Unfolded optical configuration performance for Zeiss OTUS 55mm w/ 3 passes thru vacuum barrier

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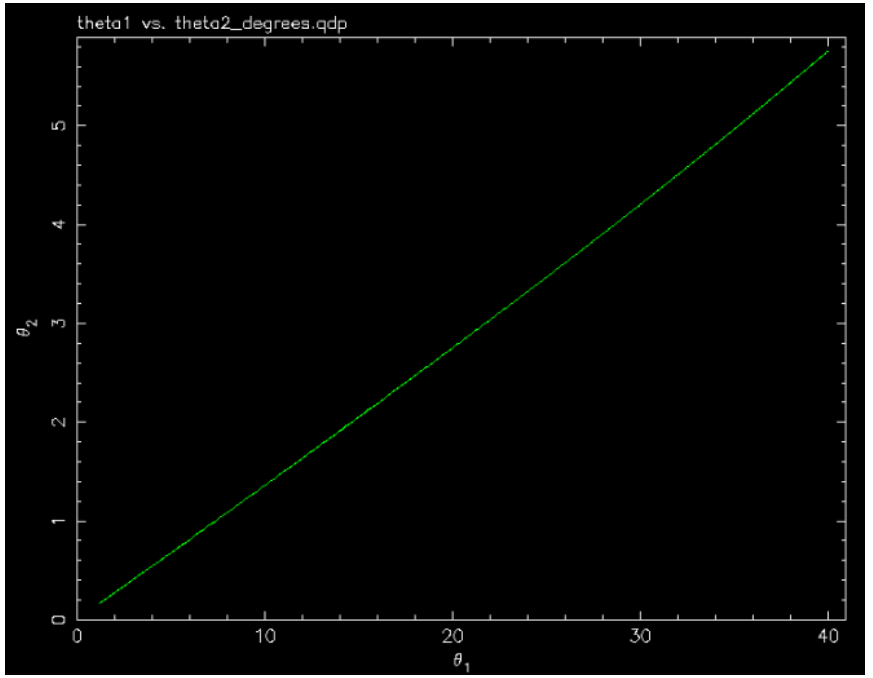
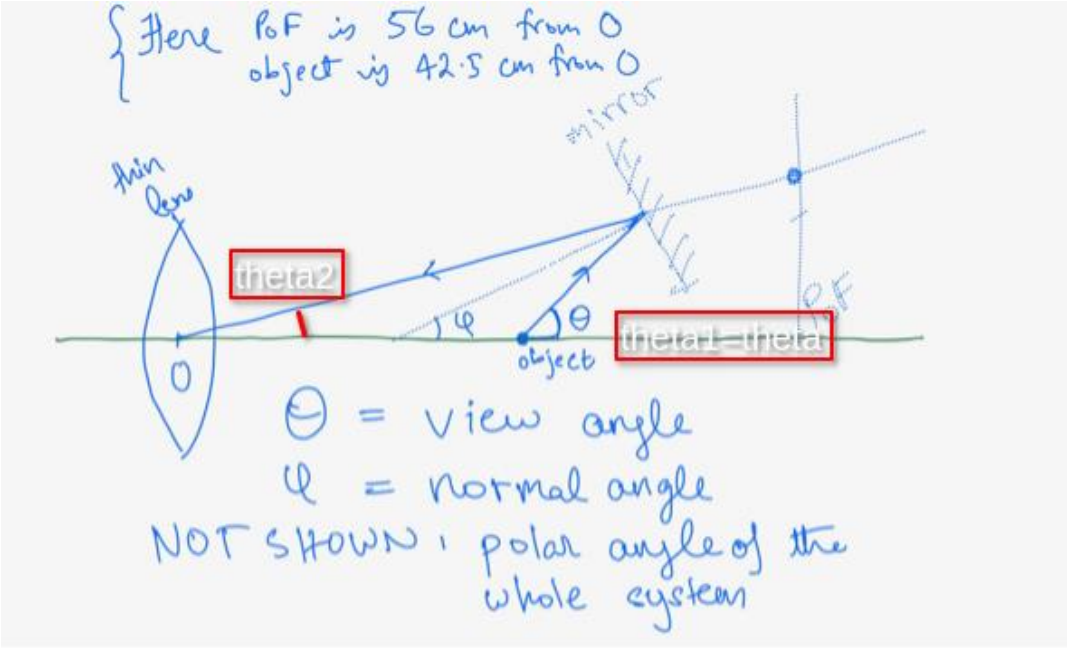
Inclusion of window aberrations in Murtaza's arraying setup including Zeiss-provided "black box" zemax files

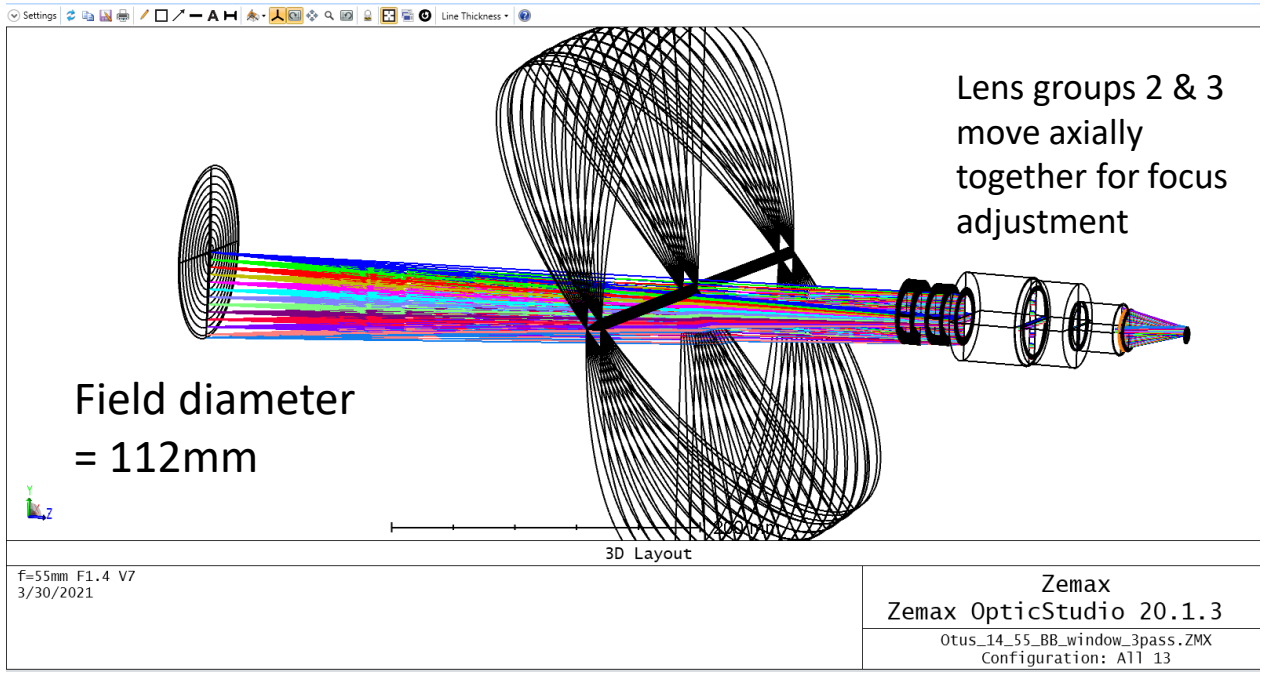
Included samples of Murtaza's tabulation into Zemax model for chief ray incidence angles against plano-plano glass elements.

$\theta_1 \stackrel{\text{def}}{=} \Theta_{\text{murtaza}}$
$\theta_2 \stackrel{\text{def}}{=} 2\varphi_{\text{murtaza}} - \Theta_{\text{murtaza}}$
in unfolded setup, coordinate break of first window surface has tilt_x = $-(\theta_1 + \theta_2)$.
Second & third windows have zero tilt.

Max field = 5.7°
Max view angle = 40°



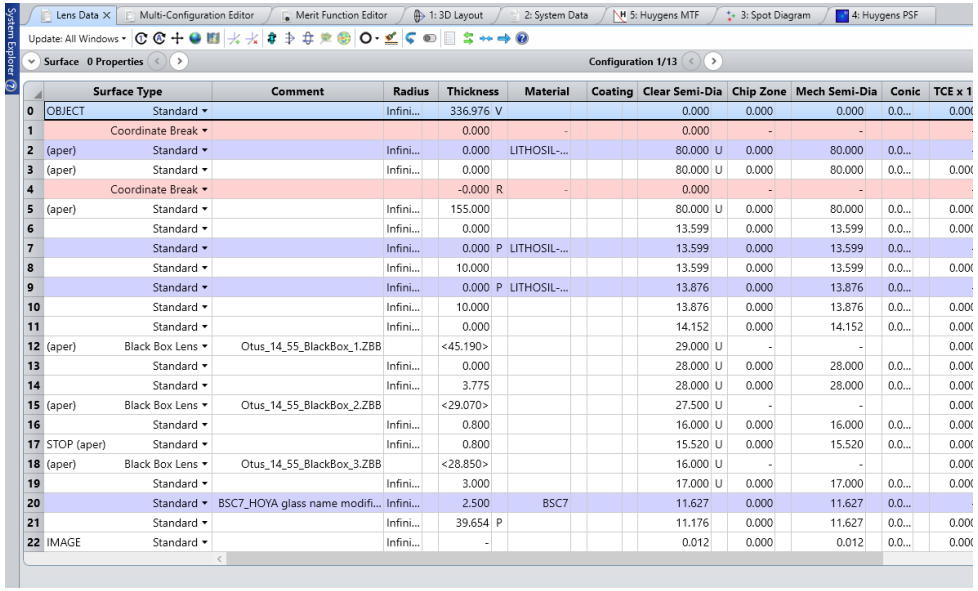




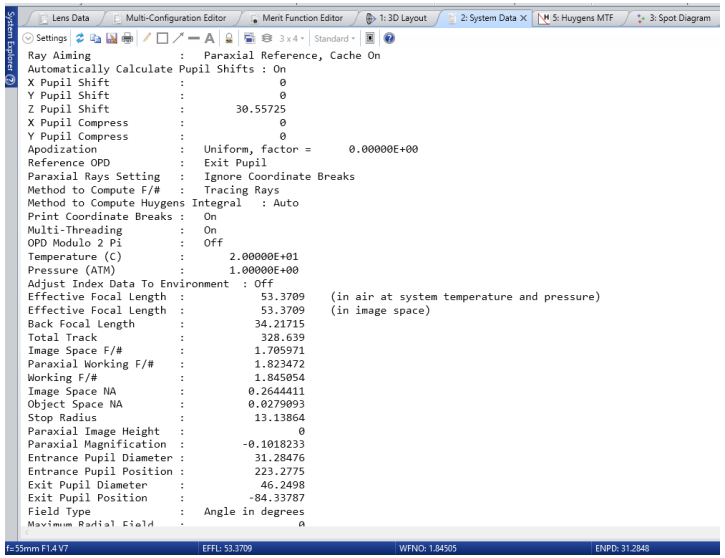
Configuration & optimization process using setup on previous slide

- 13 configurations, 1 field for each (0.0, 0.5, 1.0, .. 5.5, 5.7deg)
- Optimized on configuration 1 to set lens group position with object distance of 560mm with zero glass thickness (from entrance aperture, 48.2 mm into 1st black box group)
- Paraxial magnification for this configuration is -0.10.
- Optimized contrast for MTF(100 lp/mm), equal (tan/sag) weighting, to determine object distance for each configuration. (**in-air performance**)
- Repeated optimization now for 10mm glass thicknesses. (**thru-glass performance**)

Comparison of “in-air/no-glass” (left) to “with-glass” (right) optimizations



	Surface Type		Comment	Radius	Thickness		Material	Coating	Clear Semi-Dia		Chip Zone	Mech Semi-Dia	Conic	TCE x 1
0	OBJECT	Standard		Infini...	336.976	V			0.000		0.000	0.000	0.0...	0.000
1		Coordinate Break			0.000		-		0.000		-	-		
2	(aper)	Standard		Infini...	0.000		LITHOSIL-...		80.000	U	0.000	80.000	0.0...	
3	(aper)	Standard		Infini...	0.000				80.000	U	0.000	80.000	0.0...	0.000
4		Coordinate Break			-0.000	R	-		0.000		-	-		
5	(aper)	Standard		Infini...	155.000				80.000	U	0.000	80.000	0.0...	0.000
6		Standard		Infini...	0.000				13.599		0.000	13.599	0.0...	0.000
7		Standard		Infini...	0.000	P	LITHOSIL-...		13.599		0.000	13.599	0.0...	
8		Standard		Infini...	10.000				13.599		0.000	13.599	0.0...	0.000
9		Standard		Infini...	0.000	P	LITHOSIL-...		13.876		0.000	13.876	0.0...	
10		Standard		Infini...	10.000				13.876		0.000	13.876	0.0...	0.000
11		Standard		Infini...	0.000				14.152		0.000	14.152	0.0...	0.000
12	(aper)	Black Box Lens	Otus_14_55_BlackBox_1.ZBB		<45.190>				29.000	U	-	-		0.000
13		Standard		Infini...	0.000				28.000	U	0.000	28.000	0.0...	0.000
14		Standard		Infini...	3.775				28.000	U	0.000	28.000	0.0...	0.000
15	(aper)	Black Box Lens	Otus_14_55_BlackBox_2.ZBB		<29.070>				27.500	U	-	-		0.000
16		Standard		Infini...	0.800				16.000	U	0.000	16.000	0.0...	0.000
17	STOP (aper)	Standard		Infini...	0.800				15.520	U	0.000	15.520	0.0...	0.000
18	(aper)	Black Box Lens	Otus_14_55_BlackBox_3.ZBB		<28.850>				16.000	U	-	-		0.000
19		Standard		Infini...	3.000				17.000	U	0.000	17.000	0.0...	0.000
20		Standard	BSC7_HOYA glass name modifi...	Infini...	2.500		BSC7		11.627		0.000	11.627	0.0...	
21		Standard		Infini...	39.654	P			11.176		0.000	11.627	0.0...	0.000
22	IMAGE	Standard		Infini...	-				0.012		0.000	0.012	0.0...	0.000



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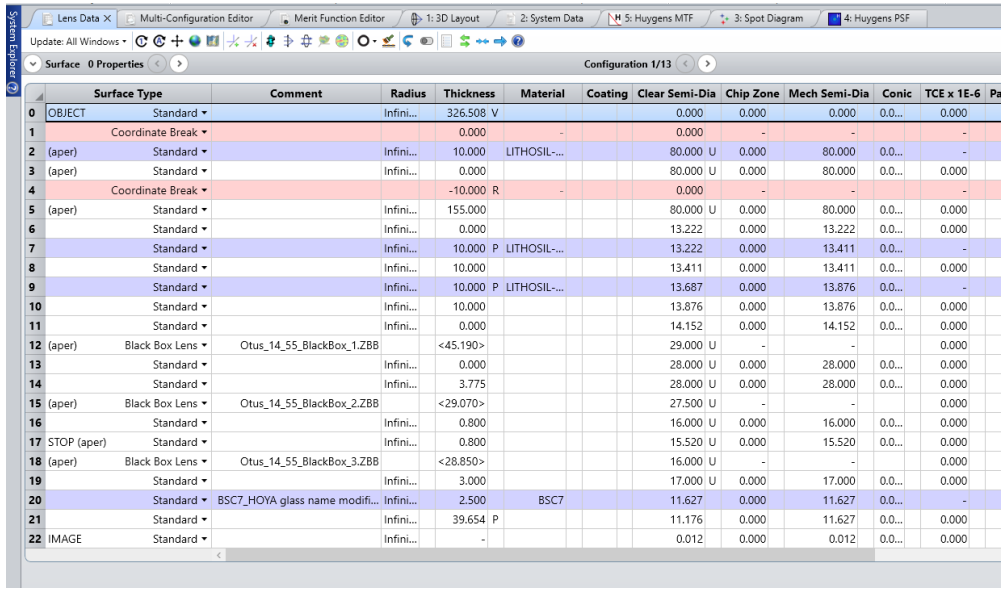
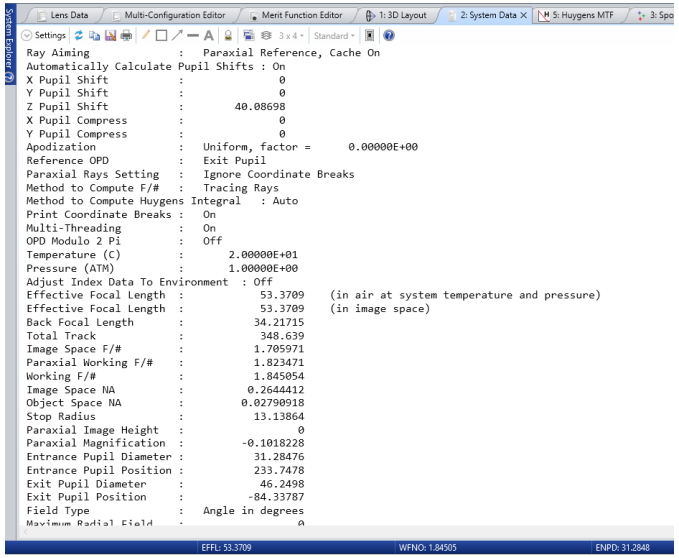
Ray Aiming              :   Paraxial Reference, Cache On
Automatically Calculate Pupil Shifts : On
X Pupil Shift           :              0
Y Pupil Shift           :              0
Z Pupil Shift           :       30.55725
X Pupil Compress        :              0
Y Pupil Compress        :              0
Apodization             :   Uniform, factor =      0.00000E+00
Reference OPD           :   Exit Pupil
Paraxial Rays Setting   :   Ignore Coordinate Breaks
Method to Compute F/#   :   Tracing Rays
Method to Compute Huygens Integral   : Auto
Print Coordinate Breaks :   On
Multi-Threading         :   On
OPD Modulo 2 Pi         :   Off
Temperature (C)         :       2.00000E+01
Pressure (ATM)          :       1.00000E+00
Adjust Index Data To Environment  : Off
Effective Focal Length  :            53.3709    (in air at system temperature and pressure)
Effective Focal Length  :            53.3709    (in image space)
Back Focal Length       :            34.21715
Total Track             :             328.639
Image Space F/#         :            1.705971
Paraxial Working F/#    :            1.823472
Working F/#             :            1.845054
Image Space NA          :           0.2644411
Object Space NA         :           0.0279093
Stop Radius             :            13.13864
Paraxial Image Height   :                   0
Paraxial Magnification  :          -0.1018233
Entrance Pupil Diameter :            31.28476
Entrance Pupil Position :            223.2775
Exit Pupil Diameter     :             46.2498
Exit Pupil Position     :           -84.33787
Field Type              :   Angle in degrees
Maximum Radial Field    :                   0
```



	Surface Type		Comment	Radius	Thickness		Material	Coating	Clear Semi-Dia		Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6	Pa
0	OBJECT	Standard		Infini...	326.508	V			0.000		0.000	0.000	0.0...	0.000	
1		Coordinate Break			0.000		-		0.000		-	-			
2	(aper)	Standard		Infini...	10.000		LITHOSIL-...		80.000	U	0.000	80.000	0.0...		
3	(aper)	Standard		Infini...	0.000				80.000	U	0.000	80.000	0.0...	0.000	
4		Coordinate Break			-10.000	R	-		0.000		-	-			
5	(aper)	Standard		Infini...	155.000				80.000	U	0.000	80.000	0.0...	0.000	
6		Standard		Infini...	0.000				13.222		0.000	13.222	0.0...	0.000	
7		Standard		Infini...	10.000	P	LITHOSIL-...		13.222		0.000	13.411	0.0...		
8		Standard		Infini...	10.000				13.411		0.000	13.411	0.0...	0.000	
9		Standard		Infini...	10.000	P	LITHOSIL-...		13.687		0.000	13.876	0.0...		
10		Standard		Infini...	10.000				13.876		0.000	13.876	0.0...	0.000	
11		Standard		Infini...	0.000				14.152		0.000	14.152	0.0...	0.000	
12	(aper)	Black Box Lens	Otus_14_55_BlackBox_1.ZBB		<45.190>				29.000	U	-	-		0.000	
13		Standard		Infini...	0.000				28.000	U	0.000	28.000	0.0...	0.000	
14		Standard		Infini...	3.775				28.000	U	0.000	28.000	0.0...	0.000	
15	(aper)	Black Box Lens	Otus_14_55_BlackBox_2.ZBB		<29.070>				27.500	U	-	-		0.000	
16		Standard		Infini...	0.800				16.000	U	0.000	16.000	0.0...	0.000	
17	STOP (aper)	Standard		Infini...	0.800				15.520	U	0.000	15.520	0.0...	0.000	
18	(aper)	Black Box Lens	Otus_14_55_BlackBox_3.ZBB		<28.850>				16.000	U	-	-		0.000	
19		Standard		Infini...	3.000				17.000	U	0.000	17.000	0.0...	0.000	
20		Standard	BSC7_HOYA glass name modifi...	Infini...	2.500		BSC7		11.627		0.000	11.627	0.0...		
21		Standard		Infini...	39.654	P			11.176		0.000	11.627	0.0...	0.000	
22	IMAGE	Standard		Infini...	-				0.012		0.000	0.012	0.0...	0.000	



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Ray Aiming              :   Paraxial Reference, Cache On
Automatically Calculate Pupil Shifts : On
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Y Pupil Shift           :              0
Z Pupil Shift           :       40.08698
X Pupil Compress        :              0
Y Pupil Compress        :              0
Apodization             :   Uniform, factor =      0.00000E+00
Reference OPD           :   Exit Pupil
Paraxial Rays Setting   :   Ignore Coordinate Breaks
Method to Compute F/#   :   Tracing Rays
Method to Compute Huygens Integral   : Auto
Print Coordinate Breaks :   On
Multi-Threading         :   On
OPD Modulo 2 Pi         :   Off
Temperature (C)         :       2.00000E+01
Pressure (ATM)          :       1.00000E+00
Adjust Index Data To Environment  : Off
Effective Focal Length  :            53.3709    (in air at system temperature and pressure)
Effective Focal Length  :            53.3709    (in image space)
Back Focal Length       :            34.21715
Total Track             :             348.639
Image Space F/#         :            1.705971
Paraxial Working F/#    :            1.823471
Working F/#             :            1.845054
Image Space NA          :           0.2644412
Object Space NA         :          0.02790918
Stop Radius             :            13.13864
Paraxial Image Height   :                   0
Paraxial Magnification  :          -0.1018228
Entrance Pupil Diameter :            31.28476
Entrance Pupil Position :            233.7478
Exit Pupil Diameter     :             46.2498
Exit Pupil Position     :           -84.33787
Field Type              :   Angle in degrees
Maximum Radial Field    :                   0
```
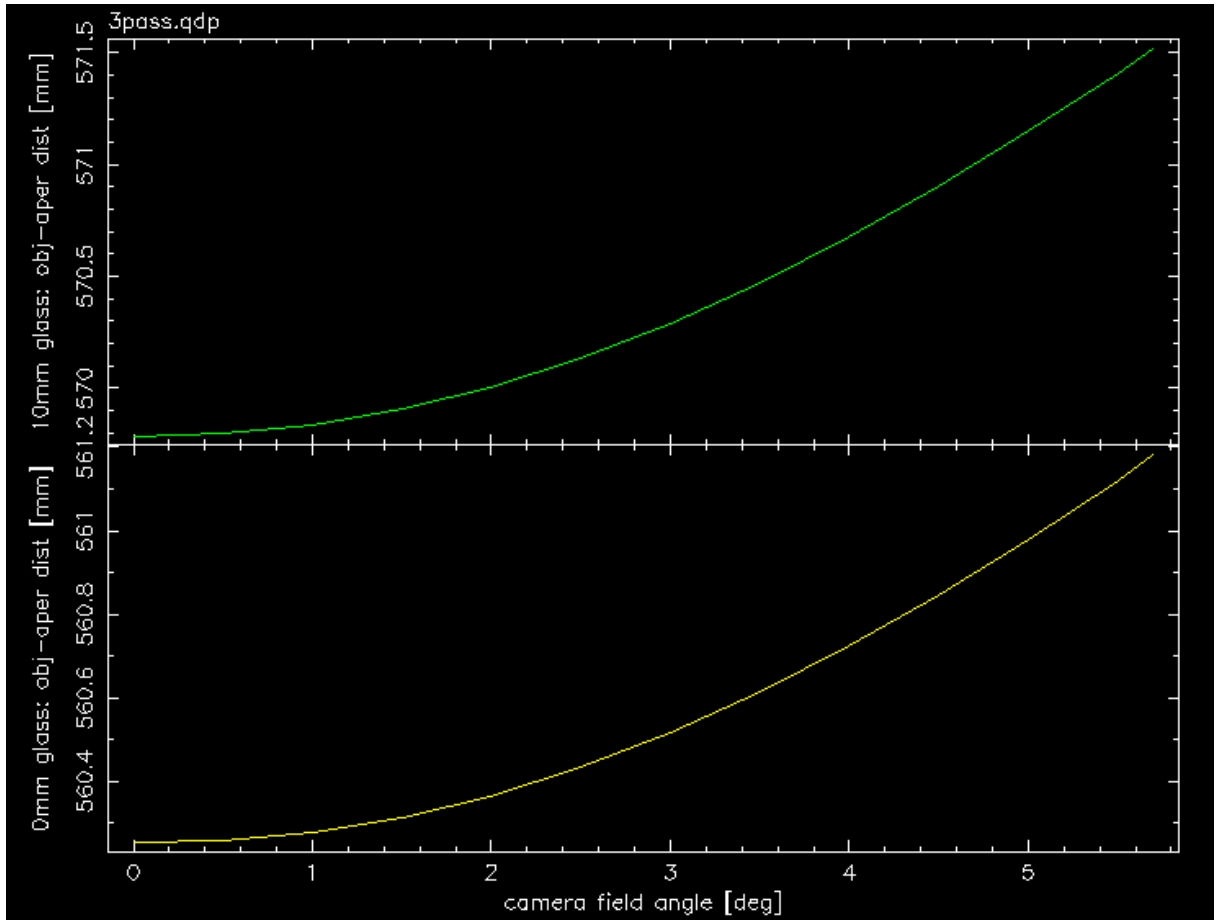

Results overview

(oops! – forgot to include object height for each field position, which is not trivially related to field angle)

	name	config01	config02	config03	config04	config05	config06	config07	config08	config09	config10	config11	config12	config13	
	field (eq. theta2)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	5.7	
	theta1	0	-3.679	-7.358	-11.012	-14.631	-18.21	-21.74	-25.214	-28.624	-31.963	-35.223	-38.397	-39.64	
	angle wrt axis in setup	0	-4.179	-8.358	-12.512	-16.631	-20.71	-24.74	-28.714	-32.624	-36.463	-40.223	-43.897	-45.34	
10mm glass	thickness(surface0)														
10mm glass	glass=10mm	326.51	326.52	326.56	326.63	326.73	326.86	327.01	327.19	327.40	327.63	327.87	328.13	328.24	
10mm glass	obj-ap	569.79	569.80	569.84	569.91	570.01	570.13	570.29	570.47	570.68	570.90	571.15	571.41	571.52	1.731676
10mm glass	(um rms)	5.02	5.02	5.02	5.01	5.01	5.00	5.02	5.05	5.13	5.25	5.42	5.65	5.70	
10mm glass	(um rms X)	3.55	3.55	3.52	3.49	3.44	3.39	3.34	3.30	3.28	3.30	3.36	3.47	3.55	
10mm glass	(um rms Y)	3.55	3.56	3.57	3.60	3.64	3.68	3.75	3.83	3.94	4.08	4.26	4.46	4.46	
0mm glass	thickness(surface0)														
0mm glass	glass=0mm	336.98	336.98	337.00	337.03	337.09	337.16	337.24	337.34	337.45	337.57	337.70	337.84	337.90	
0mm glass	obj-ap	560.25	560.26	560.28	560.31	560.37	560.43	560.52	560.61	560.72	560.85	560.98	561.12	561.18	0.926907
0mm glass	(um rms)	5.02	5.02	5.02	5.01	5.00	4.98	4.96	4.95	4.94	4.95	4.98	4.97	4.97	
0mm glass	(um rms X)	3.55	3.55	3.55	3.54	3.53	3.52	3.51	3.50	3.51	3.52	3.55	3.62	3.64	
0mm glass	(um rms Y)	3.55	3.55	3.55	3.55	3.54	3.52	3.51	3.49	3.48	3.48	3.49	3.40	3.37	
Glass contrib (rss)	glass contrib (radial rss)	0.15	0.13	0.11	0.17	0.31	0.50	0.74	1.03	1.36	1.73	2.15	2.69	2.80	
Glass contrib (rss)	glass contrib (X rss)	0.11	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	#NUM!	
Glass contrib (rss)	glass contrib (Y rss)	0.11	0.22	0.42	0.63	0.84	1.07	1.31	1.57	1.84	2.13	2.44	2.87	2.92	
10mm glass	RMS blur at object	50.19	50.23	50.20	50.13	50.06	50.05	50.18	50.55	51.27	52.45	54.22	56.50	57.02	
10mm glass	FWHM (rms) blur at object	83.57	83.63	83.58	83.46	83.35	83.33	83.55	84.16	85.36	87.33	90.28	94.08	94.94	
10mm glass	FWHM (X) blur at object	83.58	83.49	83.00	82.15	81.04	79.79	78.59	77.66	77.25	77.64	79.08	81.82	83.58	
10mm glass	FWHM (Y) blur at object	83.58	83.79	84.18	84.78	85.62	86.75	88.25	90.22	92.78	96.07	100.26	104.94	105.11	
10mm glass	tangential MTF(100)	0.70	0.70	0.68	0.66	0.63	0.60	0.57	0.53	0.51	0.49	0.48	0.48	0.48	
10mm glass	saggital MTF(100)	0.70	0.70	0.68	0.66	0.62	0.57	0.51	0.44	0.35	0.26	0.18	0.09	0.06	

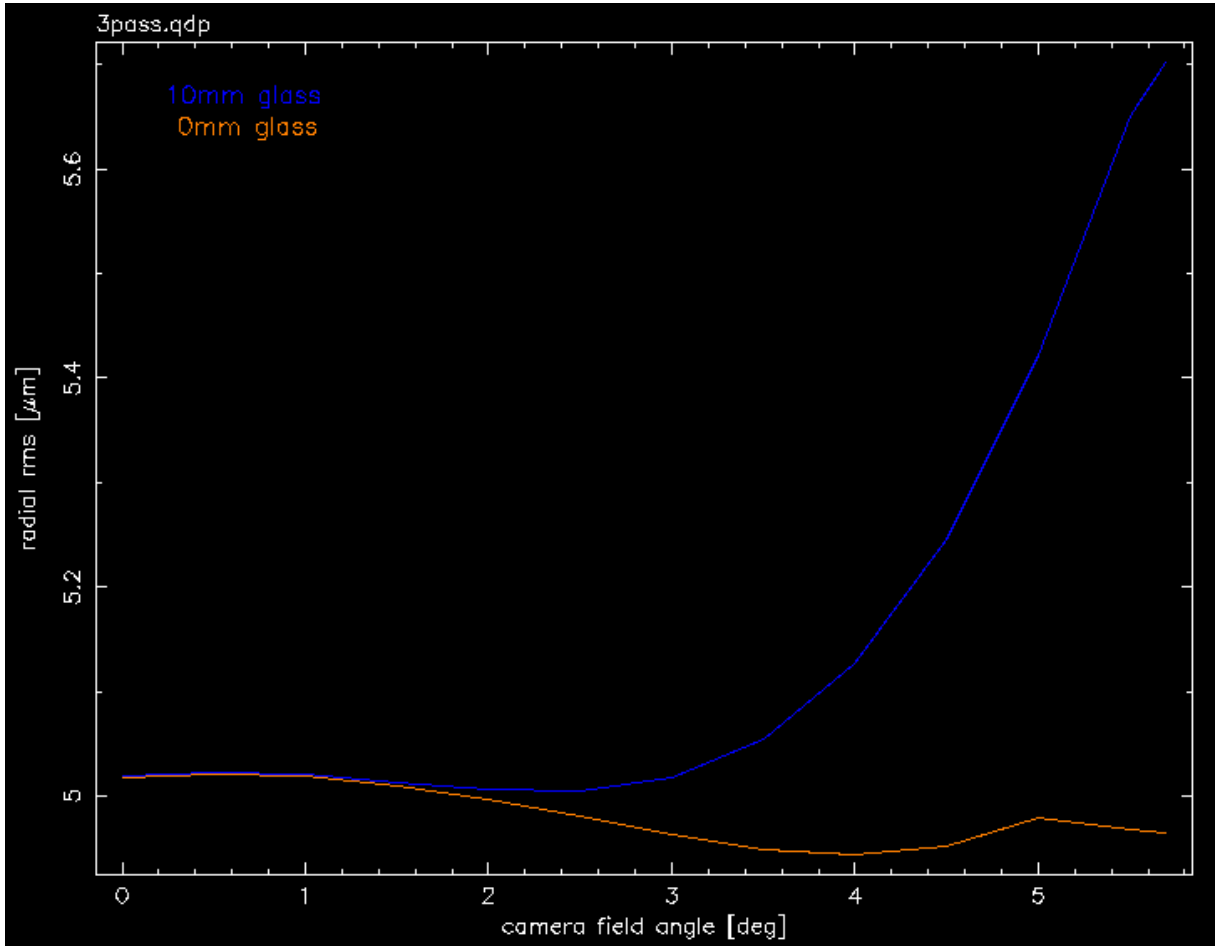
Object surface is different between 10mm and zero (i.e. ***in-air***) glass thickness



1.73mm dish

0.92mm dish

Radial rms performance comparison

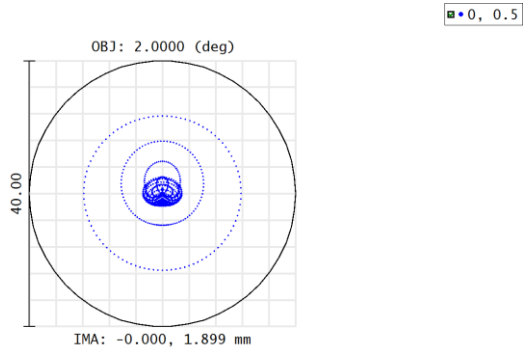


Tangential (y) and sagittal (x) rms comparison

10mm glass

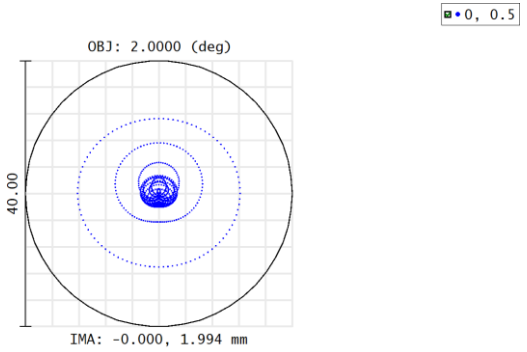
0mm glass (lens only)

2 deg



Surface: IMA

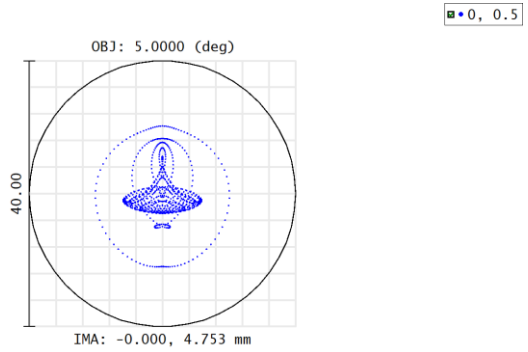
Spot Diagram	
f=55mm F1.4 V7, 3/31/2021 Units are µm. Legend items refer to Field positions Field : 1 RMS radius : 4.872 GEO radius : 11.842 Circle diam: 40 Reference : Centroid	Zemax Zemax OpticStudio 20.1.3 Otus_14_55_BB_window_3pass.zmx Configuration 5 of 13



Surface: IMA

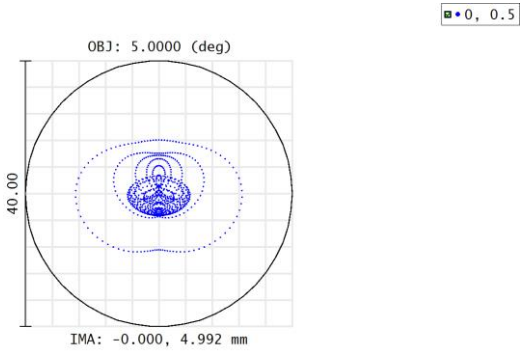
Spot Diagram	
f=55mm F1.4 V7, 3/31/2021 Units are µm. Legend items refer to Field positions Field : 1 RMS radius : 4.862 GEO radius : 12.196 Circle diam: 40 Reference : Centroid	Zemax Zemax OpticStudio 20.1.3 Otus_14_55_BB_window_3pass.zmx Configuration 5 of 13

5 deg



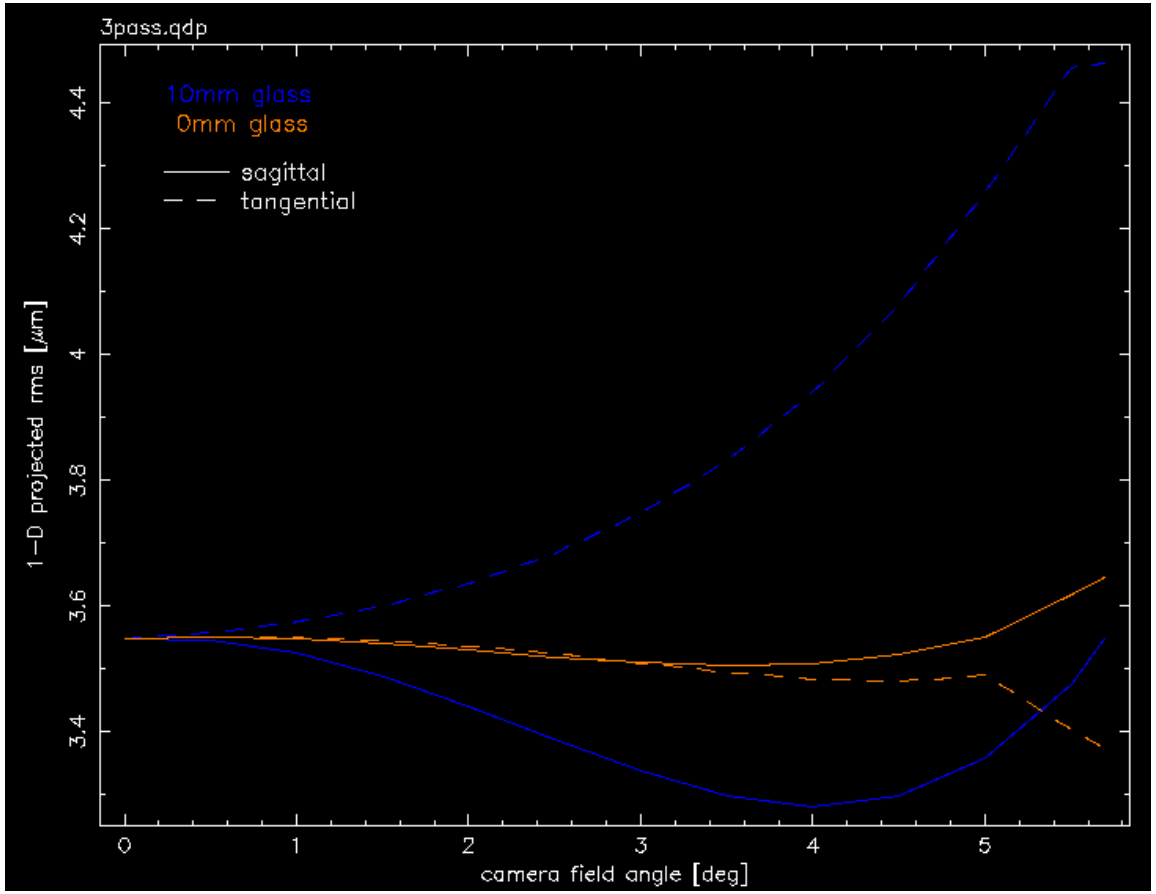
Surface: IMA

Spot Diagram	
f=55mm F1.4 V7, 3/31/2021 Units are µm. Legend items refer to Field positions Field : 1 RMS radius : 5.330 GEO radius : 11.075 Circle diam: 40 Reference : Centroid	Zemax Zemax OpticStudio 20.1.3 Otus_14_55_BB_window_3pass.zmx Configuration 11 of 13

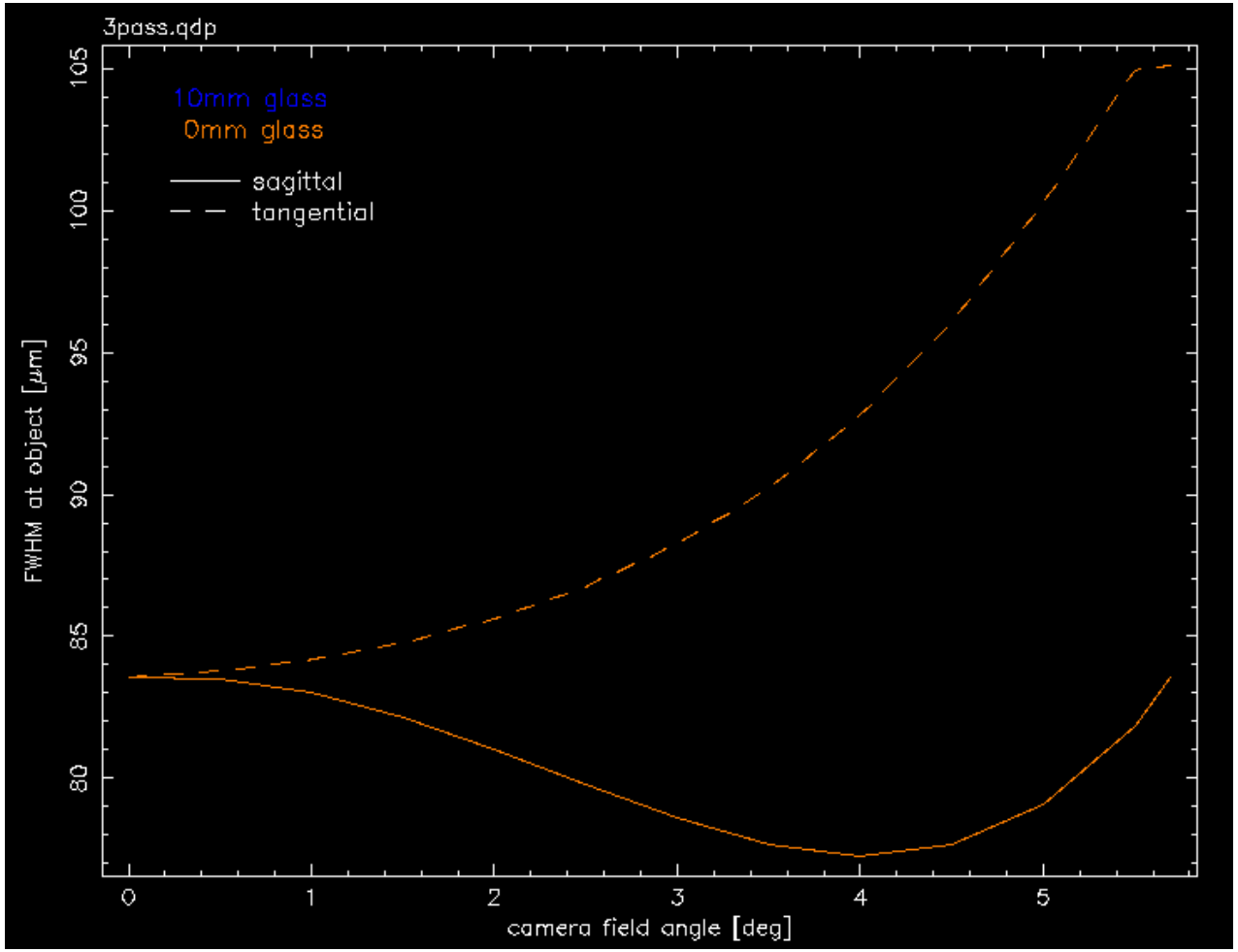


Surface: IMA

Spot Diagram	
f=55mm F1.4 V7, 3/31/2021 Units are µm. Legend items refer to Field positions Field : 1 RMS radius : 4.874 GEO radius : 12.487 Circle diam: 40 Reference : Centroid	Zemax Zemax OpticStudio 20.1.3 Otus_14_55_BB_window_3pass.zmx Configuration 11 of 13

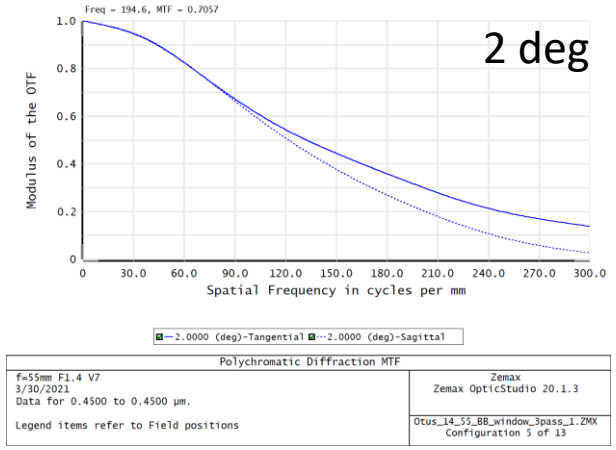


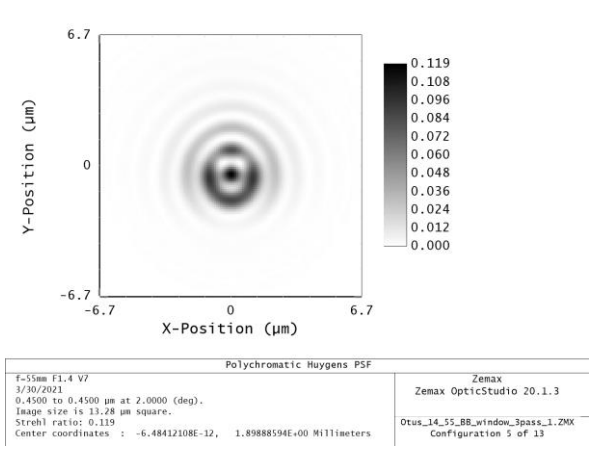
Orientation dependence of blur projected onto the object surface, assuming Gaussian form sharing rms

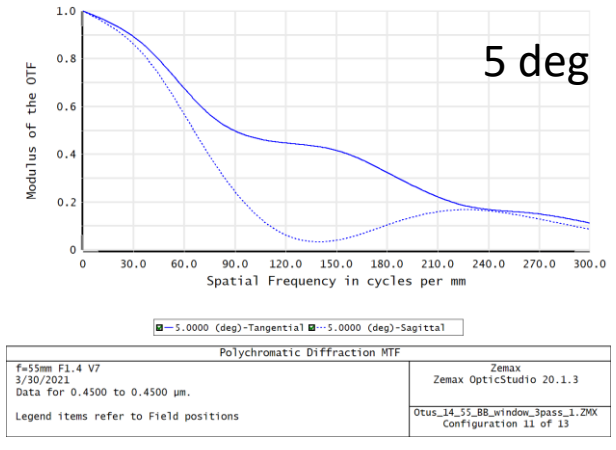


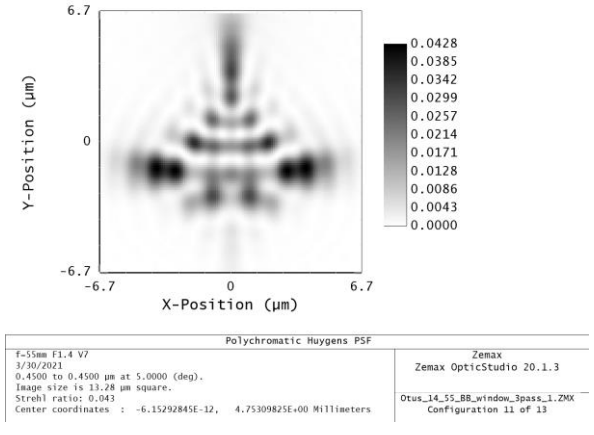
(assuming separable PSF, $FWHM_x = 2.355\ \sigma_x$ etc)

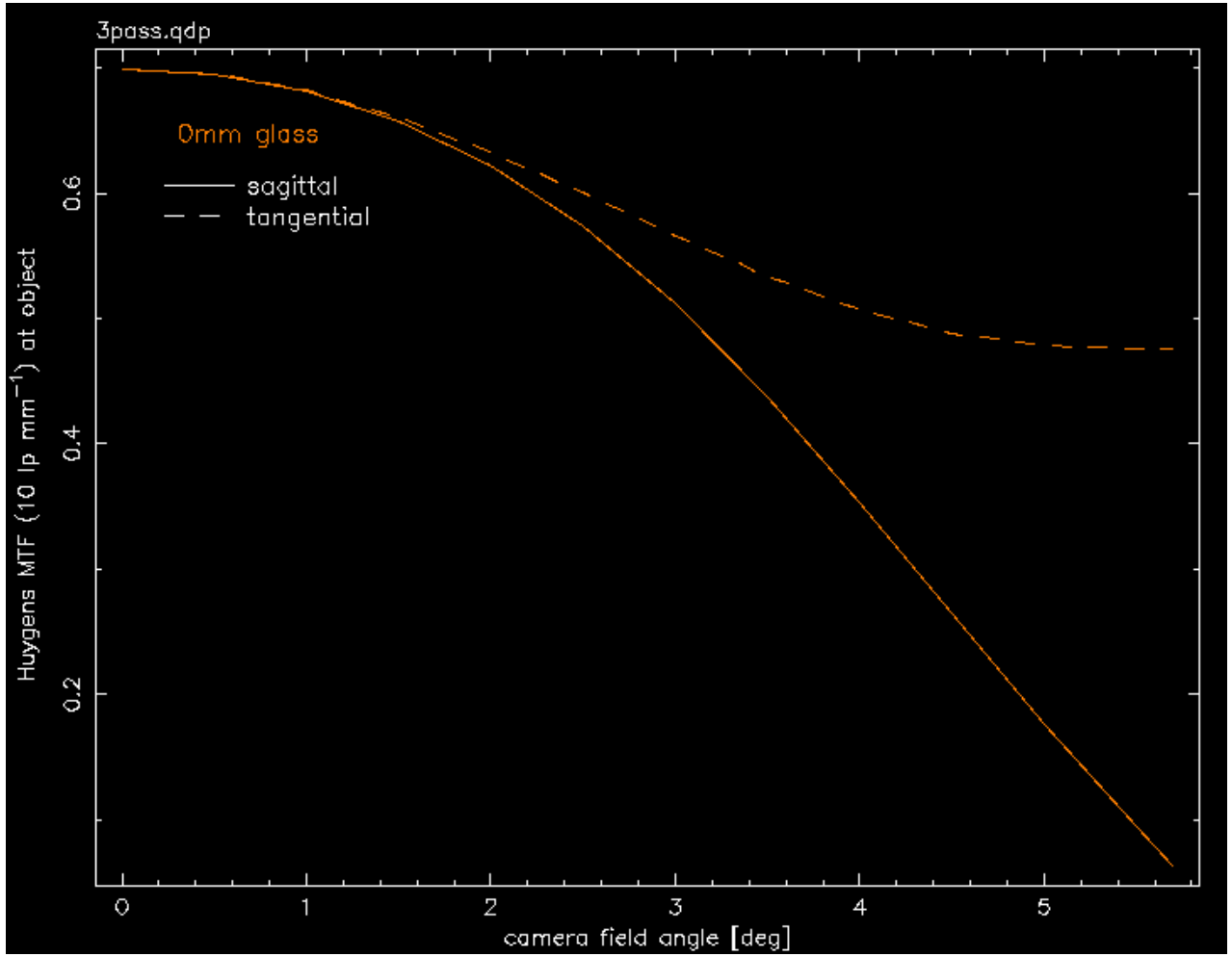
Orientation dependence of MTF (100 lp/mm at image, 10 lp/mm at object): drop in sagittal MTF appears to be PSF structure related











Summary- 120401

- Incorported 3 passes through plano-plano glass elements, representing perfect vacuum windows, into OTUS 55mm lens to image reduced 112mm field diameter for 560mm object-entrance aperture distance. Field diameter size driven by view angle constraints of the far side vacuum window. Zemax model represents unfolded configuration for a simplified geometry. Resulting magnification -0.10.
- Geometric details derived through MTF optimization.
- MTF (10 lp mm^{-1}) at object exceed 50% out to 3.0 ° field (22° view angle) but then plummet, particularly in sagittal orientation – in spite of relatively well controlled distribution along sagittal axis.
- Suspect spot structure seen in Huygens PSF that “interferes” with MTF calculation.
- Atlas of MTF(freq) available for each field position, unsure how useful they are beyond first local minimum.
- Different merit function is likely to produce modest difference in results.