Method for the design of nonaxially symmetric optical systems using free-form surfaces (Erratum)

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1 Introduction

In section six of a previous paper[1] we made an inappropriate comparison between a three-mirror telescope system designed with NURBS surfaces[2] and our three-mirror system designed with Zf(r) surfaces. We assumed that the focal length in the Chrisp paper[2] was 35.7 mm when in fact it is 35.7 cm. Thus the comparison we made is not a one-to-one, and in this errata we revise our design and comparison.

2 Scaling Up and Re-optimizing our Three Mirror Design

Scaling our three-mirror design by a factor of 10, including up to 10th order freeform coefficients to account for the larger scale in comparison to the fixed system wavelength of 3.0 μm, and carrying further the optimization which has stopped early when the $f = 35.7$ mm design reached nearly diffraction limited performance, results in the design shown in Fig. 1. The first order characteristics are given in Table 1 and this time are the same as in Table 1 of the Chrisp paper.

Attention was placed to have an F-number of 2.0 in both principal sections of the telescope as the RMS spot size highly depends on F-number. The distortion aberration, smile and keystone, of the design is 3.36%, and there is negligible image plane tilt with respect to the optical axis ray. The secondary mirror has a rectangular aperture such that the focal ratio of the system is $f/2$. To calculate the RMS spot size, a pupil grid of 64×64 rays was traced through the system. The rectangular aperture on the secondary mirror defines the aperture stop and vignettes rays outside it. Real ray aiming was used to properly fill the aperture stop. The RMS spot size for each field point was calculated with respect to the centroid. Then the RMS spot size of the average of a grid of 20×20 field points distributed over the field of view was calculated as 10.4 μm. The design update was done in Zemax OpticStudio 21.1.2 and for convenience the prescription of the system using conic XY polynomial surfaces is given in Appendix A. The lens file is available upon request.

3 Anamorphic Imaging

As the RMS spot size has a strong dependence on F-number, one way to improve it is by allowing anamorphic imaging. In this case the F-number in one of the principal system sections is increased so that the system optical throughput is conserved. According to our design approach that is based on aberration theory, the primary and tertiary mirrors introduce both uniform astigmatism and anamorphic distortion. The secondary mirror coincides with the stop and introduces only uniform astigmatism that corrects the uniform astigmatism contributed by the primary and tertiary mirrors. Both uniform astigmatism and anamorphic imaging depend on the cylindrical terms in the description of the mirrors aspheric profile.

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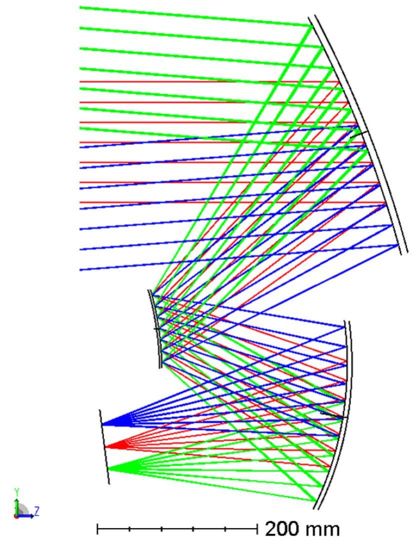

Fig. 1 Three mirror telescope re-optimized and scaled to a focal length of 357 mm.

Table 1 Design requirements for the three-mirror unobscured system.

Parameter	Requirement
Field of view (FOV)	10×9 degrees
Focal length	357 mm
Focal ratio	$f/2$

By re-optimizing the above three-mirror design to have 7.5% of anamorphic distortion, the RMS spot size further decreases to 8.7 μm or about a 38% improvement. In this case the secondary mirror has a saddle-like departure from the best fit sphere of about 441 μm RMS. The residual distortion, smile and keystone, is about 1%. The prescription for this system using conic XY polynomial surfaces is given in Appendix B. The lens file is available upon request.

4 Conclusion

We have corrected our error in the comparison we made in our paper by properly scaling up our Three-mirror system and re-optimizing it to account for the scale change, and for the fact that the optimization of the $f = 35.7$ mm system was stopped earlier when it reached close to diffraction limited performance.

The RMS spot size of our scaled-up system is 10.4 μm as averaged over the field of view. This an improvement over the 14 μm RMS spot size reported in the Chrisp paper. The RMS spot size of the anamorphic system is 8.7 μm as averaged over the field of view. These improvements are about 26% and 38% and not 40% as we had reported before. Despite these substantial improvements, we withdraw our statement that our $\mathrm{Zf}(r)$ surface can clearly best model the ideal surface because a more in-depth analysis needs to be done to support such a statement. However, according to the designs so far available for this type of three mirror system the $\mathrm{Zf}(r)$ surfaces, the XY polynomial surfaces, and the NURBS surfaces are able to model systems with similar RMS spot performance. These types of systems have the problem that the sensor at the image plane can see the primary mirror and this makes it more challenging to control stray light.

We also withdraw our statement that "Moreover, the NURBS design represents a "brute force"/"number crunching" solution." The optics industry is developing freeform optics technology, and the freeform systems work at Lincoln Laboratory at MIT is excellent as it pushes forward this technology. The FANO approach[2] is a convenient, integrated, and powerful methodology for the optical design with NURBS surfaces.

5 Appendix A

We provide the prescription, Table 2, and aspheric coefficients, Table 3, for the TMA system using a conic surface and XY polynomials. Thickness is given along the Optical Axis Ray (OAR). I is the angle of incidence of the OAR in the surface.

Table 2 Prescription data for the TMA system using conic XY polynomials.

Surface	Radius (mm)	Thickness (mm)	Conic constant	I (deg)
1	−1401.333	−347.6823	0.2638	−21.0
2 (STOP)	−375.6453	256.0945	−9.2313	33.8217
3	−411.8421	−301.1913	0.1422	−16.4357
Image				−0.0793

Normalization radius for the Extended Polynomial Surface is 10.22192 mm.

Table 3 Aspheric terms for the TMA system using conic XY polynomials.

Aspheric term	Surface 1	Surface 2	Surface 3
X2Y0	3.2153E-04	−5.7544E-03	−1.4761E-03
X2Y1	1.4606E-04	5.1525E-04	3.8279E-04
X0Y3	4.3445E-05	−8.0542E-04	2.0481E-04
X4Y0	1.3913E-06	−2.7979E-04	−2.4620E-06
X2Y2	2.3592E-06	−5.7580E-04	−8.4755E-06
X0Y4	9.2866E-07	−3.0196E-04	−3.5010E-06
X4Y1	8.2596E-09	−1.7325E-07	1.5269E-07
X2Y3	4.0782E-09	−1.9337E-06	3.5432E-07
X0Y5	1.2860E-09	−8.5291E-09	1.3306E-07
X6Y0	7.5669E-12	4.5488E-07	−2.2167E-09
X4Y2	−2.2894E-10	1.6028E-06	−8.5198E-09
X2Y4	2.4905E-10	1.4488E-06	−8.5182E-09
X0Y6	2.1289E-10	2.4474E-06	−3.8965E-09
X6Y1	−5.8251E-11	5.7677E-09	7.9889E-10
X4Y3	−8.5204E-11	−3.1556E-09	5.1720E-10
X2Y5	−7.4767E-11	1.2369E-08	7.5463E-10
X0Y7	−1.8945E-11	−1.1188E-07	1.5760E-10
X8Y0	6.4406E-13	2.6361E-09	3.8999E-12
X6Y2	−4.9525E-13	−1.0153E-08	−3.5955E-11

Table 3 (*Continued*).

Aspheric term	Surface 1	Surface 2	Surface 3
X4Y4	1.3749E-12	–1.5049E-08	–1.4482E-11
X2Y6	–5.2724E-13	1.4295E-09	–3.0817E-11
X0Y8	–3.9499E-13	–1.0439E-07	2.4443E-12
X8Y1	9.1117E-14	–5.3689E-11	–1.9841E-12
X6Y3	9.1176E-14	–2.7444E-11	2.3218E-13
X4Y5	1.8814E-13	6.5252E-11	1.5529E-12
X2Y7	9.7083E-14	–5.5014E-10	–7.4084E-13
X0Y9	2.1430E-14	2.2673E-09	1.0301E-13
X10Y0	–3.5482E-15	–9.7921E-11	–3.0768E-14
X8Y2	3.2220E-15	1.9085E-11	9.4706E-14
X6Y4	9.8922E-16	1.1719E-10	6.2869E-14
X4Y6	–5.9274E-15	–3.0730E-12	–1.3462E-13
X2Y8	3.0072E-16	–2.0390E-10	5.2789E-14
X0Y10	5.1885E-16	1.8863E-09	–1.7287E-14

6 Appendix B

We provide the prescription, Table 4, and aspheric coefficients, Table 5, for the anamorphic TMA system using a conic surface and XY polynomials. Thickness is given along the optical axis ray (OAR). I is the angle of incidence of the OAR in the surface.

Table 4 Prescription data for the anamorphic TMA system using conic XY polynomials.

Surface	Radius (mm)	Thickness (mm)	Conic constant	I (deg)
1	–1225.5204	–347.6823	0.6858498	–21.00
2 (STOP)	–275.1711	284.7921	–6.141104	33.50
3	–398.8648	–308.2814	0.1530932	–14.0520
Image				–0.0579

Normalization radius for the Extended Polynomial Surface is 10.2219 mm.

Table 5 Aspheric terms for the anamorphic TMA system using conic XY polynomials.

Aspheric term	Surface 1	Surface 2	Surface 3
X2Y0	9.3595E-03	8.6230E-02	1.8359E-02
X2Y1	1.0437E-04	–2.6665E-04	1.8555E-04
X0Y3	8.4106E-05	–7.3792E-04	1.9609E-04
X4Y0	1.8767E-06	–3.7273E-04	6.9158E-06

Table 5 (*Continued*).

Aspheric term	Surface 1	Surface 2	Surface 3
X2Y2	3.0318E-06	−8.2252E-04	5.5138E-06
X0Y4	1.3303E-06	−4.8738E-04	−1.4581E-06
X4Y1	3.3532E-09	−8.9364E-07	5.3066E-08
X2Y3	6.6555E-10	−2.9645E-06	2.0630E-07
X0Y5	2.5963E-10	−2.2830E-06	1.2680E-07
X6Y0	3.2244E-10	1.1379E-06	3.9035E-09
X4Y2	-9.4287E-11	3.3140E-06	6.0852E-09
X2Y4	7.6266E-11	3.0617E-06	1.9053E-09
X0Y6	−2.9684E-11	1.5401E-06	−3.0299E-09
X6Y1	−4.7532E-11	−4.9315E-10	3.7342E-10
X4Y3	−5.7447E-11	−5.9452E-09	4.2452E-10
X2Y5	−2.7559E-11	−9.3540E-09	3.6792E-10
X0Y7	−6.5288E-12	−5.0252E-08	1.4544E-10
X8Y0	−1.8650E-12	−4.5705E-09	−1.6386E-12
X6Y2	1.5348E-12	−1.9755E-08	−2.8276E-12
X4Y4	6.6725E-13	−3.0161E-08	−6.7596E-13
X2Y6	8.4794E-13	−1.9144E-08	−1.0688E-11
X0Y8	4.7974E-13	−5.3076E-08	6.7887E-12
X8Y1	9.0850E-14	−8.9886E-12	−1.0168E-12
X6Y3	7.7050E-14	−2.8814E-11	−4.1221E-13
X4Y5	9.8711E-14	−4.7056E-11	1.4589E-13
X2Y7	2.6198E-14	−2.6682E-10	1.5707E-13
X0Y9	8.8660E-15	1.1602E-09	−5.9718E-15
X10Y0	4.1176E-15	9.9389E-12	1.3060E-14
X8Y2	−4.6621E-15	7.0517E-11	3.6596E-14
X6Y4	1.6353E-15	1.5697E-10	4.3928E-14
X4Y6	−3.2923E-15	9.8514E-11	−1.3712E-14
X2Y8	−1.3063E-15	2.4511E-11	1.6737E-14
X0Y10	−5.8164E-16	1.2124E-09	−2.0427E-14

References

1. D. Reshidko and J. Sasian, "Method for the design of nonaxially symmetric optical systems using free-form surfaces," *Opt. Eng.* **57**(10), 101704 (2018).
2. M. P. Chrisp, B. Primeau, and M. A. Echter, "Imaging freeform optical systems designed with NURBS surfaces," *Opt. Eng.* **55**(7), 071208 (2016).

Biographies of the authors are not available.