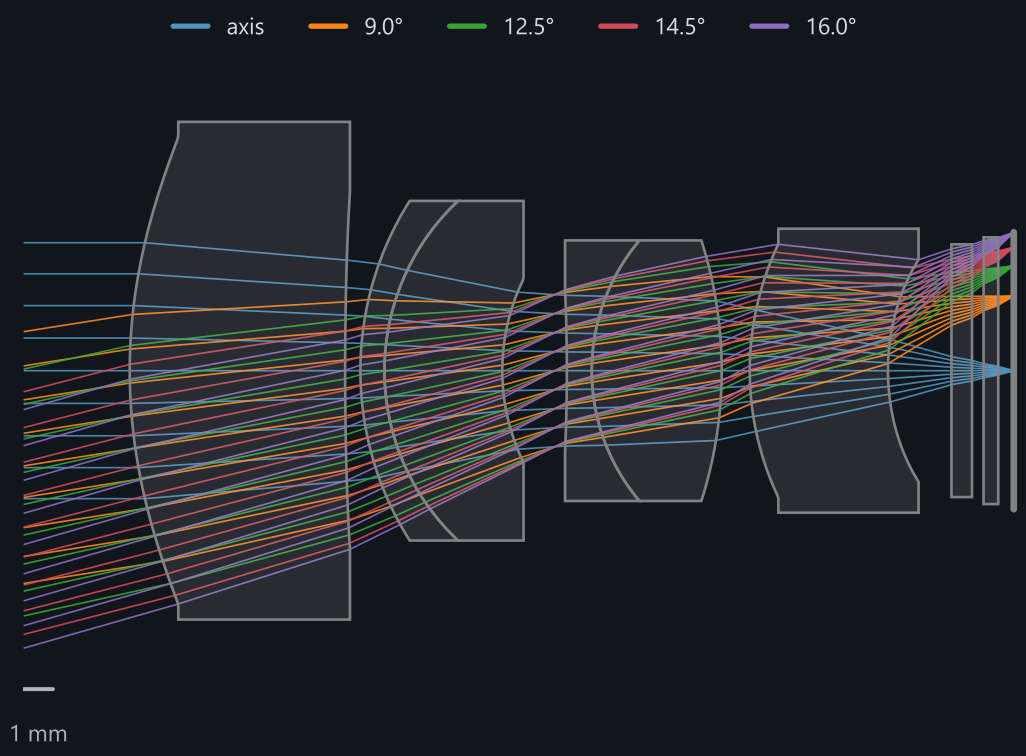
CASE STUDY 1 · VISION-ONLY CAR · 30 OCTOBER 2026

Five fixed-focus lenses for a car that sees with cameras only

A vision-only car has no lidar or radar to fall back on, so its cameras carry the whole load: a stereo pair that resolves a car at 250 m, a ring of six that sees all around to 100 m, fisheyes for the ground next to the bumpers, and two cabin cameras for the occupants. This study designs the five lenses behind those fifteen cameras on 8-megapixel automotive sensors, each focused once, at the factory, for its working distance. Every lens can be made: real catalog and glass-moulding glasses, faces shallow enough to centre in their seats, edges and air gaps that a lens shop and a barrel can hold, and a barrel with seats, spacers and retainers cut around each lens. Every optical number comes from the Paraxial API.



The far stereo lens: a six-element Double Gauss with two glass-moulded aspheres, an IR-cut filter and the sensor cover glass, focused at 250 m (rays and outlines from the Paraxial layout endpoint).

0.70
far lens MTF on axis at 119 lp/mm (half Nyquist), focused at 250 m

0.72
mid lens MTF on axis at 119 lp/mm, focused at 100 m

50 m
nearest distance at which the far lens keeps 80 % of its 250 m axis MTF

Paraxial · fea deployment · project “Vision-Only Car Demo”

THE LENSES 01

Five lens modules, fifteen cameras

The fifteen cameras use five lens designs, called modules M1 to M5 throughout this report. A module is one lens, its barrel and its sensor; every camera that uses it is the same part, mounted at a different place on the car (case study 2).

MODULE	LENS	CAMERAS	WHERE ON THE CAR
M1	Far stereo	2	Far L, Far R
M2	Mid ring	6	Mid front L, Mid front R, Mid side L, Mid side R, Mid rear L, Mid rear R
M3	Short-range fisheye	5	Fisheye front, Fisheye rear, Fisheye left, Fisheye right, Up-looking
M4	Cabin occupant	1	Occupant
M5	Driver monitor	1	Driver monitor

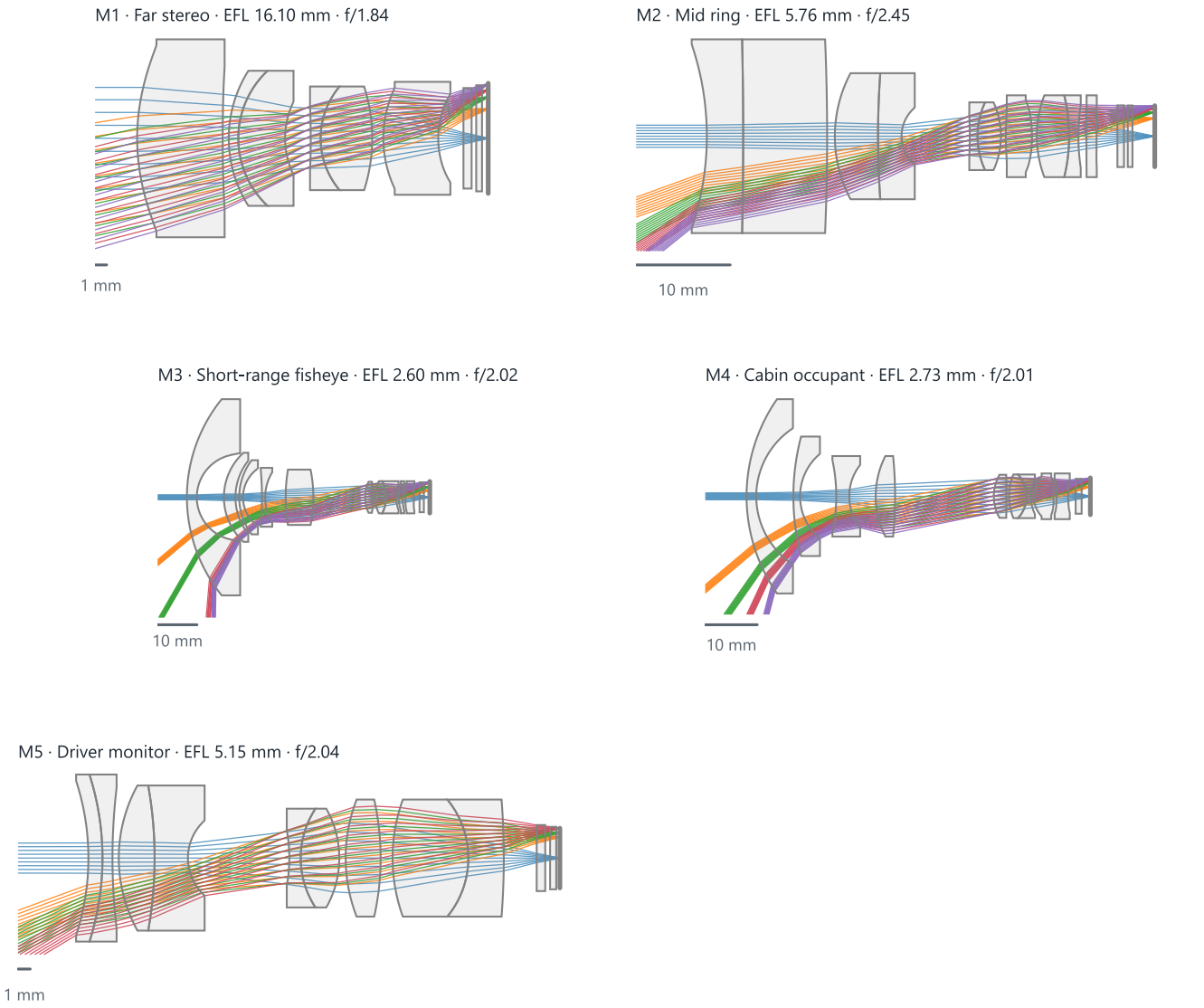


Figure 1. The five modules, each at its own scale: elements, stop, filter and sensor, with rays at the design fields (Paraxial layout endpoint). Their specifications are in the next table.

Each lens is sized from public sensor and system data (requirements_research.md) and starts from a published design: the Paraxial design search returned no usable start for these fields. The far and mid focal lengths follow from the horizontal fields the constellation needs; the fisheye is f·θ so that its 178° field keeps usable pixels at the edge.

Revision 2. The first set of lenses could not be built: element edges came out thin or negative and one lens ran into its neighbour (section 3). This revision redesigns all five to the manufacturing rules below and to production MTF limits, and two specifications changed on the way. The mid lens is f/2.4 instead of f/1.8: with buildable edges it reaches the edge goal only at f/2.4, while at f/2.0 its corner fell to 0.10–0.14. The occupant lens works at 940 nm only: with ordinary glasses its visible and 940 nm foci sit about 60 µm apart, against a ±5 µm depth of focus at f/2 and 114 lp/mm, so one fixed focus cannot serve both bands; 940 nm is the band the occupant functions use by day and by night.

Revision 3. A second review rejected revision 2 for three reasons. Faces near a hemisphere (the far lens's L2 and L3, sd/R up to 1.0) do not centre themselves in a seat: a lens centres on its seat only when

the contact angle is shallow enough for the clamping force to slide it onto the axis. Gaps of 0.12 mm (L5 to L6) leave no room for a spacer and chip the glass at assembly. And a ground convex face cannot change to a flat annulus at its edge for a seat. All five lenses were redesigned to three new rules and a mounting model that is how glass lenses are made and held (section 3).

Glass, not plastic. Every element is glass. The spherical elements are catalog glasses, ground and polished; the aspheres are precision glass-moulded (P-SK57, P-LAF37, P-LAK35, P-BK7 moulding glasses), the process automotive lens makers use for glass aspheres. Plastic is not used: its index moves about 50 times as much with temperature as glass and its expansion is about ten times larger, which a fixed-focus lens cannot follow from −40 to +85 °C (case study 4), and it takes up moisture.

LENS	EFL (MM)	F/#	HORIZONTAL FIELD	FOCUS	SENSOR	START
M1 Far stereo	16.10	1.84	27.8°	250 m	8.06 × 4.54 mm, 2.1 µm	Double Gauss (ZEBASE L_006); six elements, two glass-moulded aspheres
M2 Mid ring	5.76	2.45	77.6°	100 m	8.06 × 4.54 mm, 2.1 µm	Inverted telephoto (ZEBASE F_002); ten elements, two glass-moulded aspheres
M3 Short-range fisheye	2.60	2.02	178.0°	1.5 m	8.06 × 4.54 mm, 2.1 µm	US 8,638,507 embodiment 1, f·θ; nine elements, two glass-moulded aspheres
M4 Cabin occupant	2.73	2.01	119.7°	1 m	5.70 × 4.28 mm, 2.2 µm	The revision 2 fisheye, rescaled to the cabin sensor and refocused for 940 nm
M5 Driver monitor	5.15	2.04	60.4°	0.65 m	4.80 × 3.90 mm, 3.0 µm	Inverted telephoto (ZEBASE F_002), scaled; nine elements, all spherical

- **M1 Far stereo.** Forward stereo pair behind the windshield, 1.2 m apart; resolves to 250 m
- **M2 Mid ring.** Six around the car at 60° spacing; resolves to 100 m over 360° × −5/+20°
- **M3 Short-range fisheye.** Four short-range fisheyes (bumpers and mirrors) and one up-looking, for the ground next to the car, children and garage ceilings
- **M4 Cabin occupant.** Cabin occupant camera in the overhead console, 940 nm under the cabin's IR illuminators, all five seats
- **M5 Driver monitor.** Driver monitor on the steering column, 940 nm active illumination

RESULTS 02

What each lens achieves

The image-quality goals are production-style automotive limits: an MTF above 0.6 in the centre and above 0.4 in the outer zones, held from −40 to +85 °C (research/optics_automotive.md [O8]). The source does not state the frequency; this study applies the limits at half the pixel Nyquist frequency, on axis and at the worst field, to the API's polychromatic Huygens MTF at the working distance. The temperature range is case study 4's subject. The first revision scored itself at a single wavelength against looser goals of its own (0.5 / 0.3), which hid lateral colour.

REQUIREMENT	TARGET	RESULT	STATUS
M1 Far stereo: EFL	16.10 mm ± 1 %	16.100 mm	✓ Met
M1 Far stereo: MTF on axis at 119 lp/mm	≥ 0.60	0.70	✓ Met
M1 Far stereo: worst field MTF at 119 lp/mm, worse of T/S	≥ 0.40	0.55	✓ Met
M1 Far stereo: manufacturing rules	no shortfall	all met	✓ Met
M2 Mid ring: EFL	5.76 mm ± 1 %	5.760 mm	✓ Met
M2 Mid ring: MTF on axis at 119 lp/mm	≥ 0.60	0.72	✓ Met
M2 Mid ring: worst field MTF at 119 lp/mm, worse of T/S	≥ 0.40	0.55	✓ Met
M2 Mid ring: manufacturing rules	no shortfall	all met	✓ Met
M3 Short-range fisheye: EFL	2.60 mm ± 1 %	2.600 mm	✓ Met
M3 Short-range fisheye: MTF on axis at 119 lp/mm	≥ 0.60	0.66	✓ Met
M3 Short-range fisheye: worst field MTF at 119 lp/mm, worse of T/S	≥ 0.40	0.38	◐ Partly
M3 Short-range fisheye: manufacturing rules	no shortfall	all met	✓ Met
M4 Cabin occupant: EFL	2.72 mm ± 1 %	2.727 mm	✓ Met
M4 Cabin occupant: MTF on axis at 114 lp/mm	≥ 0.60	0.72	✓ Met
M4 Cabin occupant: worst field MTF at 114 lp/mm, worse of T/S	≥ 0.40	0.67	✓ Met
M4 Cabin occupant: manufacturing rules	no shortfall	all met	✓ Met
M5 Driver monitor: EFL	5.15 mm ± 1 %	5.149 mm	✓ Met
M5 Driver monitor: MTF on axis at 83 lp/mm	≥ 0.60	0.78	✓ Met
M5 Driver monitor: worst field MTF at 83 lp/mm, worse of T/S	≥ 0.40	0.75	✓ Met
M5 Driver monitor: manufacturing rules	no shortfall	1.406 mm short, 1 element(s) thicker than OD/2	✗ Not met

MANUFACTURABILITY 03

Lenses a shop can make, in housings that hold them

Each element is checked as it is made. A ground convex face runs out to the element's outside diameter and bears on the square inner corner of a spacer or ring just outside its clear aperture (sharp-corner contact, no angled seat); a ground concave face ends in a flat bevel, which takes a flat seat; a glass-moulded asphere has a moulded flat flange. The rules are the usual shop limits for small precision optics, tightened where the review found risk: the steepness sd/|R| at the polished edge at most 0.75 on a convex face or cemented interface and 0.85 on a concave face (a steeper face does not centre in its seat and is hard to polish); every air gap at least 0.5 mm at the vertex and at the edge, and 0.3 mm from a lens to the stop; a glass edge of at least 0.8 mm (1.0 mm above 12 mm diameter); a centre thickness of at least 0.8 mm and 5 % of the diameter; 1.1 mm from the last lens to the filter, room for the rear retainer; and no element thicker than half its outside diameter (OD : CT at least 2 : 1).

The OD : CT rule was added after revision 3's lenses were finished: thickness is a weak lever on aberrations, and left free the optimiser had grown the fisheye's L5 (SF6) to 17.8 mm on a 13 mm diameter. M3 (fisheye) and M1 (far stereo) were redesigned to it. For M3, L5 was cut to the thickness limit with its power kept (both curvatures scaled together), the image restored with the air spaces, the lens re-optimised and finished on Paraxial: L5 is now 7.05 mm on 14.2 mm, and the worst field rose from 0.24 to 0.47 at half Nyquist. For M1, L4 (10.1 mm on 11.0 mm) was walked down to 4.71 mm in three stages with every element's thickness bounded above by its OD / 2; the optimiser moved the lost glass path into L1 (4.1 → 7.3 mm, OD : CT 2.33), and the worst field at half Nyquist held at 0.50. M1's tolerancing, thermal check and CAD were rerun on the new design. By the review's decision the driver monitor (M5) was not redesigned; its front element L5 breaks the rule (OD : CT 1.55, 6.2 mm on 9.6 mm), shown in the table.

One exception: the fisheye's front cup. A fisheye catches its 85–89° rays through the side wall of a nearly hemispherical concave rear face on its front meniscus (L1): inside the glass those rays travel almost across the axis and meet the cup's wall close to normal incidence, so the cup is how the lens reaches 178°, not a defect of the design. That face is allowed past the 0.85 limit, up to the full hemisphere (the review's decision). At 89° the beam meets the cup 0.1–0.4 mm in front of its equator along the axis; the top and bottom of that beam's pupil fall past the equator and are lost, vignetting confined to the last degrees of field. The cup is polished to its rim, the rim is chamfered, and beyond it the rear of the element is a ground flat annulus, square to the axis, out to the outside diameter. L1 is held in the barrel nose between two threaded retaining rings, the front ring on its convex face (tangent contact) and the rear ring flat on the annulus, threaded into a counterbore just behind the barrel's front flange (the top of the barrel's T); the rear ring's back end is the next element's seat. L1's solid is built from this as-made section.

LENS	REVISION 2: STEEPEST FACE / CLOSEST GAP	ELEMENTS	STEEPEST FACE (SD/R, LIMIT)	THINNEST GLASS EDGE (MM)	CLOSEST AIR GAP (MM)	THINNEST CENTRE (MM)	LOWEST OD : CT	RULES
M1 Far stereo	1.00 / -10.00 mm	6	0.73 (0.75)	1.29 (≥ 0.8)	0.52 (≥ 0.5)	0.82	2.01	all met
M2 Mid ring	0.79 / 0.12 mm	10	0.76 (0.85)	0.90 (≥ 0.8)	0.52 (≥ 0.5)	0.82	2.31	all met

LENS	REVISION 2: STEEPEST FACE / CLOSEST GAP	ELEMENTS	STEEPEST FACE (SD/R, LIMIT)	THINNEST GLASS EDGE (MM)	CLOSEST AIR GAP (MM)	THINNEST CENTRE (MM)	LOWEST OD : CT	RULES
M3 Short-range fisheye	1.00 / 0.12 mm	10	1.00 (1.00)	0.85 (≥ 0.8)	0.32 (≥ 0.3)	0.82	2.00	all met
M4 Cabin occupant	0.85 / 0.12 mm	9	0.83 (0.85)	0.89 (≥ 0.8)	0.52 (≥ 0.5)	0.82	2.28	all met
M5 Driver monitor	0.80 / 0.12 mm	9	0.74 (0.85)	0.88 (≥ 0.8)	0.52 (≥ 0.5)	0.82	1.55	1 too thick (OD : CT)

Housings. Each lens sits in a barrel cut around the lens STEP file that the Paraxial CAD export writes. The stop is a shoulder machined in the bore; the elements in front of it load from the front and those behind it from the rear, each stack clamped against the shoulder by its own threaded retainer, so the bore steps down toward the stop from both ends and no element passes a smaller seat. Every element has a bore step at its own outside diameter (0.02 mm diametral clearance); spacers between neighbours are stepped where the two seats differ in diameter; convex faces bear on the square inner corner of a spacer or ring (sharp-corner contact, the ring end cut square, never at an angle), concave bevels and moulded flanges on flat ones. A spacer of 5 mm or more next to the stop is not a separate part: it is a shoulder turned into the bore, the element sitting on it (M3's L5). The barrel's outside follows its bore at a constant wall, stepping down from the large front elements toward the stop and back up toward the sensor, instead of one cylinder at the largest diameter; M3's barrel is a T, its wide front flange carrying L1 and its narrow body L2 to the filter. The filter is glued into a rear counterbore, and the rear collar is glued to the sensor holder after active alignment, the usual practice for fixed-focus automotive cameras. The barrel, spacers and retainers were checked solid against solid for overlap with every lens and with each other, and each lens solid's diameter against the seat it was cut for.

LENS	LENS SOLIDS	SPACERS	BARREL, LENGTH × MAX OD (MM)	REAR END TO IMAGE (MM)	OVERLAPS	DIAMETERS MATCH
M1 Far stereo	6	4	28.2 × Ø19.5	1.12	none	yes
M2 Mid ring	10	5	47.0 × Ø23.1	2.97	none	yes
M3 Short-range fisheye	10	8	52.8 × Ø52.5	1.21	none	yes
M4 Cabin occupant	9	7	59.9 × Ø39.9	1.38	none	yes
M5 Driver monitor	9	4	39.5 × Ø16.2	0.90	none	yes

The STEP files (lenses, housing, and both together as one assembly) are delivered with this study, one set per lens.

M1 FAR STEREO 04

Forward stereo pair behind the windshield, 1.2 m apart

EFL 16.100 mm at f/1.84 (paraxial, API), 8.064 mm sensor width, so 27.8° across the width from the real chief-ray mapping. 6 catalog glasses (N-BAF51, N-LASF41, P-LAF37, P-SK57, SF10, SF57HTultra); total track 30.1 mm.

On axis the MTF at 119 lp/mm is 0.70 and 0.45 at Nyquist; at 12.5° the worse of T and S is 0.57 and at the edge (16.0°) 0.66. Distortion peaks at 2.4 % (f·tanθ reference), lateral colour at 0.80 pixels, the chief ray meets the sensor at up to 32.2°, and relative illumination falls to 65 %.

Fixed focus. Focused at 250 m, the axis MTF at 119 lp/mm stays within 80 % of its focus value from 50 m outward (one wavelength, mean of T and S).

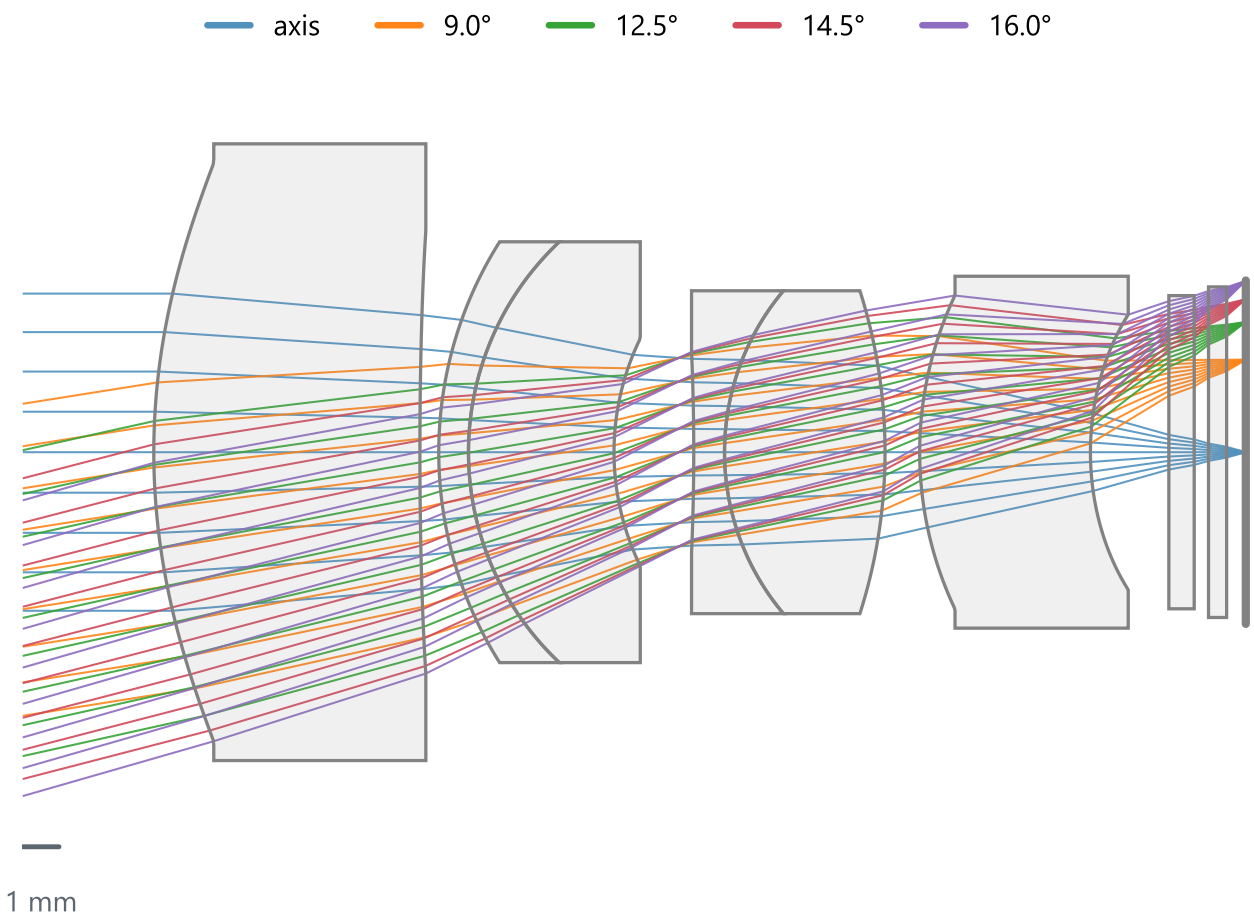


Figure 2. M1 Far stereo lens: elements as made (convex faces to the edge, concave bevels, moulded flanges) and rays from the Paraxial layout endpoint.

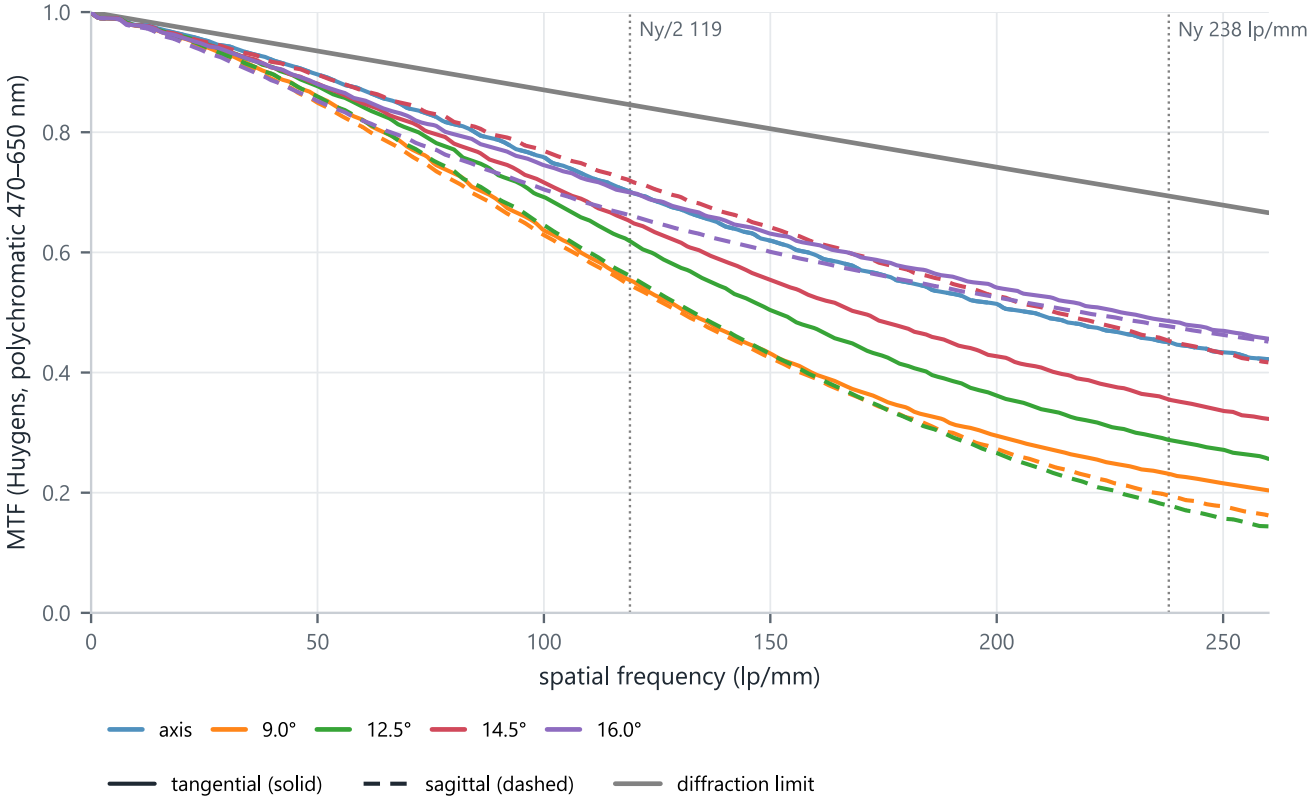


Figure 3. Polychromatic Huygens MTF at the working distance; tangential solid, sagittal dashed.

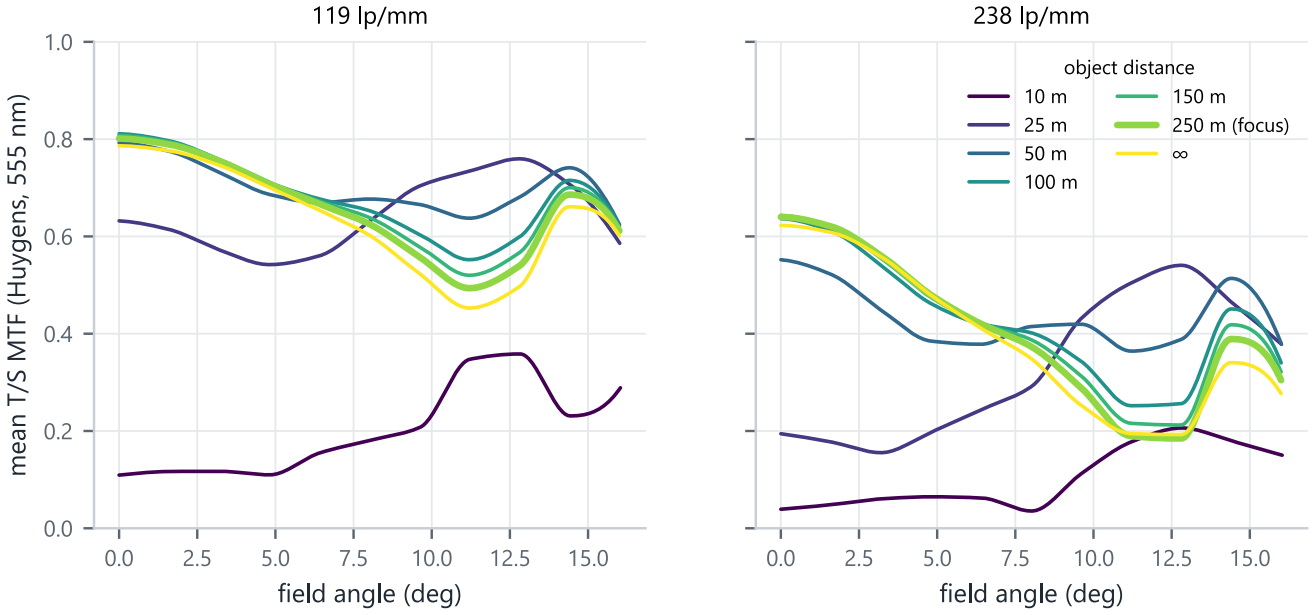


Figure 4. Fixed focus: MTF across the field for objects nearer and farther than the focus distance; the back focus is frozen.

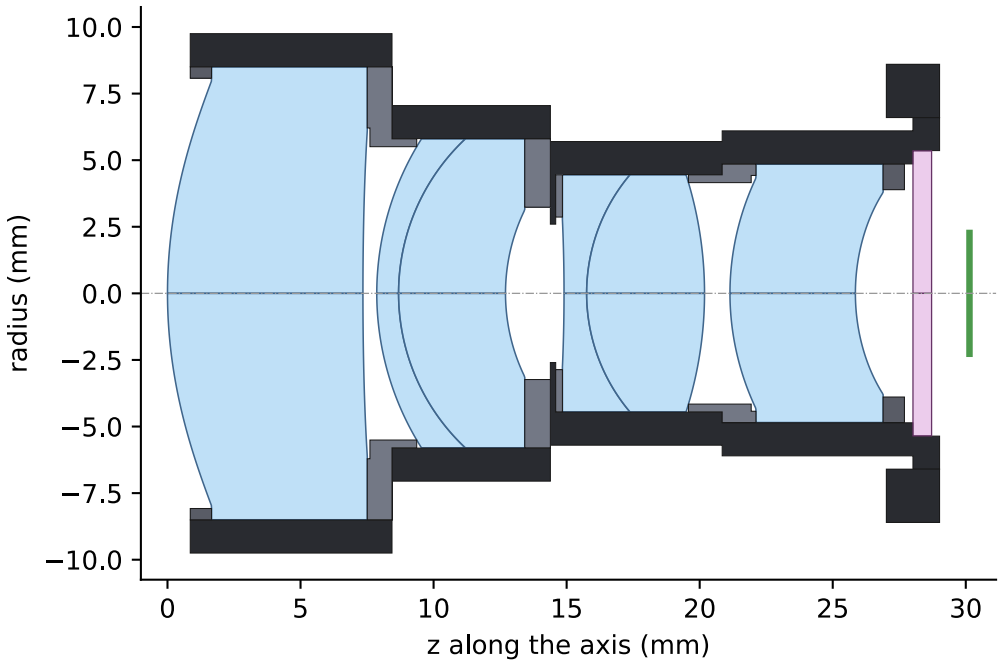


Figure 5. M1 Far stereo lens in its housing (half section): stepped barrel with its stop shoulder, square-ended spacers and rings, front and rear retainers and the bonded filter.

M2 MID RING 05

Six around the car at 60° spacing

EFL 5.760 mm at f/2.45 (paraxial, API), 8.064 mm sensor width, so 77.6° across the width from the real chief-ray mapping. 7 catalog glasses (N-BK7, N-LAF2, N-PSK3, N-SF1, N-SF4, N-SK16, P-LAK35); total track 47.6 mm.

On axis the MTF at 119 lp/mm is 0.72 and 0.45 at Nyquist; at 28.0° the worse of T and S is 0.55 and at the edge (38.8°) 0.55. Distortion peaks at 30.0 % (f·tanθ reference), lateral colour at 1.49 pixels, the chief ray meets the sensor at up to 10.9°, and relative illumination falls to 94 %.

Fixed focus. Focused at 100 m, the axis MTF at 119 lp/mm stays within 80 % of its focus value from 5 m outward (one wavelength, mean of T and S).

f/2.4. Opened to f/2.0 with buildable edges, the corner fell to 0.10–0.14 at half Nyquist (pre-design); at f/2.45 it holds 0.55. The slower lens gathers 0.64× the light of the f/1.96 first revision.

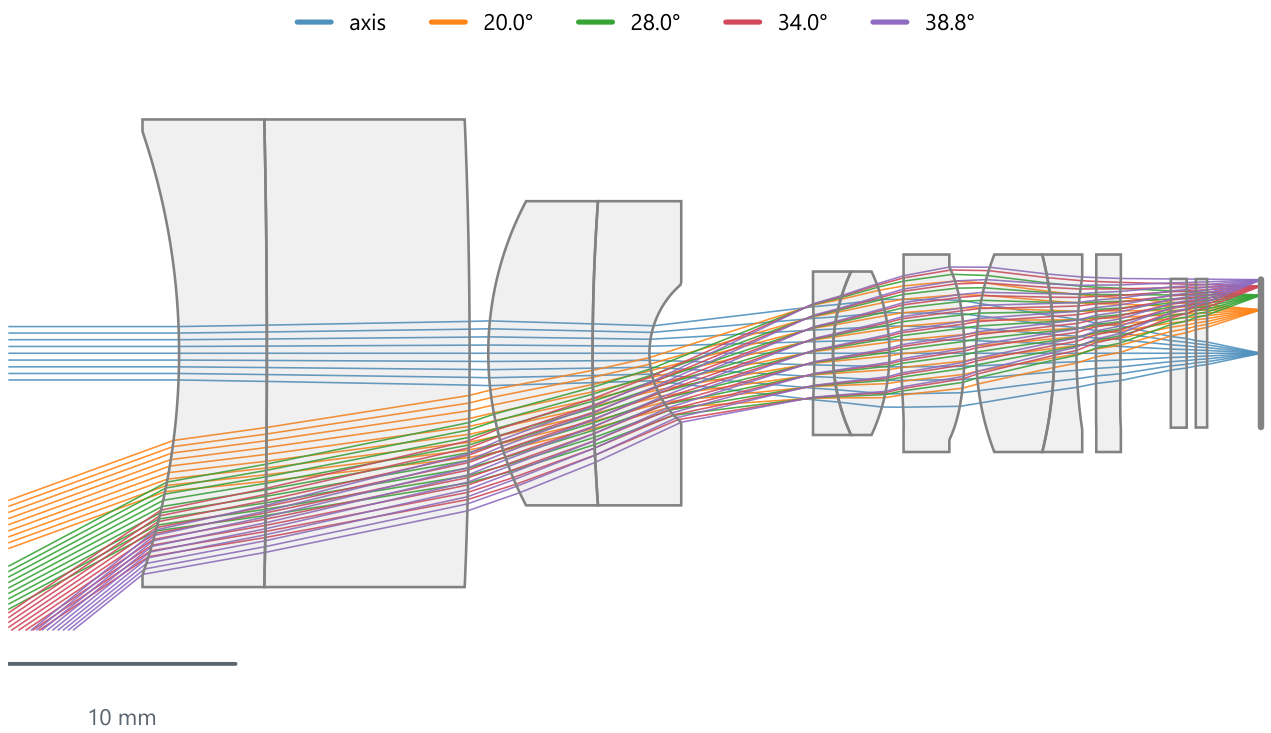


Figure 6. M2 Mid ring lens: elements as made (convex faces to the edge, concave bevels, moulded flanges) and rays from the Paraxial layout endpoint.

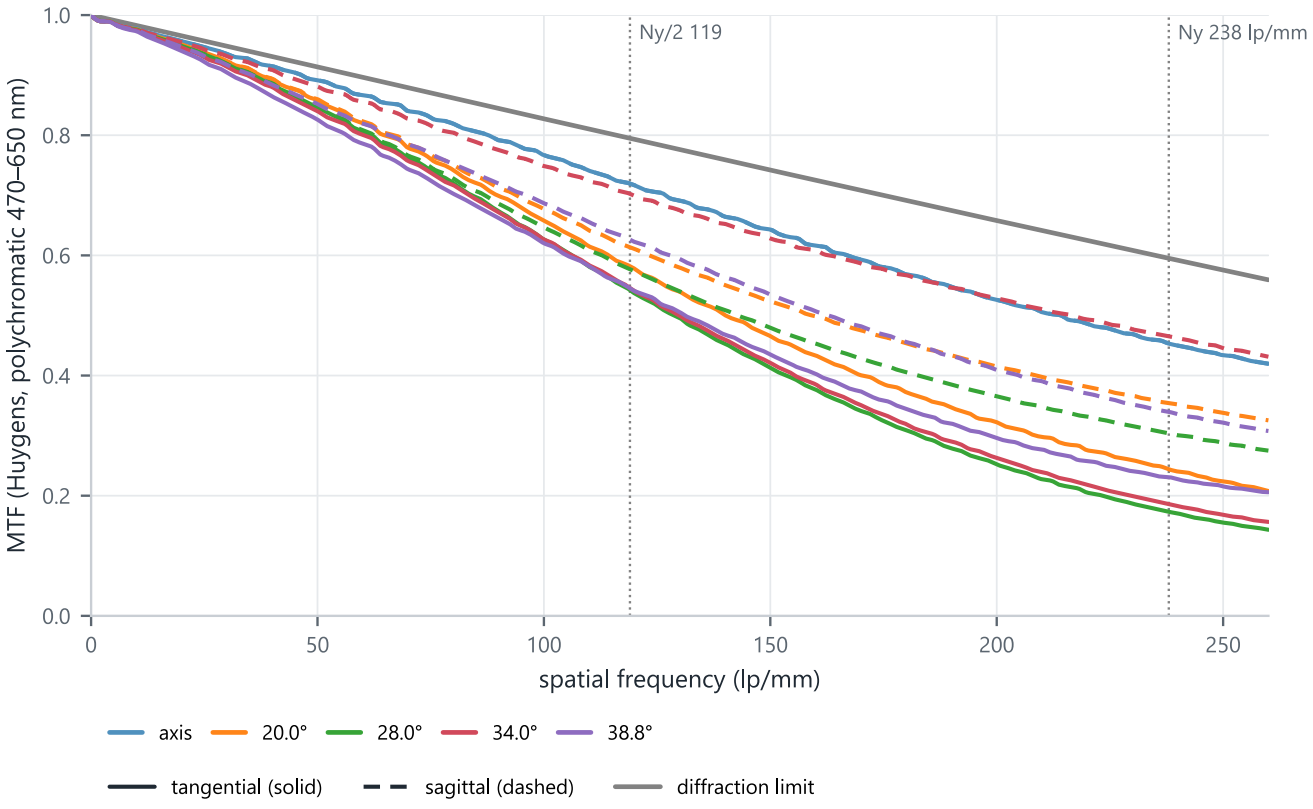


Figure 7. Polychromatic Huygens MTF at the working distance; tangential solid, sagittal dashed.

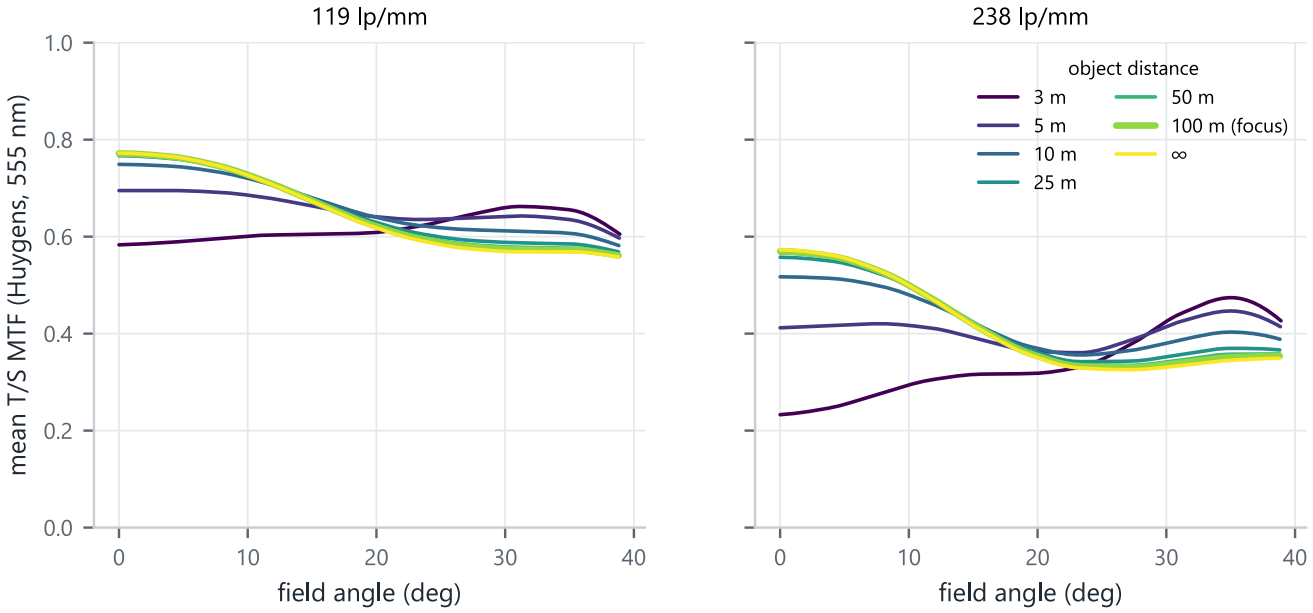


Figure 8. Fixed focus: MTF across the field for objects nearer and farther than the focus distance; the back focus is frozen.

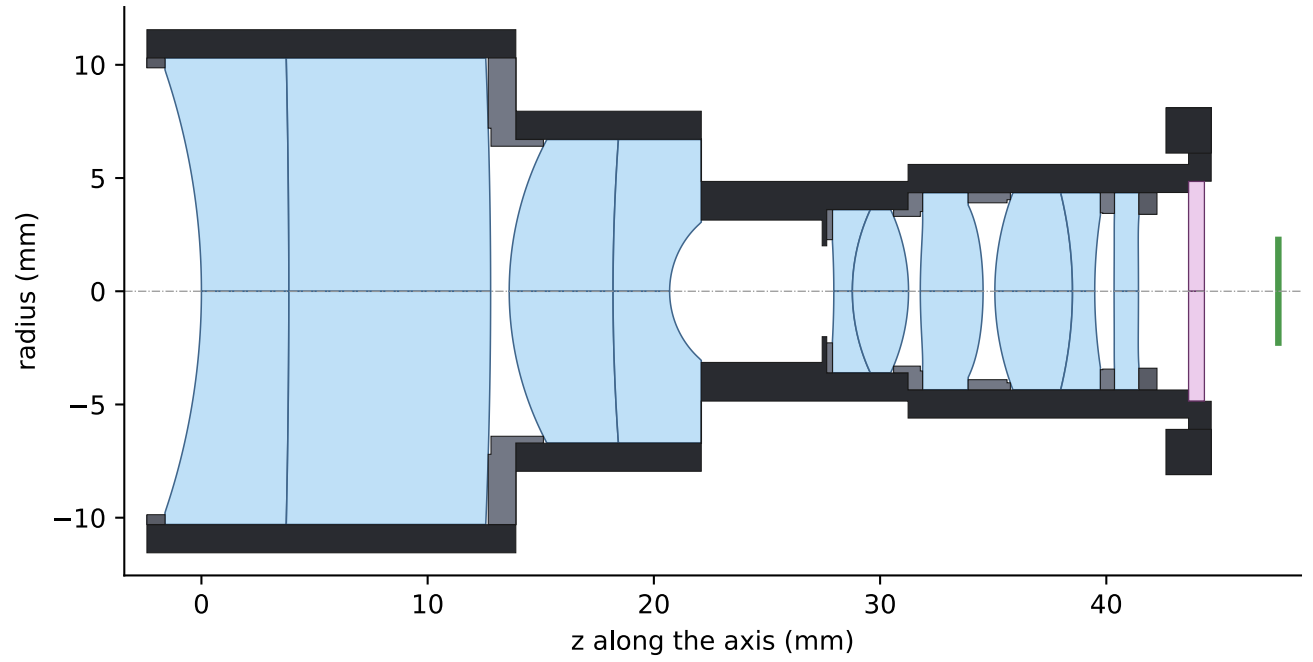


Figure 9. M2 Mid ring lens in its housing (half section): stepped barrel with its stop shoulder, square-ended spacers and rings, front and rear retainers and the bonded filter.

M3 SHORT-RANGE FISHEYE 06

Four short-range fisheyes (bumpers and mirrors) and one up-looking, for the ground next to the car, children and garage ceilings

EFL 2.600 mm at f/2.02 (paraxial, API), 8.064 mm sensor width, so 178.0° across the width from the real chief-ray mapping. 9 catalog glasses (FK5HTI, N-LAF2, N-LAF35, N-LAK12, N-SK16, P-BK7, P-LAK35, SF4, SF6); total track 61.9 mm.

On axis the MTF at 119 lp/mm is 0.66 and 0.35 at Nyquist; at 60.0° the worse of T and S is 0.58 and at the edge (89.0°) 0.49. Distortion peaks at 0.6 % (f·θ reference), lateral colour at 15823.96 pixels, the chief ray meets the sensor at up to 69.7°, and relative illumination falls to 0 %.

Fixed focus. Focused at 1.5 m, the axis MTF at 119 lp/mm stays within 80 % of its focus value from 0.5 m outward (one wavelength, mean of T and S).

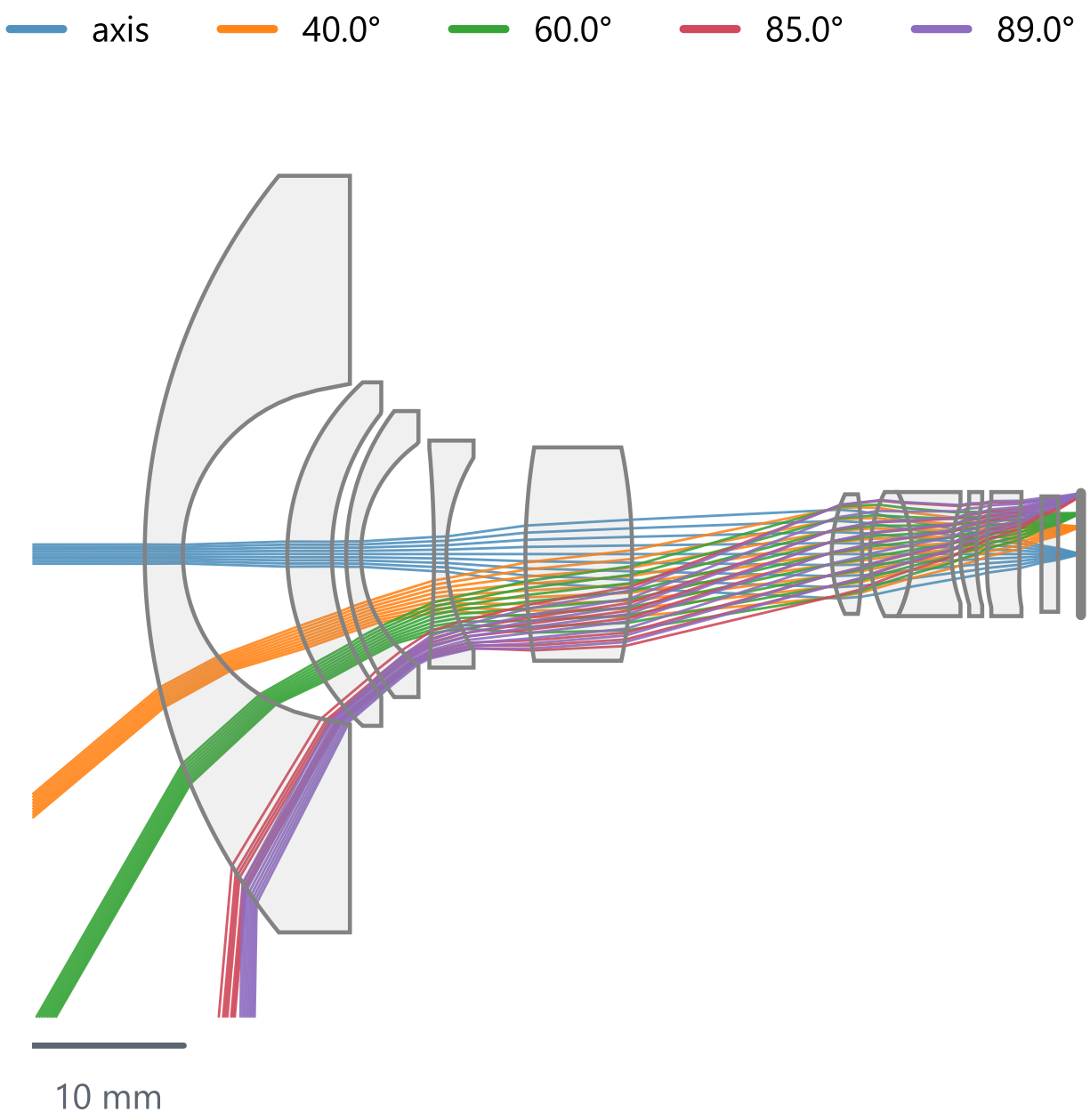


Figure 10. M3 Short-range fisheye lens: elements as made (convex faces to the edge, concave bevels, moulded flanges) and rays from the Paraxial layout endpoint.

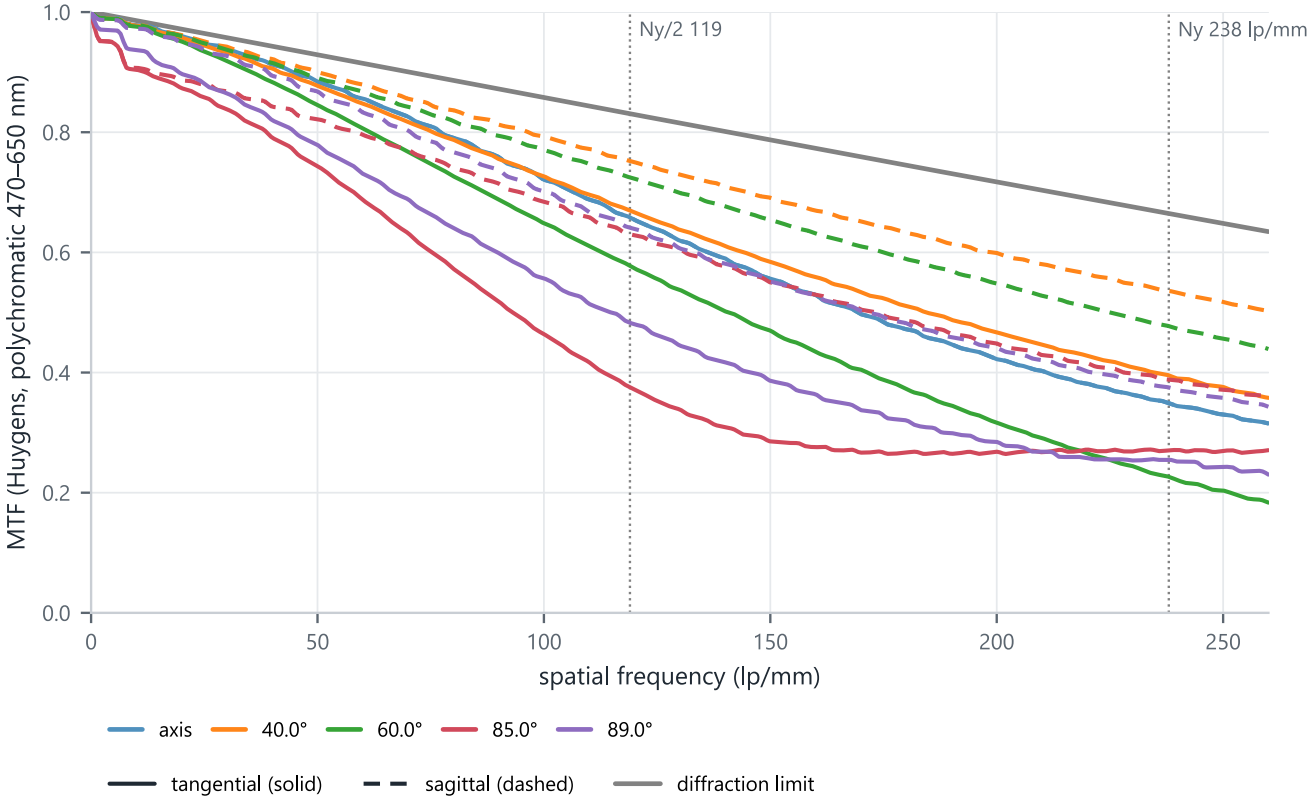


Figure 11. Polychromatic Huygens MTF at the working distance; tangential solid, sagittal dashed.

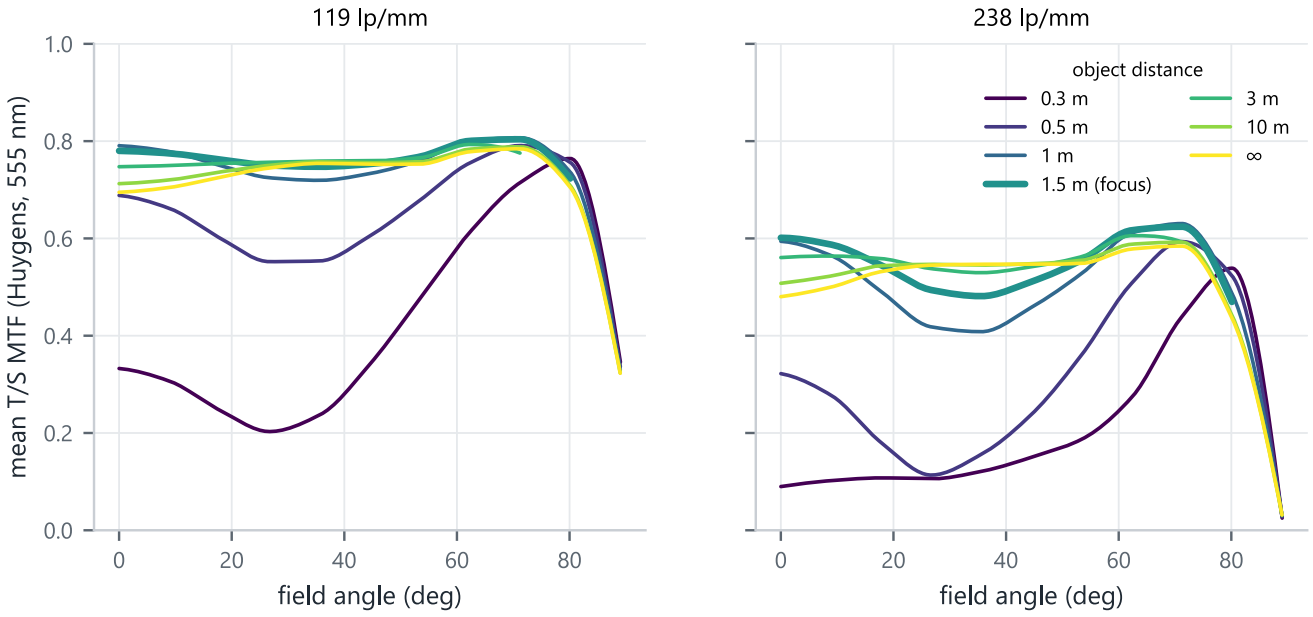


Figure 12. Fixed focus: MTF across the field for objects nearer and farther than the focus distance; the back focus is frozen.

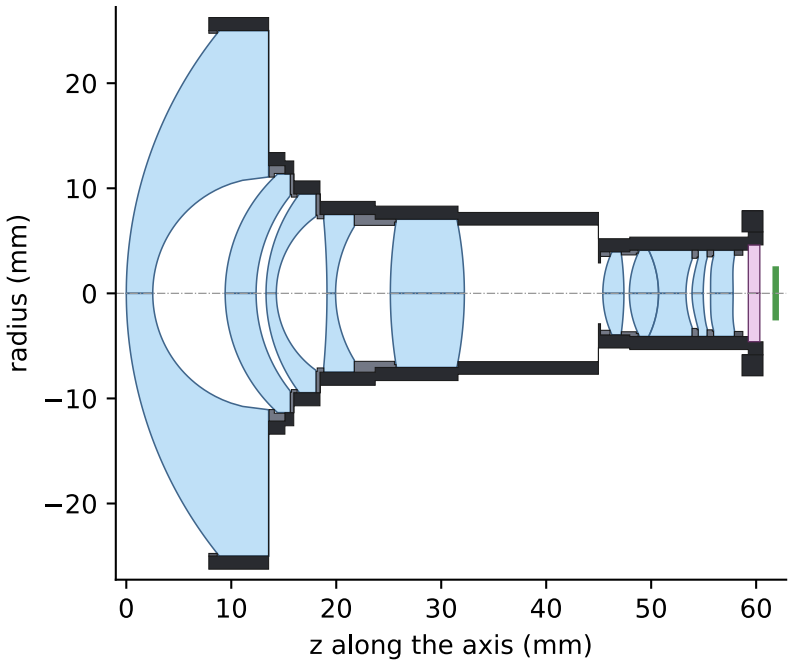


Figure 13. M3 Short-range fisheye lens in its housing (half section): stepped barrel with its stop shoulder, square-ended spacers and rings, front and rear retainers and the bonded filter.

M4 CABIN OCCUPANT 07

Cabin occupant camera in the overhead console, 940 nm under the cabin's IR illuminators, all five seats

EFL 2.727 mm at f/2.01 (paraxial, API), 5.702 mm sensor width, so 119.7° across the width from the real chief-ray mapping. 9 catalog glasses (FK5HTI, N-LAF2, N-LAF35, N-LAK12, N-SK16, P-BK7, P-LAK35, SF4, SF6); total track 66.2 mm.

On axis the MTF at 114 lp/mm is 0.72 and 0.46 at Nyquist; at 55.0° the worse of T and S is 0.70 and at the edge (75.0°) 0.67. Distortion peaks at 0.6 % (f·θ reference), lateral colour at 0.06 pixels, the chief ray meets the sensor at up to 18.2°, and relative illumination falls to 70 %.

Fixed focus. Focused at 1 m, the axis MTF at 114 lp/mm stays within 80 % of its focus value from 0.6 m outward (one wavelength, mean of T and S).

One band. The lens is designed and focused for 930–950 nm behind a 940 nm band-pass filter, the band of the cabin's IR illuminators, so it serves the occupant functions by day and by night with a monochrome image. Revision 1 tried to serve visible and 940 nm with one focus; the two foci sit about 60 µm apart, twelve times the depth of focus at 114 lp/mm.

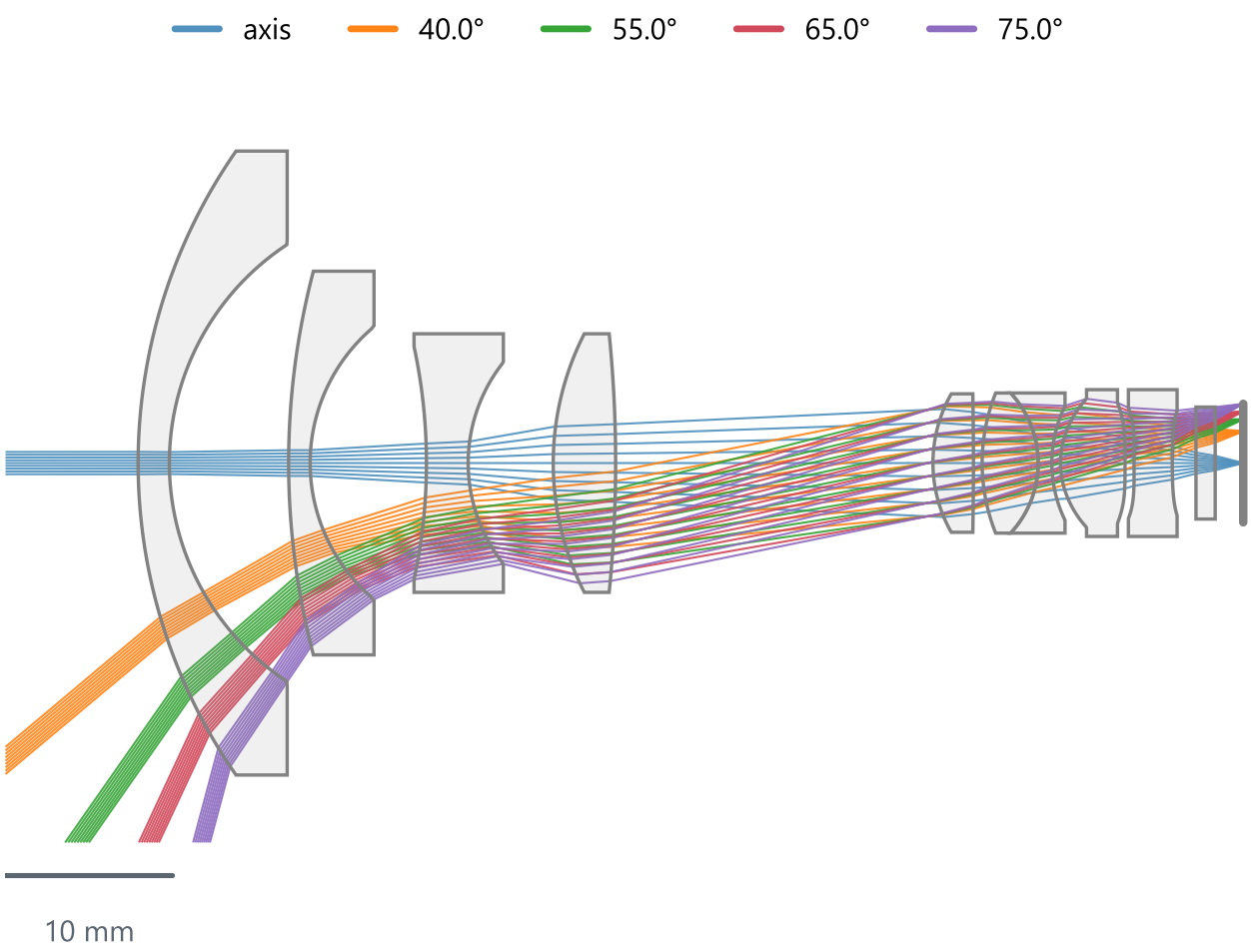


Figure 14. M4 Cabin occupant lens: elements as made (convex faces to the edge, concave bevels, moulded flanges) and rays from the Paraxial layout endpoint.

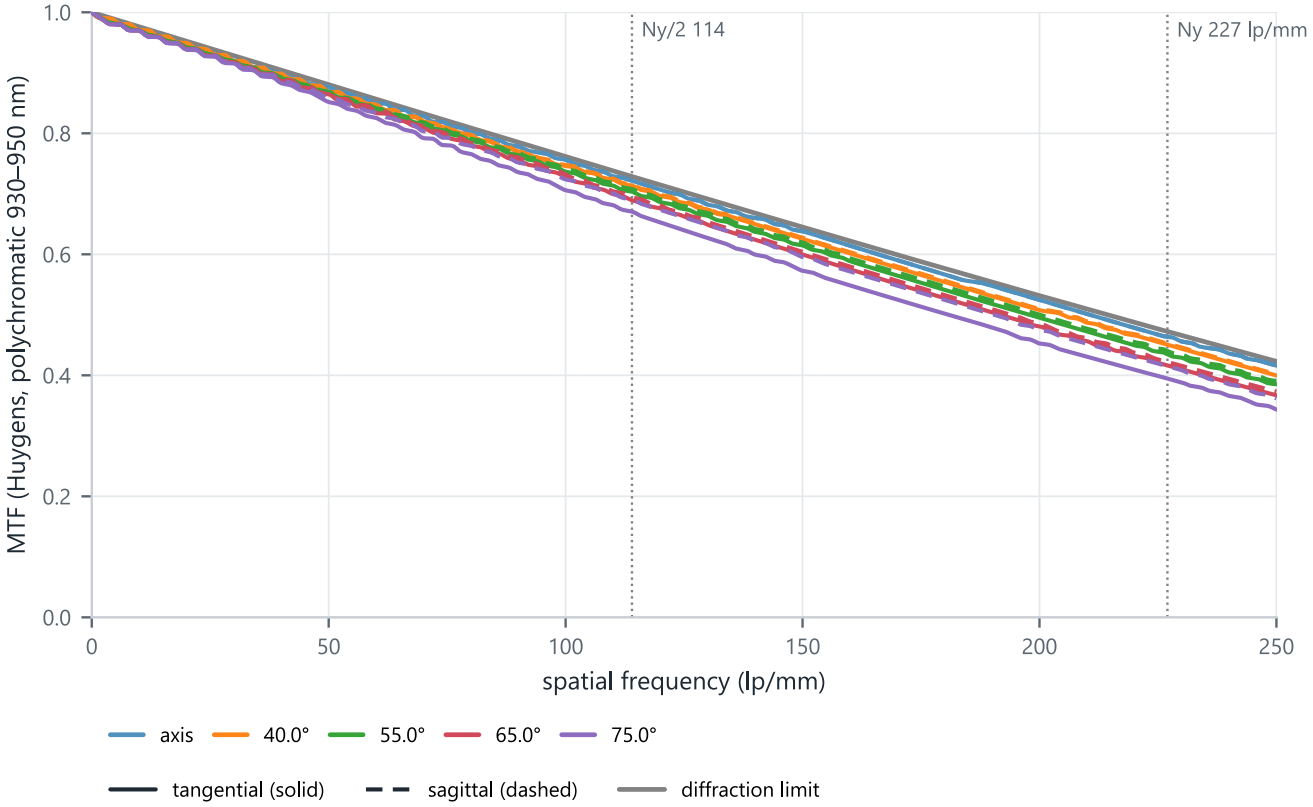


Figure 15. Polychromatic Huygens MTF at the working distance; tangential solid, sagittal dashed.

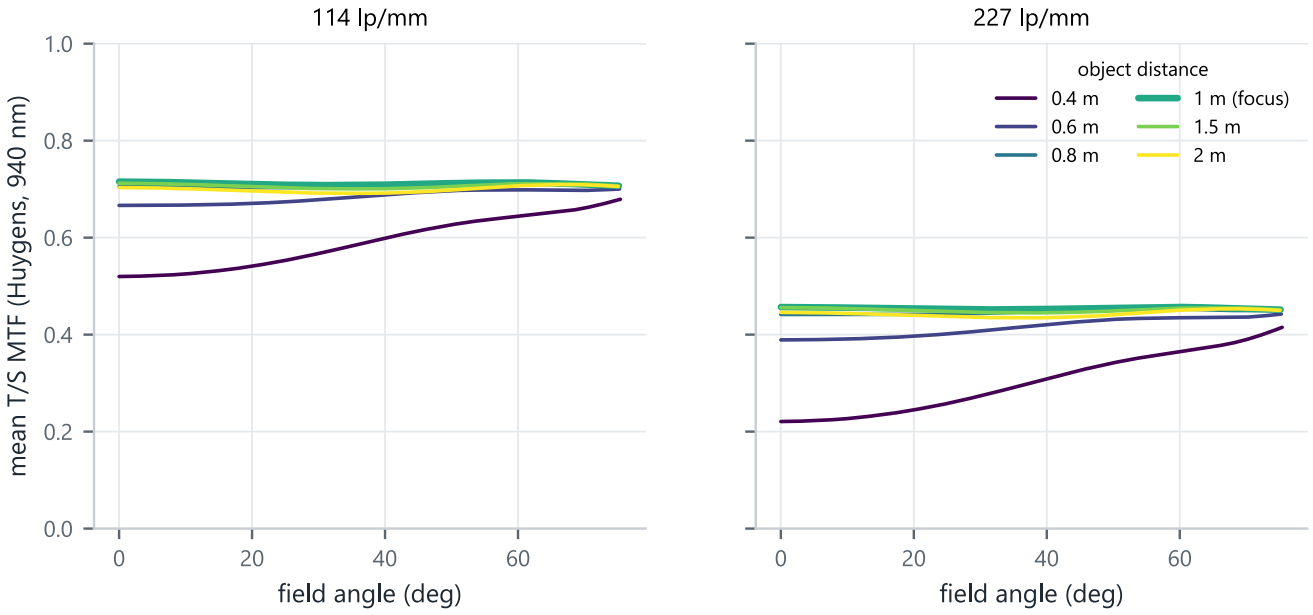


Figure 16. Fixed focus: MTF across the field for objects nearer and farther than the focus distance; the back focus is frozen.

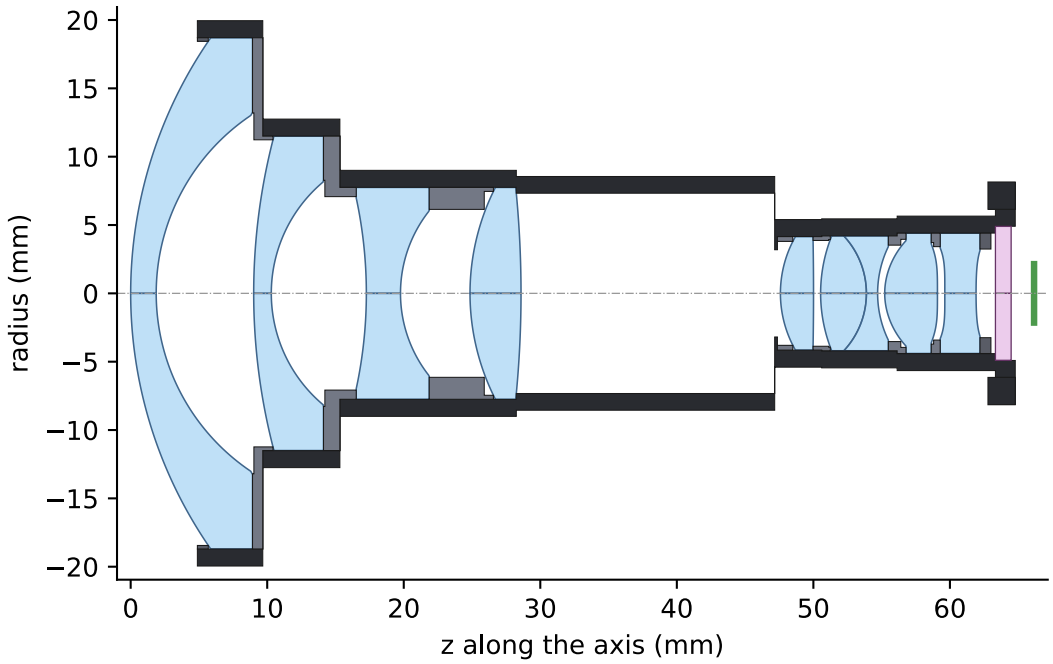


Figure 17. M4 Cabin occupant lens in its housing (half section): stepped barrel with its stop shoulder, square-ended spacers and rings, front and rear retainers and the bonded filter.

M5 DRIVER MONITOR 08

Driver monitor on the steering column, 940 nm active illumination

EFL 5.149 mm at f/2.04 (paraxial, API), 4.800 mm sensor width, so 60.4° across the width from the real chief-ray mapping. 7 catalog glasses (N-BK7, N-LAF2, N-LAK12, N-PSK3, N-SF1, N-SF4, N-SK16); total track 38.6 mm.

On axis the MTF at 83 lp/mm is 0.78 and 0.58 at Nyquist; at 20.0° the worse of T and S is 0.75 and at the edge (31.0°) 0.76. Distortion peaks at 20.9 % (f·tanθ reference), lateral colour at 0.12 pixels, the chief ray meets the sensor at up to 5.2°, and relative illumination falls to 100 %.

Fixed focus. Focused at 0.65 m, the axis MTF at 83 lp/mm stays within 80 % of its focus value from 0.65 m outward (one wavelength, mean of T and S).

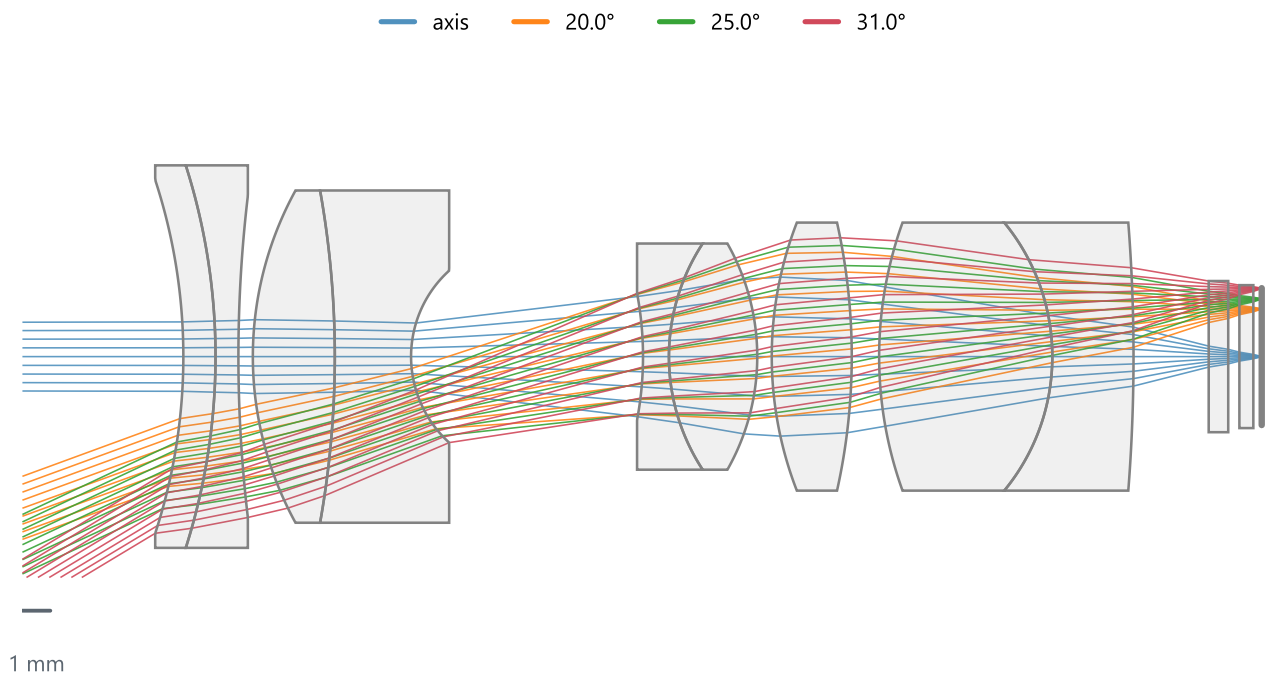


Figure 18. M5 Driver monitor lens: elements as made (convex faces to the edge, concave bevels, moulded flanges) and rays from the Paraxial layout endpoint.

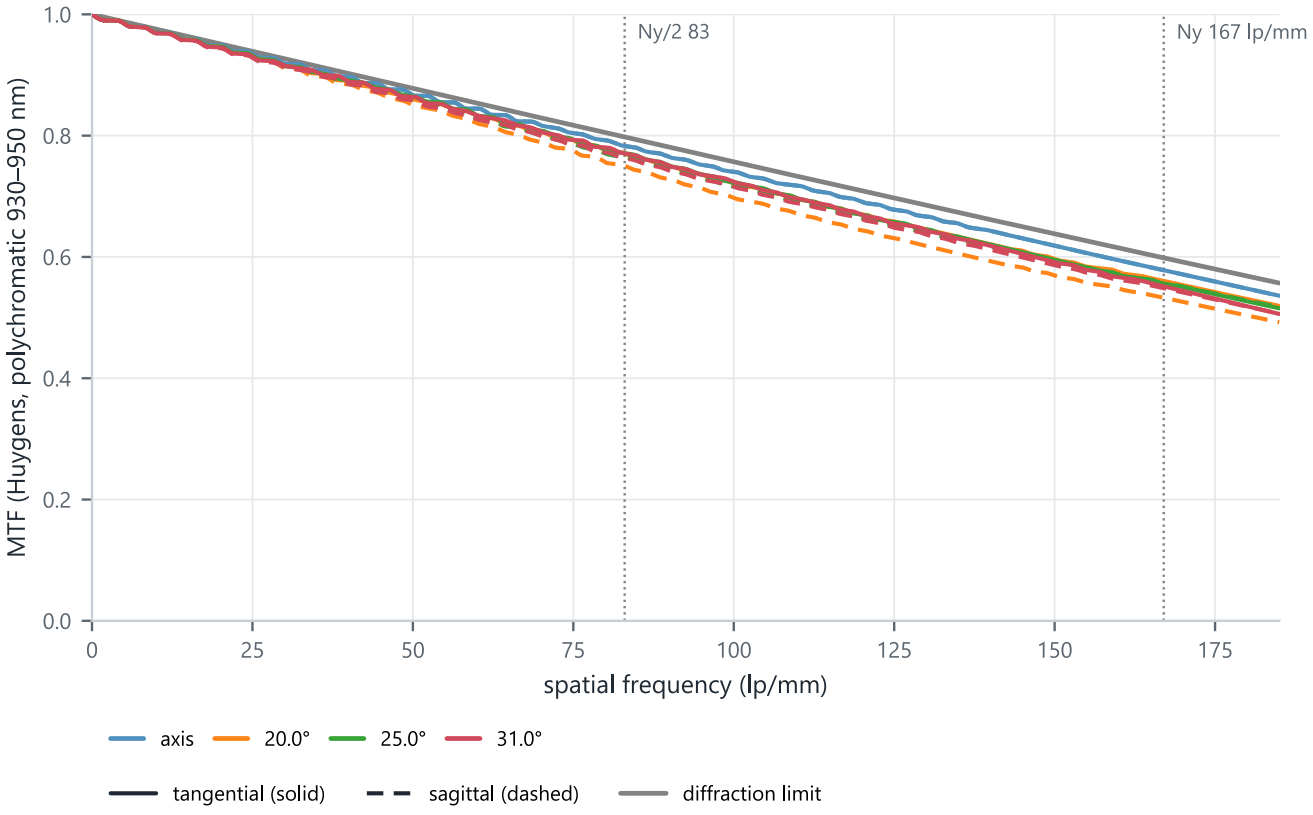


Figure 19. Polychromatic Huygens MTF at the working distance; tangential solid, sagittal dashed.

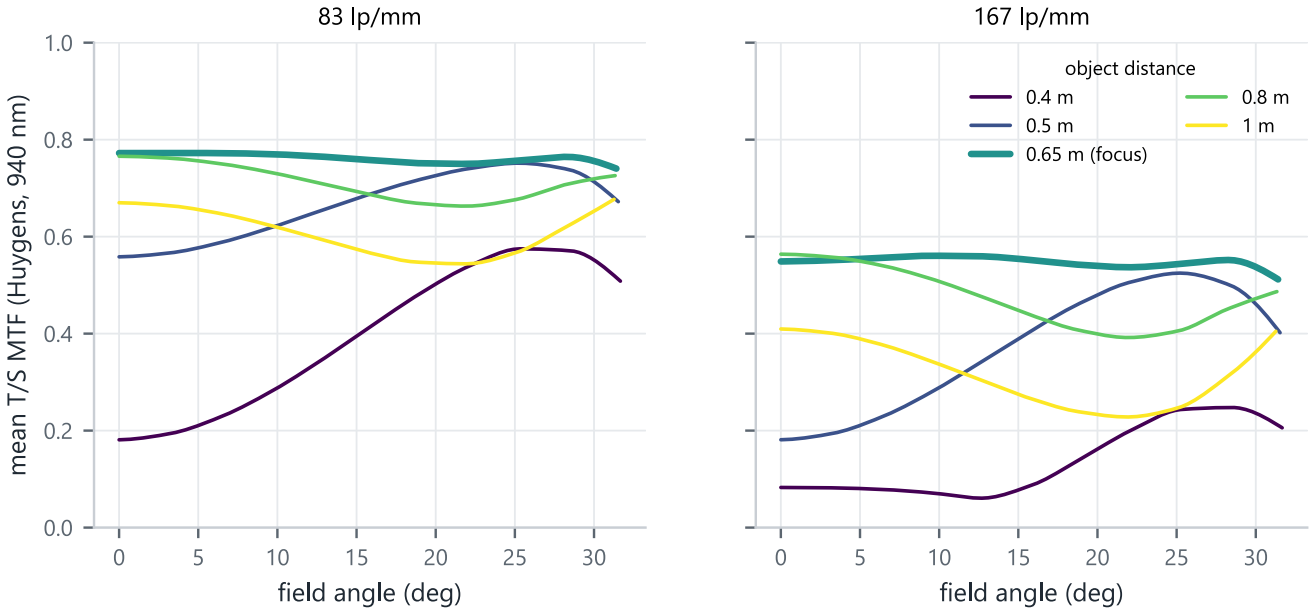


Figure 20. Fixed focus: MTF across the field for objects nearer and farther than the focus distance; the back focus is frozen.

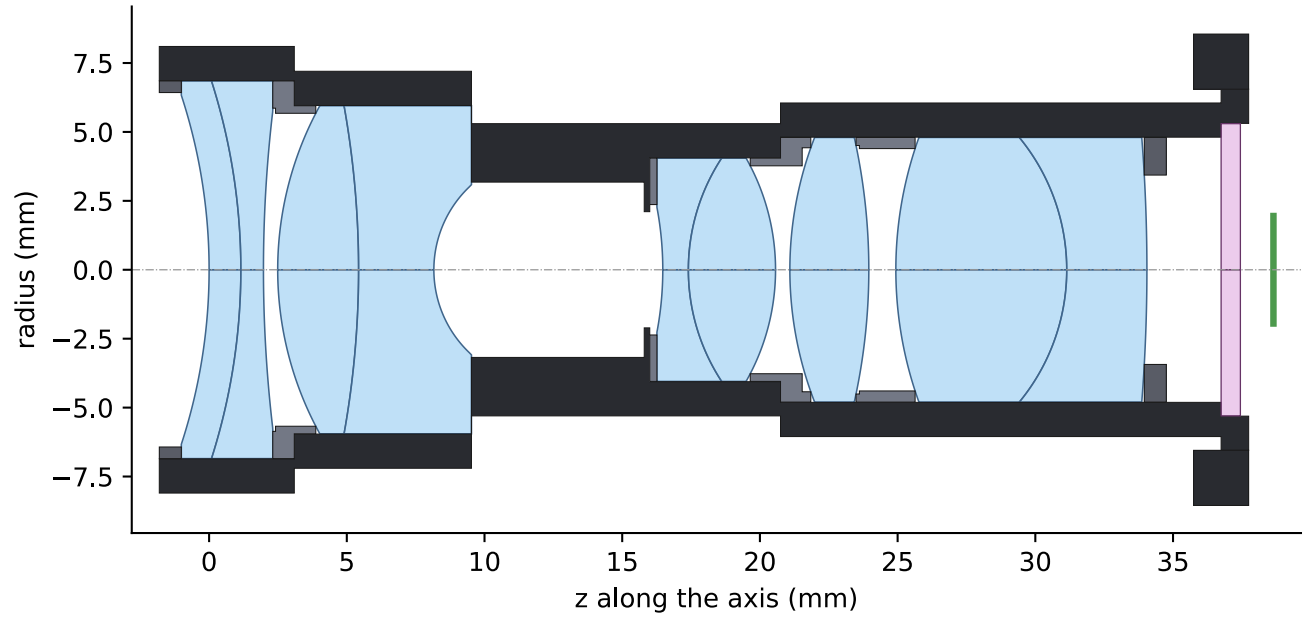


Figure 21. M5 Driver monitor lens in its housing (half section): stepped barrel with its stop shoulder, square-ended spacers and rings, front and rear retainers and the bonded filter.

TOLERANCES 09

Can the far lens be built?

No public automotive lens tolerance budget was found, so the budget is the API's own proposal (auto-assign, 120 perturbations: radii, thicknesses, decenters, tilts, index and Abbe) at two shop tiers, commercial and precision. The merit is the API's RMS wavefront; it is reported here only relative to the nominal lens, as a percentage increase.

Sensitivity perturbs each tolerance alone with the back focus as the compensator, the active alignment a fixed-focus camera module gets on the line, and sums the increases as an RSS and a worst-case stack. **Monte Carlo** builds random lenses with every tolerance at once; the compensated Monte Carlo was not available for this study, so these builds are *not* refocused and are a pessimistic bound.

TIER	TOLERANCES	RSS (REFOCUSED)	WORST CASE (REFOCUSED)	FOCUS TRAVEL, MAX	MONTE CARLO BUILDS	MEAN (NO REFOCUS)	95TH PERCENTILE (NO REFOCUS)
commercial	120	+150 %	+765 %	30 µm	200	+110 %	+316 %
precision	120	+70 %	+333 %	30 µm	200	+23 %	+98 %

Under the commercial budget the largest contributors after refocusing are:

TOLERANCE	BUDGET	SHARE OF RSS
S9 decenter y	±0.02 mm	17 %
S14 thickness	±0.025 mm	15 %
S1 decenter y	±0.02 mm	9 %
S5 decenter y	±0.02 mm	7 %
S11 decenter y	±0.02 mm	7 %
S13 thickness	±0.025 mm	6 %

The refocus travel the line needs stays under 30 µm, well inside a 1 mm active-alignment stroke. The commercial tier's 95th-percentile build without refocusing is 316 % worse than nominal; precision halves the first contributors and brings that under 99 %.

METHOD 10

How the numbers were made

Every optical number is a saved Paraxial API response and every status is computed from it. MTF is the API's Huygens MTF; the fixed-focus sweep freezes the back focus and moves only the object. The full report adds the per-lens field, focus, illumination and spot figures, the optimisation record, the scripts and run times.