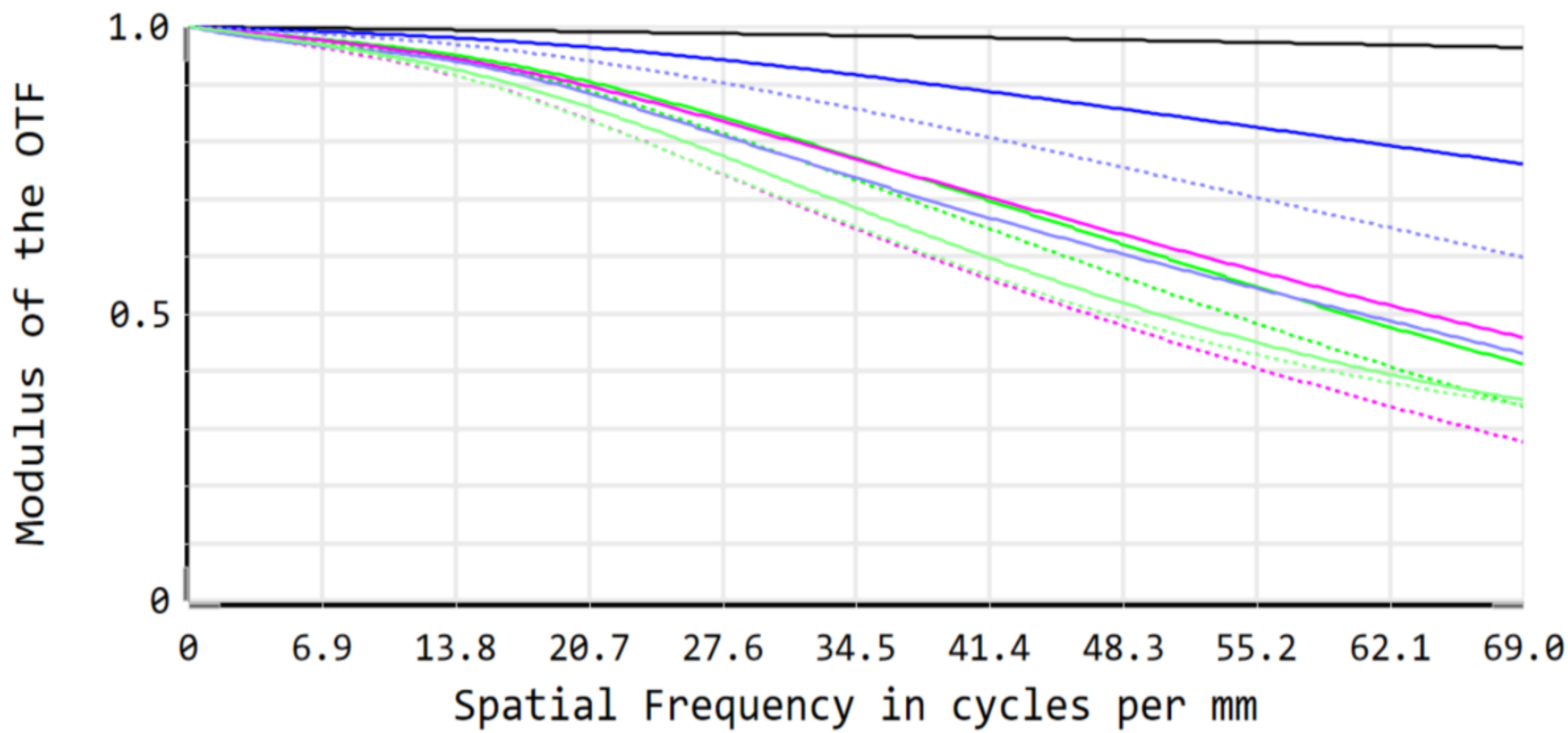
Configuration:	IV	V	VI
description	Like III +conic combiner ; Y fold; apodized pupil; polarization elements & cements ; smaller folding prism	Like II + conic combiner; Y fold; apodized pupil; polarization elements and cements No need for lateral color and distortion correction	Like I, compacted, X fold conic combiner, polarization &cements ; Eye relief 17 mm to top of splitter Lateral color and distortion corrected
field	60^0 x 36^0	60^0 x 36^0	60^0 x 36^0
size	compact	compact	compact
concerns	PBS elevated risk	Forehead clearance	-
Brightness	.8 on axis, some fall off	1	1



Performance : MTFs (10 mm apodized pupil)

POLYCHROMATIC



Field sizes are for an object at 1000 mm away

- [x] Diff. Limit-Tangential
- [ ] Diff. Limit-Sagittal
- [x] 0.00, 0.00 mm-Tangential
- [ ] 0.00, 0.00 mm-Sagittal
- [x] 289.00, 162.00 mm-Tangential
- [x] 289.00, 162.00 mm-Sagittal
- [ ] -289.00, -162.00 mm-Tangential
- [ ] -289.00, -162.00 mm-Sagittal
- [ ] 405.00, -227.00 mm-Tangential
- [ ] 405.00, -227.00 mm-Sagittal
- [x] -405.00, 227.00 mm-Tangential
- [x] -405.00, 227.00 mm-Sagittal
- [ ] 0.00, 325.00 mm-Tangential
- [ ] 0.00, 325.00 mm-Sagittal
- [x] 0.00, -325.00 mm-Tangential
- [x] 0.00, -325.00 mm-Sagittal
- [x] -577.00, 0.00 mm-Tangential
- [x] -577.00, 0.00 mm-Sagittal
- [ ] 577.00, 0.00 mm-Tangential
- [ ] 577.00, 0.00 mm-Sagittal

Polychromatic Diffraction MTF

Shootout with Hololens II

Thanks for listening!

Q & A?