Designing objectives with recurring surfaces

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Abstract

Creating an optical surface with loose abrasive blocking and grinding technique requires two spherical surface blocks per surface. Manufacturing these blocks can cost up to 5000€ per surface, drastically increasing the initial prototyping costs. This white paper introduces an optical design approach aimed at reducing the amount of necessary block pairs by defining the minimum amount of free surfaces required and reusing them throughout the optical system. Two optical design examples that employ the minimum amount of block pairs are presented.

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1 Introduction

Grinding optical surfaces with block and grinding technique is a very effective method for mass-producing high-quality and large diameter optics with glass, carbon or metal materials. This technique requires a pair of spherical surface tools or block plates, called a grinding block and a mounting block with equal but inverse curvatures machined into them.

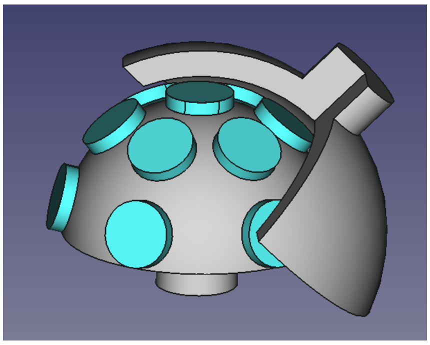

Figure 1: A convex mounting block with lens blanks attached. Above them is a section cut of the grinding block that grinds the curvature into one side of the lens blanks. Another block pair is needed for a different curvature.

1.1 Manufacturing the grinding block

The desired curvature can be manufactured into a block with CNC technology, as well as the inverse curvature block. The two blocks are then grinded against each other (using a grinding powder such as Cerium Oxide) in circular motions to smooth out any irregularities and to fine tune the curvature, which is then verified with a spherometer, a profilometer or equivalent measuring instrument.

Both blocks end up in perfectly usable condition for grinding a spherical surface to a glass blank, but only one block is used for the shaping. The inverse curvature block is used for mounting the lens blanks.

1.2 A block pair for each surface

A single surface requires both blocks, so a single custom lens with two curvatures requires four blocks to be manufactured. Similarly, each additional lens in the system that has unique curvatures requires up to four blocks. The cost of the blocks impacts budget at the prototyping stage and in every consequtive change to the curvatures. At the mass production phase, the costs from the blocks have a lesser impact, save for occasional maintenance costs from wear-and-tear.

An often used solution is to use equi-curved or plano-curved components, with a shape factor $S = \pm 1, 0$. Although using these shapes is also good for prototyping and tolerancing, it is not straightforward to achieve good aberration control with such rigid shape constraints.

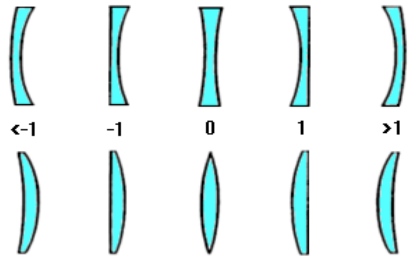

Figure 2: Shape factors S. While one block pair is capable of creating four different shapes, two block pairs are capable of creating six. With orientation included, total of ten shapes.

2 Recurring Surface Objectives RSO's

A recurring surface objective is an objective that uses (minimum of) two radii. The other surfaces all repeat the two radii or their inverse values. Glass material may freely vary.

2.1 Two block pairs for multiple shapes

Using the same block for a single component will result in a plano-curved or equi-shaped lens, both which would be acceptable shapes. Using both blocks of the same pair for grinding would result in a dome-shaped, zero power glass window, which would be optically unusable. In order to achieve shape factor $|S| > 1$, another block pair needs to be manufactured.

For our case study, our RSO's reuses two grinding blocks for as many lenses as possible, and also their mounting blocks as additional grinding blocks. This creates ten lens shapes for better aberration control.

Although shapes $S = \pm 1$ are available, our case studies avoids using them due to issues involved. Refer to discussion in chapter 4 on how best to handle flat surfaces in optical design.

The aberration control is handled more effectively with the additional shapes, though still lacking somewhat. Additional aberration control is achieved through glass material optimization. Varied indices of refraction affect surface shapes and therefore angles of incidence via fixed focal lengths. The aberration optimization through glass material still attempts to control also chromatic aberration in the following examples.

2.2 Methods for RSO

Optical design for an RSO begins with a fully optimized, custom curvature design. A completed design is needed for defining the configuration which already has a solution of acceptable quality. Transforming the custom radii into a set of few free radii and their inverse values requires cycles of optimization with a set of merit function (MF) restrictions chosen in such a way that they won't restrict the optimization of radii too much, but would still keep the design in the vicinity of a known solution. Radii are constrained one at a time between optimization cycles.

2.2.1 Broad range restrictions

Merit function restrictions are needed to contain the optimizations within the general area of the known solution. As thicknesses (and initially radii) are set as variables, these cannot be restricted individually (except for physical boundaries). Instead, a target of restriction should be chosen to contain within itself several variables (some radii, thickness, glass material), such as focal length of a lens group, or ratios of focal lengths of several groups. This would allow greater freedom for the optimization to find suitable radii but still keep the new solution close to the known one.

Multiple unrelated restrictions may be used. These could include keeping the last surface as a convex to avoid ghosting, preventing optimization from including meniscus lenses, containing track length or back focal length, keeping the relative glass cost below certain value, etc.

Initially, a restriction and it's error limits (for flexibility) should be chosen so that it would not have any kind of impact on the merit function value of the known solution. The restrictions should also be carefully crafted to avoid any overlapping with other restrictions, including the default merit function. System defining restrictions (such as system focal length) should be limited to one (or as few as possible) with a small weight factor for flexibility.

Although several glass materials will be considered, some of the glass materials will be optimized for correcting aberrations other than chromatic. Therefore optimization wavelengths should be limited to achromatic correction (or minimum possible). Chromatic correction uses Abbe numbers and partial dispersion values more than indices of refraction, so even if just an achromatic correction is specified, this would not exclude chromatic corrections for more than two wavelengths from appearing in the new solutions.

2.2.2 Optimizing after each small change

The tranformation of radii occurs in a repetitive sequence. After a suitable MF restriction is put in place, one radius is chosen as the first variable, and another radius with a value suitably close to it is linked to it using a pickup solve. System is then optimized, with the MF restrictions making sure the optimization won't differ from the original solution too much. If the MF deterioration is deemed acceptable, a second free radius is chosen as the second variable and a new radius close enough to it linked with a pickup solve. System is again optimized and evaluated.

The order of linking is determined by how much the MF deteriorates by the linking and whether the designer deems the system to be capable of recovering from the said deterioration during the next optimization cycle.

Eventually the MF is deemed to have deteriorated to unrecoverable levels. In those cases, DLS optimization can be replaced with either Hammer or Global optimization in order to use glass material optimization to consider the indices of refraction for generic aberration control as well. As long as chromatic aberration isn't too tightly controlled, this brings more freedoms to the optimization cycles without affecting the linked radii.

During the optimization, generic optical design techniques can be utilized normally at any step. Lens splitting/joining can bring differing radii closer to the chosen radius. Reversing an element (or a group of elements) or gluing can make surfaces meet the incident rays without affecting the linking.

2.3 Example: RSO 1 with fast relative aperture

RSO 1 (fig. 3) is a fast, infinity corrected, narrow-field objective. It contains six spherical surface lenses in a reverse telephoto configuration. There are two free curvatures, and the remaining surfaces either reuse those two or their inverse curvatures. RSO 1 has four distinct surface curvatures and uses four different glass materials from preferred Schott catalogue (with an average relative cost of 10). There are no planar surfaces.

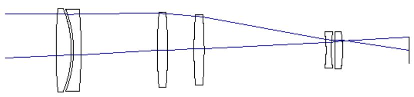

Figure 3: Layout of RSO 1: f=100 mm and a relative aperture F/3.5. Full field of view is 3°.

2.3.1 Optical analysis of RSO 1

Due to the objective having a fast relative aperture, lower-order aberrations are accompanied by higher-order aberrations, which cannot be fully corrected, but instead balanced against induced lower-order aberrations. The inflections from the balancing are prominent in the F and C lines of the ray fan plot (fig. 4) and longitudinal aberration plot (fig. 5).

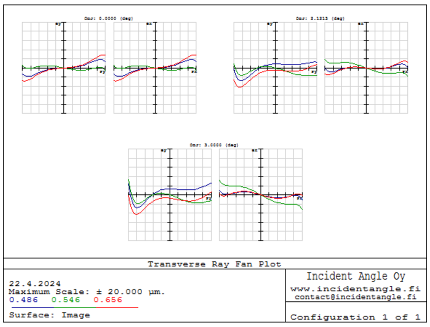

Figure 4: Ray fan plot of the F, d and C lines, with d showing a degree of undercorrection.

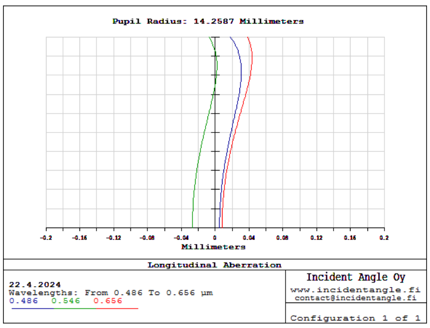

Figure 5: Longitudinal aberration.

Field curvature (fig. 6) is slightly concave, with the best image plane at the medial curvature between the tangential and sagittal curvatures. The Petzval radius is $-2.4f$, which can provide a reasonably flat field.

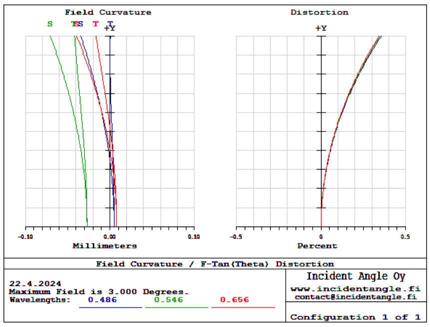

Figure 6: Field curvature and distortion.

Wavefront error (fig. 7) doesn't fluctuate and stays below $\frac{1}{6}\lambda$ within the inner half of the pupil area.

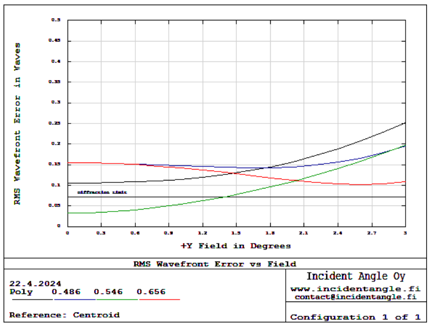

Figure 7: Wavefront error through the field.

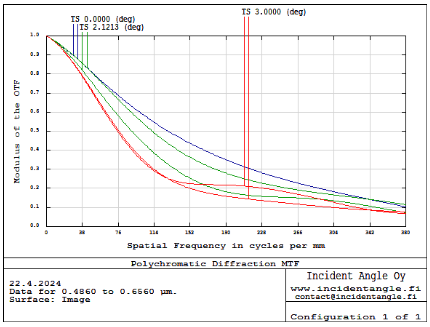

Figure 8: Polychromatic diffraction MTF.

Fig. 8 shows the polychromatic diffraction MTF curves. With illumination and sensors pixel size larger than 1.6 µm, the resolution is limited by the sensors Nyquist frequency alone.

2.4 Example: RSO 2 with wide field of view

RSO 2 (fig. 9) is a short focal length, infinity corrected, wide-field application of the concept. Like RSO 1, it contains six lenses in a similar reverse telephoto configuration, with similarly two free curvatures and the rest reusing them or their inverse curvatures. Layout uses four different glasses from preferred Schott catalogue. Average relative glass cost is less than 3. Similarly to RSO 1, RSO 2 has four distinct surface curvatures and no planar surfaces.

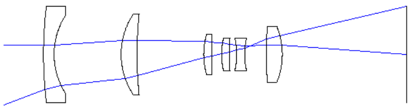

Figure 9: Layout of RSO 2: f=16.7 mm and a relative aperture F/7. Full field of view is 40°.

2.4.1 Optical analysis of RSO 2

Having a slower relative aperture, the RSO 2 shows much improved aberration control (fig. 10) than RSO 1. This can be attributed to the lack of higher-order aberrations and therefore more effective correction of lower-order aberrations.

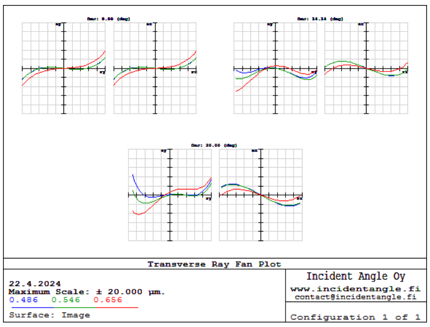

Figure 10: Ray fan plot of the F, d and C lines.

Whereas RSO 1 is well corrected between d and C lines, the RSO 2 corrects for F and d lines, which can give a reddish hue to the focused images (fig. 11).

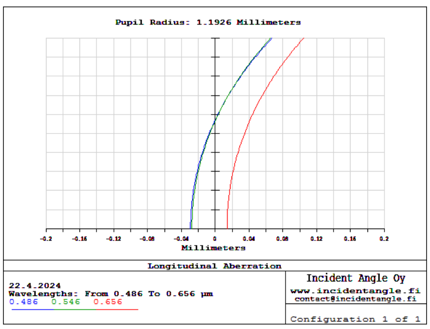

Figure 11: Longitudinal aberrations for F, d and C lines.

Due to wider field, the tangential and sagittal field curvatures (fig. 12) deviate at the edges more than RSO 1, but their curves show well-balanced median field curvature near the image plane. Also due to the wider field, distortion is more pronounced at the edges, but nevertheless comparable with RSO 1's smaller field of view. Petzval radius is $-4.1f$.

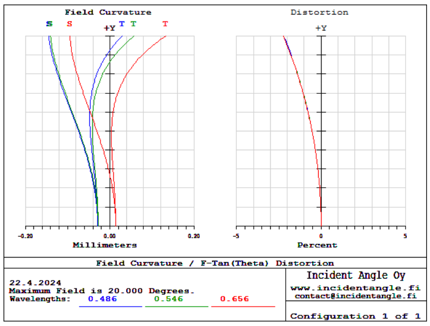

Figure 12: Field curvature and distortion.

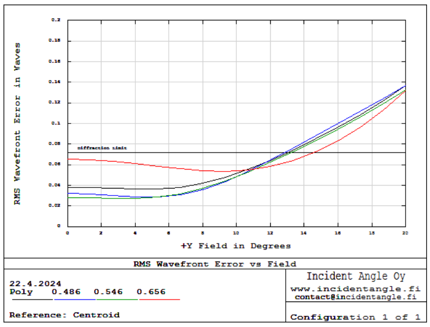

Figure 13: Wavefront error through the field.

The far superior wavefront error (fig. 13) compared to RSO 1 is due to slower relative aperture and the lack of higher-order aberrations that follows. The resolution capabilities (fig. 14) of RSO 2 is roughly half compared to RSO 1.

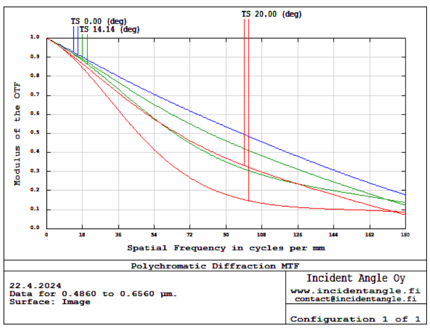

Figure 14: Polychromatic diffraction MTF.

3 Conclusion

Described here is an optical design principle[1] that cuts down prototyping costs for custom lens designs by reusing mounting blocks as grinding blocks: instead of maximum two block pairs per lens, just two pairs are needed for the whole system. The limitations from the lens shapes are mediated using varied glass materials and traditional optical design techniques. The image plane optical analysis shows that these mediations do not necessarily result in an inferior optical quality of the system, and the two examples show the versatility of the method.

The principle requires the blocks to be interchangeable in the milling machine.

4 Discussion

Included in the ten shapes available with two block pairs are flat surfaces for shapes $S = \pm 1$, which must be created using a flat block. Manufacture of such block is beyond this paper but would traditionally involve three blocks instead of two. In any case, such a block should already be at the disposal of an established manufacturer and therefore would not require manufacturing. However, the examples discussed here do not employ those, demonstrating that they can be avoided. If necessary, flats can be substituted with a very large radius convex blocks that may already be at the disposal of the manufacturer, without affecting the system performance or the need to build extra blocks. The optical axis of a curved surface can be centered to the mechanical axis of a mount (that is in contact with the optical surface) far more reliably than a planar surface.

If designed using knowledge of manufacturers existing available block shapes, initial prototyping costs could be reduced down to glass material costs and labour. Similarly, instead of reusing one of the designed free curvatures, a non-free surface in the configuration can opt to reuse manufacturers existing block shapes instead, adding shapes for better aberration control.

[1] Derived from Mikš, "One-radius triplets", Applied Optics Vol.41, No.7, 2002.