Zemax

ENVISION2019

Boston

Zemax

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Expanding Zemax Capabilities, 3 example advanced macros and custom Dlls

John Ellis

John Ellis

President

- John Ellis founded Optics for Hire in 2002.
- OFH help clients research, design, prototype and commercialize imaging and illumination optical devices.
- Their team of 15 optical, mechanical and electronics engineers provide ray tracing, custom lens designs, complete opto-electronic/opto-mechanical systems and applied optics research.

Anatoli Trafimuk

Lead optical engineer

- Anatoli started his work in OFH in 2006 as optical designer
- He is the author of all Dlls and macros described in presentation
- Anatoli has a Ph.D. from Saint-Petersburg State University Information Technologies, Mechanic and Optics focused in Optics/Optical Sciences
- He has designed hundreds of illumination and imaging optical systems

Examples

1 Making a complex Zemax macro

- The problem statement of Optics Cross Section
- Why require custom macro?
- The solution of the problem
- Examples of using macro

2 Using user defined objects in Zemax

- Why we need User Defined Objects?
- What was done by OFH
- Examples and applications of UDO

3 User defined surface for imaging

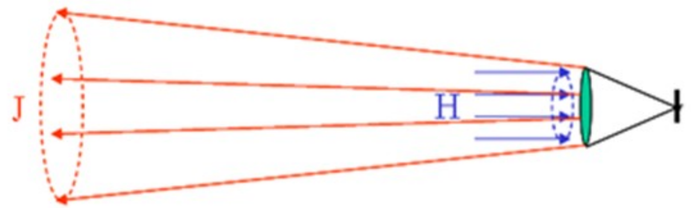
- Why do we need User Defined Surfaces?
- Freeform solution with Bezier curves

Making a complex Zemax macro for an Optical Cross Section calculation

Optical cross section calculations

- OCS is a value which describes the maximum amount of optical flux reflected back to the source.
- Optical devices such as telescopes and cameras will return some of the optical flux back to the source, since it has optics that reflect some light.
- It is very useful in LIDAR and also Radar applications.
- Zemax doesn't provide built-in optical cross-section calculations

OPTICAL CROSS SECTION (OCS)



- Definition of OCS:

$$\frac{\text{Intensity Leaving Sensor}}{\text{Irradiance Entering Sensor}} \quad \frac{J}{H} \quad \frac{(W/sr)}{(W/m^2)} = \frac{m^2}{sr}$$

- Calculated Formula is Actually "Differential" Optical Cross Section – Peak on-axis retroreflected signature
- For a Circular Mirror:

$$OCS = \frac{\rho * \pi^2 * D^4}{16 * \lambda^2}$$

Where:
ρ = mirror reflectivity
D = mirror diameter (m)
λ = wavelength (m)

- For a Sensor:

(Worst Case: Perfect Optics)

$$OCS = \frac{\rho * T^2 * \pi^2 * D^4}{16 * \lambda^2}$$

T = Single-pass optical transmission at wavelength λ

Why use a custom macro?

- The contribution to OCS from the lenses themselves is ignored in previous formula
- A tool is need to calculate the OCS contribution from the lenses.
- Custom Zemax macro is ideal. We can control the lens data as needed, with ZPL
- Compared to ZOS API a macro is simpler for the user.

The solution

- The macro stores the initial optical system. Then one by one elements are removed from the system, replaced surfaces with mirrors (mirror reflectively created by Zemax or by hand), made in sequence as elements added. And calculate the OSC of each reduced element.
- Macro uses previous formula of OSC and alternative calculation based on the method described in article “A Paraxial Approach to the Estimation of Optical Cross Section and Optical Gain” by Howard V Kennedy.
- ZPL macro contains 612 lines of optimized code, which provides main calculations and predictable error handling.
- The result is table of OCS values for each lens surface and list of some important parameters from Kennedy method.

Zemax OpticStudio 19.8 BETA Premium(7) - L107091 - 1 Double Gauss 28 degree field.zmx

File | Setup | Analyze | Optimize | Tolerance | Libraries | Part Designer | Programming | Help

ZPL Macros: Macro List, Edit/Run, Refresh List, New Macro, Macro Help

ZOS-API.NET Applications: User Analyses, User Extensions, Interactive Extension, ZOS-API Help

ZOS-API.NET Application Builders: C#, C++, MATLAB, Python

Extensions: Extension List

System Explorer

Update: None

- Aperture
- Fields
- Wavelengths
- Environment
- Polarization
- Advanced
- Ray Aimi
- Material
- Title/Not
- Files
- Units
- Cost Esti

Lens Data

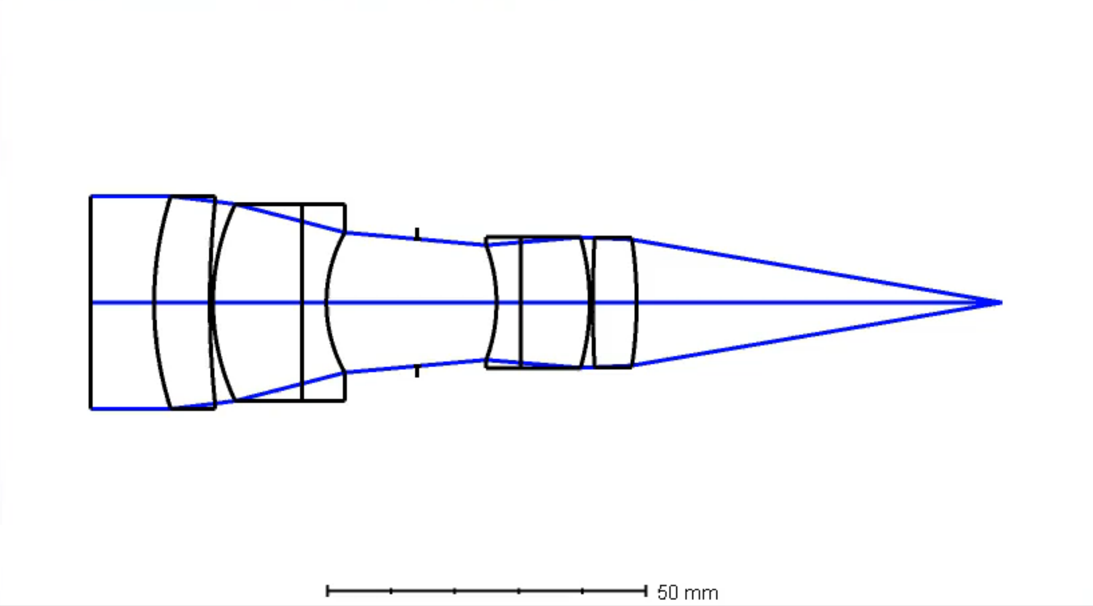
Update: None

Surface 0 Properties | Configuration 1/1

	Surface Type		Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia		Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT	Standard		Infinity	Infinity			0.000		0.000	0.000	0.000	0.000
1		Standard		Infinity	10.000			16.665	U	0.000	16.665	0.000	0.000
2	(aper)	Standard		54.153	8.747	SK2	AR	16.665	U	0.000	16.665	0.000	-
3	(aper)	Standard		152.522	0.500		AR	15.829	U	0.000	16.665	0.000	0.000
4	(aper)	Standard		35.951	14.000	SK16	AR	15.420	U	0.000	15.420	0.000	-
5	(aper)	Standard		Infinity	3.777	F5		12.719	U	0.000	15.420	0.000	-
6	(aper)	Standard		22.270	14.253		AR	10.985	U	0.000	15.420	0.000	0.000
7	STOP	Standard		Infinity	12.428			9.968	U	0.000	9.968	0.000	0.000
8	(aper)	Standard		-25.685	3.777	F5	AR	9.000	U	0.000	10.237	0.000	-
9	(aper)	Standard		Infinity	10.834	SK16		9.456	U	0.000	10.237	0.000	-
10	(aper)	Standard		-36.980	0.500		AR	10.237	U	0.000	10.237	0.000	0.000
11	(aper)	Standard		196.417	6.858	SK16	AR	10.144	U	0.000	10.144	0.000	-
12	(aper)	Standard		-67.148	57.315		AR	9.874	U	0.000	10.144	0.000	0.000
13	IMAGE	Standard		Infinity	-			0.017	U	0.000	0.017	0.000	0.000

1: Layout

Settings | Line Thickness



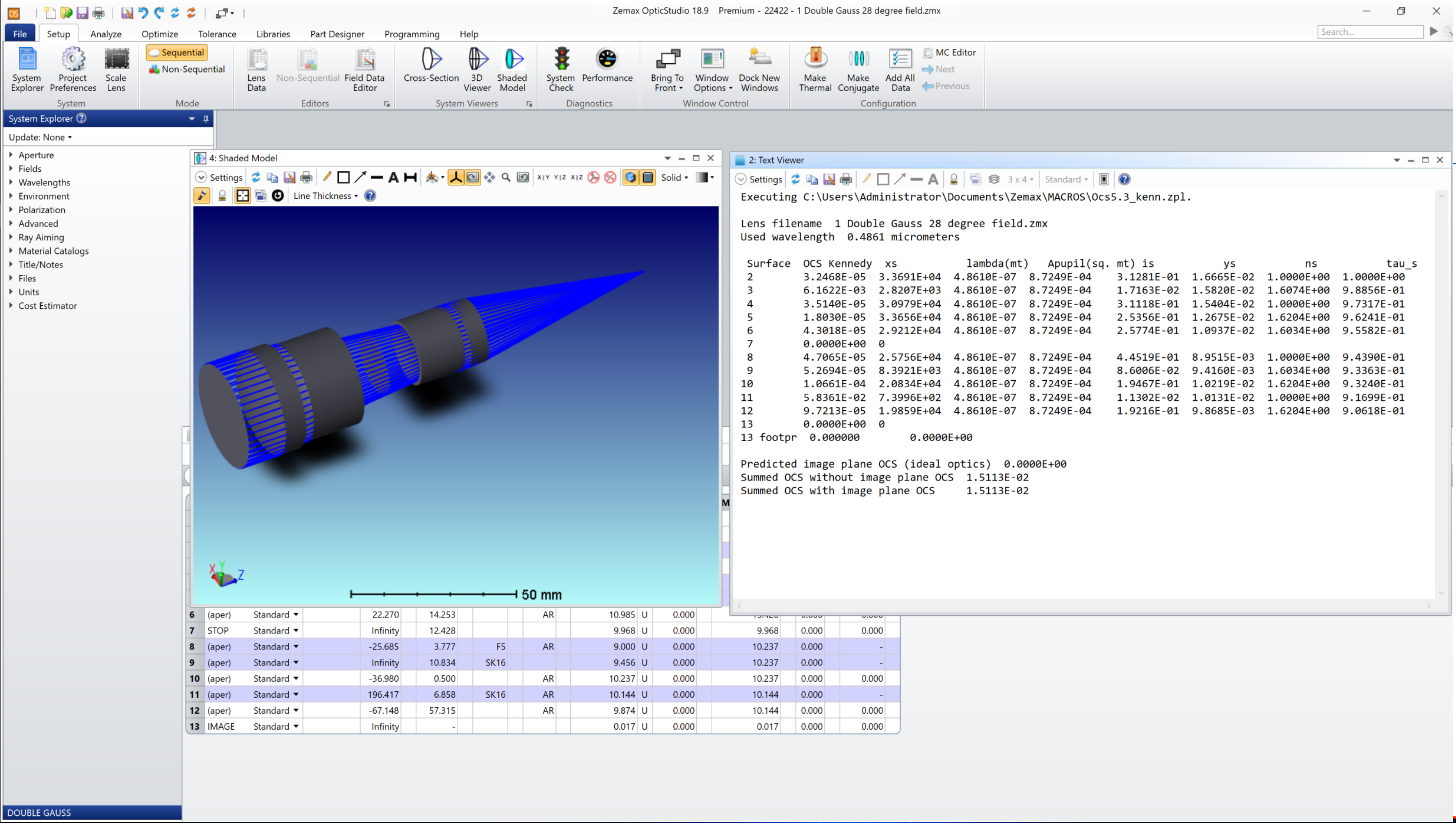
Layout

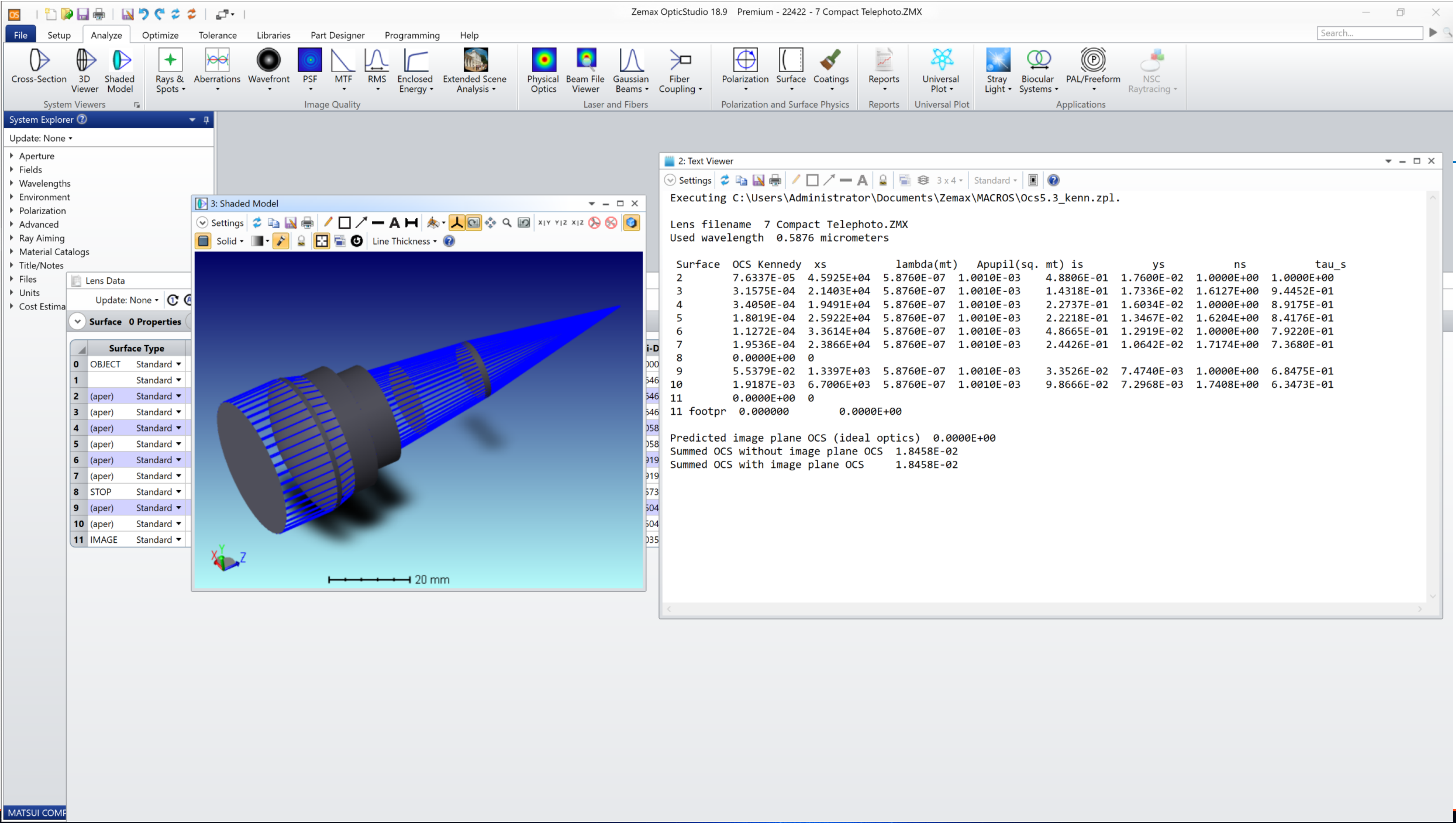
DOUBLE GAUSS
9/18/2019
Total Axial Length: 142.98842 mm

1 Double Gauss 28 degree field.zmx
Configuration 1 of 1

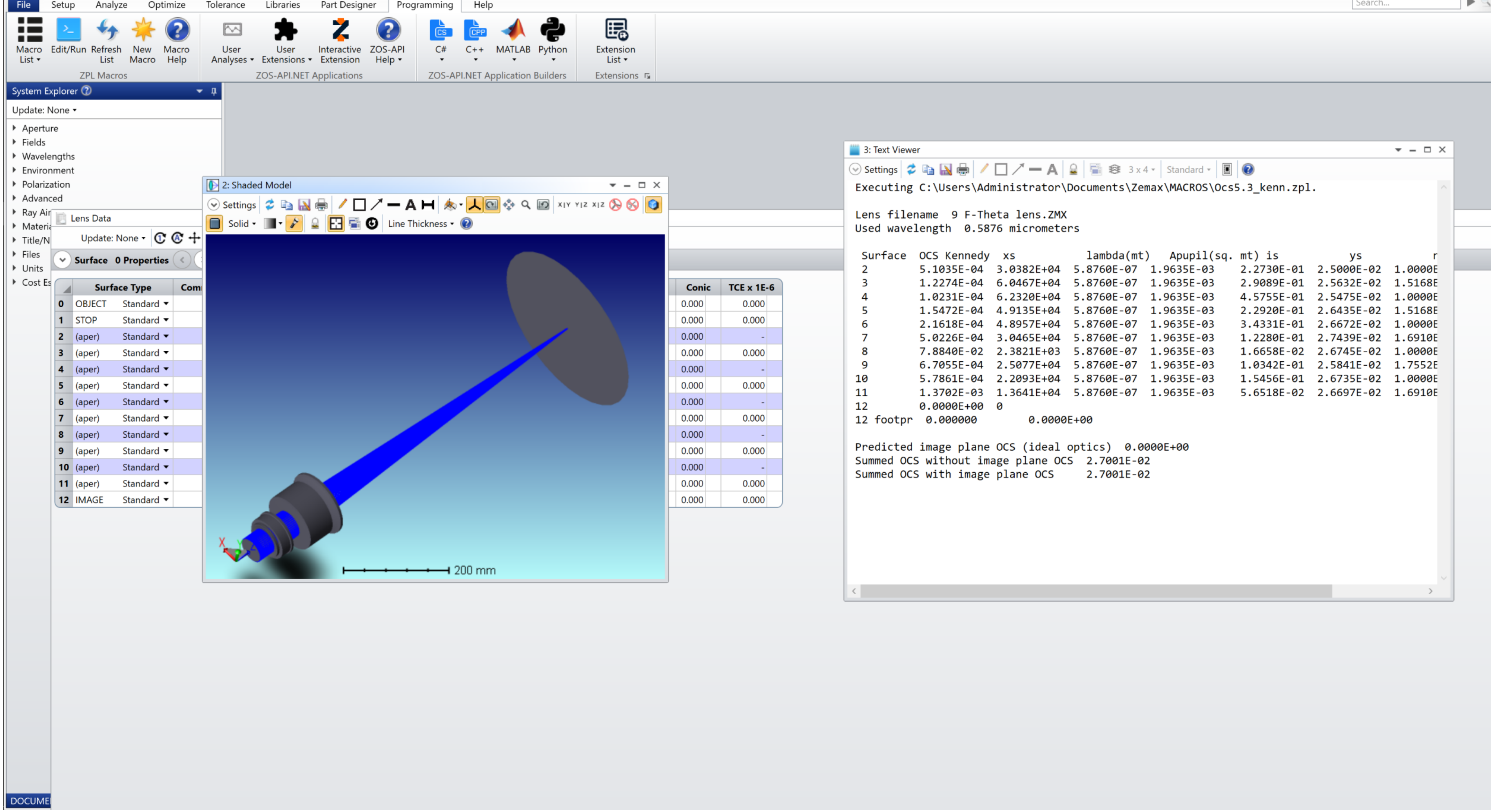
Graph | Classic

DOUBLE GAUSS | EFFL: 99.5007 | WFNO: 2.97828 | ENPD: 33.33 | TOTR: 142.988


Zemax OpticStudio 18.9 Premium - 22422 - 1 Double Gauss 28 degree field.zmx
4: Shaded Model
50 mm
2: Text Viewer
Executing C:\Users\Administrator\Documents\Zemax\MACROS\Ocs5.3_kenn.zpl.
Lens filename 1 Double Gauss 28 degree field.zmx
Used wavelength 0.4861 micrometers
Surface OCS Kennedy xs lambda(mt) Apupil(sq. mt) is ys ns tau_s
2 3.2468E-05 3.3691E+04 4.8610E-07 8.7249E-04 3.1281E-01 1.6665E-02 1.0000E+00 1.0000E+00
3 6.1622E-03 2.8207E+03 4.8610E-07 8.7249E-04 1.7163E-02 1.5820E-02 1.6074E+00 9.8856E-01
4 3.5140E-05 3.0979E+04 4.8610E-07 8.7249E-04 3.1118E-01 1.5404E-02 1.0000E+00 9.7317E-01
5 1.8030E-05 3.3656E+04 4.8610E-07 8.7249E-04 2.5356E-01 1.2675E-02 1.6204E+00 9.6241E-01
6 4.3018E-05 2.9212E+04 4.8610E-07 8.7249E-04 2.5774E-01 1.0937E-02 1.6034E+00 9.5582E-01
7 0.0000E+00 0
8 4.7065E-05 2.5756E+04 4.8610E-07 8.7249E-04 4.4519E-01 8.9515E-03 1.0000E+00 9.4390E-01
9 5.2694E-05 8.3921E+03 4.8610E-07 8.7249E-04 8.6006E-02 9.4160E-03 1.6034E+00 9.3363E-01
10 1.0661E-04 2.0834E+04 4.8610E-07 8.7249E-04 1.9467E-01 1.0219E-02 1.6204E+00 9.3240E-01
11 5.8361E-02 7.3996E+02 4.8610E-07 8.7249E-04 1.1302E-02 1.0131E-02 1.0000E+00 9.1699E-01
12 9.7213E-05 1.9859E+04 4.8610E-07 8.7249E-04 1.9216E-01 9.8685E-03 1.6204E+00 9.0618E-01
13 0.0000E+00 0
13 footpr 0.000000 0.0000E+00
Predicted image plane OCS (ideal optics) 0.0000E+00
Summed OCS without image plane OCS 1.5113E-02
Summed OCS with image plane OCS 1.5113E-02
6 (aper) Standard 22.270 14.253 AR 10.985 U 0.000
7 STOP Standard Infinity 12.428 9.968 U 0.000 9.968 0.000 0.000
8 (aper) Standard -25.685 3.777 F5 AR 9.000 U 0.000 10.237 0.000 -
9 (aper) Standard Infinity 10.834 SK16 9.456 U 0.000 10.237 0.000 -
10 (aper) Standard -36.980 0.500 AR 10.237 U 0.000 10.237 0.000 0.000
11 (aper) Standard 196.417 6.858 SK16 AR 10.144 U 0.000 10.144 0.000 -
12 (aper) Standard -67.148 57.315 AR 9.874 U 0.000 10.144 0.000 0.000
13 IMAGE Standard Infinity - 0.017 U 0.000 0.017 0.000 0.000
DOUBLE GAUSS



Zemax OpticStudio 18.9 Premium - 22422 - 7 Compact Telephoto.ZMX
2: Text Viewer
Executing C:\Users\Administrator\Documents\Zemax\MACROS\Ocs5.3_kenn.zpl.
Lens filename 7 Compact Telephoto.ZMX
Used wavelength 0.5876 micrometers
Surface OCS Kennedy xs lambda(mt) Apupil(sq. mt) is ys ns tau_s
2 7.6337E-05 4.5925E+04 5.8760E-07 1.0010E-03 4.8806E-01 1.7600E-02 1.0000E+00 1.0000E+00
3 3.1575E-04 2.1403E+04 5.8760E-07 1.0010E-03 1.4318E-01 1.7336E-02 1.6127E+00 9.4452E-01
4 3.4050E-04 1.9491E+04 5.8760E-07 1.0010E-03 2.2737E-01 1.6034E-02 1.0000E+00 8.9175E-01
5 1.8019E-04 2.5922E+04 5.8760E-07 1.0010E-03 2.2218E-01 1.3467E-02 1.6204E+00 8.4176E-01
6 1.1272E-04 3.3614E+04 5.8760E-07 1.0010E-03 4.8665E-01 1.2919E-02 1.0000E+00 7.9220E-01
7 1.9536E-04 2.3866E+04 5.8760E-07 1.0010E-03 2.4426E-01 1.0642E-02 1.7174E+00 7.3680E-01
8 0.0000E+00 0
9 5.5379E-02 1.3397E+03 5.8760E-07 1.0010E-03 3.3526E-02 7.4740E-03 1.0000E+00 6.8475E-01
10 1.9187E-03 6.7006E+03 5.8760E-07 1.0010E-03 9.8666E-02 7.2968E-03 1.7408E+00 6.3473E-01
11 0.0000E+00 0
11 footpr 0.000000 0.0000E+00
Predicted image plane OCS (ideal optics) 0.0000E+00
Summed OCS without image plane OCS 1.8458E-02
Summed OCS with image plane OCS 1.8458E-02
3: Shaded Model
20 mm


File
Setup
Analyze
Optimize
Tolerance
Libraries
Part Designer
Programming
Help
Macro List
Edit/Run
Refresh List
New Macro
Macro Help
ZPL Macros
User Analyses
User Extensions
Interactive Extension
ZOS-API Help
ZOS-API.NET Applications
C#
C++
MATLAB
Python
ZOS-API.NET Application Builders
Extension List
Extensions
System Explorer
Update: None
Aperture
Fields
Wavelengths
Environment
Polarization
Advanced
Files
Units
Lens Data
Surface 0 Properties
Surface Type
Conic
TCE x 1E-6
0 OBJECT Standard 0.000 0.000
1 STOP Standard 0.000 0.000
2 (aper) Standard 0.000 -
3 (aper) Standard 0.000 0.000
4 (aper) Standard 0.000 -
5 (aper) Standard 0.000 0.000
6 (aper) Standard 0.000 -
7 (aper) Standard 0.000 0.000
8 (aper) Standard 0.000 -
9 (aper) Standard 0.000 0.000
10 (aper) Standard 0.000 -
11 (aper) Standard 0.000 0.000
12 IMAGE Standard 0.000 0.000
2: Shaded Model
Settings
Solid
Line Thickness
200 mm
3: Text Viewer
Settings
3 x 4
Standard
Executing C:\Users\Administrator\Documents\Zemax\MACROS\Ocs5.3_kenn.zpl.
Lens filename 9 F-Theta lens.ZMX
Used wavelength 0.5876 micrometers
Surface OCS Kennedy xs lambda(mt) Apupil(sq. mt) is ys r
2 5.1035E-04 3.0382E+04 5.8760E-07 1.9635E-03 2.2730E-01 2.5000E-02 1.0000E
3 1.2274E-04 6.0467E+04 5.8760E-07 1.9635E-03 2.9089E-01 2.5632E-02 1.5168E
4 1.0231E-04 6.2320E+04 5.8760E-07 1.9635E-03 4.5755E-01 2.5475E-02 1.0000E
5 1.5472E-04 4.9135E+04 5.8760E-07 1.9635E-03 2.2920E-01 2.6435E-02 1.5168E
6 2.1618E-04 4.8957E+04 5.8760E-07 1.9635E-03 3.4331E-01 2.6672E-02 1.0000E
7 5.0226E-04 3.0465E+04 5.8760E-07 1.9635E-03 1.2280E-01 2.7439E-02 1.6910E
8 7.8840E-02 2.3821E+03 5.8760E-07 1.9635E-03 1.6658E-02 2.6745E-02 1.0000E
9 6.7055E-04 2.5077E+04 5.8760E-07 1.9635E-03 1.0342E-01 2.5841E-02 1.7552E
10 5.7861E-04 2.2093E+04 5.8760E-07 1.9635E-03 1.5456E-01 2.6735E-02 1.0000E
11 1.3702E-03 1.3641E+04 5.8760E-07 1.9635E-03 5.6518E-02 2.6697E-02 1.6910E
12 0.0000E+00 0
12 footpr 0.000000 0.0000E+00
Predicted image plane OCS (ideal optics) 0.0000E+00
Summed OCS without image plane OCS 2.7001E-02
Summed OCS with image plane OCS 2.7001E-02

User defined objects in Zemax for nonimaging optical systems design

Why use user defined objects?

- Provide built-in fully integrated, simple solution for efficient design of freeform based illumination system in nonsequential mode.
- We use simplified Bezier curves (up to 4) to create surfaces and solid objects
- User defined objects is easy way to describe the lenses based on Bezier curves.
- UDO behaves like built-in object, has fast raytrace and fully integrated in optimization.

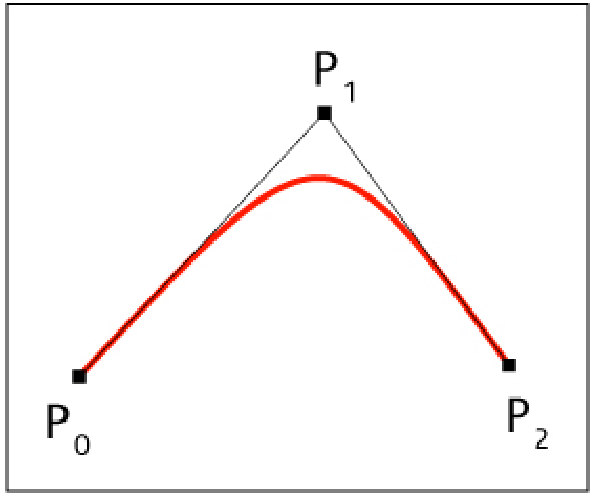
What was done by OFH

- Created 20+ freeform UDO to describe illumination systems natively in Zemax. All Dlls was written with Microsoft Visual Studio software
- All UDO has parameters for optimization its shape, control the geometry, size and special features like faceting, fillets etc.
- Created set of ZPL macro which allow scale the UDO, change their parameters, change surface properties, control the slope, control the shape and much more.
- Also there are several macro to create direct CNC machine command file for some types of UDO.

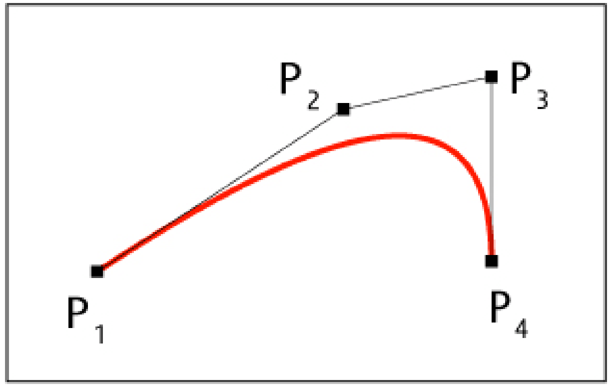
What is Bezier curve and why we use it

Bezier curve is a parametric curve used in computer graphics and related fields. The curve, which is related to the Bernstein polynomial, is named after Pierre Bezier, who used it in the 1960s for designing curves for the bodywork of Renault cars. Other uses include the design of computer fonts and animation.

The curve is simple to use. It controlled by control points set, which are just a set of numbers. Point not lie on the curve except start and end point. This is best for build freeform optical surfaces.



3-point Bezier curve.



4-point Bezier curve.

The simplified Bezier curve parametric equation

$$Bx(u) = (Px_n - Px_0)u, u \in [0,1]$$

$$By(u) = \sum_{i=0}^{n} \left(n! u^i (1-u)^{n-i} / \left(i!(n-i)! \right) \right) Py_i, u \in [0,1], i = 0..n$$

- Simplified Bezier curve.

The feature of that curve representation is that X control points equally spaced along the axis. So we use only parametrization of Y part of curve. This allow us more simple calculations while create complex objects form that curves. The raytrace for surfaces based on that curve is 30% faster rather than usual Bezier curves and up to 60% faster if use more general NURB representation.

And we remain almost all flexibility of freeform and use less variables.

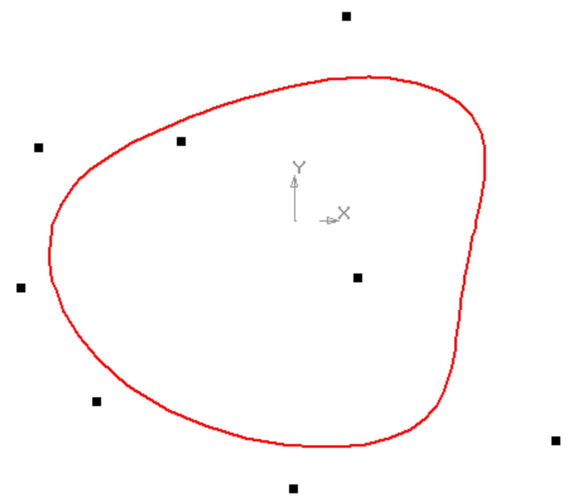
The simplified polar Bezier curve equation

$$C(t)=\begin{cases}\rho(t)=1\Big/\sum_{i=0}^{n}c_iA_{i,n}(t)\\ \theta(t)=nt\end{cases},t\in[-\Delta,\Delta],2n\Delta<\pi$$

- Simplified polar Bezier curve.

$$A_{i,n}=\frac{1}{\sin(2\Delta)^n}\frac{n!}{i!(n-i)!}\sin^{n-i}(\Delta-t)\sin^{i}(\Delta+t)$$

- Trigonometric Bernstein polynomial.



- The curve is same as previous, but defined in polar coordinates

Some important surfaces created from Bezier curves

- 3 Surface of revolution of simplified Bezier curve (TIR)
- Surface of revolution of simplified Bezier curve along simplified polar Bezier curve (Type V beam shaping)
- Surface of revolution of 4 simplified Bezier curve along simplified polar Bezier curve. Each independent curve describe the quarter of 360-degree surface. Curves use same X parametrization while Y are different.
- Extrude the simplified Bezier curve along another simplified Bezier curve

Step1: Model surface equations in MapleV5

Maple 2018 - [test2.mws - [Server 1]]

File Edit View Insert Format Spreadsheet Window Help

> `restart;`

> $A := [[0, 1], [1, 3], [2, 4], [3, 5], [4, 4.5], [5, 5], [6, 5.4], [7, 5.6]]; N := 7$

> $Bx := (t, n, sq) \to 7\,t; By := (t, n, sq) \to \sum_{i=0}^{n} sq_{i+1_2} \frac{n!\, t^i\, (1-t)^{(n-i)}}{i!\,(n-i)!}$

> $\mathrm{plot}([\mathrm{By}(t, N, A), \mathrm{Bx}(t, N, A), t = 0..1])$

> $\mathrm{simplify}(\mathrm{Bx}(t, N, A))$

> $Fx := (u, v) \to \mathrm{By}(u, N, A)\sin(v); Fy := (u, v) \to \mathrm{By}(u, N, A)\cos(v); Fz := (u, v) \to \mathrm{Bx}(u, N, A)$

>

> $\frac{\partial}{\partial v}\mathrm{Fx}(u, v); \frac{\partial}{\partial v}\mathrm{Fy}(u, v); \frac{\partial}{\partial v}\mathrm{Fz}(u, v)$

>

>

> $Lx := t \to 5 - 1.0\,t; Ly := t \to 1 - .0e\text{-}1\,t; Lz := t \to 3 + .5\,t$

> $\frac{\partial}{\partial t}(\mathrm{Fx}(u, v) - \mathrm{Lx}(t)); \frac{\partial}{\partial t}(\mathrm{Fy}(u, v) - \mathrm{Ly}(t)); \frac{\partial}{\partial t}(\mathrm{Fz}(u, v) - \mathrm{Lxz}(t))$

> $P1 := \mathrm{plot3d}([\mathrm{Fx}(u, v), \mathrm{Fy}(u, v), \mathrm{Fz}(u, v)], u = 0..1, v = 0..2\pi, style = patchnogrid)$

> $P2 := \mathrm{plot3d}([\mathrm{Lx}(t), \mathrm{Ly}(t), \mathrm{Lz}(t)], t = 0..12, y = 1..2)$

> $\mathrm{plots}_{display}(P1, P2)$

> `#NEWTON METHOD`

> $J := V \to \mathrm{VectorCalculus}_{Jacobian}(V, [u, v, t])$

> $X := \mathrm{Vector}([u, v, t]); XK := X; XK1 := X$

> $FF := X \to \mathrm{Vector}([\mathrm{Fx}(X_1, X_2) - \mathrm{Lx}(X_3), \mathrm{Fy}(X_1, X_2) - \mathrm{Ly}(X_3), \mathrm{Fz}(X_1, X_2) - \mathrm{Lz}(X_3)])$

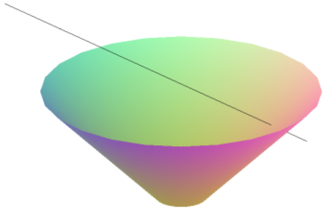
> $\mathrm{LinearAlgebra}_{MatrixInverse}(\mathrm{J}(\mathrm{FF}(X)))$

> `xk:=[1,1,1];`

> **for** g **to** 3 **do**

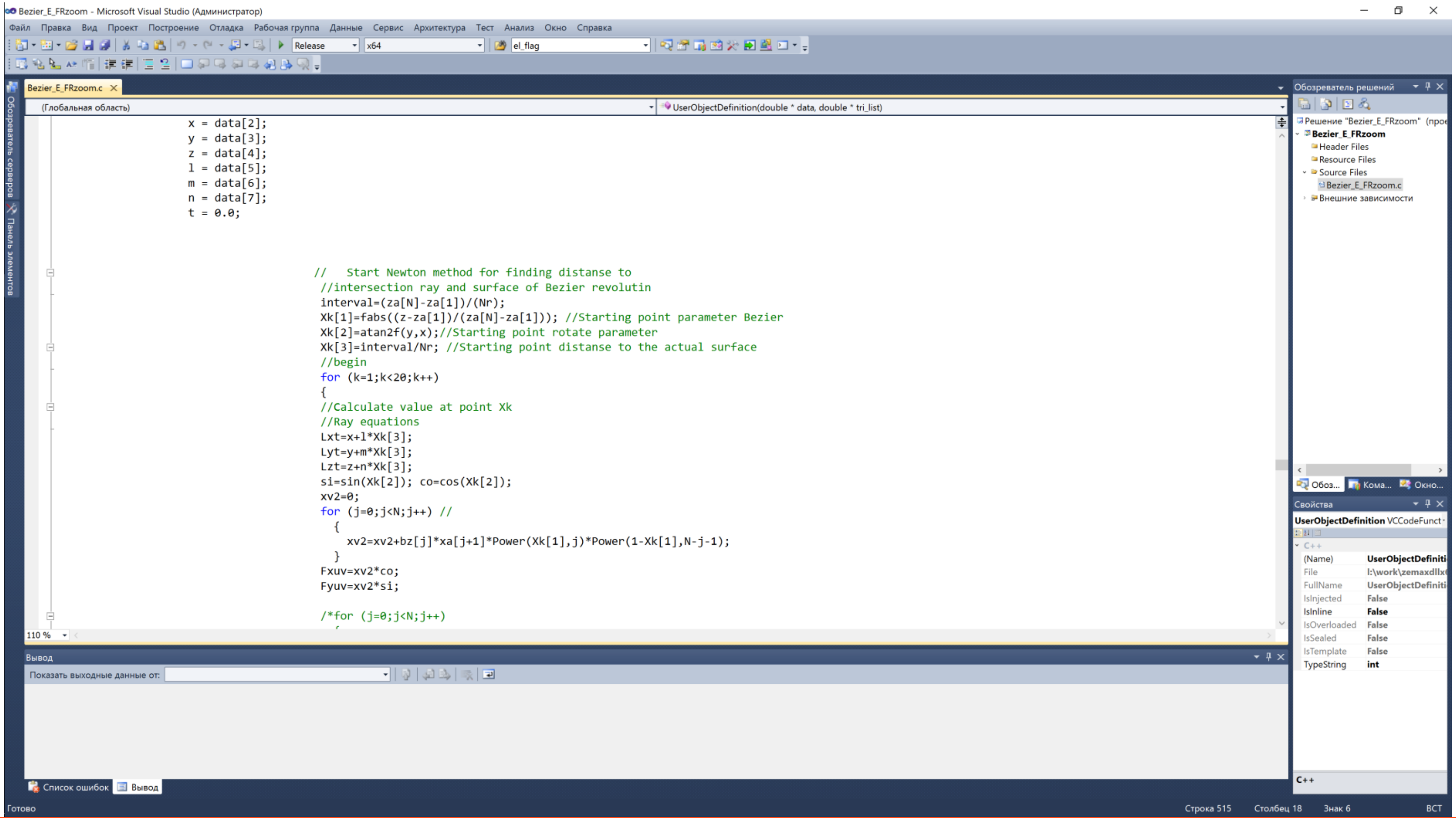
$xk1 := (x, y, z) \to \mathrm{subs}(u = x, v = y, t = z, XK - \mathrm{LinearAlgebra}_{MatrixVectorMultiply}(\mathrm{LinearAlgebra}_{MatrixInverse}(\mathrm{J}(\mathrm{FF}(XK))), \mathrm{FF}(XK)));$

$\mathrm{evalf}(\mathrm{xk1}(xk_1, xk_2, xk_3));$

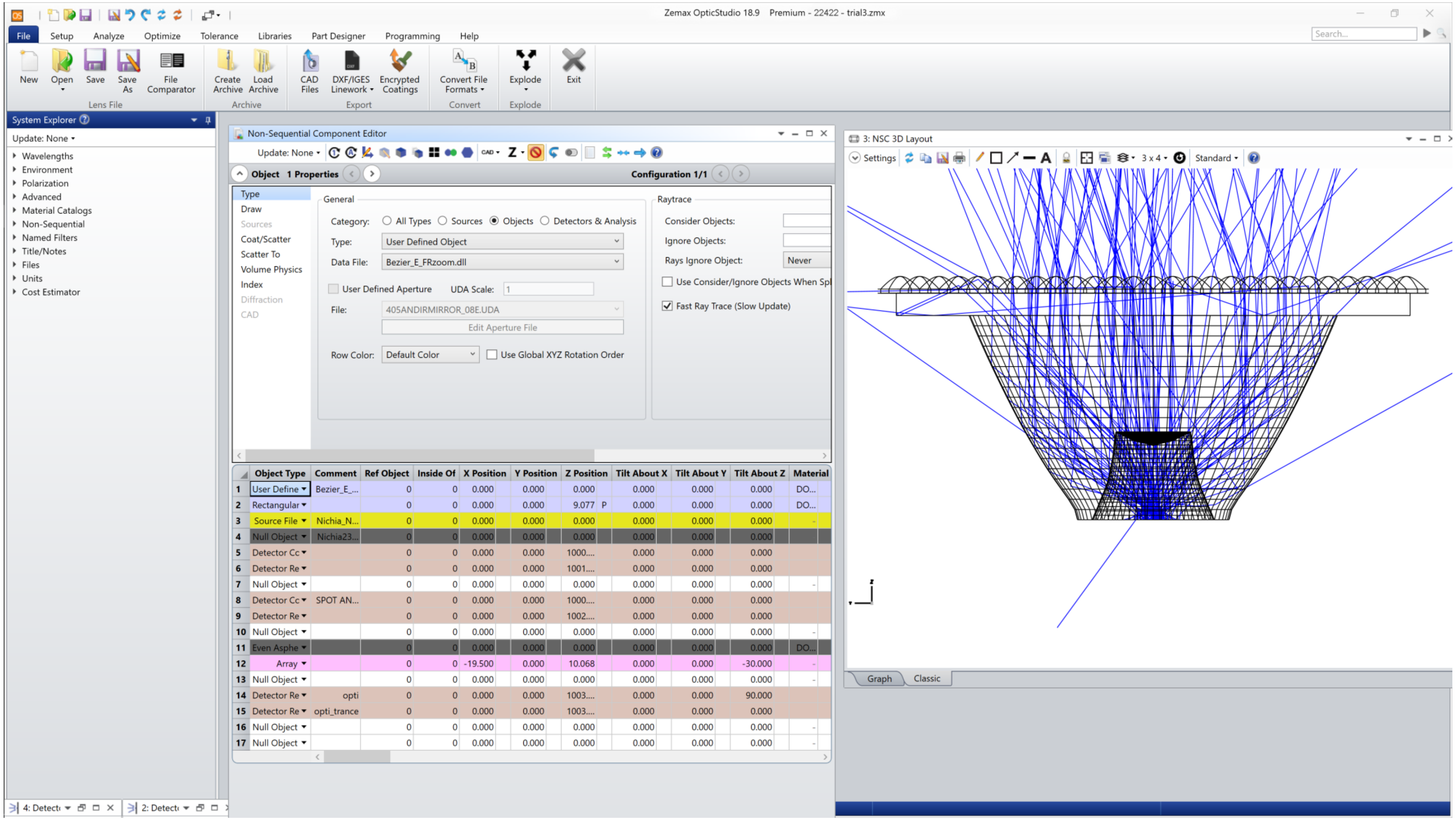


Time: 0.2s Bytes: 40.4M Available: 2.00G

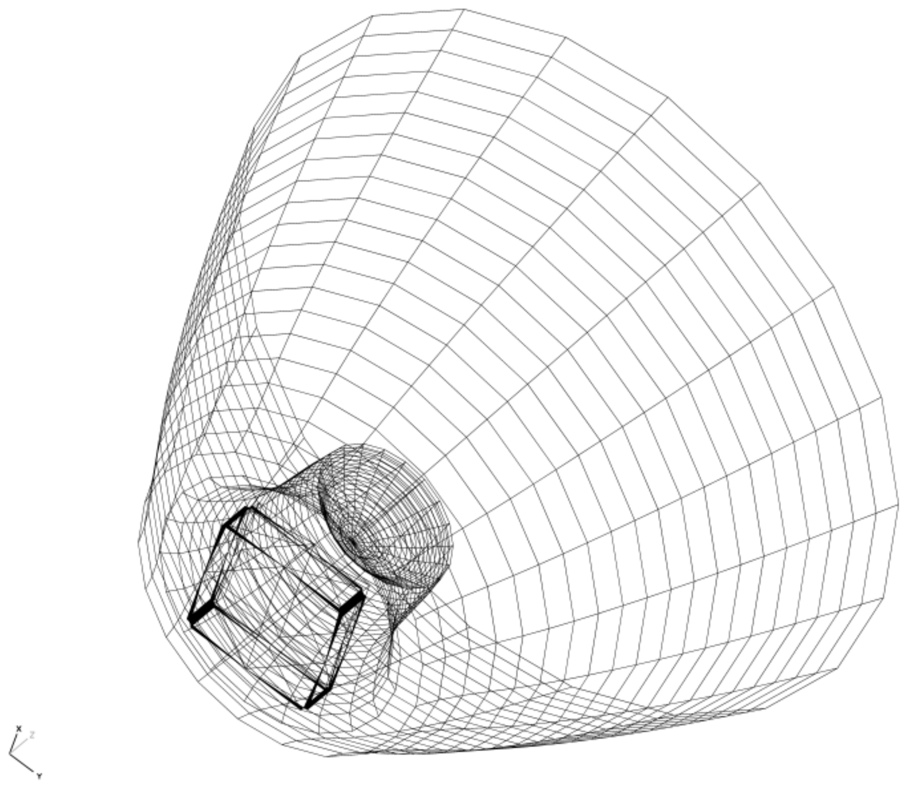
Step2: Create C++ code for surface shape and raytracing and compile it into Dll



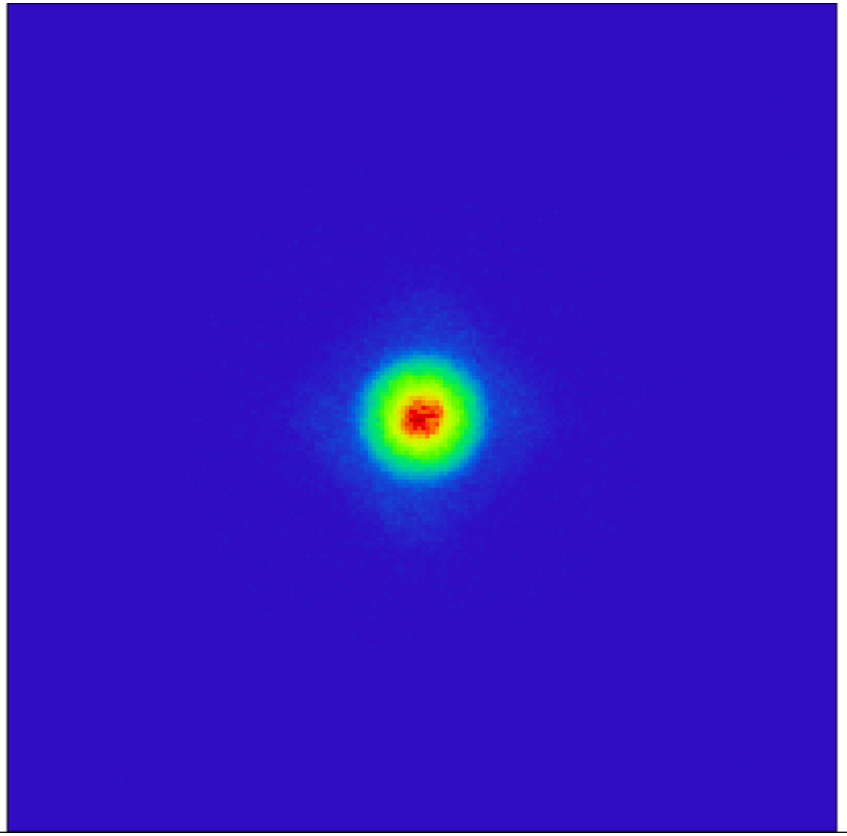
Step3: Import Dll in Zemax as User Defined Object



TIR lens designed with UDO in Zemax



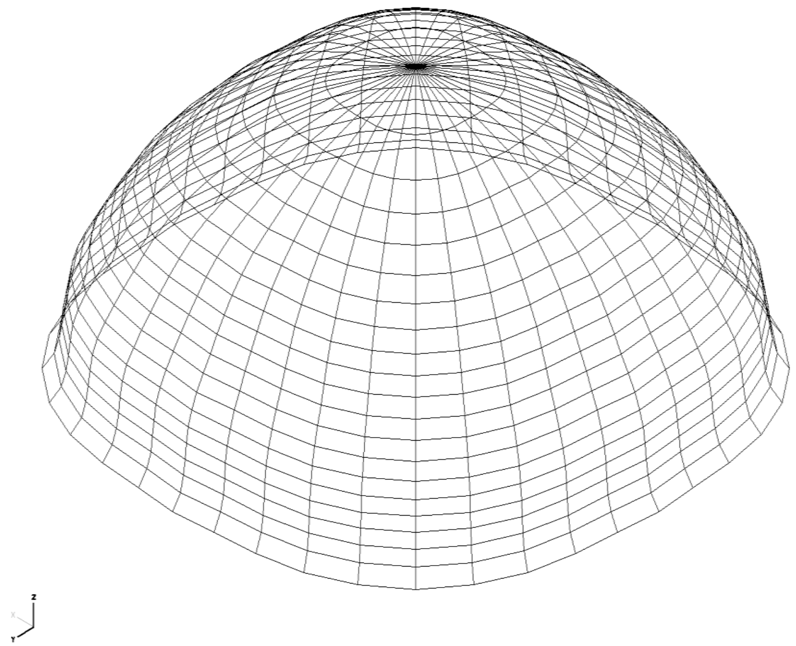
The TIR lens user object in wireframe view

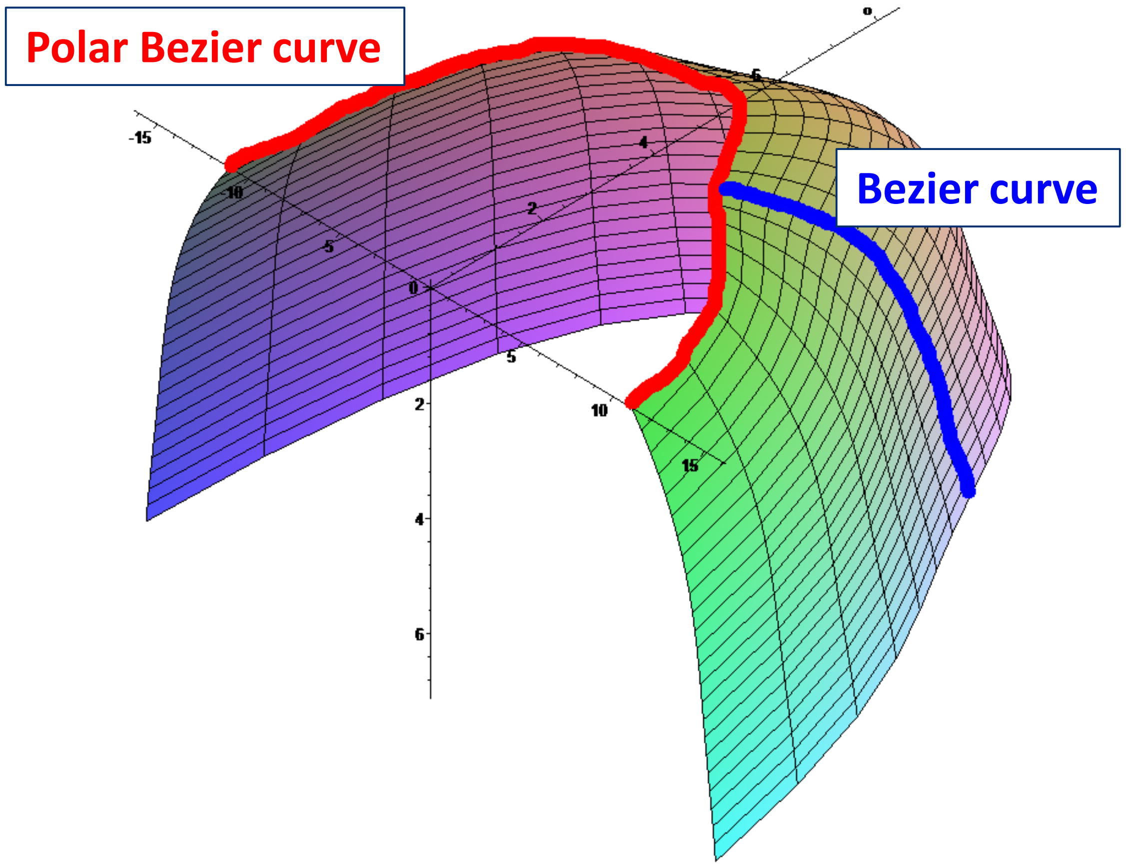


The optimized light spot shown in false color

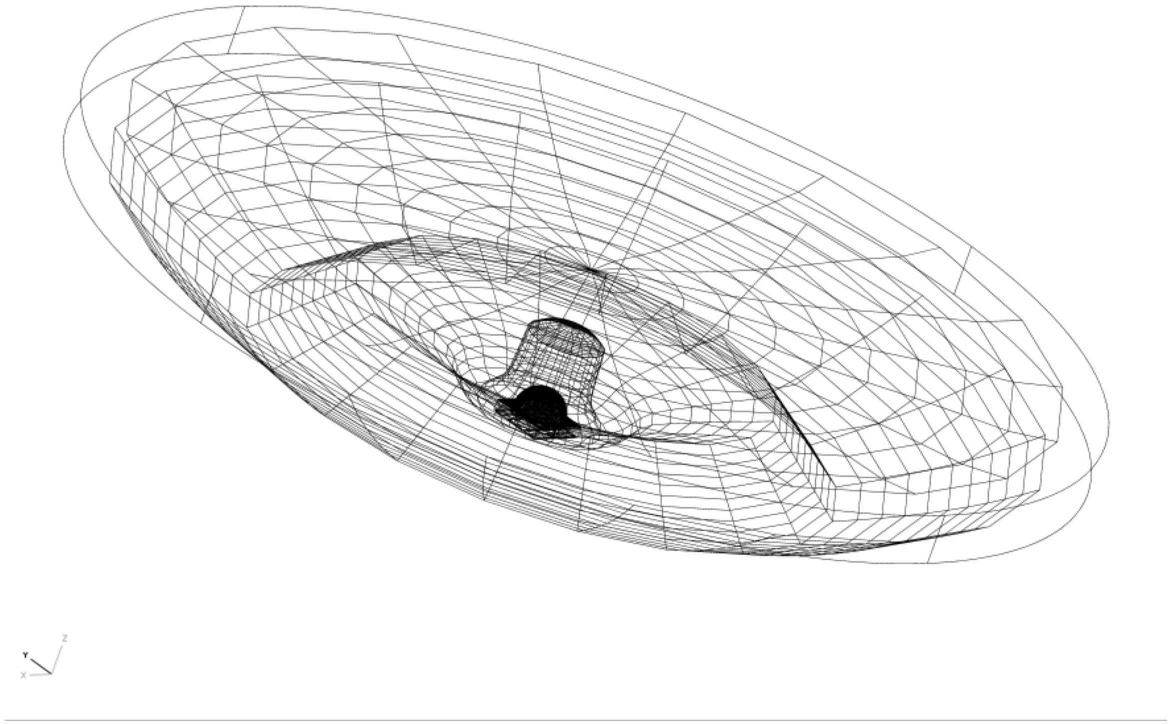
Example of surface of revolution of Bezier curve along the polar Bezier curve

$$\mathbf{F}(u,v)=\begin{cases} F_x(u,v)=\sqrt{B_y(u)\rho(v)}\cos(\theta(v)) \\ F_y(u,v)=\sqrt{B_y(u)\rho(v)}\sin(\theta(v)), u\in[0,1], v\in[-\pi/4,\pi/4] \\ F_z(u,v)=B_x(u) \end{cases}$$





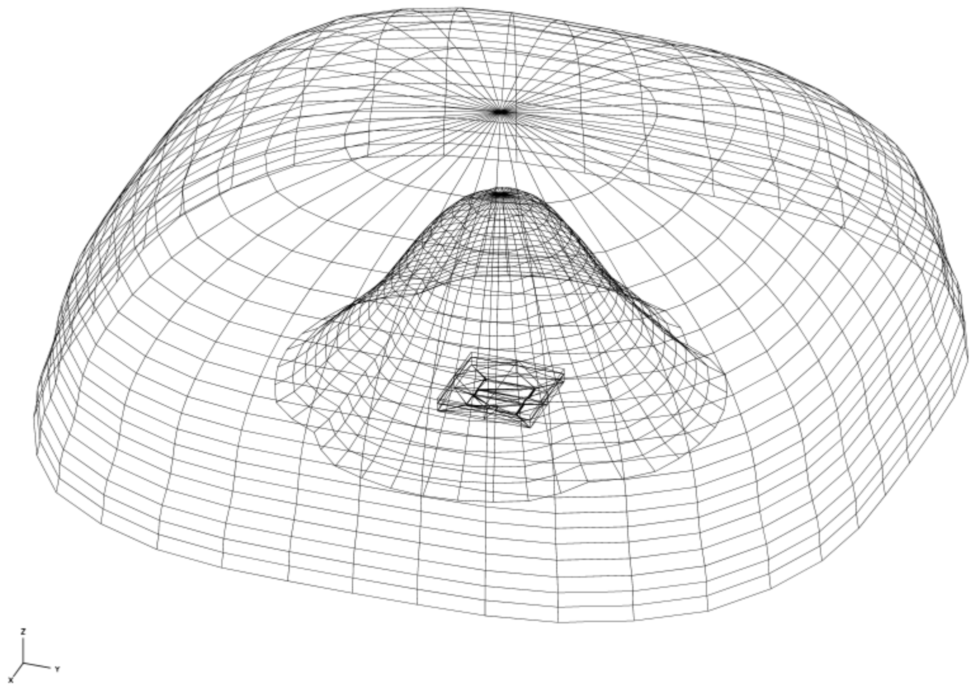
RXI lens designed with UDO in Zemax



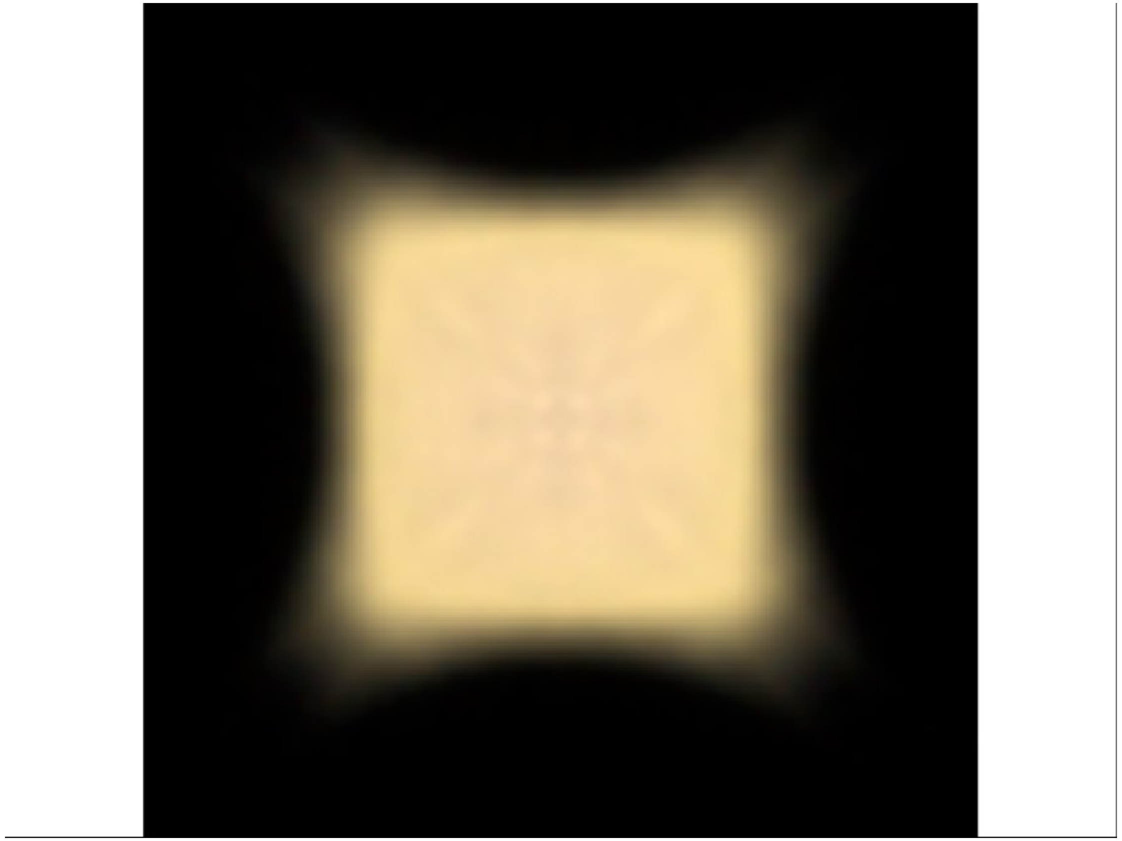
The RXI lens object in wireframe view

The optimized true color light spot

130 degree angle uniform rectangle spot lens designed with UDO in Zemax

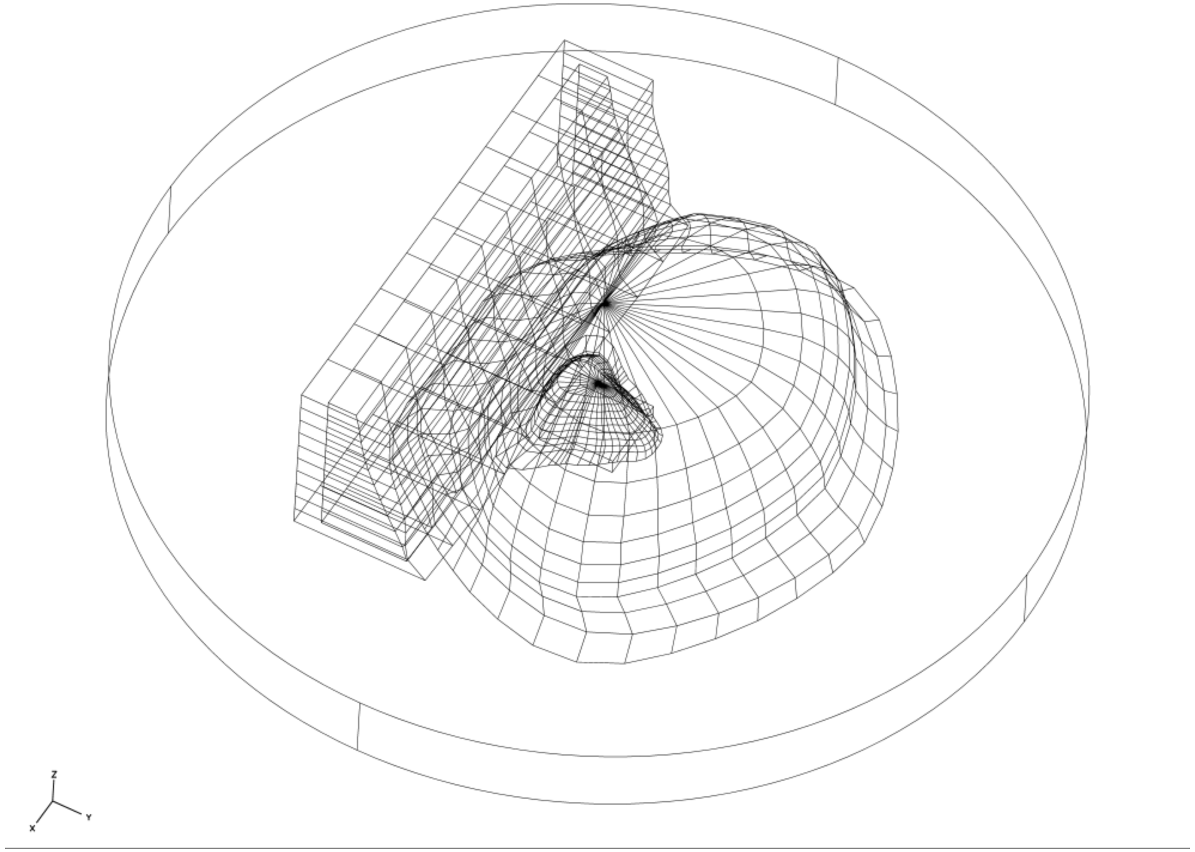


The lens in wireframe view mode

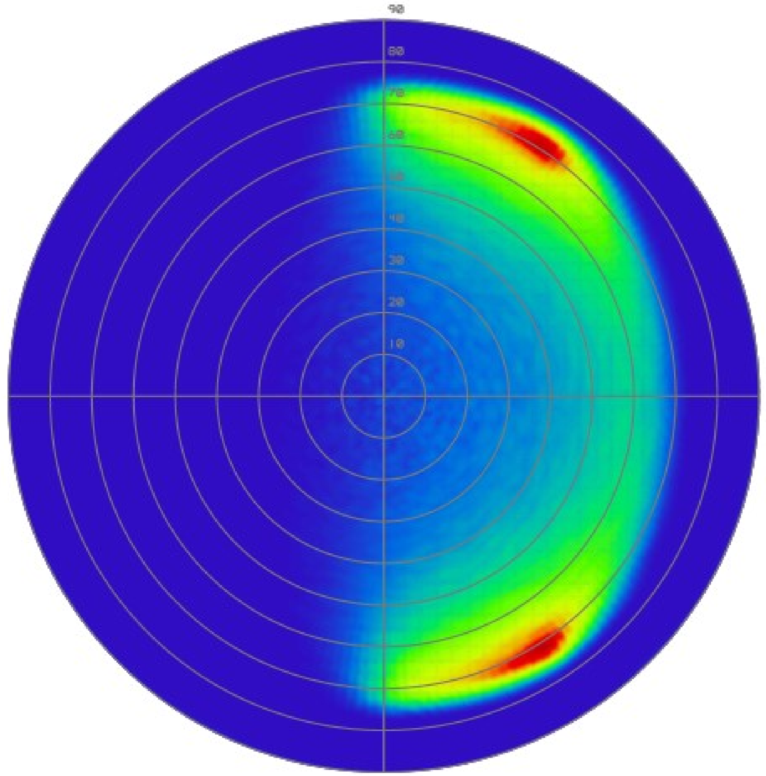


The rectangular spot in true color

Type III streetlight lens designed with UDO in Zemax

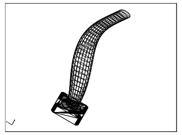


The streetlight lens

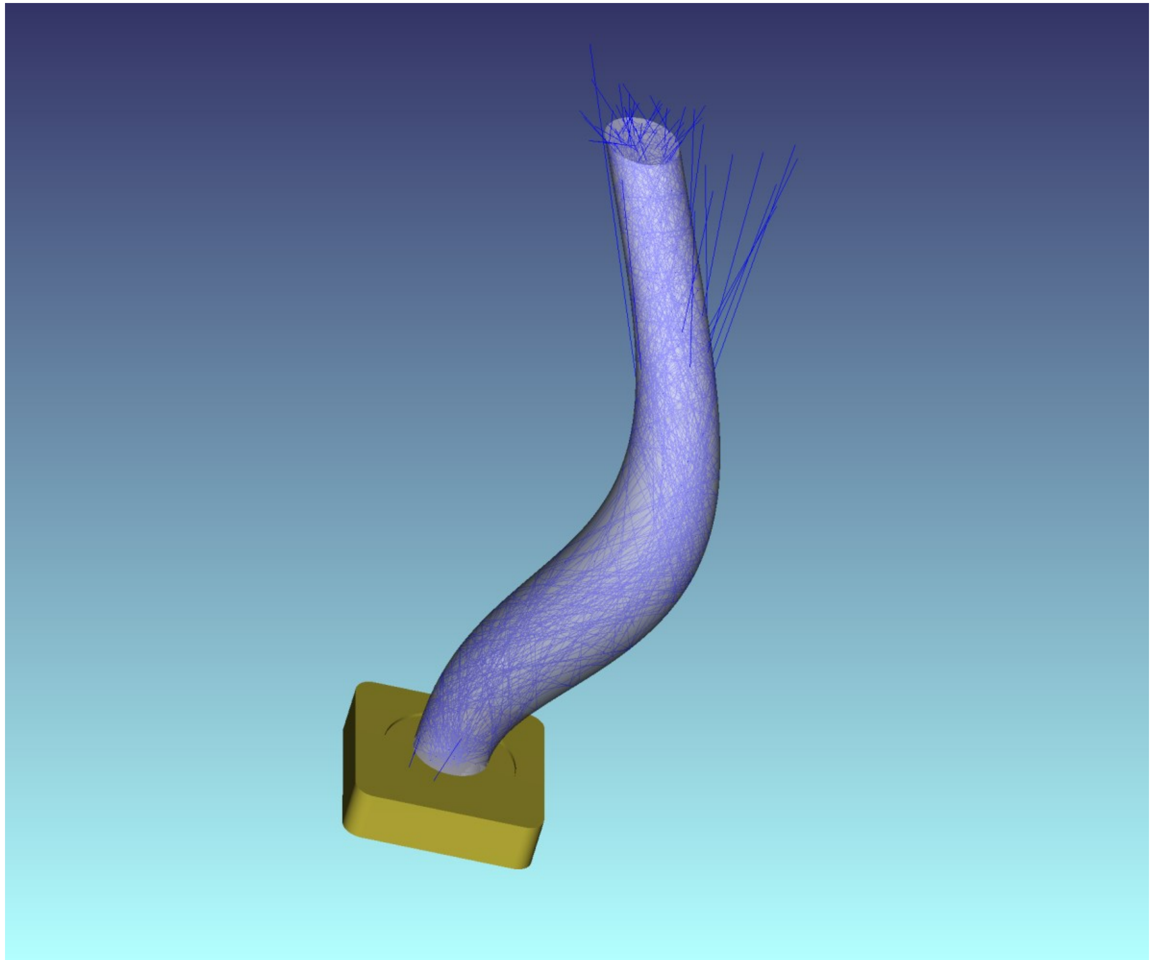


The luminous intensity polar map in false color

Lightpipe designed with UDO in Zemax



The lightpipe



The lightpipe with rays

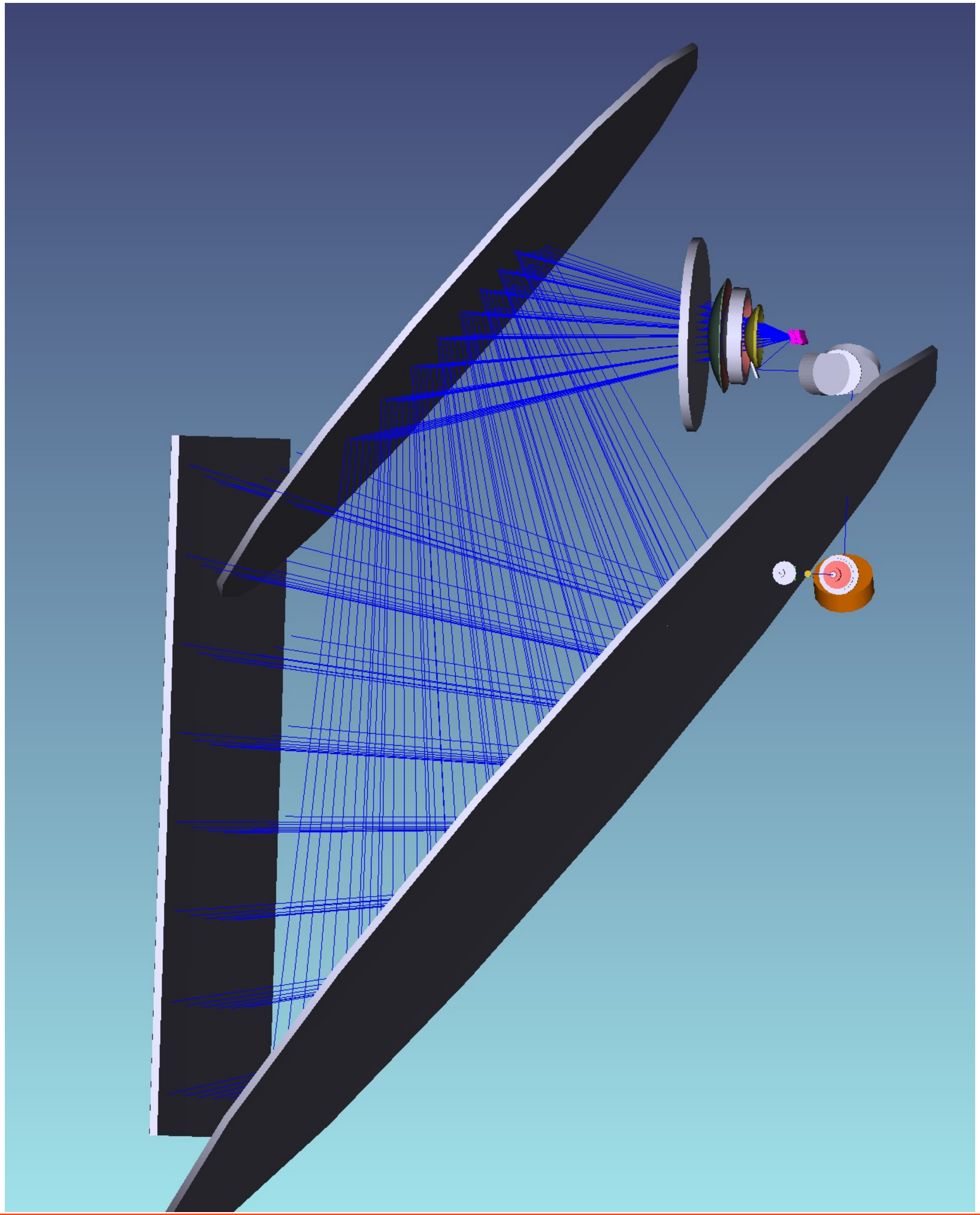
User defined surface for an imaging purposes

Why we need user defined surfaces?

- Some imaging systems require unusual mathematics to correct aberrations, especially in off-axis and tilted optical paths.
- Zemax provides the possibility to use User Defined surfaces for sequential raytracing
- It is differs from User Defined object, sequential mode uses surfaces not objects.

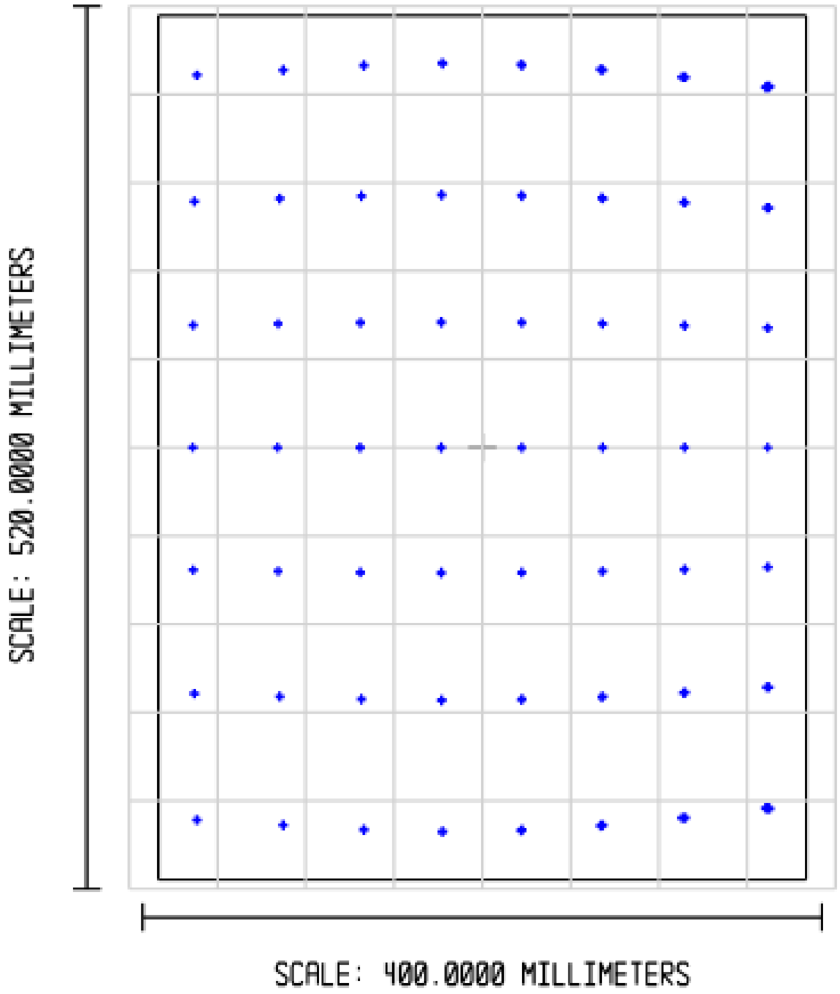
The system

The scanning system contains two fold mirrors and the scan lens, display application



The distortion problem

- The laser scanning system has some slightly distorted field points in image plane



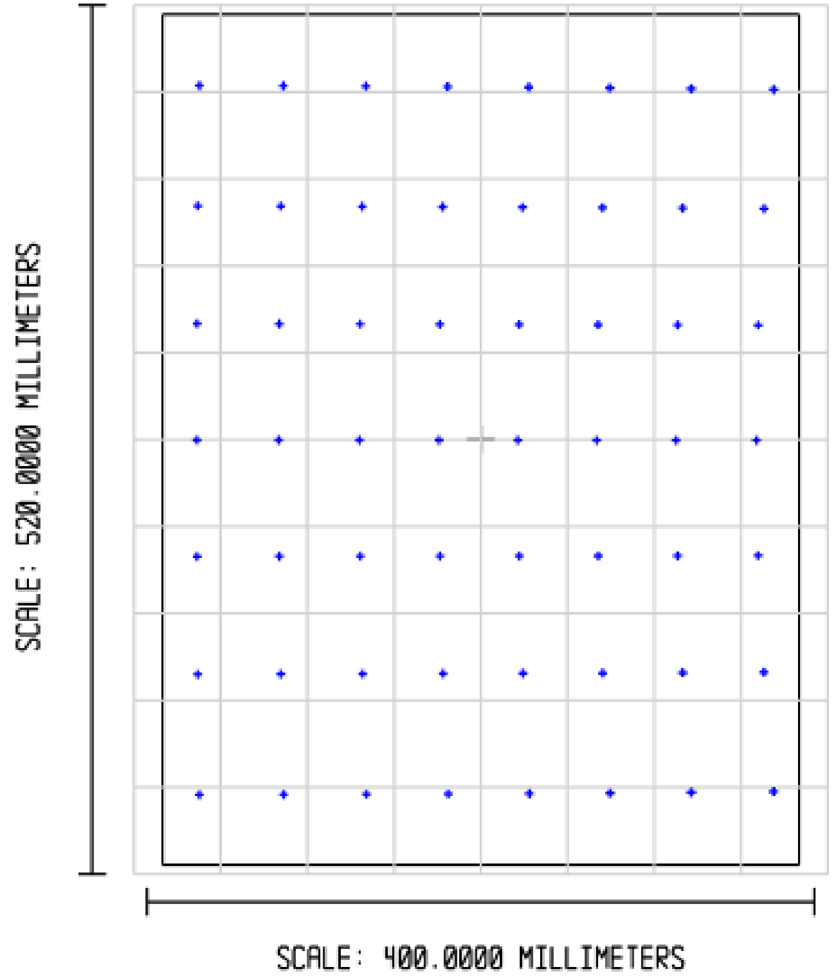
Freeform surface in Zemax sequential mode

- To describe freeform we can use geometrical mean of simplified Bezier curves along X and Y directions.
- Surface shape can be local changed over the aperture by parameters
- This surface just created with User Defined Surface in Zemax sequential mode

The surface sample

The solution

- Using freeform plate between lens and mirrors we can correct that distortion
- With using 7x7 control point grid of Bezier surface we obtain well corrected distortion



"Using User Defined Object, Macros and User Defined surface greatly expand Zemax capabilities. And with use User defined sources, scatter functions, and coatings Zemax is most powerful and flexible optical design software in the world"

Download the slides at
www.opticsforhire.com/envision
questions: john@opticsforhire.com

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