Image contrast of a 36 mm f/2 imaging lens with imposed group tilts

Eleven-lens objective of patent US 8,879,901 [1], three lens groups, 12 variants, polychromatic MTF at 50 cycles/mm

Application

A tolerance analysis starts from an image quality budget and returns the tilt that each lens group may take. The opposite question is just as common during assembly: the mount holds a group to a few arcminutes, so how much contrast does the image lose? This note imposes group tilts on an imaging lens and reads the image quality of each variant.

Modelling approach

The lens was split into three groups. Each variant tilts one or two groups about the front vertex of their first lens, and leaves every lens prescription and the image plane unchanged. The polychromatic MTF was computed at seven field points, in +Y, −Y and ±X, because a tilt breaks the rotational symmetry of the lens.

1 The lens and its groups

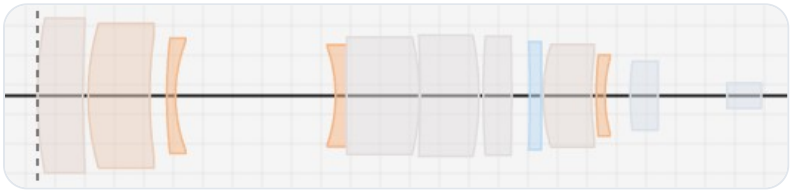


Figure 1. The lens as modelled: from left to right, the front group (three lenses), the stop, the rear group (the cemented doublet and six lenses) and the plane-parallel plate. **Table 1.** Main parameters and the three groups.

PARAMETER	VALUE
Focal length, aperture	36.0 mm, f/2.0
Half field	10.82°
Wavelengths	486.1, 587.6, 656.3 nm
Front group	L1 to L3, before the stop
Rear group	L4 to L11, after the stop
Doublet	L4-L5, inside the rear group

2 Contrast lost with each imposed tilt

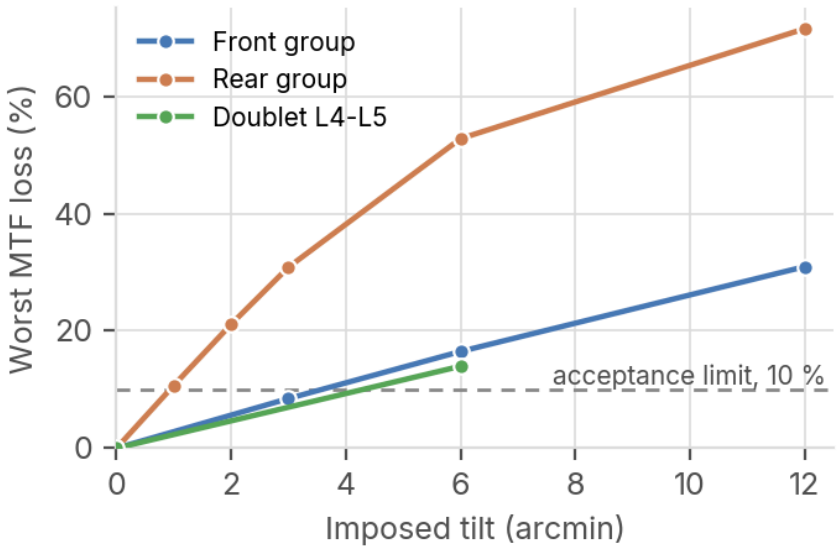


Figure 2. The largest loss of contrast over the seven field points and both orientations, at 50 cycles/mm, against the tilt imposed on one group. The dashed line is the acceptance limit of this study.

0.9′

Rear-group tilt at which the worst field point loses 10 % of its contrast. The front group reaches the same loss at 3.6′.

−31 %

Contrast lost at −10.8° Y when the rear group tilts by 3′, a tolerance often used for a lens element [2]: from 0.35 to 0.24.

8 µm per arcmin

Image shift on axis for each arcminute of rear-group tilt. The front group moves the image by 2 µm per arcminute.

Where the contrast goes, and what the mount must hold

A tilted group tilts the image surface: one edge of the field gains contrast, the opposite edge loses it.

Table 2. Worst MTF of each variant, and image shift on axis

Variant	Worst MTF (nominal)	Loss (%)	Image shift (µm)	Within 10 %
Front 3′	0.32 (0.35)	8	+6	pass
Front 6′	0.29 (0.35)	16	+12	fail
Front 12′	0.24 (0.35)	31	+25	fail
Rear 1′	0.31 (0.35)	11	-8	fail
Rear 2′	0.27 (0.35)	21	-17	fail
Rear 3′	0.24 (0.35)	31	-25	fail
Rear 6′	0.16 (0.35)	53	-50	fail
Rear 12′	0.10 (0.35)	72	-101	fail
Doublet 6′	0.45 (0.52)	14	-7	fail
Front +6′, rear −6′	0.20 (0.35)	41	+63	fail
Front +6′, rear +6′	0.14 (0.35)	60	-38	fail

MTF at 50 cycles/mm. The worst point is −10.8° Y, sagittal, except for Doublet 6′ (+10.8° Y, tangential) and Front +6′, rear −6′ (+10.8° Y, sagittal). The image shift is the position of the chief ray of the axial field on the image plane, at 587.6 nm.

Limits of the study. Tilts are about X only, without decentre or refocusing; the MTF is read at a single frequency; the 10 % limit and the 5 µm pixel are choices of this study, not values published for this lens.

Why one edge loses

A tilted group tilts the image surface. One edge of the field moves towards best focus and gains contrast; the opposite edge moves away and loses it (Figure 3). The axis does not change. The field point at −10.8° Y, already the weakest of the nominal lens in sagittal, sets the verdict of almost every variant.

What the mount must hold

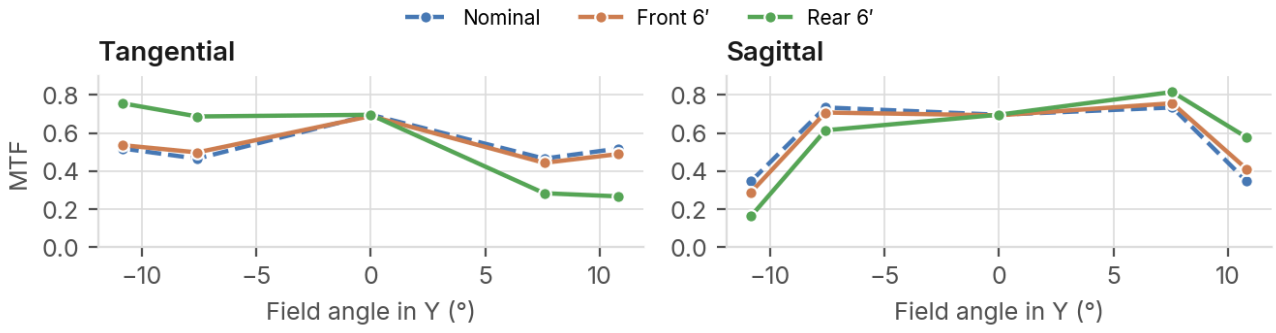
The front group stays within the limit up to about 3.6′, so a 3′ mount tolerance [2] is enough. The rear group exceeds it at 1′ and reaches it at about 0.9′. It needs a tighter mount, or an adjustment of its tilt during assembly, as proposed for the camera of [3].

For the doublet alone, the limit is about 4.3′, a linear estimate from a single tilt of 6′.

Combining tilts

Tilting both groups does not compensate. With opposite tilts of 6′, the image shifts by +63 µm and loses 41 %. With tilts in the same direction, the shifts partly cancel (-38 µm), but the contrast loss grows to 60 %.

Figure 3. MTF across the field in Y, nominal lens and 6′ group tilts



The rear-group tilt raises the contrast at one edge of the field and lowers it at the other; the front-group tilt does the same, about four times less.

In etendue

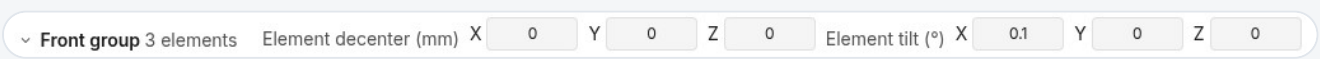


Figure 4. The front group in the surface table, variant « Front 6′ »: the group carries its element tilt, its lenses keep their values. Table view: Add a group, tick its lenses; type the tilt on the group header in each variant tab; run the MTF analysis on all variants.

References. [1] US 8,879,901. [2] S. Nam, tolerance analysis of a small camera lens, OPTI 521 report, College of Optical Sciences, University of Arizona. [3] E. Oliva et al., Concept and optical design of the cross-disperser module for CRIRES+, arXiv:1407.3057 (2014). [4] G. D. Boreman, Modulation Transfer Function in Optical and Electro-Optical Systems, SPIE Press (2001).

MTF from the FFT of the pupil function, polychromatic, equal weights; Nyquist = 1 / (2 · pixel pitch) [4].