Imaging Freeform Optical Systems Designed with NURBS Surfaces

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Abstract. The designs of two imaging freeform systems using NURBS optical surfaces are described. The first system, a three-mirror anastigmat has six times higher spatial resolution over the image plane compared with the equivalent conventional design. Analyzing the mirror surface shapes for both designs shows that the average aspheric departures per surface are the same. Alignment tolerances are tighter for the freeform design to maintain the higher spatial resolution. In the second system, a Ritchey-Chretien telescope is corrected by a two-mirror freeform system, providing a telecentric exit pupil and meeting the spatial resolution requirements for a visible to mid-wave infrared imaging spectrometer. Both of these NURBS freeform designs are possible due to a custom optical design code for fast accurate NURBS optimization (FANO), and its advantages in designing freeform systems are presented.

Keywords: optical design, aspherics, NURBS, splines, geometrical design, optimization, reflective, anastigmat

1 Introduction

The imaging freeform optical systems described here are designed using non-uniform rational basis-spline (NURBS) surfaces. Although NURBS surfaces have been widely used for illumination systems, efforts to optimize them in imaging systems have so far been largely unsuccessful; as a consequence, the optical design community has considered them unsuitable for these systems[1]. The major optical design programs CODEV[2], Zemax[3], FRED[4] are not capable of optimizing NURBS grid type (u,v) surfaces in imaging systems, a necessary step in freeform optics design.

There is no problem with raytracing NURBS grid type surfaces, which can be accomplished in LightTools[2], FRED[4] and by Zeiss[5] with their in-house code, but to succeed in designing NURBS freeform optical systems an optimization code is required.

The motivation for developing the optical design code for fast accurate NURBS optimization (FANO)[6] is based on the mathematical properties of NURBS surfaces, which make them well-suited for representing freeform optical surfaces. The most important property of a

NURBS surface is the local control of the surface shape, because it is formed from piecewise splines. Figure 1 shows a third degree NURBS surface which is formed from cubic basis splines. The surface is defined by the set of grid control points with their weights, together with the knot vectors. The red and blue rays are only affected by the grid control points in the red and blue sections, because only the 16 closest grid control points affect the surface shape at the ray intersection. To change the direction of the blue ray, its 16 grid control points can be moved, leaving the red ray unchanged.

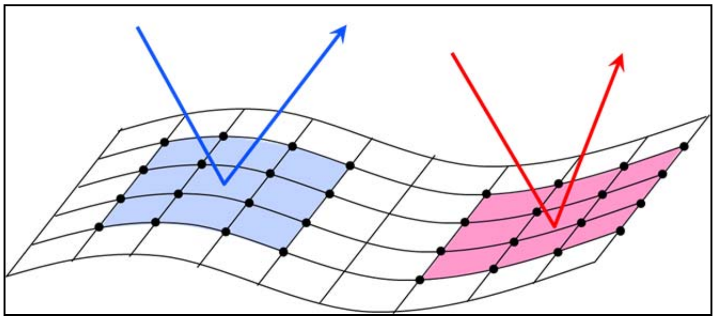


Figure 1 Rays reflecting from 3rd Degree NURBS surface.

This local control is important for more complex surfaces, which must be represented by thousands of grid control points, since each ray is still only affected by its local 16 grid control points. A consequence of this is that the matrices built from the control point variables are better conditioned for solving in the optimization.

This local ray control contrasts with a polynomial surface, where all the polynomial terms globally affect every point on the surface. As such, moving the blue ray in the example would require rebalancing all polynomial terms to leave the red ray pointing in the same direction.

NURBS surfaces also have a number of advantageous properties including the ability to perfectly represent plane and quadric surfaces, with mathematical details covered by Piegl and Tiller[7]. Compare this with Gaussian basis functions[8] where it is challenging to provide smooth plane and quadric surfaces.

2 Fast Accurate NURBS Optimization (FANO) Design Code

The FANO design code has a fast raytrace engine using optimization algorithms, designed for NURBS surfaces, with the numerical accuracy for large numbers of variables and rays. The freeform designs here typically use 2000 grid point variables and 9000 rays. FANO is written in C for portability and uses the Intel Math Kernel library for manipulation of the large matrices. Although capable of supporting different degree surfaces, all the results shown in this study are with third degree NURBS freeform surfaces. Given the large numbers of rays, FANO was designed from the outset for a fast raytrace speed. It can trace 1.25 million NURBS ray surfaces/second, 500 times faster than the commercial illumination code against which it was compared.

FANO avoids the limitations found in current optical design codes for even simple rotational NURBS surfaces[9,10], perhaps because commercial codes are designed to optimize standard optical systems with much smaller numbers of variables and rays, and with algorithms written for speed rather than precision. No success has been reported with any of the current optical design codes in optimizing imaging systems with NURBS freeform surfaces programmed into them.

FANO's structure and communication with other programs is shown in Figure 2. From CODEV, simple starting designs can be imported in the form of point clouds, which are converted to NURBS surfaces. Typically a regularly-spaced NURBS grid is used with the parameterization for the two knot vectors based on the average chord lengths over the surface. There is no export to CODEV since it cannot raytrace NURBS grid surfaces.

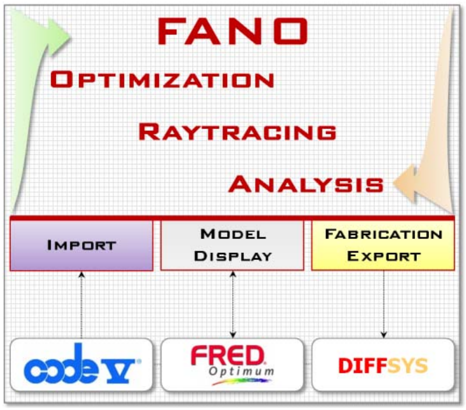


Figure 2 Fast accurate NURBS optimization program (FANO).

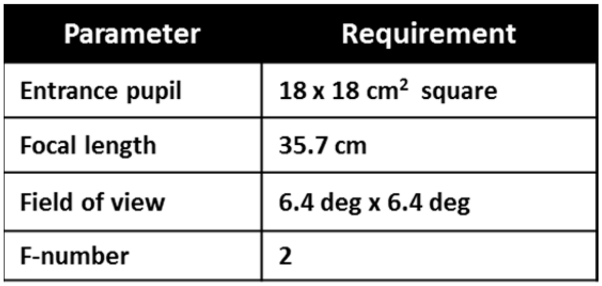
FRED can raytrace NURBS surfaces, so the file exchange takes place in two directions. FRED scripts enable the export of the NURBS surfaces and geometry to FANO, which reads in the NURBS parameters directly with no conversion necessary. In a similar manner FANO can write the same file format to FRED, which is used to confirm all analysis results and to display the resulting designs, such as the figures in this paper. FRED does have a simplex optimization, which is very limited and not suitable for large NURBS optimization problems.

The final software package DIFFSYS[11] is used for controlling Lincoln Laboratory's diamond-turning machine, a Moore Nanotech 350FG[12], which can directly diamond-turn freeform surfaces. A subroutine in FANO exports a point cloud in the correct format for import into the DIFFSYS software. DIFFSYS takes the point cloud and fits a surface to the points that the diamond tool will follow. One nice feature of DIFFSYS is that the sagittal position of any point on the interpolated surface can be output, enabling the error to be calculated from the original NURBS surface. Currently the diamond-turning machines by Moore[12] and Precitech[13] cannot accept direct NURBS input; however, Schneider Optical Machines[14] freeform diamond-turning machine UPC 400 can accept NURBS surfaces directly.

3 Freeform f/2 Three-Mirror Anastigmat Design

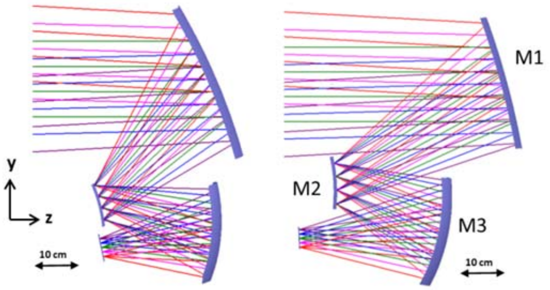
The following designs show the performance improvement made by using NURBS freeform surfaces in an f/2 three-mirror anastigmat design, with the design parameters given in Table 1. For comparison, two designs meeting the optical requirements have been created with the stop at the secondary. The conventional aspheric design is optimized in CODEV and used tilted and decentered rotational aspheric surfaces with aspheric terms up to the 14th power. The NURBS freeform design is optimized by FANO with grids of 23 x 23 for the mirror M1, 19 x 19 for mirror M2, and 29 x 29 for mirror M3.

Table 1 Three mirror anastigmat design parameters.



Parameter	Requirement
Entrance pupil	18 x 18 cm^2 square
Focal length	35.7 cm
Field of view	6.4 deg x 6.4 deg
F-number	2

The two designs are shown to the same scale in Figure 3. The same package volume was available to both design forms, implemented by letting the spaces vary, with just outer bounds on the chief ray distances between the mirrors and ray clearances controlling the mirror angles. Although the spacings between the mirrors in the NURBS design is larger in some cases, forcing the conventional design to match those spacings reduces its performance. During optimization the average geometric r.m.s. spot size is used as the merit function.

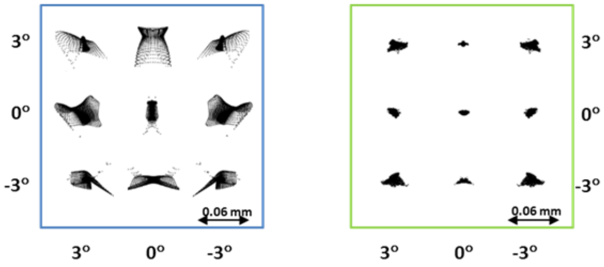


a) Rotational aspheres design

b) NURBS freeform design

Figure 3 Three mirror anastigmat f/2 designs.

The stop size was left as variable during optimization, but set to coincide with the secondary mirror. It is interesting to note that whereas in the NURBS design the primary mirror tilts to minimize the entrance beam clearance from the secondary mirror, in the conventional asphere design the beam needs to be further away from the secondary mirror to balance the tilted and decentered tertiary. The NURBS freeform design is optimized and analyzed in FANO, while using FRED for confirmation of the analysis and to display the design.



a) Rotational aspheres design

b) NURBS freeform design

Figure 4 Spot diagram comparison between designs.

The spot diagrams given in Figure 4 show the change in the aberration types between the two designs. Then in Figure 5 the r.m.s. spot sizes are mapped out over the field of view, showing the improved performance with the NURBS freeform surfaces. The average r.m.s. spot size for the conventional aspheric design is 25 microns; for the NURBS design it is 4 microns, a factor of six improvement. The NURBS design also has less variation in the r.m.s. spot size over the field of view.

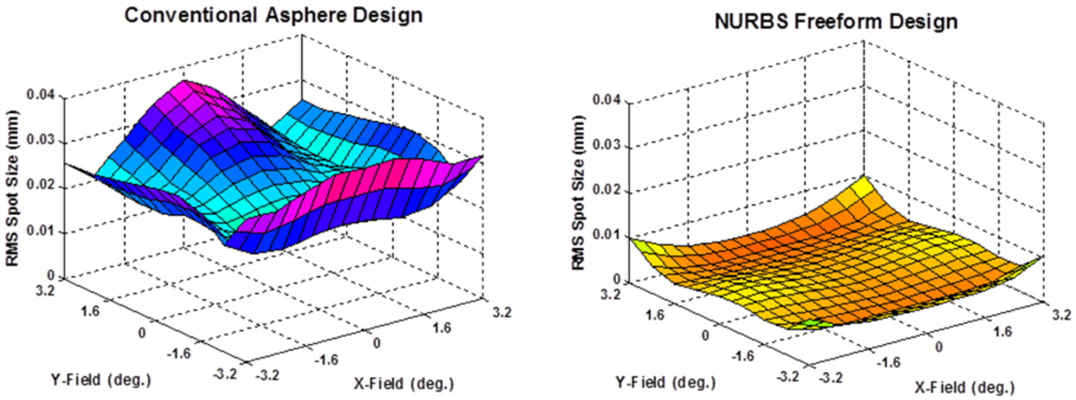
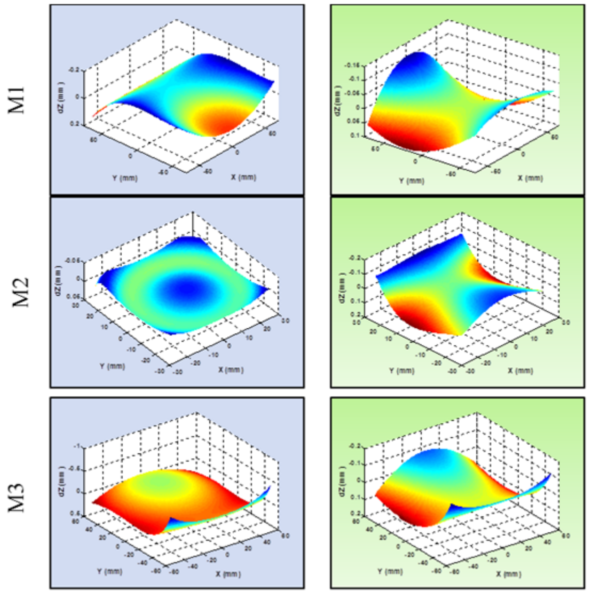


Figure 5 Field map of r.m.s. spot sizes for f/2 three mirror anastigmat designs.

3.1. Mirror Aspheric Shapes

Given the significant performance improvement, the question is how the aspheric shapes differ between the conventional aspheric design and the NURBS freeform design. This is analyzed by subtracting the best fit sphere from each surface and mapping out the aspheric deviation of the surfaces from the best fit sphere. Figure 6 illustrates the aspheric shapes for the mirrors in the two designs.



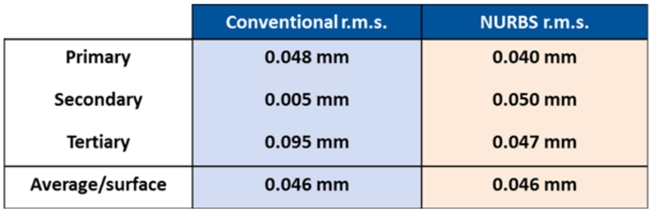
a) Rotational aspheres design

b) NURBS freeform design

Figure 6 Comparing mirror aspheric shapes.

Some interesting differences between the mirror shapes can be seen. For the primary mirror M1, the freeform design has the opposite astigmatic sign compared with the rotational aspheric design. For the secondary mirror M2, the freeform design has an astigmatic secondary, whereas there is a slight amount of spherical aberration correction in the rotational aspheric design.

Table 2 Average r.m.s. aspheric departures of the mirror surfaces.



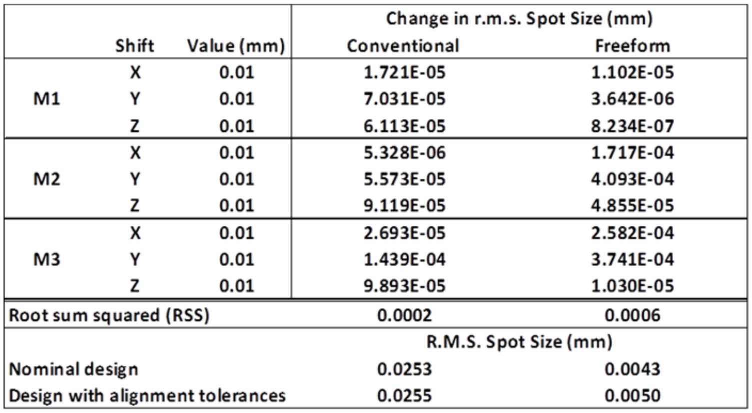
	Conventional r.m.s.	NURBS r.m.s.
Primary	0.048 mm	0.040 mm
Secondary	0.005 mm	0.050 mm
Tertiary	0.095 mm	0.047 mm
Average/surface	0.046 mm	0.046 mm

The power of the aspherics can be assessed from the average r.m.s. aspheric deviations from their best fit spheres, which are given in Table 2. Note that the average value per surface is the same for both designs, even though the NURBS freeform design does not have any constraints on the grid points limiting their aspheric powers. The improved performance is from having better aspheric shapes for the surfaces, and having even amount of aspheric contribution per surface.

3.2. Alignment Sensitivity Comparison

An initial tolerance sensitivity performed on both designs established the difficulty of aligning the higher-resolution freeform design. The results are shown in Table 3 which gives the change in the average r.m.s. spot size over the field for the mirror translations, according the coordinate axes drawn on Figure 3.

Table 3Alignment tolerance comparison.



			Change in r.m.s. Spot Size (mm)	
	Shift	Value (mm)	Conventional	Freeform
M1	X	0.01	1.721E-05	1.102E-05
	Y	0.01	7.031E-05	3.642E-06
	Z	0.01	6.113E-05	8.234E-07
M2	X	0.01	5.328E-06	1.717E-04
	Y	0.01	5.573E-05	4.093E-04
	Z	0.01	9.119E-05	4.855E-05
M3	X	0.01	2.693E-05	2.582E-04
	Y	0.01	1.439E-04	3.741E-04
	Z	0.01	9.893E-05	1.030E-05
Root sum squared (RSS)			0.0002	0.0006
			R.M.S. Spot Size (mm)	
Nominal design			0.0253	0.0043
Design with alignment tolerances			0.0255	0.0050

Each mirror is moved with a local shift, leaving the global coordinates of the other mirrors in the same place. The detector plane is used as a compensator, with its longitudinal z-position, and two tilts optimized to minimize the effect of the aberrations for each movement. For the freeform system, the decentrations of mirrors M2 and M3 introduce the largest changes in the spot size.

The root sum squared (RSS) of the individual aberrations gives their cumulative change of the r.m.s. average spot size. Adding this change to the nominal design performance (found at the bottom of the table) leads to the expected performance if the mirror translations match the 0.010 mm displacement. The increase in the r.m.s. spot size for the freeform design is a 16% increase, compared with an increase of 0.7% for the conventional aspheric design.

3.3. Freeform Telescope Demonstration

To demonstrate this freeform three-mirror anastigmat design, a half-size version is being constructed with aluminum structure and mirrors, the optomechanical design of which is shown in Figure 7. The mirrors are held on alignment fixtures to move them in six degrees of freedom during the alignment process, after which they are mounted to the structure with shims for the finished assembly. Diamond-turned fiducials on the mirrors aid in the optomechanical alignment and verification of the clocking of the freeform surfaces after generation. Mechanical structures and diamond-turned references are also accessible on the mirror feet, and can be measured without opening the optical assembly. The necessary baffles to eliminate the stray light paths within the optical system have been incorporated, although the extra front baffle is not shown in the figure.

One advantage of NURBS surfaces is their accuracy for transferring designs from the FANO optical program to Solidworks[17]. Tests show that measurement sample points on the imported cad optical surfaces in Solidworks are within ±30 pm of the corresponding sample points on the optical surfaces in FANO. The NURBS surfaces also enabled model based 5-axis machining of the mirrors without any orientation errors.

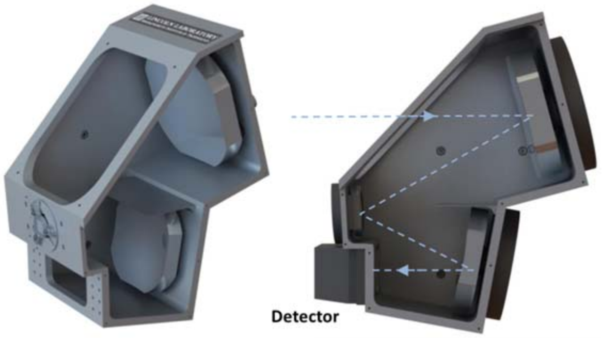


Figure 7 Optomechanical design of the freeform demonstration telescope.

Lessons learned so far have led to the emphasis of fiducials on the mirrors for checking the orientation of the freeform surfaces after diamond-turning. For importing the design into Solidworks, it was found best to import each NURBS surface separately into an optical assembly file so that the local coordinate systems for the gird points were the same between the FANO, FRED, and Solidworks models. For the diamond-turning only, being able to import point clouds leaves the process open to error since the visualization just shows the surface without the rest of the mirror structure. It is very easy to end up with the freeform surface improperly clocked on the part if not verified.

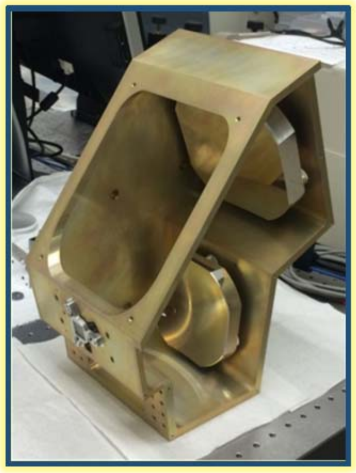


Figure 8 Freeform telescope demonstration.

For the hardware, the optical bench is assembled with the initial diamond-turned bare aluminum mirrors, as shown in Figure 8. The mirrors are checked by the use of computer-generated holograms (CGH) which help to identify any significant errors such as clocking or improper machine programming of the freeform surfaces. Initial tests of the completed assembly show the expected performance, given the figure errors of a few waves on the diamond-turned surfaces. The next stage is to have the mirrors electroless nickel-plated and figured using magnetorheological finishing (MRF), based on the measurements using the computer-generated holograms and subaperture stitching interferometry. These precise mirrors will then be aligned in the final assembly, using interferometry and computer-aided alignment techniques.

4 Freeform Correction of an f/3 Ritchey-Chretien Telescope.

In this design, freeform mirrors are used to improve the performance of a Ritchey-Chretien telescope, flattening and widening the field of view for use with an imaging spectrometer. The imaging spectrometer requires a telecentric entrance beam at its entrance slit from the telescope and covers the wavelength range from the visible to the mid-wave infrared, with the requirements summarized in Table 4. Using a reflective corrector after the telescope has the advantage that the small freeform mirrors can be easily manufactured utilizing MRF processes.

Table 4 Ritchey-Chretien Telescope Design Parameters.

Parameter	Requirement
Entrance Pupil Diameter	60.00 cm
f-number	3.00
Focal length	180.00 cm
Slit field of view	2 degrees cross track
Slit image length	~ 60 mm
Exit pupil	Telecentric
Wavelength range	400 to 5000 nm

The reflective corrector after the telescope needs to correct the aberrations of the telescope and flatten its field over the entrance slit to the spectrometer, while meeting the telecentric requirement. Fortunately, an all-reflective corrector avoids the issues of chromatic aberration, which are severe for a refractive corrector over this wavelength range, especially as the transverse color should be less than one-tenth of a pixel. Raytraces of the design are shown in Figure 9; here the telescope is followed by a two-mirror NURBS freeform mirror corrector.

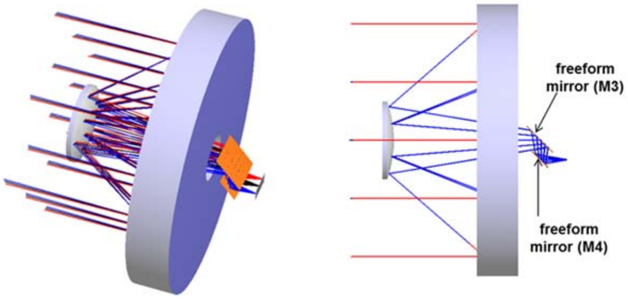


Figure 9 Ritchey-Chretien telescope with a two mirror freeform corrector.

This freeform corrector is in an interesting design space, where the beam diameters from each field point are small on the freeform surface, leveraging the ability of NURBS freeform surfaces to model complex aspheric shapes. This is illustrated by the mirrors shapes from optimizing the NURBS freeform design shown Figure 10, where M3 is based on a 25x25 grid points and M4 on a 21 x 35 grid points. The mirrors in appearance look like cylinders, but the aspheric deviations from Best Fit spheres show the complexity of the aspheric shapes. Plus, the aspheric departures from the best fit spheres are much larger than in the previous design, with a peak to valley departures of 0.8 mm for M3 and 1.2 mm for M4.

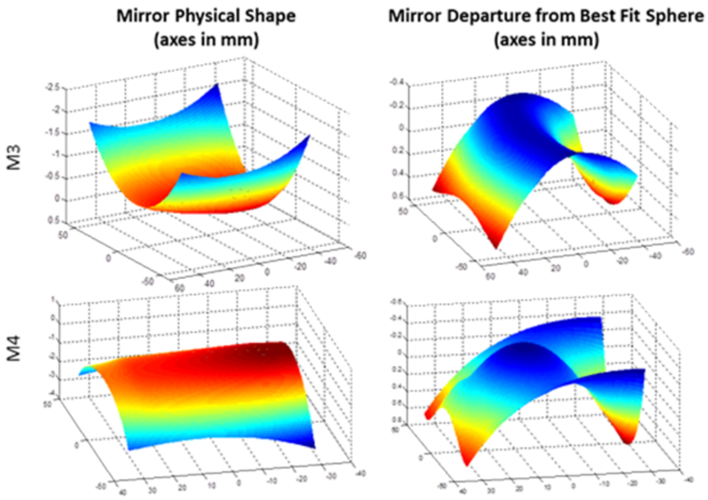


Figure 10 Mirror physical shapes and aspheric departures.

The performance of the telescope by itself and with the two-mirror freeform corrector is shown in Figure 11. The telescope by itself has an average r.m.s. spot diameter over the field of view of 380 microns, with the freeform corrector reducing this spot size to an average of 11 microns, while maintaining the advantages of an all-reflective optical system.

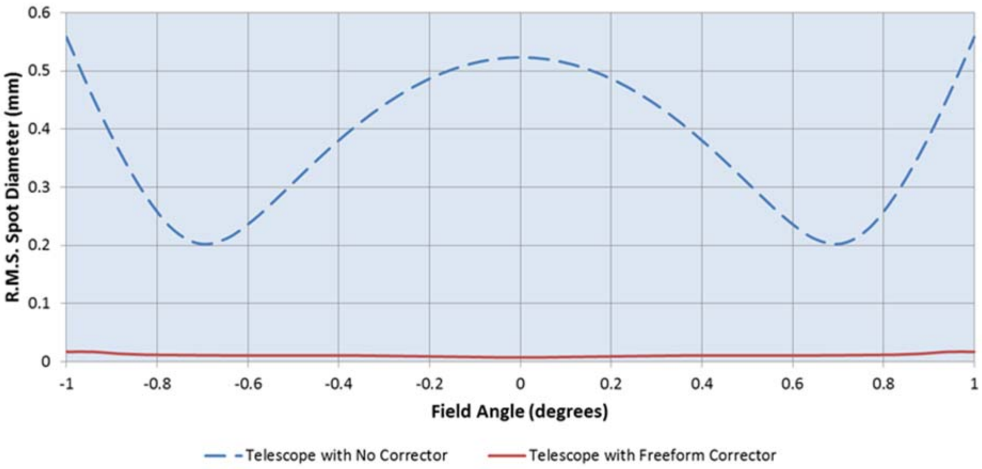


Figure 11 R.M.S. spot diameters over the field of view.

5 Conclusion

Designed with the FANO program, the two imaging freeform systems show the performance advantages from using NURBS mirror surfaces. For the f/2 three-mirror anastigmat, the spatial resolution improves by a factor of six over the field of view compared with a conventional aspheric design. Surprisingly the overall asphericity is similar to that of the conventional aspheric design, and the performance improvements are due to the aspheric shapes. For the f/3 Ritchey-Chretien telescope, the two-mirror freeform corrector reduces the 2 degree field averaged 380 micron spot size of the telescope to less than 11 microns, and provides a telecentric exit pupil for the imaging spectrometer. This all-reflective corrector design opens up new possibilities for large telescopes.

As freeform surfaces increase in aspheric complexity, NURBS surfaces will provide the way forward in freeform design, due to their local surface control and their ease of optimization with thousands of grid control points.

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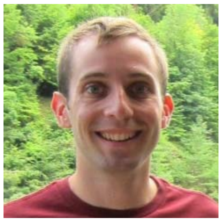

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Caption List

Fig. 1 Rays reflecting from 3rd Degree NURBS surface.

Fig. 2 Fast accurate NURBS optimization program (FANO).

Fig. 3 Three mirror anastigmat f/2 designs.

Fig. 4 Spot diagram comparison between designs.

Fig. 5 Field map of r.m.s. spot sizes for f/2 three mirror anastigmat designs.

Fig. 6 Comparing mirror aspheric shapes.

Fig. 7 Optomechanical design of the freeform demonstration telescope.

Fig. 8 Freeform telescope demonstration

Fig. 9 Ritchey-Chretien telescope with a two mirror freeform corrector.

Fig. 10 Mirror physical shapes and aspheric departures.

Fig. 11 R.M.S. Spot diameters over the field of view.

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